TV WHITE SPACES

A PRAGMATIC APPROACH

❧

Edited by

E.Pietrosemoli and M.Zennaro

Contributions by

Robert Horvitz
Ryszard Strużak
Dariusz Więcek
Steve Song
Carlos A. Afonso
Timothy X Brown
Jon M. Peha
Cristian Gomez
Mike Jensen
David Crawford
Linda E. Doyle
Alan Woolhouse
Ermanno Pietrosemoli
Sebastian Büttrich
Marco Zennaro
Andrés Arcia-Moret

December 2013

Disclaimer
The editors and publisher have taken due care in preparation of this book, but make no expressed or implied warranty of any kind and assume no responsibility for errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of the use of the information contained herein. Links to websites imply neither responsibility for, nor approval of, the information contained in those other web sites on the part of ICTP. No intellectual property rights are transferred to ICTP via this book, and the authors/readers will be free to use the given material for educational purposes. The ICTP will not transfer rights to other organizations, nor will it be used for any commercial purposes. ICTP is not to endorse or sponsor any particular commercial product, service or activity mentioned in this book.

CONTENTS

Technology

iii

ACKNOWLEDGEMENTS

PREFACE

Technologists should be grateful for the curiosity and open-mindedness exhibited by the US Federal Communications Commission (FCC) over the last several decades. Law and policy always trail the fruits of technology, mostly for the best, but the FCC has a remarkable track record of leadership that truly leverages technology to enable better use of spectrum. They led the policy of unlicensed bands, which in turn led to the incredible success stories of WiFi and RFID tags. Through TV Whites Spaces they continue to lead today.

And they have been and continue to be open to technologists with better ideas about how to share spectrum more efficiently. I hosted then Chairman Michael Powell in Berkeley in 2003, where he listened to Bob Brodersen talk about cognitive radios (new at the time), and listened to me talk about the wireless needs of developing regions. He was just one in a line of leaders proactively looking for innovative solutions. You can see his speech on innovation from that time online [1].

We are in the middle of a great transformation from a world in which spectrum is protected by strict provisioning, whether used or not, to a world in which it is protected in essence by technology. We have an incredible range of technology options that allow reuse of spectrum without hurting the primary license holder, including not only smart or "cognitive" radios and tolerant coding, but also smart antennas that reduce interference. The emphasis is really on "without hurting" —i.e. we are broadly moving to models in which infringement is more about actually hindering the primary rather than on merely using "their" spectrum. And as technology continues its inevitable rise, our ability to aggressively share spectrum well will only improve.

And we need this innovation, particularly for rural areas, but also for continued innovation along the lines of WiFi and other novel solutions. In the current regimes, no carrier buys spectrum to cover rural areas. Instead, they buy spectrum to cover (profitable) urban areas and they get the rural spectrum included essentially for free. This is a terrible model from the rural perspective: not only is the primary typically uninterested in providing service (due to cost), but anyone that might be interested is prohibited from doing so.

TV Whites Spaces offer essentially a family of new approaches to

---

[1] It was at UCSD in late 2003, online at: http://uctv.tv/search-details.aspx?showID=8436

rural connectivity. This is incredibly important and it is great to see many groups exploring that space. More important perhaps is that there is more than one possible solution on how best to use this spectrum for rural connectivity: the policy sets some basic rules, but does not actually dictate the solution. This is a critical characteristic of the modern approach.

More important still, though, is that we continue to push on this shift from strict provisioning to intelligent sharing. TV White Spaces is just one part of the spectrum, and although it is leading the way for better sharing, it would be a great loss to mankind if the rest of the spectrum did not follow in its footsteps. Beyond open minds, it will take political will to make this happen: we need stronger regulators (in most nations) that can fight two important ongoing battles: 1) the battle with (powerful) incumbent license holders that prefer strict provisioning, and 2) the battle with senior politicians that aim to maximize short-term money raised by auctions, rather than good long-term use of spectrum (they are not always the same).

This collection of articles explores both the policy and the technology around TV White Spaces. They are great articles individually, but they are strictly more powerful as a group. And as a group they continue the great heritage of mutual respect and discussion between technologists and policy makers —a heritage that includes changing the world for the better on a regular basis.

<div align="right">

PROF.ERIC BREWER
University of California at Berkeley
November 2013

</div>

INTRODUCTION

The growing demand for wireless data transmission imposes the search for alternatives to the current spectrum exploration schemes. In the long term, dynamic spectrum access seems to be the only viable solution, once the technical details for its implementation are solved. In the near term, the use of currently vacant spectrum allocated to TV broadcast is poised to alleviate the spectrum crunch while opening the path for dynamic spectrum access.

We strongly believe that presenting some of the aspects involved in the exploitation of White Spaces (WS) by a group of international experts can be useful to practitioners and regulators interested in the topic. The present work is comprised of independent pieces in which each of the authors express their own viewpoint on the matter (and not necessarily that of the organisation to which they belong). Authors from Africa, Europe, North and South America, delve into both advocacy and regulatory issues, as well as in the technical details of some of the standards envisioned for providing services over this portion of the air waves. Several measurements campaigns have shown that the TV broadcasting spectrum is mostly fallow in sparsely populated areas, specially in developing countries, for the simple reason that there is not enough return of the investment for the broadcasters to provide many simultaneous channels. On the other hand, these are precisely the areas in which Internet access is frequently lacking for the same reasons. White Spaces technology can take advantage of the improved propagation capabilities of these frequencies to provide affordable Internet access in rural areas.

Furthermore, spectrum holes are also present in densely populated areas as a consequence of the transition from analogue to digital TV, and these can be harnessed to address the requirements of wireless sensor networks. The lower frequencies as compared with the ones used for WiFi (which in some places is becoming too crowded), are less attenuated by the walls and offer an interesting alternative also for indoor Internet access, as well as for multimedia distribution.

WiFi has had an unexpected success in the traffic off-loading of cellular networks, so WS could also be deployed for this purpose.

Finally, for machine to machine applications and the "Internet of Things" paradigm WS have significant advantages both for developed and developing economies.

The first part of this booklet addresses the advocacy for White Spaces

exploitation and the pertinent regulatory issues from different perspectives, while the second part provides a glimpse about some of technicalities.

On the topic of advocacy for White Spaces:

Horvitz in chapter 2 discusses two different approaches about spectrum management, the use of a Geo-database or the unfettered access by cognitive radio techniques, with interesting historical and political insights.

Strużak and Więcek in chapter 3 draw from their vast experience in radio management to address the regulatory matters, from the international viewpoint, touching on the thorny issues of cross borders spectrum. A map of White Spaces availability in Poland is also presented.

Song in chapter 4 delves into the relevance of TV White Spaces with regards to development, assessing the relevance of unlicensed as compared with licensed spectrum.

Afonso in chapter 5 exposes the perspective from Brazil, a huge country that is becoming an important player in the technology field, providing also comparisons with the North American TV and cellular landscape.

Brown and Peha in chapter 6 present an innovative generalization of spectrum management by means of "Policy-Based Radios", driven by machine-readable documents that implement on the fly changeable rules on how to make an efficient use of the available spectrum.

Gomez in chapter 7 argues that more than a crowded spectrum we are stranded with inefficient ways of spectrum management for meeting the growing demand of wireless services.

Jensen in chapter 8 also draws from his experience in Africa and other developing countries to assess how White Spaces could be harnessed to foster connectivity.

Moving to the more technical aspects:

Crawford from Strathclyde University in chapter 9 presents the results of a White Spaces deployment in Scotland, in which the impact to and from digital TV transmission was carefully examined, quantifying the interference and the effects of the antenna height and location in the performance of both telecommunicatione systems.

Doyle in chapter 10, after discussing the Cognitive Radio, ponders about its usefulness for countries in Africa where there appear to be more cost effective solutions.

Woolhouse in chapter 11 explains that machine to machine communication, poised to play an ever increasing role according to most analysts, is constrained by the inadequacy of current protocols and exposes a brand new one, precisely tailored to the requirements of M2M, which is particularly fitted to the WS Spectrum.

Pietrosemoli in chapter 12 emphasizes the importance of Standards in

wireless technologies and summarizes the more relevant ones pertaining to WS.

Büttrich in chapter 13 makes a case for the use of green technologies, not only as the best suited to power telecommunications and networking equipment, but also as the most appropriate and sustainable source of energy for developing countries.

Zennaro and Arcia in chapter 14 show the results of spectrum occupancy campaigns conducted in several countries by means of low cost equipment that have already being instrumental in convincing regulators about the convenience of using TV WS to help alleviate the digital divide.

This is a work in progress, so we expect to be able to offer very soon a second edition of this work in which the results of some of the several pilots of WS deployments can be incorporated.

PART I

ADVOCACY

GEO-DATABASE MANAGEMENT OF WHITE SPACE VS. OPEN SPECTRUM

2

Robert Horvitz
Open Spectrum Foundation
bob@openspectrum.info

> The whole tendency of radio development has been in the direction of increasingly rigid control by patriotic politicians, who have been almost literally sitting on the doorsteps of the laboratories waiting for the technicians to appear with their inventions. It may have been to radio's advantage in a purely physical sense that it came into existence during the period of intense national rivalry which preceded the war of 1914-1918, but the coincidence meant that radio was identified from the beginning with patriotic service to the state. No other means of communication provoked intervention by the state as quickly as radio did.
>
> O. W. Riegel, Mobilizing for Chaos (Yale University Press, 1934)

Since the beginning of the 20th century, the use of radio has been the most strictly regulated medium of communication. Essentially everything is forbidden which is not explicitly authorized by your country's government. Today, students of comparative law will immediately recognize this as the "authoritarian" model, and it is found even in the most liberal democracies.

Why is that? History shows that the policy of strict governmental control is the result of 3 factors which existed when radio's first practical application emerged.

One factor was the national security importance of radio's first application, wireless telegraphy. Wire telegraphy had been a revolutionary development 50 years earlier and its links had already spread across all lands. But communicating with vessels on the high seas remained impossible until a teenage experimenter named Guglielmo Marconi figured out how to do it and made it into a business [1]. Marconi's achievement - and the frequent publication of plans in books and magazines explaining

1. Nikola Tesla proposed and demonstrated practical uses for radio before Marconi but gave his attention to the development of electrical power instead.

7

2. Books and magazines popularizing radio were as common in the first decade of the 20th century as books and magazines about personal computers in the 1980s.

3. "International Radio Telegraph Convention of Berlin: 1906" (Washington, DC, USA: Government Printing Office, 1912) http://www.itu.int/ITU-R/information/promotion/100-years/documents/1906-Berlin-E.pdf. To dispel any doubt that it was Marconi's business practices and monopoly ambitions which led to the regulation of radio, here is an account by the International Telecommunication Union's historian: *The aim of the German Government in calling the [first international conference on radio] was clear from the beginning. The chief of the German delegation, and president of the Conference, in his opening remarks stated that the development of radio, which was still in its infancy, would be unduly hampered by any attempt to monopolize facilities and that, therefore, rules should be made to block any attempt to impose one system upon others. His attack was made directly at the Marconi Company, and the Marconi Company's restrictive practices were cited as an example of an attempt to force one system on all the world.* Quote from The International Telecommunication Union: An Experiment in International Cooperation by George A. Codding Jr., (New York, NY USA: Arno Press, 1972, reprint of the E. J. Brill edition, 1952), page 84.

4. Radio is accurately described as colors the eye cannot see.

how to build simple transmitters and receivers - inspired youngsters around the world to start experimenting with radio [2]. That aroused fears about interference to diplomatic and naval message traffic, hoaxes and false emergencies being reported, messages not addressed to the public being intercepted, SOS calls being missed, etc.

So the second contributing factor was the immaturity of radio technology in those early days. Compared with what we have today, early radio equipment was dumb and primitive. Therefore, the equipment operators had to be disciplined and skillful in order to prevent chaos from making the airwaves unusable. Government regulation was another way to compensate for the hardware's inadequacy.

The third contributing factor was Marconi's solution to the problems of interference, spectrum chaos and public access to private messages: a global monopoly in radio services. The Marconi Wireless Telegraph Company claimed its patents were so fundamental that no one else had the right to produce or receive radio waves (amateur experimenters were tolerated, however, so long as they weren't paid for services). But governments did not want to depend on a foreign commercial monopoly to communicate with their own navies, so they pushed back with a treaty establishing national sovereignty over the radio spectrum, declaring that only governments had the right to regulate and authorize spectrum use.[3] Amateurs were allowed to continue experimenting but only under government license.

2.1 PHYSICS OR POLITICS?

It is important to note that claims of national sovereignty and government exclusivity in the regulation of spectrum access are not based on the physical qualities of radio waves. Radio is the same "stuff" as light [4] and no nation claims sovereignty over the colors we see, or says it owns the sunlight within its borders, or requires its citizens to get licenses for the use of candles or lightbulbs. It is often noted that radio waves do not respect national borders. That is more than a minor inconvenience, it is proof that government efforts to monopolize and dole out access to the radio spectrum derive not from physics but from a political agenda.

The key point in this discussion is that a strict authoritarian approach to regulation of radio is not inevitable, it is the result of particular historical circumstances, including the state of technology, which can change. Indeed, circumstances have changed. No company today can assert a patent monopoly over radio. Most radio uses now are short-range and personal, for business or entertainment, with no impact on national security. Pre-registration of channel assignments and official interventions to resolve interference complaints are rare now that "smart" radios have built-in channel selection and interference avoidance mechanisms. Yet the old habits and laws persist.

"Radio Nurse" Watches Child

A "RADIO NURSE" now brings the nursery into the living room, kitchen, or any other room desired. When a child is sleeping or playing in a room when no older persons are present, every sound within that room can be transmitted to any spot in the house. The outfit consists of a pickup unit, placed near the child to be "watched," and a loudspeaker, which can be placed in any convenient location.

formerly Modern Mechanix   73

Figure 2.1: Mechanix Illustrated magazine (July 1938).

2.2 UNLICENSED IS BORN

In 1938 the US Government acknowledged that it was impossible to license every radio source (every wire carrying electricity emits radio waves), nor was it even necessary when there was little risk of harmful interference. A previously unexploited loophole in the international radio treaty [5] let the FCC create a new rule freeing a few specific types of short-range communication from licensing: baby monitors, wireless loudspeakers for gramophone disk players, "carrier current" broadcasting stations, etc. For decades, the US was the only country that had such a rule [6].

As time went by, additional manufacturers sought exemption from licensing for their radio products and the FCC considered each request individually. By the 1980s, the backlog of pending applications was large and the inconsistencies among earlier decisions begged for explanation. So, in 1989, the FCC "future-proofed" its rules for license exemption by scrapping most that were application-specific, replacing them with broad categories and application-neutral rules concerning power output, bandwidth, duty cycle, out-of-band emissions, etc. That meant that they no longer had to evaluate the merits and public interest in each new product to decide if it was needed. From now on, so long as the equipment satisfied certain technical constraints, the market would

5. A simplified summary of the loophole: nations can depart from the international radio treaty so long as interference is not caused to licensed stations in other countries.
6. For insight into the evolution of license-free radio in the US, see Kenneth R. Carter, "Unlicensed to Kill: A Brief History of the FCC's Part 15 Rules," info, Volume 11, Number 5 (2009), pages 8-18 http://ssrn.com/abstract=1120465

decide if it was needed.

This new approach led to a burst of innovation unlike anything seen since the earliest days of radio. RFID, WiFi, Bluetooth and Nintendo's Wii console are some of the best known successes, with hundreds of millions of new devices sold each year. But cordless phones, "smart" wireless electricity meters, tire pressure monitoring systems, tele-medicine applications and so on, also have growing impact. In the future we are likely to see Google Glass, "smart environments" laced with wireless sensors, cars which communicate with the roadway and with each other to ensure traffic safety, and billions of objects and machines linked to the Internet. As the head of Ericsson put it, "everything that needs to be connected will be connected." [7] Of course, that assumes nearly all wireless links will be unlicensed, since there is no way for regulators to process billions of license applications.

2.3 UNLICENSED SPREADS

Two decades ago, in most countries, unlicensed radio was simply illegal. In a few others, it was a daring exception to the norm of licensed services. Now, thanks largely to WiFi and RFID's global acceptance, most countries have license-free bands. And in a few places (Europe and the US), license exemption is increasingly recognized as the new norm, with licensed radio services a shrinking part of the wireless ecosystem.[8]

Success in the marketplace usually impresses regulators more than intellectual arguments, and the overwhelming popularity and obvious benefits of WiFi, and the many applications it enables, make a compelling argument for further relaxation of radio licensing rules. At the same time, the small number of interference complaints generated by WiFi neutralizes the main argument against relaxation.

But even before WiFi existed, two people raised the level of discourse, from the practical question of whether licensing was necessary for a given application, to the general question of what is the best paradigm for future management of the radio spectrum.

2.4 DECENTRALIZING TELECOMMUNICATIONS

Paul Baran is best known as the engineer who developed "packet switching" in the 1960s. This is a flexible and highly efficient way to optimize the movement of data between nodes in a network. A remarkable feature of packet switching is that it enables networks to resist and overcome disruption without any traffic control center. The Internet is the best known implementation of packet switching. Its efficiency, flexibility, resilience and lack of centralized control have transformed communi-

7. Nithyasree Trivikram, "Ericsson CEO reveals broadband vision," ITP.net (14 February 2011) http://www.itp.net/mobile/583916-ericsson-ceo-reveals-broadband-vision

8. The European Union's Authorisation Directive (2002) established "general authorisation" (exemption from licensing) as the preferred approach to regulating radio use: "Member States shall, where possible, in particular where the risk of harmful interference is negligible, not make the use of radio frequencies subject to the grant of individual rights of use [licensing] but shall include the conditions for usage of such radio frequencies in the general authorisation...." Quoted from Article 5, paragraph 1 of "Directive 2002/20/EC of the European Parliament and of the Council of 7 March 2002 on the authorisation of electronic communications networks and services" http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:108:0021:0021:EN:PDF

Global sale of devices by type of spectrum used in 2008 and 2014
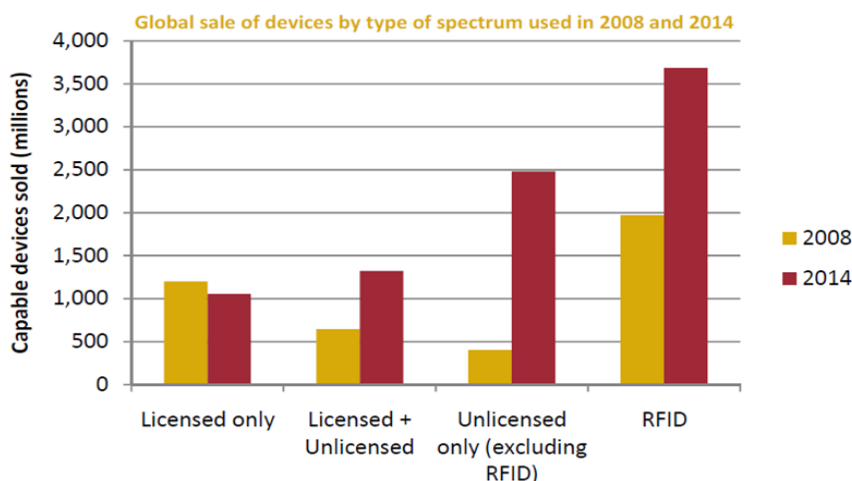
Figure 2.2: This chart shows global sales of unlicensed devices overtaking sales of licensed equipment between 2008 and 2014. (The second pair of bars, devices containing both licensed and unlicensed radios, represents cellular handsets.) Chart from Richard Thanki, "The economic value generated by current and future allocations of unlicensed spectrum," Perspective Associates (2009) http://apps. fcc.gov/ecfs/document/view?id=7020039036 On a per MHz basis, the economic contribution of some unlicensed devices (RFID and WiFi) already exceeds the economic contribution of the most highly valued licensed applications (cellular mobile and television).

cations - as well as the way knowledge is shared, business is conducted, entertainment is delivered, countries are governed, etc.

Baran's research suggested that the same principles which make packet switching resilient and efficient should work whether the net links are wired or wireless. That led him to consider the possibility of regulating radio under Internet-like rules. Might Internet-like benefits come from eliminating radio control centers?

Baran first offered these ideas publicly at a conference on Next Generation Networks in November 1994, then again, in a more polished form, at the Marconi Centennial Symposium in Bologna, Italy, in June 1995, where he was the keynote speaker. His second presentation is quoted here:

> "It is my belief that public policy might be better served if we moved to an environment of near zero regulation. In such an environment anyone and everyone would be allowed to use the spectrum, without the barriers to entry that keep out the true innovators. Of course, there will be some minimal rules necessary, such as maximum allowable transmitted power and power densities. The micro-managed regulatory approach of today, such as who can use any single frequency is neither necessary nor desirable...
>
> "Would this laissez faire form of regulation lead to chaos? Possibly, but most likely not. Consider the many millions of cordless telephones, burglar alarms, wireless house controllers

and other appliances now operating within a minuscule portion of the spectrum and with limited interference to one another. These early units are very low power 'dumb devices' compared to equipment being developed, able to change their frequencies and minimize radiated power to better avoid interference to themselves and to others. Of course that means that there will have to be enough frequency spectrum set aside to do so. But, once having done so, we would have created a communications environment able to handle orders of magnitude more communications than today...

"The Internet provides an instructive model for the future of telecommunications regulations... In the Internet, there is no central node, and only a minimal centralized management structure, limited to a few housekeeping functions... This lack of a limiting centralized structure has permitted the Internet to be responsive to a very large unregulated constituency and allowing explosive growth and with increasing usefulness to its users...

"Will [this approach] work for regulating the radio spectrum? ...Which frequency to use and when, or which form of modulation to use would be left to each user... Inexpensive microcontrollers would be used that first listen and then automatically choose preferred frequencies to avoid other signals in the band. It is really a matter of being a good neighbor. The smart transmitter reduces its power level to that needed to produce an error free signal and no more. A pristine pure slice of spectrum to have error-free performance is not required when using digital modulation. Digital logic on a chip implements error correcting codes that convert a small amount of redundancy in transmission robustness enabling even highly corrupted signals to be cleaned up to emerge error free..."[9]

9. Paul Baran, "Is the UHF Frequency Shortage a Self Made Problem?" Marconi Centennial Symposium, Bologna, Italy (23 June 1995) http://wireless.oldcolo.com/course/baran2.txt

A few months later, Eli Noam, an American academic and radio amateur who worked for a while in a regulatory agency, built on Baran's ideas, giving them a free-market twist and introducing the phrase "open spectrum". Noam is also worth quoting at length:

"[Radio license auctions] are good for now, but there is a better next step, a free-market alternative to the present auction system: an open entry spectrum system. In those bands to which it applies, nobody controls any particular frequency. In this system no oligopoly can survive because anyone can enter at any time... There is no license, and no up-front spectrum auction. Instead, all users of those spectrum bands pay an access fee that is continuously and automatically determined by the demand and supply conditions at the time,

12

i.e. by the existing congestion in various frequency bands. The system is run by clearinghouses of users....

"To allocate access one need not grant permanent allocation rights, but rather to charge an access fee that is set dynamically at a level where the available capacity is fully utilized. The access fee would be an 'edge price', and give any users of the spectrum the right to enter information into the spectrum 'cloud'. Because demand for transmission capacity varies, the access fee would also vary - a high fee where demand is high, and zero when there is excess capacity...

"In 1995, the computer company Apple applied to the US government to allocate a spectrum band for all types of new digital applications, open to all comers. Why not expand this concept and dedicate a few bands to the open-access, access-price model... Better to approach spectrum use in a pragmatic and searching fashion than with an ideological mind set that equates the free market with one and only particular technique. Auctions are fine for today, but we should be ready to take the next step...

"The proposed open spectrum access system will not be adopted anytime soon. But its time will come, and fully bring the invisible hand to the invisible resource."[10]

10. Eli M. Noam, "Taking the Next Step Beyond Spectrum Auctions: Open Spectrum Access," IEEE Communications Magazine, Volume 33 (December 1995) http://www.columbia.edu/dlc/wp/citi/citinoam21.html

Note that neither Baran nor Noam argue for zero regulation. Both support minimal regulation, without agreeing on what that means. Baran's model is based on the Internet, where contention is resolved statistically, without pricing, while Noam's is based on a frictionless free market, with dynamic pricing. But both would agree there's room for more than one minimalist approach.

2.5   OPEN SPECTRUM APPROACH

In May 2001, the New York University's Information Law Institute and Harvard University's Berkman Center for Internet and Society, organized a meeting to launch the Open Spectrum Project, whose aim was "to understand what is the best regulatory environment for license-free operation and to place that understanding on the public agenda. The project brings together engineers, economists, technologists, and communications law specialists to design the best of all possible regulatory worlds, and to identify viable alternatives to that best case."[11] This meeting marked the beginning of Open Spectrum as a movement and those who attended became leading spokesmen for this new paradigm. Some of the core texts produced by the attendees include:

11. "Developing a New Spectrum Policy" http://www.law.nyu.edu/

Yochai Benkler, "Some Economics of Wireless Communications," Harvard Journal of Law & Technology, Volume

16, Number 1 (fall 2002), pages 25-83 http://jolt.law.harvard. edu/articles/pdf/v16/16HarvJLTech025.pdf

Dale Hatfield, "Spectrum Management Reform and the Notion of the 'Spectrum Commons'," Southern African Journal of Information and Communication, issue number 4 (spring 2005) http://link.wits.ac.za/journal/j0401-hatfield-spectrum.pdf

Kevin Werbach, "Open Spectrum: The New Wireless Paradigm," New America Foundation, Spectrum Series Working Paper #6 (October 2002) http://werbach.com/docs/new_wireless_paradigm.htm

Kevin Werbach, "Radio Revolution: The Coming Age of Unlicensed Wireless," New America Foundation (December 2003) - http://werbach.com/docs/RadioRevolution.pdf

Jon M. Peha, "Emerging Technology and Spectrum Policy Reform," ITU Workshop on Market Mechanisms for Spectrum Management (Geneva, January 2007) - http://www.itu.int/osg/spu/stn/spectrum/workshop_proceedings/Background_Papers_Final/Jon%20Peha%20ITU%20spectrum%20workshop.pdf

Michael Calabrese, "The End of Spectrum 'Scarcity': Building on the TV Bands Database to Access Unused Public Airwaves," New America Foundation, Working Paper 25 (June 2009) - http://www.newamerica.net/files/nafmigration/Calabrese_WorkingPaper25_EndSpectrumScarcity.pdf

Two points should be emphasized for the discussion which follows: the first is that it is no accident that the conception and promotion of Open Spectrum began in the US. The US had made an earlier and bigger commitment to the development of license exempt radio than any other country, probably as a result of the US Constitution's First Amendment, which basically forbids the passage of laws restricting freedom of speech and press. The real question, for readers of this booklet, is: can Open Spectrum gather support and have a policy impact in countries without a free speech tradition? Our assumption is that it can, although it might take longer and require broad coalition building and sustained promotion.

The second point is that the success of Open Spectrum hinges on the development of radios smart enough to manage their own frequency use while minimizing interference. Otherwise, lawmakers will not change the existing institutional framework. Radios fully capable of frequency
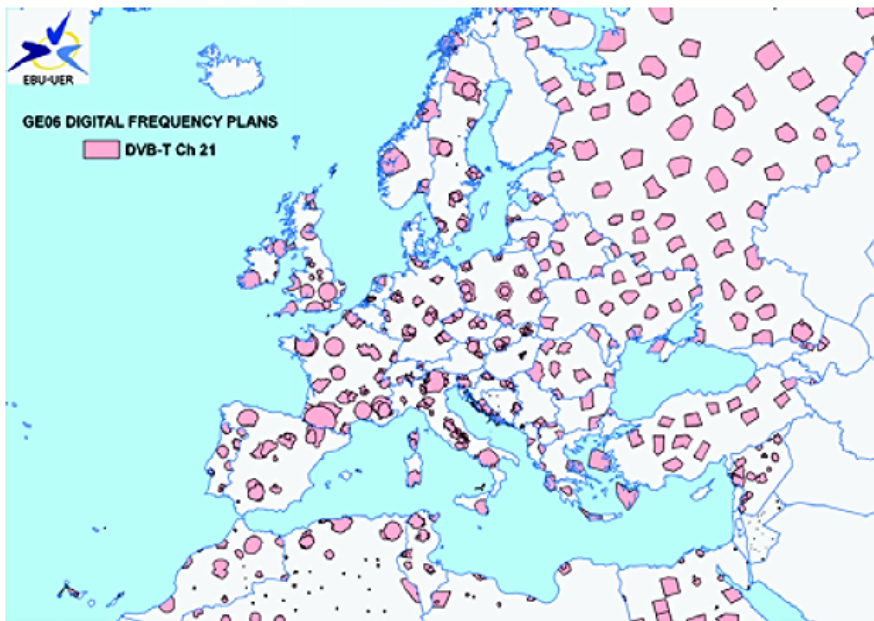
Figure 2.3: Map of DVB-T plan entries in UHF channel 21 in Europe and neighbouring countries.

self-management are already being produced (for the military, at high cost). But more testing is needed to convince skeptics, and more investment in large volume production is needed to bring the cost down. We aren't there yet, which is why TV white spaces are important - or rather, why they could be important (see the discussion below). In any case, they provide a business opportunity for turning automated, dynamic, license exempt frequency management into mass market products.

In 2002, the FCC surprised everyone by asking whether new applications might be allowed to use TV white spaces on a license exempt basis.[12] "White spaces" are areas where the assignment of specific TV channels is forbidden in order to protect stations using those channels elsewhere. To cite a recent European example, Figure 2.3 shows a map[13] showing the "white spaces" which protect digital TV stations using channel 21 in the pink areas. Note that the white spaces are actually larger than the areas of broadcast coverage.

One reason why TV white spaces are so large is that the band planners assumed only TV stations would use these channels and TV stations transmit at high power so they need to be widely separated. However, it is possible for low-power devices to operate completely within a white space so their signals do not impinge on the broadcast coverage areas. This was the insight that led the FCC to suggest opening white spaces to low-power uses.

The FCC has been careful to assert application neutrality for the TV white spaces, even while suggesting that rural broadband ought to be the prime beneficiary. In fact, more white space is available in rural areas than in cities, and the superior range, foliage penetration and

12. "ET Docket No. 02-380: Notice of Inquiry in the Matter of Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band," US Federal Communications Commission, released 20 December 2002 http://apps.fcc.gov/ecfs/comment/view?id=5508555784

13. Map reprinted from Terry O'Leary, Elena Puigrefagut and Walid Sami, "GE-06: overview of the second session (RRC-06) and the main features for broadcasters," EBU Technical Review 308 (October 2006) http://tech.ebu.ch/docs/techreview/trev_308-rrc-06.pdf

14. "Studies have consistently shown that 700 MHz can provide broadband service in rural areas at half to one third the cost of the 1900 MHz personal communications services frequencies used by the cellular carriers... 700MHz can provide broadband services in rural areas at one fourth to one sixth the cost of the 2400 MHz WiFi [frequencies]... What this means is that rural areas that were previously 'unreachable' can now get broadband service on an affordable basis." Testimony of Charles C. Townsend before the US Senate Committee on Commerce, Science and Transportation (12 July 2005) http://www.commerce.senate.gov/pdf/townsend.pdf

15. Steven K. Jones, et al., Evaluation of the Performance of Prototype TV-Band White Space Devices, Phase II, Report FCC/OET 08-TR-1005, FCC Office of Engineering and Technology (October 2008) http://apps.fcc.gov/ecfs/document/view?id=6520183093

16. The FCC recently published a pamphlet for small businesses on how to comply with US white space rules, particularly when designing and deploying equipment http://transition.fcc.gov/Daily_Releases/Daily_Business/2013/db0422/DA-13-808A1.pdf

17. Maziar Nekovee, "Impact of Cognitive Radio on Future Management of Spectrum," CROWNCOM (2008) http://arxiv.org/pdf/0903.0276.pdf

18. See, for example, "ECC Report 186: Technical and operational requirements for the operation of white space devices under geo-location approach," CEPT (January 2013) http://www.erodocdb.dk/docs/doc98/official/pdf/ECCRep186.pdf or V. Chen, ed., "Protocol to Access Spectrum Database," draft-ietf-paws-protocol-04, Internet Engineering Task Force (7 May 2013) - http://tools.ietf.org/html/draft-ietf-paws-protocol-04

non-line-of-sight propagation of UHF signals can make Internet access economically viable in places where WiFi and cellular infrastructures are too costly - in areas of low population density.[14]

2.6 SPECTRUM OCCUPANCY ASSESSMENT

But for white space devices (WSDs) to know what frequencies and power levels are safe to use at a given location, they either need to monitor the radio spectrum to see what channels are free, or they need to know their location so they can ask a geographic database to tell them what is allowed.

When the FCC launched their white space inquiry, they were unsure which frequency management system to support: spectrum monitoring, geo-database lookup or both. But after testing some WSD prototypes,[15] they decided that monitoring was not yet sufficiently reliable, so portable devices that rely only on monitoring were given a lower power limit than devices using geo-database lookup.[16] Since the two frequency management techniques were proposed and discussed as alternatives, few people noticed that they have very different political implications. This is unfortunate and WSDs advocates should think carefully about the consequences of arguing for a politically risky system which could delay the development of genuinely smart radios while believing they are advancing the cause of Open Spectrum.

Earlier in this chapter we noted that smart radios which can independently and successfully manage their own frequency use eliminate the need for strict government control of spectrum access.[17] That makes them a force for liberalization and vital for the implementation of Open Spectrum. But a radio which simply follows instructions given by a database - which cannot make independent judgments and does not recognize or learn from patterns in the signal environment - cannot be considered smart or independent. In fact, it is a slave, and standards and regulatory documents describe it that way.[18]

Far from being a liberalizing force, database slaves represent a drastic extension of regulatory control into the radio domain which has been the freest (license exemption). Licensing is superfluous because database control is an even stricter form of regulation.

16

2.7 CONCLUSIONS

Geo-database control of WSDs has been tested in China, France, Germany, Indonesia, Japan, Kenya, Malaysia/Singapore, Slovakia, South Africa and the United Kingdom. India may join this group soon.

Belgium, Denmark, Finland, Latvia, Philippines, Poland and the UK say they will authorize geo-databases for WSDs; the US[19] and Canada[20] have already done so.

Geo-databases are increasingly seen as the solution to coexistence problems throughout the spectrum: location-aware power limits at 2.4 GHz will enable WiFi to operate at higher powers where interference is not a risk; in the 3.6 GHz band, they will help satellite systems co-exist with terrestrial microwave links, military radars and 4G cellular networks; at 5 GHz, they are expected to protect radars from the spread of unlicensed radio LANs; the US considers them essential for sharing government frequency bands with private industry.

One feature that makes them so desirable to regulators is that they solve the problem of how to clear a license exempt band for re-allocation to licensed use. The problem has been stopping the use of unlicensed devices whose authorization has lapsed, when the regulator has no idea who owns the devices or where they are located. This is solved by the geo-database's requirement that all connected devices seek frequent re-authorization (every 15 minutes in some countries): The regulator can simply tell the database to stop re-authorizing the devices. And the problem of unknown owners and locations is also solved, at least in the US: "FCC rules... require that a 'Fixed WS Device' MUST register its owner and operator contact information, its device identifier and location..."[21] Repressive regimes can cite that precedent in imposing similar requirements.

The US Commerce Department's Spectrum Management Advisory Committee is so enthused about database-connected devices that they want to make them the new norm for license exempt radio:

> "[The National Telecommunications and Information Administration], in coordination with the FCC, should further study the regulatory treatment under the current unlicensed framework for 'cheap, dumb' devices. The Committee generally recommends that in the future 'unconnected' devices should be restricted to legacy bands of spectrum where they are already prevalent (e.g., 900 MHz, 2.4 GHz). Policymakers should consider whether such devices should even be further restricted in the future, phasing out their access to very high-quality bands over an appropriate time period..."[22]

Note that this recommendation is still only a proposal. But the possibility of connected slave devices leading even US regulators, with

19. The FCC selected 11 firms to administer the databases. Two merged, so now there are 10. "FCC Chairman Genachowski Announces Approval of First Television White Spaces Database and Device," FCC press release (22 December 2011) http://www.fcc.gov/document/chairman-announces-approval-white-spaces-database-spectrum-bridge

20. Canada initially licensed the use of TV white spaces for broadband access in remote rural areas. This has recently been supplemented with a license exempt, application neutral approach as in the US. See "Framework for the Use of Certain Non-broadcasting Applications in the Television Broadcasting Bands Below 698 MHz," Industry Canada (5 April 2013) http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10494.html

21. IETF, "Protocol to Access Spectrum Database" - see note 20, supra.

22. CSMAC Unlicensed Subcommittee, "Presentation of Final Report of Recommendations," US Department of Commerce Spectrum Management Advisory Committee (24 July 2012) http://www.ntia.doc.gov/files/ntia/publications/unlicensed_subcommittee_finalreport072420122.pdf

their liberal orientation, to phase out access to license exempt spectrum for non-slave devices should make us think very, very, very carefully about the consequences of promoting geo-database look-up systems for WSDs.

The decade-long struggle to introduce WSDs in the US, and now in a growing list of other countries, has been fueled by the hope that WSDs will make possible cheaper broadband access in rural areas and a new wave of innovation as has happened at 900 and 2400 MHz. A low-cost, low-density technology is surely needed, especially in Africa. However, the temporary but total cutoffs of Internet access in Egypt, Libya and Syria make one wonder if it is wise to give government-sanctioned control centers a "kill switch" for broadband access.[23] In the US, geo-database administration has been privatized.[24] But in other countries it might be a government function.

We certainly support the development of rural broadband. But from an Open Spectrum perspective, reliance on geo-database control to accomplish that involves a degree of political risk that may be unacceptable in certain countries. Regulators regard spectrum sensing as too unreliable now, but that is the approach which leads to autonomous device operation and less risk of government disruption of private communication channels. It will be a harder road, with success less certain, but at least that path leads to where we want to be.

23. "Internet censorship in the Arab Spring," Wikipedia http://en.wikipedia.org/wiki/Internet_censorship_in_the_Arab_Spring. All these shutoffs were attempts by governments to stifle or silence public protests. The term "kill switch" is used by CSMAC in one of their recommendations.

24. "White Space Database Administrators Guide," FCC Encyclopedia http://www.fcc.gov/encyclopedia/white-space-database-administrators-guide

REGULATORY ISSUES FOR TV WHITE SPACES

Ryszard Strużak and Dariusz Więcek
National Institute of Telecommunications
Poland
struzak@gmail.com
dariusz.wiecek@gmail.com

3

This chapter discusses current issues of spectrum regulations related to TV White Spaces, with focus on dynamic spectrum management and cognitive radio. It is based on recent studies conducted in the framework of the International Telecommunication Union (ITU). National aspects are also discussed, with a few examples from the United States and European Union.

3.1   INTRODUCTION

The ability to carry energy and messages at a distance with the speed of light, and at no cost, made the spectrum of radio waves a valuable resource from which everybody could profit. However, due to the laws of nature, various applications of radio waves can interfere with each other and - if incorrectly used - can nullify the benefits they could offer. To avoid such interference, each application requires some free amount of radio frequency spectrum, and to assure it, an appropriate spectrum management is necessary. To be effective, any spectrum management system should include sound spectrum regulation, planning, engineering, monitoring and enforcement. Three objectives shape any spectrum management system: conveying policy goals, apportioning scarcity, and avoiding conflicts, with due regard to social, political, economic, ecological, etc., aspects. The society is composed of various groups, each with its particular interests and goals. As a consequence, probably there is no spectrum management possible that could fully satisfy all those interested. Conflicts might arise between those who have access to the spectrum resource and those who have not, between competing uses of the spectrum, etc.[1]

The capacity a communication system provides is ultimately limited by the spectrum available to that system. The number of radio systems

1. R. Struzak: Introduction to International Radio Regulations; in S. Radicella (ed.): ICTP Lecture Notes No. 16, Trieste 2003, ISBN 92-95003-23-3; http://publications.ictp.it/lns/vol16.html

in operation worldwide is already enormous and continues to increase. Most of suitable frequencies have already been occupied and in some frequency bands and geographical regions there is no place for new radio systems. Cloud-based applications, which exchange data back and forth with distant datacenters instead of storing them locally, increase the spectrum occupation further. To solve spectrum problems, numerous organizations have employed thousands of experts. The International Telecommunication Union (ITU), a specialized Agency of United Nations, is one of them.

3.2 SPECTRUM REGULATIONS

ITU assembles 193 countries (grouped in three ITU Regions) to assure, among others, rational use of the spectrum/orbit resources through the consensus-based decision process, *"taking into account the special needs of developing countries"*. The ITU mission involves:

- Ensuring meeting the specific needs of countries through mechanism of the World and Regional Radio Conferences, International Conventions/Agreements, etc.

- Coordinating the efforts to eliminate and prevent harmful interference between radio stations of different countries,

- Studying and recommending technical and operational standards by Radiocommunication Study Groups and Assemblies.

Other tasks include global standardization and development. The mission is accomplished in the spirit of collaboration and mutual trust.

3.2.1 *International Regulations*

How the spectrum/orbit resources are used has profound impact on the society, on its prosperity, security, culture, and education. Keeping the ITU mission in mind, the ITU members have agreed upon common Radio Regulations[2] that aim at assuring inter-communication among various systems, assuring rational use of spectrum, and preventing mutual interference. Radio Regulations have the status of an International Treaty, and each government warrants they are respected under its jurisdiction. Traditionally, the use/management of the spectrum/orbit resources on the international forum bases on a few general principles:

- The spectrum/orbit resources are public. The uses of these resources are based on the common administrative regulations and allocations of frequency bands (and orbital parameters for satellite communications). These regulations and allocations are set through the mechanism of international consultations, negotiations, and consensus.

- Every country has an equitable and free access to spectrum/orbit resources: no fee mechanism has been envisaged on the international scene for the use of spectrum/orbit resources.

- National sovereignty is a "sacred" principle in the ITU. Each country decides about its uses freely, as long as it respects the international regulations and agreements in force. On that basis, many countries have introduced a national system of fees. Some countries have created an internal spectrum market, although not everywhere with success. We will come back to that in section 2.5 below.

The uses made of the spectrum/orbit resources have been based on the Table of Frequency Allocations of Radio Regulations. *Allocation* means the distribution of a frequency band to a wireless service, *allotment* - to a country or area, and *assignment* - to an individual radio station. Some allocations are worldwide, others are regional, i.e., uniform throughout a particular region. A country can make an assignment to an individual station or to a group of stations when needed. This is the so-called *ad hoc* frequency distribution method. An alternative is *a priori* frequency distribution. They differ in the time horizon taken into account. For services subject to a priori planning, an assignment in accordance with the plan receives protection from any other assignment. In the case of ad hoc managed services, the protection is given in accordance with the priority of registration dates - a system frequently described as first-come, first-served.

3.2.2   Frequency Planning

International frequency plans, which are subject to a priori frequency planning, are coordinated among all those interested at competent radio conferences. A frequency plan assigns appropriate technical characteristics to radio stations in specific frequency bands, for specific applications and geographic regions. The name "frequency planning" remained from the early days of radio, when only operating frequency of radio stations was coordinated. International plans are general and contain minimal number of details. In contrast, national assignments include all the details necessary to operate the station properly. In such plans, specific frequency bands and associated service areas are reserved for particular application well in advance of their real use. Such a distribution of the spectrum resource is made on the basis of the declared needs of the parties interested. That principle was also used at the ITU Regional Radiocommunication Conference RRC Geneva 2006 in planning the digital terrestrial broadcasting service[3]. Advocates of the a priori approach indicate that an ad hoc method is not fair because it transfers the entire burden to the latecomers, which are forced to accommodate their requirements to those of the existing users. Opponents, on the other

3. Final Acts of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting service in parts of Regions 1 and 3, in the frequency bands 174-230 MHz and 470-862 MHz (RRC-06), International Telecommunication Union, Geneva, 2006

hand, point out that a priori planning freezes the technological progress and leads to "warehousing" the resources. Critics of a priori planning indicate that it is impossible to predict future requirements with a degree of accuracy, and that any plan based on unrealistic requirements has no practical value, blocks frequencies, and freezes the development. Indeed, the technological progress is very fast, and the plan may become outdated before is implemented. What is important is that there is no mechanism to limit the requirements, as the spectrum/orbit resource is available at no cost at international planning conferences. Although the ITU Convention calls for minimizing the use of these resources, each country has an incentive to overstate its requirements, and there are few accepted or objective criteria for evaluating each country's stated needs. Under these circumstances, it is easy to make a case that common plans are not only difficult to construct, but lead to a waste of resources as frequencies and orbit positions are "warehoused" to meet indeterminate needs. Radio Regulations differentiate between *primary* and *secondary* services. Those qualified as "primary" (or "co-primary") enjoy the full protection rights in relations to other stations. Stations of a secondary service shall not cause harmful interference to, and cannot claim protection from *stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date*. However, they can claim protection, from harmful interference from stations of the same or other secondary services [4].

3.2.3   Radio Conferences

Radio Regulations are regularly reviewed by the competent World Radio Conferences (WRCs) or Regional Radio Conferences (RRCs), in order to keep pace with technological, political, and economic changes; only these organs are authorized to make changes in the regulations. Every ITU member state is obliged to incorporate these modifications into its national regulatory legislation as soon as possible. For television, the regional conference RRC Geneva 2006 decided that all analog TV transmissions have to be replaced by digital ones [5] and this has already happened in most European countries. In 2012, the World Radio Conference[6] has opened the way for the practical use of *cognitive radio systems (CRS)*, which earlier was considered as a possibility in distant future[7], and such systems are being introduced.

The RRC GE Geneva 2006 conference was called to coordinate the transition from analog to digital television and to produce a plan satisfying more than 70 thousand broadcasting requirements throughout the planning area of the ITU Region 1 and part of Region 3. This planning area embraces all European and African countries plus some Asian ones. Most of the original requirements were mutually conflicting. To solve these conflicts, almost 1000 experts from over 100 countries came to Geneva to work together during 34 days (and late evenings). They negotiated the national proposals that had been submitted and discussed

4. Radio Regulations, International Telecommunication Union, Geneva 2012, RR5.28 to 5.30

5. Final Acts of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting service in parts of Regions 1 and 3, in the frequency bands 174-230 MHz and 470-862 MHz (RRC-06), International Telecommunication Union, Geneva, 2006

6. Final Acts of the World Radiocommunication Conference WRC-12, International Telecommunication Union, Geneva, 2012

7. Mitola J: Cognitive Radio: an integrated agent architecture for software defined radio, Dissertation, Doctor of Technology, Royal Institute of Technology (KTH), Sweden, 2000

during the six years of the pre-conference period. The proposals were an-alyzed from the viewpoint of satisfying the national needs while avoiding unacceptable interference to neighboring countries. It was an iterative approach, which required complex computer simulations after every modification. The volume of necessary computations exceeded the ca-pacity of the ITU computer network, and computing resources of other entities in the region, such as the CERN's supercomputers, had to be em-ployed. Finally, a common reference plan (about 2000 pages in length) was accepted that will serve as a basis for designing the national digital TV plans in the frequency bands 174-230 MHz and 470-862 MHz in the planning area. The transition from analog to digital television releases a large amount of spectrum for other uses, the so-called *digital dividend*. Advances in signal processing and single-frequency networks (SFNs) made possible the delivery of digital TV programs using only a part of the spectrum required by analog TV.

3.3 DYNAMIC SPECTRUM ACCESS AND COGNITIVE RADIO

Until recently, the spectrum has been accessed to transmit (and/or to receive) signals in the fixed radio frequency slots dedicated to specific services in specific regions, on what is known as fixed spectrum access (FSA). The Frequency Allocation Tables in Radio Regulations set pre-cisely such a mode of operation. In this mode, the assigned frequency band cannot be changed during the license validity (an exception is Fre-quency Hopping (FH) systems, where the carrier frequency varies, but only within the assigned band). Special methods have been developed to use optimally the spectrum resources in that mode[8]. The Dynamic Spectrum Access (DSA) concept frees radio systems from that restric-tion. It may be seen as a generalization of FH systems, in which not only the carrier frequency can vary, but also the assigned frequency band. In static conditions, where the spectrum users operate at fixed frequency bands assigned to them, Administrations can set up static coexistence (compatibility) conditions for the new systems. Such solutions have been in use for a long time e.g., in the case of earth satellite stations sharing frequencies with terrestrial radio-relay links. However, the static sharing conditions may be not applicable, and the a priori sharing conditions may be insufficient, if the signals change their power, direction of ar-rival, etc. In such case the Dynamic Spectrum Access concept has to be applied, which requires that existing technical, legal, and other aspects must fit the actual local conditions. The Dynamic Spectrum Access Systems can switch automatically from one band to another. In this way, the spectrum previously allocated for exclusive use can be shared - at a given time in a particular region - with a new user, under the condition that the potential interference levels are kept within acceptable limits.

8. R. Leese, S. Hurley (eds.): Meth-ods and algorithms for Radio Chan-nel Assignment; Oxford University Press 2002, ISBN 0-19-850314-8

9. ITU Report SM. 2152, Definitions of Software Defined Radio (SDR) and Cognitive Radio System (CRS), International Telecommunication Union, 2009

Such a mode of operation is also known as "Opportunistic Spectrum Access (OSA)". However, to exploit that method, advanced hardware - cognitive radio - has to be used. ITU experts have defined a Cognitive Radio System (CRS) as *a radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained* (ITU-R Report SM.2152[9]). Cognitive Radio (CR) technology is seen as a future solution for increased radio spectrum demands. It allows increasing spectrum efficiency and increased number of radio services in operation in the same place and/or time by using Dynamic Spectrum Access (DSA) techniques, but it is complex and not cheap.

3.3.1 Decisions of WRC Geneva 2012

The agenda of World Radiocommunication Conference (WRC) Geneva 2012 included considerations of regulatory measures in order to enable the introduction of software-defined radio and cognitive radio systems (agenda item 1.19). Two major proposals were submitted in this connection. One was to keep the current Radio Regulations as they are, without change. The second proposed the preparation of a new Resolution on regulatory measures for the CRS Systems, which could delay its introduction. After discussions, the Conference decided that no change to the Radio Regulation, nor special Resolution on CRS regulatory issues are needed. The prevailing argument was that CRS is a new technology rather than a new service, and that the present Radio Regulations are adequate to assure sufficient protection of the existing radio services when the new technology is introduced. From the regulatory viewpoint it means that CRS can operate in any frequency band under the condition that they not violate the current RR in the country and in neighboring countries. It is possible to introduce CRS at any frequency band under the condition that other services already operating, or planned, are adequately protected. It implies that protection criteria are specified in the Radio Regulations, or agreed among the parties interested, which is not easily achieved. It is very difficult to establish protection criteria if the service, devices, and deployment details are unknown because both services and devices are still in the planning phase and may be produced and deployed in an unspecified future. In such a case, when a CRS device is not ready for deployment, only some general assumption can be taken into account: for example the assumed basic spectral masks, or reference deployment scheme. In such a preliminary phase usually one uses very approximate theoretical models. More exact models often require detailed experimental data, on, for instance, the degree of devices' nonlinearities. In some cases, the necessary data can be taken from other systems that employ similar components, for which the protec-

tion criteria in similar conditions have already been established and are available. Such an approach was used, for instance, during preparation of the ECC Report 159 and its amendments[10] [11] [12] where, in evaluation of 470-790 MHz TV white spaces, the protection criteria were taken from the measurements of DVB-T against LTE, in the LTE bands. At the same time the WRC12 conference admitted that CRS is a new technology, not fully established yet. It recommended Administrations to participate actively in studies on the *deployment and use of cognitive radio systems* (Recommendation 76) and invited Administrations participating in these studies to take into account that *any radio system implementing CRS technology needs to operate in accordance with the provisions of the Radio Regulations; and that the use of CRS does not exempt administrations from their obligations with regard to the protection of stations of other administrations operating in accordance with the Radio Regulations* (Resolution ITU-R 58). Along the same line, the ITU Radiocommunication Assembly (Geneva 2012, RA12) [13] resolved *to continue studies for the implementation and use of CRS in radiocommunication services; to study operational and technical requirements, characteristics, performance and possible benefits associated with the implementation and use of CRS in relevant radiocommunication services and related frequency bands; to give particular attention to enhancing coexistence and sharing among radiocommunication services; [and] to develop relevant ITU-R Recommendations and/or Reports based on the aforementioned studies, as appropriate* (Resolution ITU-R 58). It means that further studies are to be focused on the coexistence and sharing among radiocommunication services i.e., on compatibility issues and spectrum sharing criteria. Comparing the Frequency Allocation Tables with local (actual) spectrum occupancy it can be found that the dynamic/opportunistic spectrum access can be introduced not only in TV bands, but also in other bands. Indeed, any part of the spectrum (civil or military) with fixed transmissions (e.g., fixed services, broadcasting services, fixed radars etc.) can be seen as a potential region for better spectrum use via DSA and CR systems. Also mobile operators might dynamically access spectrum portions granting, buying, or borrowing them when they are not used. This would allow better spectrum utilization but also liberalization of spectrum access.

3.4 WHITE SPACES IDENTIFICATION AND INTERFERENCE AVOIDANCE

TVWS, or Television White Space, refers to frequencies allocated to a TV broadcasting service but not used locally. TV White Space Spectrum Systems (TVWSSS) are seen nowadays as one of promising solutions for realizing the Dynamic Spectrum Access concept in practice. White spaces can be identified using three methods: spectrum sensing, pilot

10. ECC Report 159, "Technical and operational requirements for the possible operation of cognitive radio systems in the 'white spaces' of the frequency band 470-790 MHz" Cardiff, January 2011

11. ECC Report 185, "Complementary Report to ECC Report 159. Further definition of technical and operational requirements for the operation of white space devices in the band 470-790 MHz", 2013

12. ECC Report 186 "Technical and operational requirements for the operation of white space devices under geo-location approach", 2013

13. Book of ITU-R Resolutions, Radiocommunication Assembly RA-12, Edition of 2012, Geneva 2012

channel (beacon) and geolocation database, which can be used independently or in combination. Such kind of operation may be considered as "third-rate" status (after the primary and secondary services) of the CRS opportunistic services. The CRS have to protect other radio services working in the same geographic and adjacent areas, in the same and adjacent frequency bands, etc. This implies establishing criteria and mechanisms allowing full protection of all incumbents. The protection mechanism can be derived when compatibility criteria are known, and current and planned spectrum usage is controlled.

Spectrum sensing. Spectrum sensing by the CRS devices was found as a natural solution for learning about the existence of other incumbent radio services and controlling the device emission parameters. It means that the CRS devices continuously detects current spectrum usage and learn from it about the current spectrum situation. However such solution is still under research. First of all there is "hidden node" problem - where the sensing device is hidden and cannot sense primary signals, for example, due to obstruction (hills, buildings, trees, etc.) on the receiving path. In such situation it can declare "free spectrum" when in reality it is occupied. Trying to increase the accuracy of the sensing and solving the hidden node problem with a single device could lead to the situation where the required sensing level is very low and practically impossible to implement in some frequency bands (as it is in case of TV UHF band). Also in case of very short time transmissions (burst, PMSE, M2M etc.) where the device is only active in very short time period, it is very difficult to detect the transmission and avoid interference. Some improvement is offered by Cooperative Sensing (CS), where many devices together are sensing the spectrum and exchanging the information that they collect. This may solve the problem of the hidden node, however, it is more complicated solution which cannot be used without recurring to additional protection mechanism, when, for instance, some channels have been previously allocated by administrative decisions but are not currently in use. Furthermore, this does not work in protecting the receive-only services, such as radioastronomy.

Pilot channel (beacon). One of possible solutions for protection of the incumbents is the pilot channel (beacon). Here a dedicated channel is used to inform every WS device about the current spectrum usage and free channels available. However, it could be difficult to find a common world-wide (or regional-wide) frequency allocation for such special pilot channel due to different frequency allocations in different countries. In fact such channel could be allocated for each country separately but in that case many frequency pilot bands around the World can complicate the wireless mass market. Also different interference problems between stations transmitted beacons in different regions have to be mitigated. Such solution has met with limited success so far, since alternatives (especially geolocation databases) seem to be more promising. However if some operators may use their own transmission channels (e.g. GSM or Wireless Internet operators) - the information on

the available spectrum can be sent via a conventional GSM/UMTS/LTE channel or via ISM/RLAN band.

Geolocation Databases. Geolocation database is now considered as the most promising solution because it can be used as one simple solution solving all problems (protection of reception-only devices, hidden node problem, sensing level etc.) for all types of transmissions and frequency ranges. It stems from the fact that every regulatory provision for any radio systems can be registered in a controlled database, along with rules that will determine the White Space Spectrum availability. The WS device has only to determine its location (using e.g., GPS), send its geographical coordinates to the database and asks it (directly or via a Master device) which channels are available under specific conditions (transmit power, antenna heigth, mode of operation, etc.). Data in the database can be easily changed, which offers additional flexibility of spectrum usage and protection of incumbents. The database can also include "safe harbor" channels for special applications, e.g. Program Making and Special Events (PMSE) channels, which may be reserved for local PMSE and be forbidden for CRS. Additional spectrum-related operations can be performed with on-line real-time access to the database. Such operation is necessary to assure, for instance, protection of the WS CR devices that just have channels access for a limited time. Other possible applications are discussed in the section below.

3.5   NATIONAL REGULATIONS AND TV WHITE SPACES

National regulations can add specific requirements to those internationally agreed as long as they do not violate the international treaties in force. On that basis, for instance, national spectrum licensing fees have been obligatory in most countries, and only a minuscule portion of the spectrum is open for license-free operation. This is in spite of the fact that no country pays any spectrum fees and the radio spectrum is considered as a *common heritage of humanity*. The current spectrum management practices are inherited from the times when radio was mainly under the state monopoly and the governments agreed that access to the spectrum resources should be at no cost for them. Within a country, the government can control strictly who, how, where and when, uses the spectrum by issuing licenses. This is done by three different mechanism: administrative adjudication where licenses have been awarded (almost) for free, on the basis of the "first come - first served" rule; by lottery; or by comparative hearings (called sometimes "beauty contests"). However, the world has changed. The state monopoly has been abandoned in most countries; the importance of private sector and international corporations is growing. Some economists have put forward the concept of spectrum management through market forces. It

is based on the idea of replacing the administrative licensing system by a competitive market mechanism. The full control by the government (and parliament) is replaced by the supply-demand-price game with minimal governmental intervention, if any. The licenses are granted to the highest bidders. It is based on the theory that the spectrum does not differ from other natural resources that have been managed in such a way since a long time, like coal or oil. For the time being, that approach has been limited to selected frequency bands, services, and countries, and has found as many supporters as opponents. The main declared benefits of that approach is that (1) the market mechanism tends to match automatically the demand to the available resource capacity, as it does in other sectors, and (2) the market-based spectrum management is inexpensive. With an unregulated market, there will be no spectrum scarcity (for those who are rich enough to buy it). In addition, selling the spectrum is an easy way to feed the government's budget, a very tempting proposition for some politicians. In 1995, for instance, two pairs of 15-MHz bands aimed at providing personal communication services in the 1900 MHz region, for were auctioned in the USA for a total of 7.74 thousand millions of USD. But not all auctions were so successful. The opponents to spectrum market say that the spectrum differs significantly from other resources and privatizing it would be a serious mistake leading to irreparable losses in the future. There are numerous examples where the unregulated market approach has led to irreversible environmental disasters, not mentioning global crises. Auctions do not stimulate the use of the most efficient technology for the use of frequency. They only let a successful bidder push smaller operators out of the market, and build a monopoly. Note that on top of the mentioned amount paid in the USA, the successful bidders had to pay all the expenses for relocating thousands of microwave transmission facilities that were already using that spectrum. But the total expense has always been put on the shoulders of the final users. Market forces ignore social aspects and - as Garrett Hardin noted - add the PP-CC (privatize profits and "commonize" costs) game to the price-supply-demand interplay. A sound alternative to spectrum market is spectrum sharing in the license-exempted frequency bands like ISM/WiFi/RLAN at 2.4 and 5 GHz. It has resulted in the decades-long growth of various applications and services, with minimal management costs. The license-exemption approach could easily be applied in the TVWS spectrum; indeed it is not restricted to any specific frequency, and could be applied in any band (with appropriate technology).

Possible uses of TVWS are being intensively studied in several countries (e.g., USA [14] [15] [16], UK [17] [18]) and discussed at international forums (e.g. ITU and CEPT) and standardization groups (e.g. IEEE 1900.x, 802.22, 802.11af, and ETSI RRS).

In some countries preliminary regulatory provisions have already been proposed. This is because of the good propagation characteristics in the UHF TV frequency bands, which is important for business

14. FCC 10-174 Second Memorandum Opinion And Order Adopted: September 23, 2010

15. FCC 12-36 Third Memorandum Opinion And Order Adopted: April 4, 2012

16. FCC 12-118 Notice Of Proposed Rulemaking Adopted: September 28, 2012

17. OFCOM, Implementing geolocation, Consultation, Publication date 9 November 2010

18. OFCOM, Implementing Geolocation Summary of consultation responses and next steps Statement Publication date: 1 September 2011

opportunities: the UHF bands are called the *"gold spectrum resource"*. TV signals to be protected are (almost) stationary. Due to the fixed characteristics of the broadcasting stations (under control by the Administrations) they do not change frequency, direction-of-arrival, etc. Therefore, it is possible to estimate spectrum availability in any given location (e.g., pixel-square 100 x 100 m) under a specified transmission scheme, and such estimation can be reliable and valid for a relatively long time. Such estimations of spectrum availability have been calculated in several countries [19] [20], an example is discussed in section 3.6 below. The amount of TV WS spectrum availability depends on the methodology, propagation models, and the data used that may differ from country to country. Introducing Dynamic Signal Access systems in a country requires changes in national regulatory procedures in the licensed frequency bands. Currently, in each country there exist only fixed frequency assignments. DSA requires a new kind of license that allows for dynamic change of the frequency band in short time period (possibly even in the bands allocated to primary services) that could be shared by a number of users simultaneously in a dynamic way. Such "new vision" in spectrum management requires advanced radio technologies. *Cognitive radio* technology may need to be applied and the whole regulatory regime reviewed. For example real-time access to databases controlled by the Administration or by *"spectrum brokers"* may be needed. The databases would include the geographical locations, frequency channels, radiated power, etc. of the existing or future (licensed) users. Legal consequences of possible errors in these databases would have to be taken into account. Precise technical coexistence conditions have to be defined and relevant requirements established and enforced by the Administrations. The non-interference requirements may have to be determined in real-time and signal parameters changed automatically. In this connection, it might be necessary for Administrations to prepare and publish detailed databases of the licensed users (see below for more details). In the current regulatory framework, all primary services are protected and any transmission that could interfere (harmfully) with primary users is not allowed. If a new service is to be introduced in the country (or in neighboring countries), detailed protection conditions of the existing primary services have to be established to assure their adequate protection and keep interference levels safely below harmful limits. Currently it can take months (or even in some cases years) to negotiate and agree detailed technical conditions of such spectrum sharing issues with all neighboring countries. However this was aimed to situation where new (non-CRS) services have fixed frequency range and near-fixed technical characteristics. In the case of CRS, however, that case is more complicated and can change dynamically on both sides of the border. It could lead to the situation where it is difficult to coordinate different CRS standards and systems implemented by the Administrations. In such cases common technical CRS standards or common coexistence technical standards (or at least common database

19. D.Więcek, Methodology of White Space estimation in TV bands based on the ITU GE06 technical conditions, COST IC0905 TERRA 3rd Workshop, Brussels, 21st June 2011

20. J. Zender, K. Ruttik, QUASAR - TVWS Assessment in Europe, COST TERRA 2nd Workshop - Lisbon January 19-21 2011

settings) could help the Administrations involved.

3.5.1 *Use of Geolocation Databases*

If an Administration wishes to use a geolocation database only as a protection mechanism of the incumbents, the coordination process with neighbors may be limited to the technical details of the database only. In such a case databases for neighboring areas may have special conditions, or may even be compiled by the neighbors. They can offer additional "safe margin" solutions: their data can be easily modified, if needed and as needed, without changing the implementation requirements (hardware and software) of the terminals. For instance, the data on maximum permissible powers, antenna heights etc. can be adjusted/modified in the database at the operational phase, in order to modify the interference scenario. It gives the same effect as modifying directly the protection requirements depending on the current contents of the database. Reaching technical agreements with neighbors may base on common technical protection requirements but can also involve different solutions for both border sides. In such coordination, using general CRS data (e.g., mode of operation, spectrum masks, technical standards) is more practical than using specific device data because it eliminates the need for additional coordination when the device data change. The Cognitive Radio Systems can be incorporated as additional (primary or secondary) services, provided that they protect all incumbent services (and also secondary in many places) working in the country and in its neighbors. A CRS device can operate in any type of service i.e., mobile, fixed, broadcasting, satellite etc., for which appropriate frequency ranges are allocated. As the WRC12 decided, for regulatory purposes, there is no need to define an additional "service" dealing with Software-Defined Radios, or Cognitive Radios. These technologies can be seen as an alternative to OFDM, CDMA etc. However, due to the capability of dynamically accessing different parts of spectrum allocated to different radio services in different countries, special attention to the CRS implementation is necessary in the national regulatory framework. Preparation of national databases requires first deciding which technical data are needed for CRS to operate. The basic data include at least spectrum masks, but more details may be needed, such as e.g. full technical specifications/ standards. Because of the nature of CRS and mandatory protection of all other existing services, technical data in the databases cannot be "agnostic" i.e., technically neutral due to the fact that protection of incumbents depends on detailed technical data of the CRS used. Some administrations may wish to implement only selected/accepted (by them) technical CRS standards/solutions in specific regions, and may not wish to implement others because, for instance, not all transmission types may be allowed in a specific country. Other administrations may wish to accept all CRS devices that fit the spectrum mask and other general parameters, to assure flexibility or technological neutrality. Those might be the type

of transmission, maximum antenna height or accuracy of geographical location, etc. However, allowing different types of radio transmission means that special attention has to be given to the adjacent frequency bands, or that larger separations of the CRS devices might be necessary, thus decreasing the number of devices allowed to operate in the protected area. But from the market point of view such neutrality solution opens markets for many possible solutions. Implementations fitting only the spectrum mask and general technical requirements allows increased competition and is more open to future (different) standards.

3.6 EXAMPLES

Figure 3.1 is an example of a map showing the availability of TVWS spectrum in a country. It is a graphical presentation of simulation calculations and analysis of the signals' strength, at UHF frequency range (470 - 790 MHz, UHF TV channels nos. 21 to 60). The analysis was done for some 600,000 points (raster of 1km x 1km) of Polish territory using the PIAST system [21]. Terrain irregularities were taken into account, but not buildings, trees, etc. A generic fixed-type WS device of 30 dBm EIRP power with omnidirectional antenna at 10 m above ground level was assumed, as well as standard outdoor fixed TV reception conditions. Protection of all relevant TV transmitters was taken into account[22]. The colors of individual pixels in the figure indicate the number of TV channels that a generic WS device can use without causing unacceptable interference. The average number of TV channels available in this example amounts to 14.5. With 8 MHz per channel it gives more than 100 MHz. Note that amount could be higher or lower depending on the assumed antenna height or the degree of protection.

The first national regulatory provisions introduced in the USA and UK set up only some basic technical data to be coordinated. For instance, the FCC (USA) rules define only a fixed maximum EIRP at fixed distance from the border of TV service area. The work performed in the UK (OFCOM) and other regulatory bodies shows that more complex regulations could be needed. Because of the varying number of active CRS devices, dynamic change of frequency band, and other variables, it is difficult to coordinate with neighboring countries such systems on the basis of the existing regulatory procedures. For example it is difficult to estimate (and coordinate) such "traditional" and conventional variables used in frequency coordination as "maximum permissible interference levels" or "required protection ratios" or "maximum transmitted powers". This is because of dynamic location of the CRS devices, dynamic transmission scheme (usage of current frequency during short period time) or difficulties in estimating the cumulative effect of many interferers operating simultaneously.

The protection requirements may differ among countries for various reasons, e.g., because of different technical standards. For instance, in

21. Platform IT for Analysis of Systems in Telecommunications (PIAST); National Institute of Telecommunication, Wroclaw Branch, Poland: http://www.piast.edu.pl

22. D.Więcek, Methodology of White Space estimation in TV bands based on the ITU GE06 technical conditions, COST IC0905 TERRA 3rd Workshop, Brussels, 21st June 2011
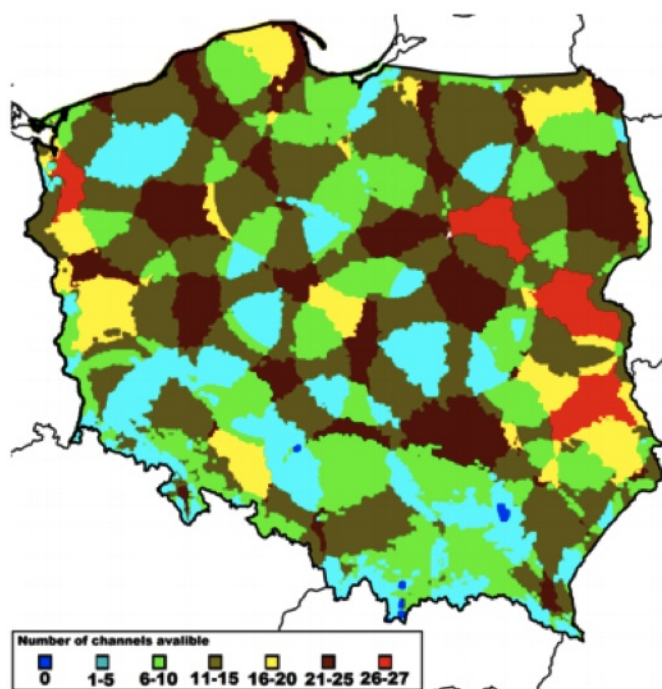
Figure 3.1: Result of the analysis of TV White Spaces availability in Poland. Source: ECC Report 185

23. ECC Report 185, "Complementary Report to ECC Report 159. Further definition of technical and operational requirements for the operation of white space devices in the band 470-790 MHz", 2013

24. ITU-R, Recommendation P.1546-4 "Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 300 MHz," International Telecommunication Union, Geneva, Oct 2009

25. ITU-R, Recommendation P.1812-2: A path-specific propagation prediction method for point-to-area terrestrial services in the VHF and UHF bands, International Telecommunication Union, Geneva Feb. 2012

26. ITU Report ITU-R SM.2028-1 Monte Carlo simulation methodology for the use in sharing and compatibility studies between different radio services or systems, International Telecommunication Union, Geneva 2002

27. G. Hufford et al., U. S. N. Telecommunications, and I. Administration, A guide to the use of the ITS irregular terrain model in the area prediction mode . US Dept. of Commerce, National Telecommunications and Information Administration, 1982

the USA the broadcasting standard ATSC uses 6 MHz channels, while the European DVB-T/T2 system uses 8 MHz; there are also other technical details. For example the minimum protected field strength (which depends on the reception mode: roof or street, fixed or portable, indoor or outdoor), minimum required separation distance, or "percent of location probability degradation" (ECC Report 159[23]). In some countries investigations were performed, looking for the "real conditions" protection and "interference limited coverage" or "interference limited service area", taking into account also interference coming from other broadcasting stations. Results obtained with a geolocation database data depend also on the propagation models used. Different propagation models [24] [25] [26] [27] may give different estimations of spectrum availability. No agreement exists over which model should be used. In some countries different propagation model are used for the wanted signal and for the interfering signals: signal coverage from broadcasting stations is calculated differently that of WS devices. This may give different results, even if the countries use the same data and methodology in other applications. Furthermore, the technical standards used for the calculation (802.22, 802.11af, LTE, etc.), the Spectrum Masks, Adjacent Channel Leakage Ratios (ACLRs) and Spurious Emission Limits, have strong influence on spectrum availability estimations, especially in the case of adjacent channels, where different protection ratios exist depending on specific EMC systems characteristics. It means that there is no single view of the protection requirements of the TV services - even in the case of using the same system (e.g., DVB-T/T2 in Europe), the same ITU

32

Region, and with the same calculation methodology for the TV White Space availability estimation. This can cause different estimations and different regulatory decisions among countries. Each Administration is sovereign in setting its own regulations following its national policy of spectrum usage, type and level of protection, as well as in deciding about the WS devices and standards to be used under its jurisdiction. It means that every Administration may wish to develop its own methodology and establish its own geolocation databases. All these facts mean that spectrum availability evaluations, spectrum maps, and geolocation databases can differ from country to country. This is also because of differences in the TV reception modes and spectrum occupation, as well as in the protection requirements. As a consequence, there may be more TV channels available for CRS in one country than in others, even in the same geographical ITU Region and the same WS device. Such a situation exists now in Digital Terrestrial Television (DTT): in some countries many multiplexes exists but in some others only a few. One foresees (e.g., in ECC Report 185) that every country will prepare its requirements and databases of available TVWS spectrum, using its specific methodology. In bordering areas these have to be coordinated and accepted by the National Regulators of the neighboring countries. It may be needed to exchange data from the databases to get acceptation of other Administrations. In some cases different methodology and different spectrum availability need to be established for the bordering areas if the Administrations have different views of the situation. Such different approaches in different countries can cause also situation where in some of them market for new TV WS systems and applications (e.g. M2M, "super WiFi" etc.) will grow while in others might wither for lack of business interest. Administrations wishing to increase deployment of radio systems in rural areas have to be careful about estimating available TVWS spectrum, because even small differences in these details can produce different results. Consequently, different estimates of the potential CRS market can be obtained. As in many other cases, where Administrations stimulated market growth, an involvement of the Administration is needed, especially in an early stage of CRS implementation. If a national spectrum market exists and license-paid scheme of TVWS could be accepted, the national regulations would need on-line electronic licensing procedures in which paper documents would be unnecessary in the process of spectrum assigning. Granting licenses via on-line spectrum auctions could be arranged, where the pieces of White Space spectrum could be sold to the highest bidder automatically (if the spectrum market is accepted). Using Internet real-time access to databases, licensing system, and paying system, would lead to a fully electronic form of future frequency assignments procedures. That would certainly require regulatory amendments.

3.7 FINAL REMARKS

It is generally accepted that improved spectrum availability benefits the society at large, as do advances in hardware and software. These directions have to complement each other and match local conditions. Even the best technology is useless if the regulations curtail its operation, or the devices are inappropriately deployed. This chapter has presented a flexible approach to spectrum access that could be widely implemented in future. However, further studies, political support, and adequate financing are necessary for that to happen. For practical reasons, countries are starting with the new approach to national radio regulations in the "license exempted" frequency bands. After such "experimenting" with geolocation databases and other new elements, it might be easier to extend it over the UHF TV band. That part of spectrum is especially attractive because of its inherently better propagation conditions at long distances. Combined with high-gain antennas it could offer an inexpensive solution for the long-distance broadband access problem in many developing regions. Eventually, technology could remove the need for many spectrum management functions. Numerous functions could be automated to free the management process from the "human factor" and make it more objective and neutral. Future wireless devices would "negotiate" among themselves how to "best" use the available resources. Principles, criteria, and algorithms to be embedded in such automates would be mediated at conferences. However, in view of enormous investments in the existing (old) equipment still usable, it would not happen soon and everywhere. The Dynamic Spectrum Access and Cognitive Radio discussed above are the first steps in that direction. Setting national radio regulations in an uncoordinated way may lead to national differences. Harmonization of national rules, geo-databases, and propagation models used is necessary to avoid a regulatory patchwork that would fragment the wireless TVWS market and make the international commercial success much harder to achieve. Without such a harmonization, national decisions about channel availability may be inconsistent, which would make it impossible, even for the same WSDs, to operate across the border, as it was the case at the beginning of wireless services some hundred years ago. It would also nullify the Internet Engineering Task Force's work in ensuring that the protocol for accessing geo-databases is globally uniform, like HTML.

3.8 ACKNOWLEDGMENT

SPECTRUM AND DEVELOPMENT

4

Steve Song
Network Startup Resource Center
USA
stevesong@nsrc.org

In the field that has come to be known as Information and Communication Technologies for Development or ICT4D, the management and regulation of electromagnetic or wireless spectrum has evaded most donor programmes and debates. Broadly speaking ICT4D is a field that looks at the impact of information and communication technologies (ICTs) on development and explores how equity, rights, and social and economic development can be positively affected by access to ICTs. ICT4D embraces both policy and technology in a quest to create equitable access for all. In this article, I will make the case that the absence of debate or action on the regulation and management of wireless spectrum now stands as a gap in development thinking about ICTs.

4.1   WHY WORRY ABOUT SPECTRUM?

Why should wireless spectrum be given special consideration? For much of the developing world, wired technologies, especially in rural areas, are simply not practical. In the industrialised world, wired technologies feature heavily in the last mile for high-speed data whether via an ADSL-enabled copper telephone line or via a the coaxial copper cable provided by a cable television operators. However copper-based last mile solutions present particular challenges in poor countries. The roll-out cost of copper infrastructure is comparatively high, and often not practical in lower-income countries, even less so in sparsely populated rural areas. The steadily increasing value of copper as a commodity also makes it a target for thieves. Fibre optic cable infrastructure is another important connectivity technology especially for national and international communication backbones but it is currently only viable as a last-mile solution in wealthy communities. Satellite-based infrastructure is also a powerful technology for delivering access in remote areas but it too is currently not cost-effective as a last mile technology.

This means that when talking about affordable, ubiquitous access to communication in developing countries, wireless technologies offer the most hope for effectively bridging the digital divide. And indeed, the mobile phone has become more or less synonymous with access in the South. Much has changed since mobile networks first began rolling out in the early-to-mid nineties in the South. When the first mobile operators were granted licenses to use wireless spectrum to build their networks, they were simply given the spectrum at no charge. There was plenty of available spectrum to go around. Today popular spectrum bands are auctioned for large amounts of money, often running into the billions of dollars. Because so much money is now at stake concerning spectrum, the process of making new spectrum available has become complex. It is increasingly hard to ensure that spectrum is made available in a timely manner and to the entities that are most likely to serve a country's strategic interest. As ICTs become increasingly valuable to government, industries, and citizens alike, demand for spectrum has steadily increased. Yet the process of making spectrum available and managing it as a resource still fails to feature in ICT4D initiatives and strategies.

4.2 SO WHY DON'T WE TALK ABOUT SPECTRUM?

One possible answer to why spectrum doesn't feature significantly in ICT4D lies in its multi-dimensional complexity. It is a daunting issue to address, requiring technical, economic, and legal expertise. Here are just a few of the dimensions in which spectrum is a challenge to understand and manage.

Technical complexity. What we understand about wireless spectrum is in flux. Eighty years ago the only way to manage spectrum was to give exclusive rights to a spectrum holder and ensure that significant "guard bands" or gaps between spectrum holders existed in order to prevent interference. Transmitters were obliged to operate at comparatively high power outputs in order to reach the comparatively "deaf" receiver devices. Today wireless communication technology continues to increase in efficiency and in its ability to mitigate interference. There are limits to this, however, and understanding how to maximise the efficient use of spectrum is an ongoing technical challenge which attracts a lot of R&D investment. Understanding the trends and changes in spectrum technology is essential to understanding how to regulate it.

Money and Corruption. As the business of telecommunications has become more lucrative, an increasing premium has been put on access to spectrum. As a result, regulators find themselves managing a resource worth millions of dollars to interested parties. Where that much money is on the table, ensuring fair play in the national strategic interest can be

a challenge. Spectrum auctions have emerged as the de facto mechanism for dealing with licensed spectrum yet effective auction design and execution is a challenge even in well-resourced regulatory environments. Success in this area doesn't just involve designing an optimal auction but also creating a sufficiently well-organised and disciplined process that doesn't attract legal challenges from disgruntled parties.

Market and Manufacturing Complexity. Spectrum usage is dependent on having technology capable of using a given set of frequencies and this, in turn is entirely dependent on manufacturers producing transmitters and receivers for those frequencies. Many technologies only become practical when manufactured at scale so there is a kind of catch-22 with new technologies that requires commitment from manufacturers to support specific standards and frequencies. In the past, the trend in spectrum allocation has been to tie a particular spectrum band to a particular technology. This has led to chunks of spectrum lying fallow because the markets and manufacturers did not follow the path that regulators expected. Today, there is an increasing emphasis on technological neutrality in spectrum allocation but this can be challenging because some technologies, for example those that require paired spectrum, are dependent on spectrum allocations being organised in a particular manner.

The Challenge of Coordination. Prior to the advent of mobile telephony and wireless broadband technologies, the availability of spectrum exceeded demand and incentives to coordinate spectrum allocation existed but were often trumped by local or regional priorities. So while there is broad coordination in general areas of spectrum use, there are critical variances in the details. This has led to the need for mobile phones that operate in three, four, or more spectrum bands in order provide a working service internationally. Regulators today find themselves in a catch-22 situation where they recognise the need to harmonise spectrum but are tempted to act individually because the pace of international coordination is so slow.

Institutional Capacity. When it comes to effective regulation of spectrum, there is a clear need for the technical, economic, legal, and administrative capacity within every country to address the above issues effectively. For developing countries, this is often the most significant challenge as communication regulators are typically under-resourced and sometimes insufficiently independent of state and industry alike. Because so much money is on the table, regulators are often outmatched by their wealthy industry counterparts.

4.3   WHERE DO THINGS STAND?

In poor countries, regulators and governments are caught between the growing market demand for more spectrum and the need for more human and financial resources to manage the increasingly complex web

of issues including spectrum auctions, technological advances, regional harmonisation, not to mention vested interests. This is compounded by the fact that decisions about spectrum can have consequences that can last a generation or more. The interplay of investment, evolving technical standards, and administrative complexity tends to make this a very slow moving decision-making environment. This means that not only does it take a long time to introduce new spectrum regulation but also that strategic errors in regulation can take many years to undo. South Africa is a good example of how challenging it can be to carry out a spectrum regulation change. In May of 2010, the South African communication regulator, ICASA, announced an auction of spectrum in the 2.6 GHz and 3.5 GHz bands[1]. The auction was plagued with problems. Insufficient attention was given prior to the auction to the need to migrate incumbents within the 2.6 GHz band in order preserve technological neutrality. Build-out requirements for the spectrum licenses were claimed to be unrealistic by some major players[2] and other factors were criticized as well. For nearly two years the regulator went through an on-again, off-again process with the auction. Ultimately the auction was withdrawn and three years later the spectrum remains unavailable. Worse, trust in the regulator's capacity to successfully carry out a spectrum auction has been undermined.

4.4 UNLICENSED VERSUS LICENSED SPECTRUM

Standing in stark contrast to the traditional method of assigning spectrum through exclusive-use licenses is the world of unlicensed spectrum. Unlicensed spectrum is regulated but instead of being managed through a licensing process, it is regulated through the technical specifications imposed on devices operating in spectrum designated as unlicensed. Typically this means that the power output of these devices is required to be much lower than is found in licensed environments. The lower power output limits the ability of any device to interfere with another and any device operating in these bands must be tolerant of interference. Originally conceived for non-communication-related use of radio spectrum, the Industrial, Scientific, and Medical (ISM) bands have come to be dominated by popular communication technologies such as WiFi, Bluetooth, and Near Field Communication. The success of these technologies, WiFi in particular, is something to consider in the context of spectrum management strategies. The ultimate use of the ISM bands was not predetermined. WiFi emerged as a success story more through a process of natural selection than by design. Its success has eclipsed all expectations. According to market research firm IHS[3], in excess of 2.14 billion WiFi chipsets will ship in 2013 - 20% more than in 2012. WiFi technology is emerging as a critical part of mobile broadband

1. Icasa's broadband spectrum auction: all the details - 28 May 2010 http://www.techcentral.co.za/icasa-spectrum-auction-all-the-details/14669/

2. Vodacom may walk away from spectrum auction - 17 June 2010 http://www.techcentral.co.za/vodacom-may-walk-away-from-spectrum-auction/14998/

3. Small Cells with WiFi Set to Reshape Wireless Communications Market - May 15, 2013 http://ihs.newshq.businesswire.com/press-release/design-supply-chain/small-cells-wi-fi-set-reshape-wireless-communications-market
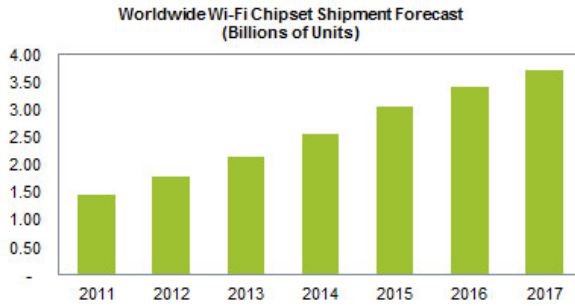
Figure 4.1: Worldwide WiFi Chipset Shipment Forecast

infrastructure.

According to a survey of Android devices by mobile analytics vendor Mobidia[4], WiFi predominates as the access technology for smartphone and tablet data. This research is corroborated by reports from Nielsen[5] that WiFi also dominates smartphone data in the UK with only 22% of data traffic travelling via mobile networks. It is interesting to note that this dominance has evolved without the intervention or design of mobile operators.

The success and importance of WiFi to broadband strategies has begun to receive some attention in the industrialised world but receives almost no attention in debates on bridging the "digital divide". A recent ITU / Unesco report entitled The State of Broadband 2012: Achieving Digital Inclusion for All[6] mentioned WiFi only twice. As a broadband connectivity success story, unlicensed spectrum is under-represented. We rely on WiFi connectivity everywhere we go yet it is seldom mentioned in a strategic context, perhaps because its growth has occurred so organically.

4.5 TV WHITE SPACES SPECTRUM - A NEW FRONTIER

While the existing unlicensed spectrum technologies have gone from strength to strength, a new opportunity for unlicensed spectrum use has emerged in the form of TV White Spaces spectrum. Originally conceived of as a technology that could take advantage of the guard bands or "white spaces" that were left between television channels to prevent interference, TV White Spaces (TVWS) spectrum is a secondary spectrum technology that can take advantage of unused television spectrum in a dynamic manner. In the US and the UK, communication regulators have endorsed

4. http://www.mobidia.com/products/whitepaper-download/

5. WiFi delivers over three-quarters of all UK smartphone data - 15 Nov 2012 http://www.nielsen.com/uk/en/insights/press-room/2012/wi-fi-delivers-over-three-quarters-of-all-uk-smartphone-data.html

6. ITU Unesco - Broadband Commission - September 2012 Broadband 2012: Achieving Digital Inclusion for All http://www.broadbandcommission.org/Documents/bb-annualreport2012.pdf

Figure 4.2: Global smartphone originated data traffic distribution (Source: Mobidia)

TVWS regulation and the commercial scale-up of TVWS technology has begun.

4.6 WHAT PROMISE DOES TV WHITE SPACES TECHNOLOGY HOLD FOR THE DEVELOPING WORLD?

There are three key reasons why TVWS technology holds tremendous promise for the developing world:

Low Risk Regulation. Because TVWS is a secondary-spectrum-use technology, there is no need to re-allocate spectrum in order to regulate its use. It doesn't commit the regulator to giving away a spectrum band for years to come and doesn't expose the government to the challenges of spectrum auctions which range from stalled processes (as we have seen in South Africa) to widespread corruption (as we have seen in India[7]). Whether TVWS succeeds in its potential to spur the same innovation and market development that has happened in WiFi is a risk for the market not for the regulator.

Availability of Television Spectrum. The profusion of terrestrial broadcast channels in use in North America and Europe may limit the impact of TVWS applications in these regions. However, a region like Sub-Saharan Africa (SSA) is very different. Most countries in SSA have few terrestrial broadcast channels in use, leaving large amounts of television spectrum available for use. This is even more true in rural areas where TVWS show their greatest potential. The flexible nature of TVWS technology means that more spectrum can be taken advantage of in the least serviced areas. Of course this doesn't preclude using

7. India's 2G Telecom Scandal Spans the Spectrum of Abuse - 02 Dec 2010 http://knowledge.wharton.upenn.edu/india/article.cfm?articleid=4549

40

television spectrum for other purposes too such as digital terrestrial TV and mobile broadband.

A Great Rural Technology. While mobile technology has been an access boon for the developing world, mobile operators still struggle to deploy access in rural areas where low incomes and sparse populations do not make a viable economic proposition for the establishment and maintenance of mobile base stations. TVWS has specific advantages that make it well-suited to being a complementary access technology. First, TVWS use of the UHF spectrum band offers better propagation characteristics than other technologies higher up in the spectrum band. This means that individual base stations can reach further, thereby lowering the total number of base stations required for a given areas. Second, UHF spectrum doesn't require direct line-of-sight between radios. This will also lower the cost of deployment thereby reducing the need for high towers and more complex network design. Finally, the market cost of TVWS devices[8] will be closer to that of WiFi equipment than traditional wireless broadband equipment used by licensed spectrum operators.

Opportunity for Entrepreneurship. Perhaps the least acknowledged benefit of TVWS regulation is the opportunity that it will offer to entrepreneurs. Rising demand for licensed spectrum has raised the bar for market entry so high that none but the wealthiest of investors can get involved. The high cost of entry also raises the risks of market entry. By contrast, TVWS technology will open up rural broadband service delivery to an entire generation of entrepreneurs interested in providing local, competitive broadband services. If TVWS technology lives up to its promise, it will not only provide opportunities to small entrepreneurs but perhaps will also provide the foothold they require to nip at the heels of and ultimately challenge the market hold of incumbent operators.

8. TV White Spaces Aims To Bolster Net of Things - 4 March 2013 http://www.eetimes.com/design/microwave-rf-design/4410924/TV-white-spaces-spec-aims-to-bolster-Net-of-Things

NEW COGNITIVE RADIO TECHNOLOGIES, WHITE SPACES AND THE DIGITAL DIVIDEND IN THE BRAZILIAN CONTEXT

5

Carlos A. Afonso[*]
Instituto Nupef
Brazil
ca@cafonso.ca

In the recurring debate in Brazil (a country with nearly 200 million people, 8.5 million km², and 5,565 municipalities), on the approaches to broadly democratize quality access to the Internet, there is an outcry of mobile phone operators who try to convince the public that mobile connectivity will be the "definitive" solution to this democratization. Brazil's telecommunications have been privatized in 1998, and the mobile market is now dominated by four transnational corporations (Vivo/Telefónica, TIM, Oi/Portugal Telecom, and Claro). A fifth European company (GVT/Vivendi) does not offer mobile services. These five transnationals also own the major fiber backbones and satellites.

To reinforce this perception, they promote, through their corporate association, statistics conglomerating cell phone (prepaid and postpaid) contracts and fixed broadband contracts, without any distinction regarding prices, quality, and availability. The four major cell phone operators are systematically in the consumers' lists as paradigms for bad service, breached contracts and very high prices (still among the highest in the world). Numbers are concentrated in the most developed cities, while service in poorer regions is of even lower quality or even non-existent. In fact, most of the Brazilian population considered by these operators as "connected to the Internet" still uses prepaid phones and very rarely browse the Internet.

Depending on the will of these companies, access will follow a caste

---

[*]This text is part of a continuing work on the theme of open spectrum for community applications by Instituto Nupef1 in Rio de Janeiro. It is adapted from a paper published in Nupef's magazine poliTICs.

structure - the ones who can pay hefty prices and live in more developed areas will have the best mobile service in their smartphones. They usually are the ones who also have a good fixed broadband connection at home. Prices in these cities are driven a bit down because these are the markets where all five companies try to compete for broadband service, either fixed or mobile. Most of the others will have to accept a very restricted mobile access to the Internet and, if they are lucky, a low-speed fixed broadband connection at home.

However, wireless services both in urban and rural areas can go well beyond mobile services based on a cellular network. Beyond what is already generally known in domestic and community applications using unlicensed or "light-licensed" bands of the so-called "WiFi" spectrum (in most countries using the 2.4 GHz and the 5.8 GHz bands), new techniques of digital radio communication have emerged which make highly efficient use of the available spectrum either in primary or secondary use modes. In particular, there is a new breed of software radios known as "cognitive radios"

Also, one ought to keep in mind the need for significant investments in fiber backbones through which data to and from millions of cell phones, wireless networks, and fixed connections circulate. Data presented by Cisco[1] estimate that global mobile data traffic will grow 26 times from 2010 to 2015 in mobile networks, when about 230 petabytes per day (or 2.67 terabits per second) will be transported - especially due to the growing demand for mobile video and access to Internet cloud services.

Besides expanding on the number of base stations (the mobile network's "cells") to relieve congestion on the existing ones (in Brazil there may be up to ten times more cell phones per base station than in the USA or Europe), it is necessary to invest in backbones which transport calls and data among these stations and from them to the Internet. Optical fiber branches of these backbones ought to reach all municipalities, with abundant, future-proof physical capacity, offering one or more points of presence with the guarantee of isonomic access at reasonable prices to community, research, and municipal networks, as well as to local entrepreneurs who may provide a number of Internet services. These are prerequisites to enable broad use of the new radio technologies in boroughs, cities, sparse urban communities and the rural areas in each municipality.

1. Cisco, Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010-2015, February 2011.

5.1   WHICH SPECTRUM ARE WE TALKING ABOUT?

Electromagnetic radiation becomes more directional and more vulnerable to physical obstacles and climatic conditions as the frequency increases. While AM radio (frequencies between 535 kHz and 1.65 MHz in

the Americas) or traditional tropical or short wave radio may reach thousands of kilometers, FM radio and television in VHF or UHF channels barely go beyond the horizon without the help of repeaters.

Certain frequency bands are designated by the International Telecommunication Union (ITU)[2] as unlicensed, with power and antenna gain limitations that restrict the range. These are used for home wireless phones, remote controls, and "bluetooth" devices. It is up to the regulator in each country to establish the specific requirements for commercial or non profit usage, and different strategies have been adopted in regard to the WiFi devices. In order to operate in these bands with longer range or higher power (for example, in community networks, municipal networks, local wireless access providers) a license is required in many countries.[3]

Most bands are licensed and rigorously controlled exclusively for specif use by certain operator in a given geographical area. The allocation of these bands is done through bids, auctions or authorizations of several types, usually at very high prices, accessible only to larger telecommunications and media companies.

Brazil considers the spectrum to be an asset of the commons - it cannot be bought or sold. For licensed portions of the spectrum, licenses are issued (through bidding, auctions or other granting forms) for primary use in certain regions for a limited time, subject to renovation under certain conditions. No one can "own" spectrum in Brazil - or at least this is what the law says. Also, even in the case of unlicensed spectrum bands, equipment must be certified by the telecommunications regulator.

WiFi radios are well known as software-driven radios which use spread spectrum techniques to share the unlicensed bands with many other radios in a given area. These are frequently used in community and municipal networks, as well as for local commercial services. A typical application in a community network is the use of dual-band radios which operate simultaneously in the 2.4 and 5.8 GHz bands - where the higher frequency is used to interconnect the radios, thus extending the network range, and the lower is employed to distribute the signal in each small area.

Recent advances which combine computing power, information logistics and advanced digital radio techniques have led to what is known today as cognitive radios. These are software radios specially conceived to operate in several frequencies in programmable automatic mode, either by accessing data in a remote database to obtain available frequencies in its operating area (information logistics), or through sophisticated sensing algorithms to detect available frequencies (computing power), thus even allowing for secondary use (i.e., coexisting with the primary use allocated by the regulator) of frequencies without affecting their primary use. As an example, an operator might hold a primary use license in the 700 MHz band, but uses only certain portions of it in each region - a cognitive radio can identify which portions are not in use every fraction of a second and operate in these frequencies, thus

2. http://itu.int

3. Brazil maintains two types of "light licenses" for wireless services networks, which are required even if unlicensed devices are used if they reach beyond the operator's premises or operate at 400 mW or more. For commercial operation the license is known as SCM and requires a single payment of about US$200. For non profit operation (community or municipal networks) there is the SLP license, at the same cost.

providing other services.

Cognitive radios are already capable of operating in several portions of the spectrum, expanding its data transmission capacity. One example is a radio capable of operating in any frequency between 100 MHz and 7.5 GHz delivering up to 400 Mbps.[4]

5.2 THE DIGITAL DIVIDEND AND WHITE SPACES

Each country has its own spectrum attribution table (which defines which services should be run on which chunk of spectrum), generally compatible with the attribution proposals agreed upon at the ITU. The "beach front property" of the spectrum is currently between 50 MHz and 6 GHz. This includes all FM and TV (analog and digital) bands, as well as the numerous frequency bands for mobile telephony and point-to-point/multipoint data links, among several others.

Television channels in the Americas are in the ranges 54-88 MHz and 174-216 MHz for VHF (channels 2 to 13) and 470-890 MHz for UHF (channels 14 to 83). The range 88-174 MHz is allocated to FM radio, aeronautical radio services, and ham radio. Analog TV channels in Brazil broadcast with the PAL-M standard - a variation USA's NTSC using the European PAL color standard. As with NTSC, each channel bandwidth is 6 MHz. Channel 37 is reserved for radioastronomy, and channels 53 to 83 (698-890 MHz) are reserved for mobile terrestrial services to be granted to operators of 4G/LTE services.

Since digital TV uses less spectrum than the analog one, the transition to digital has produced what the ITU calls "digital dividend". Also, in analog broadcasting a blank (non used) channel is required between two contiguous channels to avoid interference - these empty channels are called "white spaces". Thus, channels 2 and 4 can coexist in a given area, but channel 3 must remain empty. With digital broadcasting this separation is no longer required, as the technology enables the use of adjacent channels without mutual interference.

The new opportunities for efficient use of the spectrum in community networks, particularly with cognitive radios, are significantly enhanced with the availability of channels from white spaces and gains from the digital dividend. These frequencies propagate to far longer distances than the ones currently used for WiFi. This offers an exceptional opportunity to connect sparse communities in rural areas, especially because there are no plans to extend fiber to these communities.

Digital TV is regulated in Brazil by decrees 4901/2003 and 5820/2006, with the creation of the Brazilian digital TV system (Sistema Brasileiro para Televisão Digital, SBTVD[5]). The regulator has defined 45 channels (UHF channels 14 to 69, in the range 470-806 MHz)[6]. The current holders of analog channels have been automatically assigned digital

4. "Frequency-Hopping Radio Wastes Less Spectrum", Technology Review, June 13, 2012, http://www.technologyreview.com/news/428182/frequency-hopping-radio-wastes-less-spectrum

5. http://en.wikipedia.org/wiki/SBTVD

6. The complete list of channel distribtuion in Brazilian cities is on Wikipedia: http://pt.wikipedia.org/wiki/Anexo:Lista_de_canais_da_televis%C3%A3o_digital_brasileira

channels. The bandwidth for each channel continues to be 6 MHz, and commercial channels are not allowed to operate with multiprogramming - this is only allowed for public services.[7]

SBTVD is a modified version of the Japanese platform ISDB-T, and is known internationally as ISDB-Tb. This modified version has also been adopted by Argentina, Chile, Peru, Venezuela, Ecuador, Paraguay and Costa Rica. Several other contries in Latin America and in Africa have also adopted or are considering adoption of the Brazilian system. ISDB-Tb uses H.264 (MPEG-4 AVC) for video compression and a middleware developed in Brazil - the Ginga system. In April of 2009 the ITU certified the Ginga-NCL module and its programming language NCL/LUA as the first international recommendation for interactive digital multimedia environments for digital TV and IP-TV (ITU recommendation H.761).

Each channel allows broadcasting of one program in full high definition (1080p) or simultaneous broadcasting of a high definition channel (720p) and a standard channel (480p) - this latter form is the one being adopted by the main broadcasters already operating digital TV services.

While full transition to digital TV in Brazil is not expected to complete before 2020, the use of white spaces with cognitive radios is possible right now, depending only on regulatory decisions.

5.3   ADVANCES IN DEVELOPED COUNTRIES

The first commercial network using white spaces was deployed in Wilmington, North Carolina, culminating a regulatory process initiated by the Federal Communications Commission (FCC) in May, 2004, when a public consultation on the use of unlicensed devices on unused TV channels was issued [8]. As a result, in September 2006, the Engineering and Technology Office of the FCC announced a "projected schedule for proceeding on unlicensed operation in the TV broadcast bands" [9].

Given its propagation characteristics, the Wilmington network enables a far easier positioning of certain connected devices and services, like the municipal network of monitoring cameras, public vehicles communication, and the activation of local WiFi access points. Interference with the existing TV channels is avoided because the radio must consult a database of occupied broadcasting channels before transmission is allowed.

The USA has been pondering the destination of analog TV channels for digital applications since 2002. At the end of 2008 the FCC agreed to open the white spaces for unlicensed or light-licensed use. In September 2010, the FCC approved rules to operate radios in white spaces, as well as in free channels left by the transition to digital TV. To enable automatic channel selection by the cognitive radios a central geolocation database providing information on free channels has been activated.

7. "TV Digital: Minicom permite compartilhamento de multiprogramação," SINRAD-DF, 13/março/2012, http://www.radialistasdf.com.br/noticia2.php?id=758

8. http://www.forbes.com/sites/elizabethwoyke/2012/01/26/worlds-first-commercial-white-spaces-network-launching-today-in-north-carolina/

9. US Federal Communications Commission, "Office of Engineering and Technology Announces Projected Schedule for Proceeding on Unlicensed Operation in the TV Broadcast Bands", DA 06-1813, ET Docket Nr. 04-186, Sept.11, 2006.

10. http://www.ieee802.org/22

Radios thus check this database to obtain a list of available channels in its area of operation, in order to protect the primary user of the spectrum from interference. A total of 48 analog TV channels, spanning 288 MHz of bandwidth, can be accessed for unlicensed or light-licensed use. Meanwhile, a new standard for cognitive radio for these applications was developed by the IEEE (802.22) [10] and published in 2011.

The FCC has been supporting since 2009 (through regulatory measures and concrete experiments), the use of cognitive radio technologies in municipal and community networks. This has stimulated manufacturers to launch commercially available cognitive radios for these applications. With these advances, network architectures can be optimized for the coverage of large areas with the adequate combination of cognitive radios in the TV bands with WiFi radios in the 2.4 GHz and 5.8 GHz bands, as well as underlying fiber, thus significantly increasing the options at hand for the design of optimal municipal networks.

In August, 2011, Industry Canada carried out a public consultation for the possible use of unlicensed cognitive devices using white spaces or free channels below 698 MHz. Since September 2010, Canada follows a policy of light licensing for these bands, similar to the USA's. For applications in rural areas, also under light licensing, Canada reserved the ranges 512-608 MHz and 614-698 MHz. Other countries which have progressed with similar rules are Finland, the United Kingdom [11] and Japan. The European Union is working to define similar common rules.

11. In the United Kingdom the following bands are available for unlicensed or light-licensed use: 566-590 MHz (current UHF channels 33 to 35) and 806-854 MHz (VHF channels 63 to 68). The ranges 470-550 MHz, 790-806 MHz and 630-790 MHz are reserved for digital TV, totalling 259 MHz of spectrum, or 34 8 MHz channels. Some minor variations might happen with the relocation of bands currently being used for radar and radioastronomy.

The advance of cognitive radio technologies enables numerous applications for secondary use of the spectrum. With the use of advanced modulation technologies (like the ones currently deployed with 4G/LTE networks) data densities of 15 bit/Hz or more can be reached. On a white space 6 MHz channel, with this density data transmission can theoretically reach 90 Mbps (compared to 20 Mbps of digital TV broadcasting). As already mentioned, a radio can combine several channels to increase throughput.

In the 450 MHz band there are already commercial devices and concrete examples of deployment of cognitive radio for interconnecting offices in companies which traditionally use this band for its internal networks [12]. In this case there should be flexibility in the regulation to allow for secondary use, especially in rural areas and to connect sparse communities.

12. See the example of Petrobras in Brazil at http://convergenciadigital. uol.com.br/cgi/cgilua.exe/sys/ start.htm?infoid=27950

5.4 PERSPECTIVES IN BRAZIL AND ITS REGION

While in the USA and other developed countries there has been a significant advance in regulatory strategies associated with cognitive radio technologies to enable its broad deployment to optimize spectrum usage at the edge, in Brazil and other countries of the region these initiatives

have been timid at the best. Communities and local governments, without qualified information, are unable to demand proper regulations to facilitate licensing in the available chunks of the TV bands, and the regulatory agents are basically concentrated in responding to the commercial demands of the large media and telecommunications companies.

The digital dividend is a specially delicate case, since the current holders of analog TV channels (large media networks) have plans to occupy these channels for their own future digital services - and they of course also eye the white spaces. On the other hand, under the argument of "spectrum crunch", mobile phone companies are also disputing these bands. A report for AHCIET and GSMA [13] argues that coverage of mobile broadband could be from 75% to 95% in Argentina and Brasil, from 53% to 90% in Colombia, from 39% to 94% in Mexico, and from 65% to 89% in Peru [14]. But the outcome of these disputes is not clear. Just as the telecommunications companies seek to offer multimedia services (IP-TV and others), the current media companies wish to provide digital wireless services in these bands.

In this dispute around white spaces and the digital dividend, media companies in Brazil argue that it is too early for the regulator to take decisions on these channels, and that the telecommunications operators already retain a lot of spectrum which they use inefficiently. According to the calculations of one of the corporate media associations (ABERT) [15], the telecommunications companies in the country already hold spectrum equivalent to a total range of 795 MHz, while in the USA, where usage is much more intense, this total is 574 MHz - and in both countries there is evidence of inefficient spectrum usage [16]. ABERT also argues that the claimed need of 1,280 MHz of additional spectrum for a sample of 14 countries is not confirmed in practice.

The Ministry of Communications (MiniCom) informs that the re-attribution of these channels will only happen when the transition to digital TV is complete. Civil society organizations which monitor spectrum policy in Brazil insist that attribution and distribution of spectrum ought to be decided on the basis of public consultations with society and not just taking into account business models. The Brazilian Constitution foresees a pervasive public TV system, but this has not advanced as it should, partly because of the alleged "lack of spectrum". However, digital TV provides an exceptional opportunity to realize in full the constitutional goal [17].

While in the USA, Canada and Europe practically the bulk of regulation for community use has already been established or is in its final stages, with actual commercial or community installations already in operation in some municipalities, in Brazil Anatel is concentrated only in the licensing of mobile services in the 4G/LTE modality in the range 698-806 MHz [18]. For ITU's Region 2, Recommendation 224 defined this range for mobile services. This ITU Recommendation was discussed in the Interamerican Telecommunications Commission (CITEL, a commission of the OAS [19]) in 2006, which defined the ranges 698-764 MHz

13. http://www.ahciet.net

14. Study by Telecom Advisory Services LLC (TAS) for the GSMA and AHCIET. See http://convergenciadigital.uol.com.br/cgi/cgilua.exe/sys/start.htm?infoid=27781

15. http://www.abert.org.br

16. Luís Osvaldo Grossman, "Teles e radiodifusão afiam disputa pelo 700 MHz", Convergência Digital, Nov.25th, 2011, in http://convergenciadigital.uol.com.br/cgi/cgilua.exe/sys/start.htm?infoid=28199

17. Intervozes is one of these civil society organizations, http://www.intervozes.org.br, and another one is Nupef, http://www.nupef.org.br

18. Anatel, Portaria 681, Aug.6th, 2012.

19. http://web.oas.org/citel/en/Pages/default.aspx

and 776-794 MHz for mobile services, and the ranges 764-776 MHz and 794-806 MHz for governmental use - but so far there has been no formal adoption of this recommendation by the member countries.

Local governments and entrepreneurs, as well as community organizations and movements for digital inclusion, ought to proactively support a public policy allowing for unlicensed or light-licensed use of spectrum currently not in use (or that can be used in secondary mode), employing the new radio technologies at the edge of the network. These opportunities also require a policy to ensure isonomic access to backbones through points of presence in each municipality with an affordable cost/benefit ratio, as well as stimulus to deploy local fiber networks. It is hoped that the national broadband strategies supported by the federal government contemplate these prerequisites to stimulate innovation and digital inclusion at the edge.

POLICY-BASED RADIOS

6

Timothy X Brown
University of Colorado, Boulder
USA
Carnegie Mellon University
Rwanda
timxb@colorado.edu

Jon M. Peha
Carnegie Mellon University
USA
peha@cmu.edu

This paper describes a new radio technology, denoted policy-based radios, which has the potential to enable greater access to the radio spectrum while enhancing and simplifying spectrum management. Spectrum management faces both challenges and opportunities in developing countries. The role for policy-base radios in this environment is described as well as key design decisions for their use.

6.1 INTRODUCTION

Broadband access is key to economic growth in the modern interconnected economy. Ironically, recent decisions by the U.S. Federal Communications Commission (FCC) [1][2][3] will soon yield a new commercial wireless technology that may be even more useful for the expansion of broadband access in developing countries than in the U.S. The FCC opened the door for "TV white space" devices that operate in spectrum allocated to television. These devices use geolocation technology and a database of TV transmitter locations to avoid harmful interference to TV. Several other nations led by the U.K. are also in the process of making it legal to use this technology.

TV white space devices are a special case of so-called *policy-based radios*, which are radios governed by policies that are machine-readable and easily modified. The ability to customize policies and even change them over time brings a flexibility that can greatly enhance effective

1. Federal Communications Commission, Second Report and Order and Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Nov. 14, 2008.
2. Federal Communications Commission, Second Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Sept. 23, 2010.
3. Federal Communications Commission, Third Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, April 5, 2012.

use of spectrum, especially in developing nations which have spectrum needs and resources that are somewhat different from the economies that tend to drive demand for wireless devices. Nevertheless, there are challenges to applying policy-based radio technology in order to meet the broadband needs of developing countries. There are significant differences in regulation, how the network will be used, and the underlying infrastructure that need to be addressed. Many countries have high-capacity transmission networks, but are severely limited in last-mile connections. Rwanda for instance has 2,300 kilometers of fiber optic cables connecting distant parts of this small country but limited distribution and access to the end users. Last-mile connectivity could be provided by policy-based radio devices. For instance, TV white space frequencies are better suited to provide coverage in hilly or densely foliated terrain than higher frequencies. Moreover, if there were regulatory reform, the amount of spectrum that could be available to policy-based radio devices is likely to be much greater in places in developing countries than in major U.S. and U.K. markets, because there is spectrum that remains fallow in developing countries in part because this spectrum is unavailable in the largest markets; this prevents manufacturers, standards bodies, and regulators from unleashing wireless devices in these bands that would only be useful in smaller markets.

This discussion suggests that policy-based radios will have a role to play in broadband access. This paper argues that these radios can play a significant role for spectrum regulators to manage many aspects of the radio spectrum. Though there remain challenges to the widespread use of policy-base radios, which we discuss, the technology has developed to the point where its use should be considered.

6.2   CHALLENGES TO SPECTRUM MANAGEMENT

Spectrum management faces several challenges especially in developing countries. For instance, Africa falls within the International Telecommunication Union's Region 1 for the purpose of managing the global spectrum. Region 1 also includes Europe and the Middle East and so supports diverse economies. Africa's population density is about one fifth of Western Europe's and the per capita GDP is about 22 times smaller. From these figures we can expect that the spectrum needs of Africa may differ from other parts of Region 1. Within Africa there are also many differences between countries.

Country spectrum regulators need to balance competing needs on several levels. First, they must balance allocations for individual countries versus the larger Region 1. Deviations from Region 1 band plans can lead to interference at international borders that is difficult to manage. Second, they must balance custom radio applications versus regional

and global standards. Modern radio equipment is complex. Managing and maintaining radio software and hardware leads to costly devices unless these fixed engineering costs can be spread across many units. So, spectrum managers must avoid disqualifying the use of low-cost commodity radios through non-standard allocations. Third, though a non-standard allocation today may be consistent with current uses in adjacent countries and current technologies, spectrum use evolves continuously. As countries develop, previously under-used bands in bordering countries become more used within existing allocations making cross-border interference challenges more acute. We would also expect that regional allocations will change to accommodate changing use of the radio spectrum. Even within existing allocations, new services that are socially and economically important can emerge. In short, spectrum regulators need a future-proof technology that allows them to unlock the spectrum's potential both today and in the future.

Historically, spectrum allocations have been "hardcoded" in the radio devices themselves. For instance, the allocation to broadcast radio is encoded in the tuners of the millions of consumer radios sold. This static coding in the radio devices is a drag on change and innovation. Because of this drag, allocations have tended to be static with very infrequent changes. Spectrum allocations continue long after the original utility has subsided and there is significant "friction" to changing allocations. As a result, when new spectrum needs arise spectrum is not available. This leads to spectrum hoarding and spectrum warehousing whereby spectrum licensees fight to keep their spectrum even when their spectrum use is socially suboptimal.

While spectrum is fully allocated, paradoxically, studies show that much of the valuable spectrum is underutilized for much of the time. The result is a gross under-utilization of the spectrum. Spectrum measurements even in large cities of countries such as the United States and Great Britain show that no transmissions can be detected from a fixed receiver in the vast majority of spectrum at any given time [4]. In a particular frequency band, if there are regions in which new devices can be allowed to transmit without causing harmful interference to any incumbent systems, then these regions are referred to as spectrum *white spaces*. White-space sharing occurs when devices are allowed to transmit when and only when they can determine that there is white space. Moreover, even when spectrum is in use, it may be possible for additional devices to operate without causing harmful interference under the right technical constraints. This is referred to as gray space sharing [5]. Opportunities for both white space sharing and gray space sharing are inevitable because of the relatively static way spectrum has traditionally been managed. For example, a license-holder may be given exclusive rights to transmit at all times throughout a large region, when it only wants to operate in part of the region for part of the time. Note that white space can change over time, e.g. if that license-holder decides to deploy transmitters in new locations, or if a TV broadcaster changes its antenna or transmit power.

4. Federal Communications Commission. In the matter of Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies, (ET Docket No. 03-108) and Authorization and Use of Software Defined Radios (ET Docket No. 00-47), ET Docket No 03-222 Notice of proposed rulemaking and order. Dec. 30, 2003.

5. J. M. Peha, "Spectrum Sharing in the Gray Space," Telecommunications Policy, Vol. 37 No. 2-3, March, 2013, pp. 167-77.

That is why the flexibility inherent in policy-based radios is important.

Attempts to share spectrum are common but they are not always successful. In the United States, for example, garage door opener manufacturers were allowed to operate in a radar band on a secondary basis. Eventually, these secondary users became so prevalent that the primary user was required to invest to mitigate the growing number of interference cases. It is worth noting that it was not the primary user that was suffering harmful interference but rather the garage door openers. Moreover, the interference problems were unexpected, but because the garage door openers were already widely deployed with hard-coded sharing policies, there was no easy way to change the technology so that interference would not be problematic. This cost the primary user. Thus, it is understandable that primary license holders are reluctant to share their spectrum with even the most benign of other services. More flexible technology may reduce such problems, and thereby encourage greater sharing.

Moreover, there is particularly great opportunity in developing countries for sharing. In Rwanda, for instance, there is a single TV channel in use (although there are multiple transmitters on this channel according to the DVB standard). Currently there are plans for at most two other TV transmitters. This implies that only 24 MHz is occupied out of the 320 MHz allocated to TV broadcasting. In addition to TV there are many other spectrum bands that may be unused in a developing country such as maritime bands in landlocked regions, and satellite downlink bands far from any satellite users,

Based on these arguments, it is clear that there needs to be a mechanism to reduce the friction associated with spectrum sharing, to increase the ability of countries, especially developing countries, to flexibly allocate and reallocate spectrum.

6.3 COGNITIVE AND POLICY-BASED RADIOS

A policy-based radio is a "radio in which the behavior of communications systems is governed by machine-interpretable policies that are modifiable," where a policy is a "set of rules governing radio system behavior" [6]. Policies can be relatively static to describe conventional spectrum allocations, or they can describe dynamic spectrum sharing. They can encode hardware limits, such as the allowed tuning range of the underlying frequency agile radio, as well as bands to be avoided. In this way the policy-based radio is a unified mechanism to reason about multiple facets of spectrum use.

These policies may be established by regulators, standards bodies, manufacturers, system operators, or more likely some combination thereof. Thus, it is possible to change how a policy-based radio is al-

6. SDR Forum, "Cognitive Radio Definitions and Nomenclature," SDRF-06-P-0009-V1.0.0, Sept. 10, 2008.
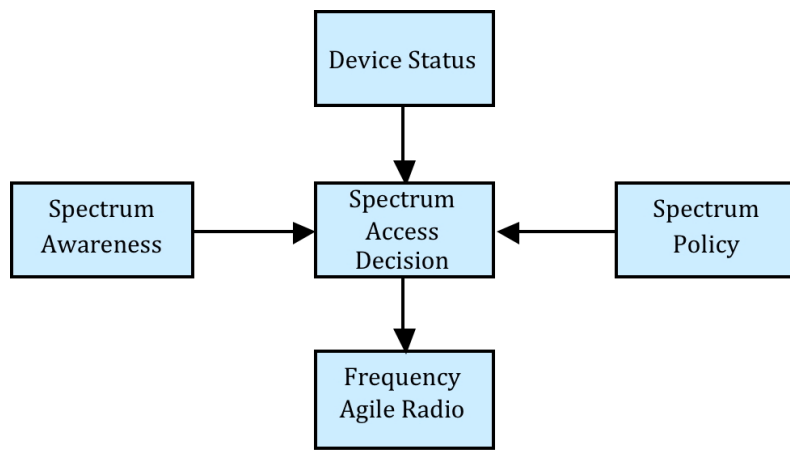
Figure 6.1: Functional blocks of a cognitive policy-based radio

lowed to access spectrum simply by modifying a few input files. This modification may happen when the device is produced, perhaps to take a mass-produced general-purpose policy-based radio and then customize it at little cost for different national markets. On the other hand, modification may occur after the system has already been deployed, perhaps to keep pace with changing regulations, or to shift out of a band after unexpected harmful interference has been observed.

The concept of a policy-based radio can be made even more powerful when combined with that of *cognitive radio*, *software-defined radio*, or both. A cognitive radio is a "radio or system that senses, and is aware of its operational environment and can dynamically and autonomously adjust its radio operating parameters" [7]. One way that a radio may be reconfigured in this way is to make use of spectrum that it somehow senses is available. A software-defined radio is a radio that can be reconfigured through software, as opposed to hardware modifications. Great progress has been made in recent years on making policy-based radios, cognitive radios, and software-defined radios that are cost-effective, and although the concepts are orthogonal, they are also mutually reinforcing in the realm of spectrum access. As an example, Figure 1 shows a radio that is cognitive, since it has sensing in the form of spectrum awareness, the ability to reconfigure in the form of frequency agility that can alter frequency and modulation, and a cognitive or decision-making capability. The radio is also policy-based, since decisions are made in consideration of spectrum policies that are modifiable.

The choice of bands is a so-called *spectrum access* decision that is based on several factors. *Device status* is information such as the device location. *Spectrum awareness* is how the cognitive radio discovers what frequency bands are not being used by an incumbent user and thus potentially available. We focus here on methods that combine the device status and spectrum policies. *Spectrum policies* are machine readable

7. Radiocommunication Study Groups, "Working Document Towards A Preliminary Draft New Report: Software Defined Radio In Land Mobile Services," International Telecommunications Union Document 8A/121-E, 15 September 2004.

rules that specify in what frequency bands the radio is permitted (or prohibited) to transmit, at what locations, when they can be accessed, and under what conditions. Thus to transmit in a band requires that the band is within the capabilities of the radio, not occupied by an incumbent user, and that there is a policy stating that its use is appropriate for the application. The spectrum access decision is not an isolated and fixed decision. Both the transmitter and receiver must find and agree on a common spectrum band in a so-called rendezvous process. As conditions change such as a change in location the radios must make a handoff from one band to another in what is denoted a spectrum handoff [8].

8. I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, "NeXt generation dynamic spectrum access cognitive radio wireless networks: A survey," Computer Networks, 50(13), 2127-2159, 2006.

6.4 ADVANTAGE OF POLICY-BASED RADIOS FOR SPECTRUM SHARING

Policy-based radios present several advantages for spectrum sharing.

6.4.1 *Making more spectrum available*

The policy-based radio allows finer-grained allocations of spectrum over time, frequency, and location. A policy can be thought of as a time-limited lease that specifies a period over which a right to access the spectrum within the applicable technical constraints is valid [9]. The period can range from a short term such as a fraction of an hour to long terms that extend into months. The periods have start and stop times and may be valid starting at some future time. The policy can specify daily or weekly schedules of allowed operation. The policies can allocate large allotments of spectrum but can as well specify down to individual channels or sub-channels. The policy can specify frequency-dependent power limits. Locations can be precisely defined to protect incumbent users while maximizing the area where a band can be used.

9. J. M. Chapin, W. H. Lehr, "Time-limited leases in radio systems," IEEE Communications Magazine, vol. 45, no. 6, pp. 76-82, June 2007.

As an example, policies to operate in and near a radar band would first define areas around the radar sites where the band cannot be used, which are known as *exclusion* zones, and areas where the band can be used. If gray-space sharing [10] is supported, there will also be areas where usage is allowed, but only within specific technical constraints carefully designed to protect the radar from harmful interference [11]. Policies for allowing spectrum use directly in the band would have larger exclusion zones, while adjacent bands may have smaller exclusion zones. The policies would be valid for a month at a time and renewed at, say, weekly intervals. The result is a seamless access to the band over time. When a new radar is to be installed, the new radar site will be incorporated into new policies and the radar operator can have confidence that the old policies will expire within a month freeing up the spectrum around the new site. Similarly, if an existing radar is upgraded to a new technology,

10. J. M. Peha, "Spectrum Sharing in the Gray Space," Telecommunications Policy, Vol. 37 No. 2-3, March, 2013, pp. 167-77.

11. R. Saruthirathanaworakun, J. M. Peha, and L. M. Correia, "Opportunistic Sharing between Rotating Radar and Cellular," IEEE Journal on Selected Areas in Communications, Vol. 30, No. 10, pp. 1900-10, Nov. 2012.

this may lead to changes in the size of the exclusion zone, or changed in the policies governing gray-space sharing.

More generally, policies address the problem of static spectrum management. Fine-grained allocations foster more efficient use of the spectrum with greater communication capacity to support future growth and innovation in wireless applications. More importantly, policy-based radios can use such allocations automatically while still adhering to stakeholder requirements. This automation provides government regulatory flexibility that is not currently present and promotes better use of the spectrum. Spectrum regulators such as the FCC in the United States, recognize that policy-based radios can be applied to dynamically reuse white spaces in licensed spectrum bands, thereby efficiently utilizing under-utilized spectrum [12].

6.4.2   Making spectrum management simpler and more reliable

Spectrum does not come from a single source. The spectrum used by an end user may come directly from a top-level national spectrum regulator or it may come from spectrum assigned to intermediate spectrum brokers, frequency coordinators, or service providers. Policies can encode the delegation of spectrum management from a top-level allocation to a spectrum manager through sub-policies and sub sub-policies that further delegate spectrum management. Coordination can be delegated to the lowest level that is sufficient. A specific policy would need to have its provenance traced through parent policies back to a trusted source. Since the policies are machine readable it is easy for end-users, intermediate spectrum managers, or national spectrum regulators to automatically check them for logical consistency and to detect potentially conflicting allocations. Further, using cryptographic digital signatures, the policies can be authenticated as being valid without malicious or benign errors. This policy distribution concept has been described by Brown and Sicker[13].

6.4.3   Making spectrum regulations evolvable

Policy-based radios allow regulators to adopt spectrum policies with the expectation that those policies will evolve over time, which has great advantages. One of those advantages is the use of strategies that deliberately learn from experience. When spectrum is shared, there is often some degree of uncertainty regarding the risk of harmful interference. Since regulators are usually obligated to protect incumbent systems, this uncertainty leads to very conservative rules. Moreover, once these rules are in place, they are hard to change. Currently, spectrum technical rules are often written into federal regulations, and changes are slow and difficult, in part because transparent administrative procedures are inherently slow compared to the pace of innovation in wireless technology,

12. Federal Communications Commission, Spectrum policy task force report, (ET Docket No. 02-135), Nov. 2002. http://hraunfoss.fcc.gov/edocs_public/attachmatch/DOC-228542A1.pdf

13. T. X Brown, D. Sicker, "Secure Distribution of Spectrum Policies to Cognitive Radios in Unmanned Aircraft Systems," Proc. AIAA Infotech Aerospace Conf., Atlanta, Apr. 20-22, 2010

and in part because some changes face stiff resistance from existing users since those changes can make radios obsolete. As a result, excessively conservative choices in rules may persist for years or decades. Policy-based radios enable spectrum managers to flexibly change rules over time to incorporate experience in the field and track new technology. For instance, the policy for secondary use in a radar band may start with policies that have large exclusion zones and low power limits. With experience these policies may be relaxed or tightened to manage the interference to the radar. Further, parallel policies can require, say, spread spectrum to promote alternate technologies.

Policy-based radios also help regulators address the challenge of usage flexibility. As discussed by Peha[14], one of the dilemmas that regulators face is how much technical flexibility to give license-holders and unlicensed spectrum-users. It is often possible to reduce the risk of harmful interference when systems must coexist, provide some degree of interoperability, or leave the door open for technologies not yet invented to share a band efficiently by imposing some technical limits on devices, but doing so also limits innovation in ways that may turn out to be significant. In the past, finding the right balance has meant predicting the future, but this is not necessary with policy-based radios. For example, perhaps a shared spectrum band was created with few constraints on devices. Over time, it is determined that devices interfere with each other in unexpected ways. This occurred in unlicensed bands when WiFi devices were found to cause harmful interference to bluetooth devices. At the time, the only option was to change the technologies, and wait for legacy devices to reach their end of life. Had these been policy-based radios, an additional option would have been available to regulators: they could have split the unlicensed band into two pieces, each with more technical constraints than were initially imposed, and one better suited for WiFi and the other better suited for bluetooth.

6.4.4   Facilitating spectrum leasing to increase efficiency

The right to access spectrum can be obtained from either of two very different sources: a regulator and a spectrum license-holder [15]. In addition to giving regulators greater ability to safely make fine-grained time-limited policies, policy-based radios bring these same capabilities to license-holders. As discussed in Section 2, some spectrum held by license-holders is typically unused, in part because of coarse spectrum allocations that cover a large region when the spectrum is needed in only part of the region, or that cover all time even though the spectrum is used only occasionally. Moreover, since spectrum is difficult to obtain, users may warehouse it for future applications, or even hoard it to prevent competition, which causes more spectrum to be unused for extended periods.

License-holders can lease their unused spectrum temporarily to other parties. Spectrum leasing became legal in the U.S. in 2003 and

14. Jon M. Peha, "Spectrum Management Policy Options," IEEE Communications Surveys, Vol. 1, No. 1, Fourth Quarter 1998.

15. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

2004 [16] [17]. Because license-holders can be paid for these arrangements, they have incentive to maximize the amount of spectrum in use. While the idea of leasing is not new, the policy-based approach gives incumbent users the ability to embed powerful and precise control over secondary users into these arrangements. Machine readable policies can precisely define lease terms in a leasing agreement, and make it easier for lessees to follow these terms strictly. Moreover, these machine-readable policies are time-limited, which limits the risk even if the terms are found later to be unfavorable to either the lessor or lessee. Thus, the policy-based approach could encourage more spectrum holders to lease their spectrum.

For instance, a spectrum holder that operates in an urban area may lease spectrum for a service in rural areas. Similar to the spectrum regulator in the previous section, the spectrum holder can start with conservative leasing terms for short trial periods that with experience evolve and extend for longer periods. If interference is found to be problematic the spectrum holder could choose to not renew the short-term lease or to appropriately modify the terms.

As a result of this greater control both before and after a lease, more spectrum will be offered up for leasing. Other users may be more willing to share spectrum such as between different government agencies. Further spectrum that has been allocated at the Region 1 level to services that are unused in individual countries can be made available in a controlled way. Spectrum that is tied up because of these inefficiencies can be unlocked by spectrum managers through policy-based radio technology.

6.5   STAKEHOLDER REQUIREMENTS

One of the many uses of policy-based radios is to allow new users to share spectrum with an existing spectrum user. In this model the existing spectrum user is denoted the *incumbent*, and the new user that is attempting to use the spectrum is denoted the *entrant*. The incumbent and the entrant as well as the regulator have requirements that a spectrum sharing approach must meet.

The incumbent is most concerned with assured coexistence and compatibility to avoid harmful interference. They are also concerned with their rights to use the spectrum or to change and upgrade incumbent operation without limitations imposed by the new entrant. They want to avoid the earlier radar band example where a change in the incumbent operation led to a complaint by the garage door opener new entrant. The sharing arrangement should be secure, trusted, and enforceable.

The new entrants also are concerned with coexistence and compatibility and to not be subjected to unreasonable interference protection criteria. Further, since they are accessing the spectrum on a secondary basis, they want assurances that the spectrum sharing scheme will con-

16. Federal Communications Commission, Report and Order and Further Notice of Proposed Rulemaking, in the matter of Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, WT Docket No. 00-230, Oct 2003.

17. Federal Communications Commission, Second Report and Order, Order on Reconsideration, and Second Further Notice of Proposed Rulemaking, In the Matter of Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, WT Dkt No. 00-230, Sept. 2004.

tinue and they can design long-lived hardware and services around the scheme. They also want assurance that the scheme will produce sufficient useful spectrum.

The regulator is concerned with making sure that the spectrum sharing schemes are both flexible to allow the greatest utility in sharing but also low-cost and easy to manage by the regulator. As a principle, the regulator should avoid over specifying the technical details of sharing since best practices will evolve with experience.

6.6   SPECTRUM ACCESS THROUGH POLICY-BASED RADIOS

Spectrum access is the process by which the policy-based radios choose which frequency bands to communicate. It consists of several dimensions related to the type of spectrum, which parties control its use, and how it interacts with applications. Conceptually, spectrum access can be thought of as having an appropriate policy that permits usage of a specific band for a specified period. This section is the most detailed in order to highlight the rich set of options available to the regulator provided by policy-based radios.

6.6.1   Types of Spectrum Access

There are many different policies regarding spectrum access, any one of which can in theory be written in machine-readable form, albeit with a large number of fields. A system may be granted exclusive access, or it may share spectrum with others. If there is sharing, there are two fundamental traits that define the nature of the sharing [18]. First, there can be *primary-secondary* sharing, where primary devices are relatively unconstrained and secondary devices are prohibited from accessing the spectrum in a manner that causes harmful interference to a primary device, and there can be sharing among *equals*, where all devices have equal priority and equal responsibility to avoid interference to the others. Primary-secondary sharing is preferable when one kind of system is more important, or when one kind of system is already deployed and cannot easily be changed. Thus, we can deploy policy-based secondary devices without making any changes to the legacy primary systems. In the TV band, for example, we currently have both kinds of sharing [19]. Television broadcasters have primary rights, but secondary users must share spectrum with each other as equals, and tolerate each other's interference. Policies can specify both types of access.

For both sharing among equals and primary-secondary sharing, sharing can be based on *cooperation* or *coexistence* [20]. With cooperation, systems communicate with each other to avoid harmful interference, whereas with coexistence, devices may sense each other's presence but never explicitly communicate. Policies for this kind of sharing may

18. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

19. Federal Communications Commission, Second Report and Order and Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Nov. 14, 2008.

20. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

mandate that a specific listen-before-talk (LBT) mechanism be used in this band, for example, or that all transmissions use spread spectrum modulation. Cooperation can generally lead to higher levels of spectrum efficiency, but then devices must be required by some authority to be designed to be interoperable. Thus, for example, a policy in a band with cooperation may require devices to listen for "beacons" in a specific signalling band, and cease all transmissions in the band once a beacon is detected.

With any of the forms of sharing described above, it is possible that a band may contain only licensed devices, only unlicensed devices, or some of each. Licenses are permission from a regulator to transmit, and they usually (although not always) come with some guarantee of exclusivity. Licenses always include constraints on how the spectrum can be accessed which must be included in machine-readable policies. The level of flexibility varies considerably, from FM radio where the location, power, and modulation scheme of all transmitters is specified to the most flexible cellular licenses which allow use of almost any technology provided that interference caused to adjacent bands and adjacent regions is below given thresholds. Unlicensed devices are allowed to operate without explicit permission from a regulator, but they do so contingent on following whatever rules were established for the band. These are the rules that must be included in machine-readable policies.

6.6.2 Control of Spectrum Access

Spectrum access is controlled by policies. What are the mechanisms to distribute and manage policies that underpin the control of spectrum access? To address this question, it is necessary to examine where the policies come from, where they are ultimately used, and how the process is mediated.

Where do Policies Come From

Control over spectrum can be delegated through the leasing and sub-leasing of spectrum through policies. Policies originate from base spectrum regulatory authority. These can sublease to other agencies which in turn sublease, eventually leasing to a user.

The policies used to access spectrum must be valid in three ways. First, they must come from a source which is authorized to issue a policy. An end user needs to see not only the final policy, but also the chain of policies tracing back to a trusted root source. Because policies might be corrupted or maliciously modified in transit, the policies need to be cryptographically protected with a digital signature so that the end user can verify that each policy originated from the purported source [21]. Second, they must be consistent and not contradict other policies. The characteristics of the policies such as the spectrum bands and time period for each sub-policy must be a subset of the higher-level policies.

21. W. Stallings, Network security essential: applications and standards, Upper Saddle River, NJ : Prentice Hall, 2000.

22. IEEE 1900.5 Working Group on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications

Further, there may be other prohibitive policies that exclude use in certain bands. The end-user must validate the policy it uses against these other policies. To enable this validation and reasoning, the policies must be written in an appropriate machine readable form [22]. Third, they must apply to the situation that they are being applied. The end-user must validate that it meets the location, type of communication, and other conditions of the policy before it uses the policy.

The base authority can grant such spectrum policies to multiple sub-entities which in turn can grant them to multiple sub-sub-entities. This process produces a distributed policy tree with each node only required to a) store the chain of policies to the root of the tree that validates its authority and b) manage issuing policies to their direct child nodes. Policies can be issued with the *entire chain in every policy* so that a child policy includes the parent, grandparent, etc. policies. This simplifies the policy validation since every policy contains all the required information for the end user to validate the policy. However, in an environment where a child policy changes often, this increases the burden on the system since the entire chain has to be sent every time. An alternate approach is a web approach where the *chain must be assembled from multiple policies*. Here the challenge is that the end user needs to have access to and be able to find all the policies in the chain. This can be simplified by embedding short "resource locator" information about the needed higher level policies. In this case, the parent policies are stored and only the child policy changes. Note that the public keys required for the digital signatures can be distributed either *embedded in the policies themselves* or according to a *separate infrastructure for distribution*.

Where are Policies Used

The end user of a policy could be the radio at either side of the connection. The side receiving the policies would control the choice of frequency band. The choice could be made by *the transmitter* or *the receiver*. In using a policy, it is possible for the two policy-based radios to be widely separated. Thus, in applying the policy the end-user must consider the situation at both sides of the connection. In some cases, both sides of the connection may hold their own set of policies and neither is controlling the choice. Because they are widely separated they may hold different spectrum awareness views. In the worst case, there may be no connection and the problem is for the radios to find a common spectrum band to *rendezvous* in order to start communication [23]. Policies can also go to some other *third party* controlling entity that acts on their behalf. Some policies are *open-ended*; anyone holding the policy that meets the conditions of the policy may use the policy. Other policies are assigned to use by specific end users.

23. I.F. Akyildiz, W.Y. Lee, M.C. Vuran, S. Mohanty, "NeXt generationdynamic spectrum access cognitive radio wireless networks: A survey," Computer Networks, 50(13), 2127-2159, 2006.

In the above example, the policy's authority follows through specific organizations. More generally, these policies are mediated by a *spectrum manager*. The spectrum manager is responsible for gathering policies from appropriate agencies and distributing them to sub-lessees. A spectrum manager may be an agent within an organization or a separate designated third party.

There are several models for how spectrum policies can be distributed. In a *shared* model, a policy may give access to a set of end-users who must coordinate their access. At one extreme, the access is open-ended in terms of the number of users who are given access and as to the period that it is available. There may be operational limits to the number of users on a band (only so many radios can be at a location) or other limits (a band that is busy will simply not be used). Such shared use works better when there are rules or etiquette (e.g. listen before talk) to manage communication. To avoid channels from becoming overloaded and unusable, a *limited shared* model may be used where the set of users that have access are limited in number or time. At the other extreme is a *dedicated* model where a spectrum band may be given to only one end-user at a time. The limited and dedicated models require the spectrum manger to track which users have active policies at any given time. To better control the access, the spectrum manager may flag a policy as being *terminal*, meaning that it cannot be subleased further.

Policies can be created on an *as-needed* basis whereby the spectrum manager issues policies to the end user to fulfill specific needs. Policies can be *negotiated* whereby the end-user may make a request to a spectrum manager for a policy to fill a specific need. The spectrum manager responds with a policy that meets the request or with a message that the request cannot be met. In the latter case, the end user may make a revised request seeking to find the spectrum it needs. Policies can also be *premade* and warehoused in a database accessible to end users. Here a user visits the database, downloads suitable policies and makes its own decision about which policy to use. The premade model works best for distributing shared policies and for storing higher level policies that users can use to validate end-user policies. This section emphasizes the flexibility with which spectrum access can be managed through the use of policies. The design choices are summarized in the table below.

Table 6.1: Design Choices

Property	Design Choices
Spectrum priority	Unlicensed
	Licensed
Sharing priority	Primary-secondary
	Equals
Sharing mechanism	Cooperation
	Coexistance
Policy authentication	Entire chain in every policy
	Chain must be assembled
	from multiple policies
Public key distribution	Embedded in policies
	Separate infrastructure
Policy choice	By transmitter or receiver
	Assigned by third party
	Rendezvous
Policy assignment	Open-ended
	Specific end users
Spectrum exclusivity	Open shared (unlicensed)
	Limited shared
	Dedicated
Policy creation	As-needed
	Negotiated
	Premade

6.7   GETTING STARTED

The previous sections describe the flexibility that is possible using policy-based radios. How does a regulatory authority get started? The regulator should choose a set of bands that has suitable characteristics such as being underutilized in geographic areas of interest, relatively stable incumbent users, sufficient spectrum to be useful for entrants, and available radio equipment to operate in the spectrum. In the US and UK, they have selected TV white space access in TV bands because it provides a large amount of spectrum for broadband access in rural areas and is of sufficient interest that radio manufacturers have developed broadband access radio equipment to operate in the band.

In many countries, the users of a band are not fully documented. There may be informal agreements or simply "squatters" using the band without permission. The US, for instance, has many wireless microphones operating in the TV band. To understand the actual use may require surveys of known spectrum managers as well as field surveys with a spectrum analyzer and other measurement tools.

At this point the regulator needs to develop a regulatory framework

for entrant operation in the band. The US and the UK both have significant work in this area [24] [25]. However, experimental licenses, and test deployments may be a useful approach as is being done in many countries.

A policy database needs to be created with policies that protect the incumbent users while giving access to the entrants. The capabilities of the database depend on the expected usage. A simple web interface with downloadable lists of policies may be sufficient for a small scale or relatively static scenario. More demanding scenarios will require more powerful database mechanisms.

The regulator may wish to license outside parties to play important roles rather than play all those roles itself. In the case of TV white spaces, for example, the U.S. has certified a dozen different entities to operate the databases that a white space device must query periodically to find out which bands are available at its location [26]. While the FCC will remain involved in the data that goes into the database, the FCC can leave all interactions with end users to the operators of these databases. Since the entire system depends on correct operation of the databases, the FCC must certify database operators.

An alternative to this approach would be for a regulator to provide a spectrum license to a *band manager*, an approach that was made legal in the US in 2004 [27], and leave nearly all of the technical decisions to the band manager. This band manager may even be a profit-seeking company and may charge for access. Where there is concern that one band manager may act as a monopolist, it is possible to create multiple bands with different band managers. The band manager approach is likely to be effective in some cases, and ineffective in others depending on transaction costs relative to the value of the spectrum lease [28]. Standardized machine readable policy languages will lower transaction costs and foster competition between bands.

When there is sharing, regulators also need ways of mitigating the effects of harmful interference, both a priori and a posteriori. Beginning with the former, as with traditional radios, processes will likely be needed to certify that policy-based radios are safe. However, as discussed by Peha[29], certification is more complex with policy-based radios, in part because the behavior of these radios can change when the policy inputs change, and in part because there may be many heterogeneous devices interacting with each other. Regulators around the world are working on improving certification.

Regulators also need processes to respond to harmful interference after it has been found to occur. Given that the policy-based technology allows rapid changes in devices that have already been deployed, it would be best if the regulatory decisions that might motivate such changes could also be rapid, perhaps facilitated by forums where those operating in a given band can meet directly to discuss problems without requiring all communications to pass through the regulator [30].

24. Federal Communications Commission, Third Memorandum Opinion and Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, April 5, 2012.

25. Ofcom, "TV White Spaces: A consultation on White Space Device Requirements," November 22, 2012.

26. Federal Communications Commission, Order, in the matter of Unlicensed Operation in the TV Broadcast Bands, ET Docket No. 04-186, Jan. 26, 2011.

27. Federal Communications Commission, Second Report and Order, Order on Reconsideration, and Second Further Notice of Proposed Rulemaking, In the Matter of Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets, WT Dkt No. 00-230, Sept. 2004.

28. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

29. J. M. Peha, "Sharing Spectrum through Spectrum Policy Reform and Cognitive Radio," Proceedings of the IEEE, Vol. 97, No. 4, pp. 708-19, April 2009.

30. J. M. Peha, "Spectrum Sharing in the Gray Space," Telecommunications Policy, Vol. 37 No. 2-3, March, 2013, pp. 167-77.

6.8 CONCLUSIONS

Policy-based radios are a flexible technology that supports different spectrum sharing models to enable access to more spectrum. Fallow and underutilized spectrum can be used through time-limited policies so that a spectrum manager can manage when, where and how spectrum can be accessed. By resolving the static allocation issues spectrum holders would be more willing to offer up spectrum thus making more spectrum available and less spectrum left fallow. This technology is especially important in developing countries which have underutilized spectrum that can be employed for economic growth while not precluding the use of future radio advances. This paper describes the key issues for regulators to consider in the use of policy-based radios in an effort to promote how they would be used in practice.

TV WHITE SPACES: MANAGING SPACES OR BETTER MANAGING INEFFICIENCIES?

7

Cristian Gomez *
Radiocommunication Bureau
International Telecommunication Union
cristian.gomez@itu.int

This paper[1] reviews relevant regulatory aspects concerning the operational implementation of Television White Space (TVWS) devices in some parts of the spectrum allocated to TV broadcasting. The term TV White Spaces usually refers to unoccupied portions of spectrum in the VHF/UHF terrestrial television frequency bands in some geographical areas. Trials and tests are currently underway in several countries and some commercial applications are emerging, looking at improving the utilization of the highly valued UHF spectrum resource through sharing its use with the primary terrestrial television service. Wireless broadband applications are the main focus of trials, nonetheless, the usefulness of this highly sought-after spectrum is also being considered for other applications, such as machine-to-machine communications (M2M). The low-power nature of all these alternative wireless applications is being proposed as appropriate for operation under a license-exempt[2] regulatory framework, in compliance with technical and operational specifications.

As the title of this paper suggests, there are different approaches and considerations currently being reviewed for TV white spaces. From the operational and technical aspects of accessing varying degrees of idleness of UHF television spectrum through —**managing the spaces** —to aspects concerning long-term international planning of the UHF spectrum resource as part of national ICT strategies through —**better managing inefficiencies**. These approaches are intended for improving the efficiency of the spectrum resource use, through accessing idle spectrum to deliver low-cost implementation and rapid development of user applications, and/or by planning an internationally harmonized

1. The text of this article is based on the ITU discussion paper of the same title, presented at the Global Symposium for Regulators 2013, Warsaw, Poland. The full text of the discussion paper is available at: http://www.itu.int/en/ITU-D/Conferences/GSR/Documents/GSR_paper_WhiteSpaces_Gomez.pdf

2. License-exempt framework refers to devices operating on a non-interference/non-protection basis in compliance with technical specification and/or band rules without the need for an individual device license.

---

* Disclaimer: the views expressed in this article are those of the author and do not necessarily reflect the opinions of ITU or its membership.

spectrum use from which economies of scale can be obtained (end-user devices in particular).

This paper also examines aspects of wireless markets and sustainable development of ICTs in relation to TVWS implementation, international regulatory developments of the spectrum, spectrum management and licensing frameworks. Finally, the article offers conclusions in the form of discussion of regulatory and policy questions that may need further exploration prior to implementing TVWS on a large scale, in order to take into account spectrum regulatory developments at the international level.

7.1   FINDING THE WHITE SPACES: INSTANCES OF TVWS AVAILABILITY

There are different ways in which TVWS can arise at any given location. Nonetheless, the amount of spectrum available in the form of TVWS can vary significantly across different locations and will depend on various factors, including: geographical/temporal features, the level of inter-ference potential to and from the incumbent TV broadcasting service coverage objectives and related planning and utilization of broadcasting, as well as the nature of the application intended to use white spaces (receiver sensitivity, required transmitted power etc.). These instances of TVWS availability can be categorized (not restricted to) as follows:

a. Frequency: to avoid interference within broadcasting, idle channels are purposely planned in the TV band in some geographical areas.

b. Deployment: available TV white spaces may be used given that the height of the TVWS transmit antenna and its installation site (as well as the aggregate emissions of the numerous TVWS devices) are planned in technical compatibility with nearby or surrounding TV broadcasting reception in order to avoid interference.

c. Space/distance: geographical areas that are outside the current planned TV coverage and therefore no broadcasting signals are currently present.

d. Time: a TVWS could become available when a broadcasting emission is off-air; hence the licensed broadcasting transmitter is not using the assigned frequency channel during a specific period of time (e.g. nighttime). However, this type of availability can be subject to change if the broadcaster decides to modify hours of operation.

Further, in the case of digital terrestrial television (DTT), white space availability by means of "frequency"(channel idleness) could vary greatly across regions. TV white spaces may be less prevalent if the
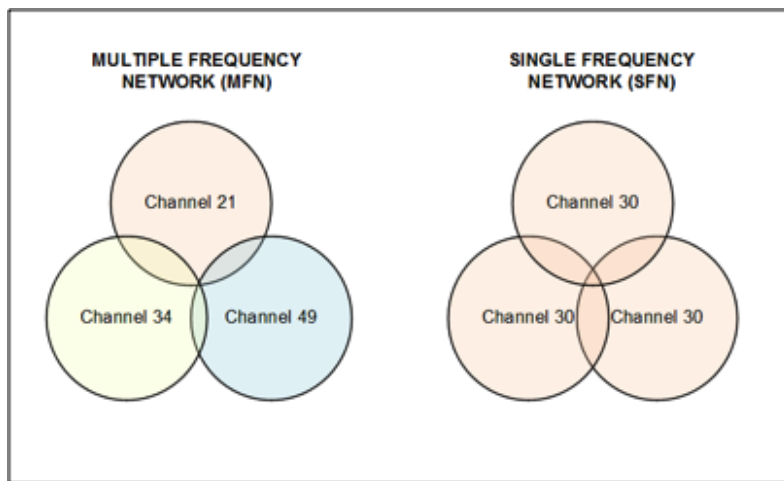
Figure 7.1: Single frequency networks use the same frequency to transmit the same programme in a given region, providing increased spectrum efficiency.

digital broadcasting network uses the adjacent channel rejection capabilities of digital technology to its full extent (and therefore fewer guard channels are needed). Also, digital TV systems permit the use of Single Frequency Networks (SFNs), in which several transmitters can use the same frequency channel without interference. The increasing use of SFNs is becoming a key element in frequency planning of television broadcasting to enable the allocation of the digital dividend(s) to mobile services. As a result, a channel that may be available at one time for TVWS may become unusable as a result of the introduction of new TV transmitters in the same SFN. Therefore, for better utilization of TVWS spectrum and for estimating the bandwidth available in the short, medium and long terms, it would be preferable to define how this part of the spectrum will be used in the future (i.e. which part for broadcasting and which part for mobile).

It is important to mention that UHF television broadcasting has been allocated as a primary service across all regions of the world, within the ITU's International Table of Frequency Allocations (part of the International Radio Regulations[3],"RR"). As per Radio Regulations, a primary service is awarded protection from harmful interference arising from secondary services, or from devices not classified as primary or secondary and operating in the same frequency bands (as the case of devices using the spectrum opportunistically, such as TVWS devices). It is important to note also that, in turn, while secondary services cannot claim interference protection from primary services, they are protected from harmful interference arising from radio devices operating opportunistically. Considering this, TVWS equipment is being developed to operate opportunistically on non-interference/ non-protection basis, under a license-exempt regime, similar to low-power/ short range devices used in ISM bands (e.g. 802.11 WiFi devices). TVWS radio emissions are to be properly controlled in order to avoid harmful interference into primary

3. Radio Regulations are available for download for free at: http://www.itu.int/pub/R-REG-RR

69

and secondary services.

It is also necessary to take into consideration that often the usage of the UHF band is not limited to broadcasting. The Radio Regulations allocate portions of the UHF band to several other radio services, such as fixed, mobile, radionavigation either on a primary or secondary basis (also some countries used these bands for SAB/SAP[4] devices on licensed basis). These allocations are utilized in a number of countries for various radio applications, thus in these countries, the utilization of white spaces on non-interference basis is more complex.

7.2 MAIN DRIVERS FOR THE RESEARCH OF ALTERNATIVE FORMS OF SPECTRUM UTILIZATION

The increasing demand (see Figure 7.2) for wireless connectivity as part of the evolution of ICTs in the "digital information era" is driving the research of alternative forms of spectrum utilization in recent years. Securing access to efficient and sustainable ICT infrastructure has become a major goal worldwide, especially considering the vital role that ICTs play across all areas of human life, such as education, health, science, financial markets, security and civil protection, media, entertainment and business development, amongst others.

With a steep increase in the demand for mobile connectivity, comes the inevitable pressure on the supply side of the resource (the radio spectrum). Noting that, while levels of spectrum demand are likely to vary across different regions depending on factors such as population density, geographic characteristics, and scale of development of broadband fixed networks, the rise of advanced consumer mobile devices and data-demanding mobile applications has considerably increased the usage of bandwidth in mobile spectrum bands in both mobile networks (e.g. 3G & 4G) and license-exempt local area networks (e.g. WiFi access).

Also, emerging economies are embracing more and more the benefits of wireless broadband communication (and therefore realizing more value from the radio spectrum as a national infrastructure resource), which provides a more affordable and flexible alternative for providing internet access to citizens and contributes in a more expeditious way to reducing the digital divide. Thus, one could also infer that the increase in demand for mobile wireless access and the consequent growth of mobile networks could also be a contributing factor to an increase in demand for ancillary wireless platforms in other frequency bands, intended to support the operation of mobile networks, such as terrestrial or satellite links used for backhaul.

Taking into account the previously described ICT ecosystem, one could also describe the need for more efficient forms of spectrum utilization according to the level of market development:
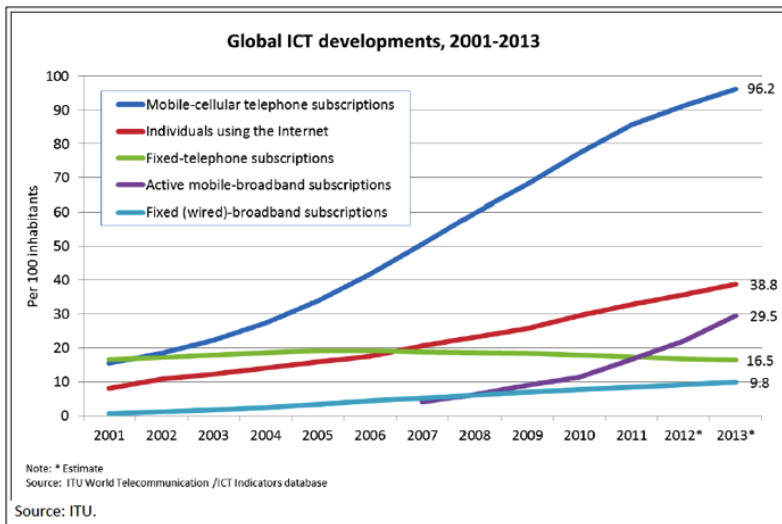
Figure 7.2: Global ICT Developments, 2001-2013

Source: Cisco.
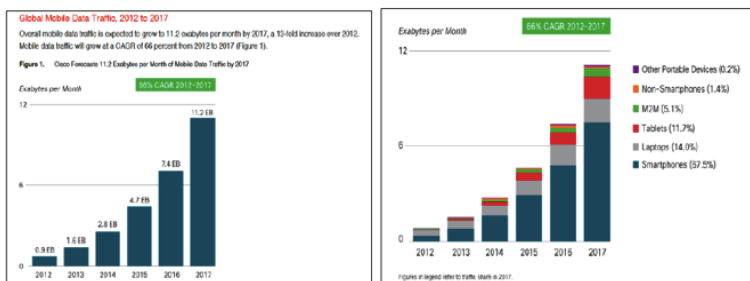
Figure 7.3: Global mobile data traffic forecast and Smartphones lead the data growth.

a. **Mature markets with highly developed infrastructure:** the need for more efficient forms of spectrum utilization is driven here mainly by factors such as increasing bandwidth bottlenecks caused by the growing uptake of data-intensive applications (see Figures 7.3 and 7.4) and rapid consumer adoption of novel mobile products. In the presence of bandwidth bottlenecks, potential regulatory choices for addressing such issue would strive to achieve improved spectrum efficiency through exploring forms of dynamic spectrum access and more efficient use (i.e. cognitive radio, spectrum aggregation), sound alternatives for spectrum sharing, and forward-looking spectrum planning and refarming (and avoidance of spectrum fragmentation). In these markets, the main objective is to match spectrum demand, given that spectrum utilization in such markets is bandwidth intensive due to the high density of users.

There are however some limitations to the use of TVWS to provide mobile broadband access to the mass consumer market (similar to cellular networks):

- Availability of TVWS spectrum in urban areas is likely to be
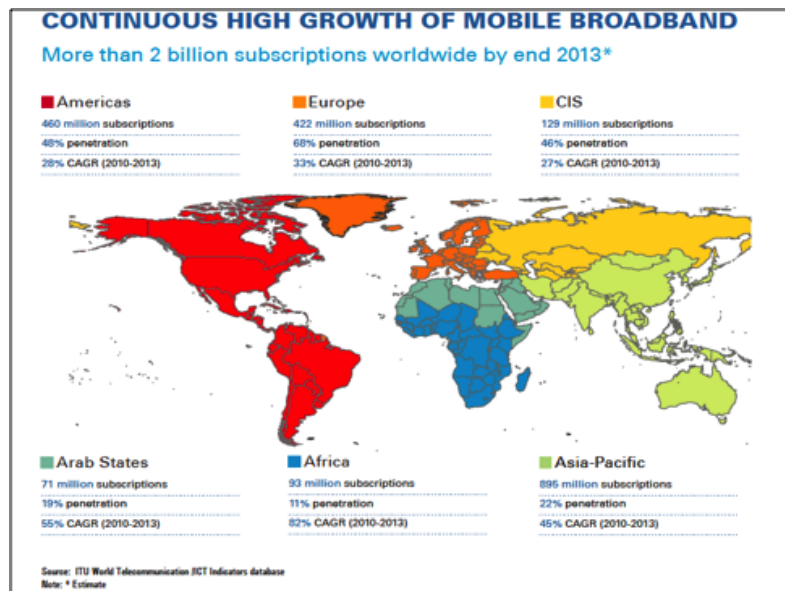
Figure 7.4: Mobile broadband growth figures per region.

small where digital television has been deployed.

- Potential for *aggregate interference* from large numbers of ubiquitous license-exempt TVWS users into the primary service (television reception).
- Self-interference within the TVWS network may also be a limitation.

Cost-benefit analyses would therefore be needed also in order to assess the relative benefits of providing only a modicum addition to the overall bandwidth pool available to users at the cost of setting up interference-limited new infrastructure for wide-area coverage. This is one of the main points of divergence between TVWS and WiFi devices used in higher frequency bands: the low-power/short range use of license-exempt WiFi devices prevents them from creating detrimental interference levels, provides for higher frequency re-use and requires a low-cost, small infrastructure footprint.

Moreover, a mismatch situation would inevitable be prevalent, where there is high demand for bandwidth but a very low TVWS bandwidth supply. Considerations in this regard would include assessing the frequency re-use capabilities of TVWS networks in bandwidth limited scenarios, balancing download and upload requirements, costs considerations for network infrastructure deployment and client's service delivery.

Costs considerations would also include an assessment of the trade-offs arising from replicating existing cellular infrastructure.

b. **Rural regions with sparsely distributed population:** the low consumer base characteristics of such regions, along with potentially

more challenging geographical features, has contributed to the lack of connectivity in such areas. Reaching these regions by means of fixed-line infrastructure is capital-intensive; therefore low short-term return on investment (ROI) levels would discourage providers from considering such an option. A wireless alternative is a more cost effective choice; especially those alternatives than can achieve large coverage areas with fewer base stations (and therefore lowering the cost of the wireless infrastructure).

Such alternatives can include mobile networks in lower frequency bands (i.e. the UHF bands below 1 GHz, where signals propagate further, thus achieving larger coverage) as well as satellite-based solutions, and lower-frequency fixed broadband wireless access (or combinations of all these alternatives). Therefore, the rural scenario represents a challenge but also has a great potential, since in terms of spectrum availability, the reverse situation to case a) occurs here: in rural areas, depending on the coverage obligations imposed to broadcasters, a larger supply of spectrum may be available for wireless broadband delivery.

In order to provide broadband coverage through TVWS to these large rural areas, there is an inherent need to build infrastructure: base station towers and backhaul links are needed before the user can access the network through some form of end-user equipment (be it mobile, nomadic or fixed to the customer premises). While in general broadband access provided through wireless networks would be much less cost intensive than fixed-line wired solutions, investments in wireless infrastructure are not insignificant; even if a kind of license-exempt regime is used by TVWS networks, together with appropriate regulatory measures. This cost of investment aspect may have an impact in terms of ROI for commercial providers considering TVWS network deployment, given that while the spectrum supply is high, the customer demand side is low. Further concerns may arise for investors also from the viewpoint of service protection and spectrum security of tenure: such an opportunistic spectrum use has no interference protection guarantees and has no future certainty with regard to regulatory changes arising from the reallocation of the spectrum to a different primary allocated service.

In summary, TVWS alternatives are being tested in pre-identified local areas of some countries as an option for addressing connectivity needs ranging from spectrum-congested zones in highly developed metropolitan areas (with varying degrees of UHF TV spectrum idleness) to large geographical rural areas lacking access infrastructure and needing lower-cost deployment alternatives (areas with low use of UHF TV spectrum). Considering the similar trend of increasing demand for wireless broadband across mature markets as well as in developing and rural markets, the need for efficient and sustainable spectrum use be-

comes extremely important for policy makers, regulators and the private sector. Collaboration of all these stakeholders is necessary for achieving not only efficient use of the spectrum resource but also to ensure sustainability of the ICT ecosystem. The ITU Radiocommunication Sector is providing this unique global and collaborative forum for reaching international agreement on the use and harmonization of radio technologies and systems. ICTs will continue to face increasing demand in terms of spectrum access in congested areas, as well as network expansion demands in rural regions seeking to breach connectivity gaps.

7.3 ON-GOING DEPLOYMENT OF DIGITAL TELEVISION BROADCASTING AND SPECTRUM PLANNING ASPECTS

The progress made in digital technologies has permitted the evolution of terrestrial television, making it more spectrally efficient by allowing, through digital compression techniques, the transmission of multiple high-quality TV programmes in one single spectrum channel (where before it was possible to transmit only one programme per channel with analogue TV). Such advancement resulted in the opportunity to reallocate new available UHF frequencies as a result of the analogue TV to digital TV transition (the **Digital Dividend**) for other uses, namely by wireless broadband applications, in response to the rapidly growing demand for mobile bandwidth[5].

The digital dividend is more fully realizable only once the transition from analogue to digital terrestrial television (DTT) is completed and the "switch-off" of analogue TV is carried out. Only then, the vacated UHF TV frequencies can be fully deployed for use by other services such as the mobile service, as the nature of the mobile service (bidirectional) is not technically compatible to share the same spectrum with TV broadcasting (unidirectional). If both services were to operate using the same frequency bands, harmful interference could occur, rendering both services useless. The operational nature of TV broadcasting (primary service), requiring fewer high-power transmitters at known fixed sites and receive-only user equipment (the TV receiver sets, at unknown fixed and mobile locations), makes up the current scenario for technical co-existence between opportunistic license-exempt TVWS devices and the incumbent service (coordinated through TVWS geo-location and database-managed channel use). A change in nature of the primary service, for instance from broadcasting to mobile (where simultaneous transmission and reception takes place from base stations and ubiquitous end-user devices), may lead to an incompatibility with TVWS networks, with possible financial, legal and/or other implications. This is because the mobile service tends to provide continuous coverage to ensure communications at any given location, resulting in a more

5. The ITU report "Exploring the Value and Economic Valuation of Spectrum" provides further insights into the economic value aspects of spectrum: http://www.itu.int/ITU-D/treg/broadband/ITU-BB-Reports_SpectrumValue.pdf

difficult identification of available white spaces, as compared with TV broadcasting, in particular considering the longer-range propagation properties of UHF spectrum.

Further, modifications in coverage objectives of transitioning broadcasting networks would also require some assessment. For instance, DTT in the UHF bands has been implemented fully in some countries, but in others, the implementation process has been slower or has not started yet. For regions or countries where channel utilization by the primary DTT service is still undergoing planning and coordination, there is still a degree of uncertainty with regard to the "final" DTT coverage footprint. Such probability of change in DTT networks is not restricted to transitional aspects but also to the future spectrum needs of the broadcasting service in the UHF bands.

In this sense, a realistic figure of the bandwidth available for the opportunistic secondary use of TVWS can only be obtained once analogue TV switch-off is achieved and the final DTT coverage is in place (especially if DTT is deployed using SFN). An example of such situation can be found in the African continent, part of the Geneva 06' Agreement[6] (GE06 Agreement) for regional coordination of digital broadcasting, and where DTT transition is currently ongoing. Such a situation implies that, since the full coverage objectives of DTT have not been reached or implemented yet in some areas, a white space that appears currently vacant may not be available later on. This situation is particularly relevant in border zones, where frequency coordination is critical for avoiding cross-border harmful interference.

The above situation highlights well the importance of technically sound spectrum management[7], which has been achieved through the collaborative efforts of countries, (a) at regional level by adopting coordinated and harmonized spectrum decisions, reflected for instance in Regional Agreements (such as the ITU GE06 Agreement) and (b) at global level, by updating the international Radio Regulations . Such updates are conducted on the basis of collaborative technical studies (ITU-R Study Groups[8]) carried out jointly by the ITU Membership: Member States, and other stakeholders (operators, manufacturers, academia, etc).

On this basis, changes in spectrum allocations and updates to the RR are made by consensus between Member States at the World Radio Conferences[9] (WRCs) and also common regional frequency plans are agreed through Regional Radio Conferences[10] (RRCs). ITU-R study groups also adopt technical standards and harmonized spectrum use (ITU-R Recommendations, Reports and Handbooks) as well as best practices on radiocommunication matters. Within this framework, ITU-R is currently undertaking multiple studies to develop technical recommendations on the use of new technologies such as Software Defined Radio (SDR) and Cognitive Radio Systems[11] (CRS) , which are relevant to the development of radio systems using white spaces. Further, at the last World Radio Conference (WRC-12), the subject of SDR and CRS was addressed and it was concluded that the RR was providing enough

6. Geneva 06 agreement can be found at: http://www.itu.int/ITU-R/terrestrial/broadcast/plans/ge06/

7. Definition of spectrum management (as per Study Group 1 brochure): Spectrum management is the combination of administrative and technical procedures necessary to ensure the efficient utilization of the radio-frequency spectrum by all radiocommunication services defined in the ITU Radio Regulations and the operation.
8. Information on ITU-R Study Groups can be found at: http://www.itu.int/en/ITU-R/study-groups/Pages/default.aspx

9. Information on WRCs can be found at: http://www.itu.int/ITU-R/index.asp?category=conferences&rlink=wrc&lang=en
10. Regional Radio Conferences: http://www.itu.int/ITU-R/index.asp?category=conferences&rlink=rrc&lang=en

11. Resolution 58 (2012): studies on the implementation of cognitive radio systems: http://www.itu.int/pub/R-RES-R.58-2012

flexibility at it stands to enable the use of CRS in accordance with its provisions, recognizing in particular the obligations of administrations in preventing interference (see Recommendation 76, WRC-12).

Additionally, at WRC-12, countries in ITU-R Region 1 (Europe, Africa and Middle East) agreed on planning an extension of their digital dividend band (790-862 MHz), allocating the band 694-790 MHz for the mobile service on a primary basis, and to start its operation in 2015 (Resolution 232, WRC-12[12]). Appropriate measures will be taken at WRC-15[13] in response to agenda item 1.2, which states: *"to consider to examine the results of ITU-R studies, in accordance with Resolution 232 (WRC-12), on the use of the frequency band 694-790 MHz by the mobile, except aeronautical mobile, service in Region 1 and take the appropriate measures"*.

Such decisions echoes other discussions and studies carried out in Europe and the USA after WRC-12 on the long-term approach for reallocation of UHF spectrum, in order to respond to the increasing bandwidth demand of mobile services. Further, in July 2013, under the African Telecommunications Union and ITU auspices, the Sub-Saharan African countries agreed on modifications to the GE06 Plan in order to allocate the 694-790 MHz band to the mobile service[14].

Finally, it was also agreed at WRC-12 to consider and to take appropriate action on agenda item 1.1 of WRC-15, which states: *"to consider additional spectrum allocations to the mobile service on a primary basis and identification of additional frequency bands for International Mobile Telecommunications (IMT) and related regulatory provisions, to facilitate the development of terrestrial mobile broadband applications, in accordance with Resolution 233 (WRC-12)"*. These regulatory developments are significant indicators of the ongoing international revision of UHF spectrum utilization, requiring due consideration in terms of the inclusion of opportunistic TVWS systems in the planning of UHF spectrum allocations in the mid and long terms.

7.4 TVWS EQUIPMENT STANDARIZATION AND SPECTRUM HARMONIZATION

Several frequency bands have been allocated worldwide in such a way that they allow the operation of devices on license-exempt basis (e.g. ISM bands) across different spectrum frequencies. These bands accommodate a variety of devices and applications, being wireless LANs (e.g. WiFi) one of the most commonly known. Wireless LANs operate mainly in the 2.4 GHz band (with a total of 100 MHz of bandwidth) and in the 5 GHz band (5.150-5.350 MHz and 5.470-5.725 GHz, with a bandwidth of approximately 455 MHz[15]) in accordance with ITU Resolution 229 (Rev.WRC-12). There is also an allocation in the UHF band at 900 MHz in ITU-R Region 2 (Americas) between 902-928 MHz (totaling 26 MHz

12. WRC-12 Resolution 232 can be found at: http://www.itu.int/oth/ R0A0600004B/en

13. WRC-15 agenda item 1.1 and 1.2 can be found at: www.itu.int/ ITU-R/go/rcpm-wrc-15-studies

14. See http://www.itu.int/ITU-R/ terrestrial/broadcast/ATU/index. html

15. Based on FCC's 5 GHz license-exempt regulation FCC 13-22, found at: http://www.fcc.gov/ document/5-ghz-unlicensed-spectrum-unii

of bandwidth). The combined total for all three license-exempt bands used by wireless LANs is around 581 MHz of bandwidth.

TVWS device specifications are for instance currently being developed for Wireless Regional Access Networks, IEEE 802.22 WRANs (point-to-multipoint), and 802.11af for lower-power operation in a "hot-spot" fashion. The development of both standards is based on similar operational characteristics of devices using ISM bands and referred to above: license-exempt devices sharing the band with other TVWS applications. The deployment of TVWS devices could involve very large numbers of devices scattered across different areas and serving different purposes, and therefore, some assessment will be necessary to determine the levels of interference that a combined deployment scenario would represent, and its impact on TVWS bandwidth availability. Then, the potential wireless ecosystem in the UHF bands would involve the primary service(s) sharing the band with wireless microphones (and also licensed SAB/SAP devices in some countries), TVWS opportunistic devices broadband (such as IEEE 802.22 and IEEE 802.11af), TVWS for machine-to-machine communication and any other TVWS application that may arise.

Frequency bands utilized for license-exempt applications such as those used by WiFi devices, have been used to host large numbers of ubiquitous devices, which share those frequencies collaboratively (using low power levels, short range transmissions and channel control schemes) and operate *without an expectation of QoS*. As mentioned earlier, no individual license is required for operation in these bands, but compliance with technical and operational parameters is necessary in order to avoid harmful interference into other services. Moreover, increases in transmit power exceeding the limits prescribed for license-exempt devices would either reduce the number of users at a given area or cause interference intra-service or to licensed services in adjacent bands. Therefore, the usefulness of license-exempt bands relies on the ability of low-power/short range devices to contain their emissions within the prescribed limits (power limits and frequency boundaries).

ITU-R studies are on-going in response to Resolution ITU-R 58[16] on the implementation and use of CRS technologies, in particular in the mobile services, and may lead to the development of new ITU-R Recommendations or to the revision of existing ones referred to in the RR.

16. Resolution ITU-R 58 can be found at: www.itu.int/pub/R-RES-R.58

7.5 CONCLUSIONS

One aspect of international spectrum planning, in terms of harmonizing spectrum allocations, relates to the potential impact that such harmonization may have in driving local markets. This impact can be expected to translate into long-term benefits (i.e. economy of scales of devices, overall advancement of the ICT sector and related contribution to GDP,

job market creation and support to innovation and entrepreneurship). It is therefore significant, from the regulatory perspective, to identify the potential trade-offs of TVWS spectrum decisions in relation to the outcomes set within the national ICT strategy.

A long-term national ICT strategy, including the planning of wireless broadband connectivity, will need an assessment of *costs, scalability, resiliency and sustainability* of the countries' national wireless access infrastructure, if this strategy is set to support rural communities and its enterprises.

- **Costs:** there are significant connectivity costs down the transmission chain and the last mile is only one section of the chain. For instance, backhaul options are relatively low cost in comparison to fiber or wired options but there are costs of interconnection and data traffic from the backhaul to the ISPs[17] or the telecommunication infrastructure provider's core network. Then, the costs of all the transmission components need to be considered in order to establish the overall level of funding required for subsidizing the service costs incurred by the rural customer base.

- **Scalability:** ventures to provide connectivity in rural areas may start with a low number of users but one would expect that, as the rest of the network matures onto newer or updated platforms, the last mile component will also experience changes in demand in terms of user density or application-based bandwidth demand. The critical factor here would be to ensure that future bandwidth bottlenecks are avoided at the last mile level, in order to prevent potential disruptions or to restrict users to a sub-optimal access solution due to lack of planning or insufficient infrastructure resources.

- **Resiliency:** this aspect involves having an access infrastructure that can endure potentially disrupting and critical situations, by means of system redundancy, prompt turnaround in front of system failures and appropriate user support services.

- **Sustainability:** a reasonable level of long term certainty would be expected throughout the national network and its outreaching branches, in order to support national economic objectives that would include, amongst other, *attaining and maintaining a competitive position amongst regional and global economies, in order to attract foreign and local investment.* If emerging rural businesses are to be supported by new infrastructure and investments are to be made, then rural communities and entrepreneurs will expect to have a reliable wireless infrastructure (one that will not create more costs for users in comparison to other available solutions) in the medium and long terms.

As deployments of advanced mobile networks move forward, for example, through the use of the digital dividend spectrum, it is expected that markets with high levels of spectrum harmonization of their digital dividends will benefit from increasing economies of scale, while ensuring that connectivity platforms evolve in tandem with user demands. Moreover, cost efficiencies (and innovation) are more likely to occur where investment opportunities can find a market environment with future projections, through the adoption of scalable ICT platforms. Trading strategies for the mid and long-terms are also closely linked to harmonized spectrum allocations, in the sense that a closer alignment with regional and international standardization will enable access to global markets (i.e. more hardware choices and sourcing of expertise). Further, spectrum harmonization simplifies cross-border coordination, allows interoperability and reduces instances of spectrum inefficiencies at border areas due to interference caused by mismatch of dissimilar wireless systems operating in the same geographical area.

On the basis of the above considerations, the following questions would need to be addressed in adopting national ICT strategies:

a) What can be the potential outcomes of early policy decisions on TVWS?

Early implementation (without regulatory safeguards) through the use of idle TV spectrum presently available would endeavor to obtain immediate benefits of connectivity, provided the available spectrum is properly identified and used on an interference controlled basis. Some benefits can include reaching earlier those small communities in need of connectivity, and their earlier familiarization with wireless platforms and applications. Some uncertainties would include DTT transition not being completed, leading to unclear levels of future availability of spectrum for TVWS service provision. Also, there can be uncertainty with regard to potential changes in the regulatory environment and TVWS spectrum security of tenure, should there be a redefinition of the current primary service in the mid to long-term, resulting in financial losses for TVWS broadband service providers and users. While TVWS equipment standards are still under development and economies of scale are still pending, more clarity is needed to understand the current TVWS business case and to understand the type of service that consumers are to expect.

b) What are some of the current regulatory challenges for TVWS implementation?

One of the main tasks of a national regulator with respect to deployment of TVWS devices would be to ensure their compatible operation with incumbent services and licensed applications. TVWS devices are supposed to work on a non-interference and non-protection basis, which requires the knowledge about other radio systems in operation in the

same geographical area. Initially, the acquiring of this knowledge was seen through sensing of electromagnetic environment and choosing unused frequencies. Due to the current need for the development of more advanced and reliable solutions in spectrum sensing (to handle hidden obstacles and account for the requirements posed by very sensitive and expensive receivers) the sensing function has been replaced by geo-location databases containing information of other radio applications and neighboring TVWS. Moreover, aggregate interference into the primary service, as well as intra-service, will need particular attention especially in urban scenarios.

The establishment, maintenance and dynamic update of such databases may represent an added complexity for national authorities and would require thorough studies and trials. This aspect is especially important in the border areas, where the knowledge about radio systems used in the neighboring country is necessary. Exchange of database information would also be needed to avoid cross-border interference.

c) Could some form of security of tenure be needed to provide predictability and a long-term space for opportunistic TVWS applications?

Perhaps, other regulatory approaches could consider alternatives for creating a regulatory environment and a space where TVWS wireless broadband applications can access spectrum not only in the short-term but also in the longer-term. The challenge is that TVWS applications are "what they are" while they operate opportunistically within the currently available gaps in spectrum allocated to television broadcasting but, what would happen if the allocation changes or if digital TV broadcasting networks expand their coverage? Would TVWS broadband applications be adaptable enough to continue serving consumers or would they require regulatory measures to ensure their long-term success? Any investment and business case needs to have a stable regulatory environment where wireless technologies can develop in a scalable way, for the benefit of users and service providers. Evolutionary changes in the regulatory environment for wireless, which we are experiencing specially in the highly sought-after UHF spectrum, can have massive impacts on services that are not planned to adapt to those changes or not planned within a forward-looking regulatory framework.

d) How does a potential TVWS broadband solution fit into a long-term national ICT strategy?

There are many views on the TVWS subject and, through this paper, it is hoping to contribute in the advancement of alternatives for TVWS by industry and regulators, in order to achieve the greatest benefit from the spectrum resource for society as a whole. Considering that spectrum regulation is a complex and interwoven mix of disciplines (policy, legislative, regulatory, economic, technical and operational), there is

definitively no silver bullet to tackle all the challenges. Notwithstanding this, sustainable development of ICTs and efficient spectrum use are necessary goals as we move forward with new developments, such as dynamic spectrum access and TVWS.

Currently "ICT underserved" rural areas represent a challenge for policy makers and regulators in terms of achieving national ICT objectives. In allocating spectrum to operators, coverage obligations have been implemented in many countries to increment the broadband capacity levels of rural regions, with the expectation that spectrum resources licensed to operators will further serve the socio-economic and developmental needs of rural communities, as well as maximizing economic benefits in urban areas. Alternative forms of spectrum utilization (such as dynamic spectrum access and TVWS) are interesting approaches to economically complement rural broadband needs, therefore their appropriate development and maturity are encouraged and envisaged for the benefit of users.

In conclusion, it is important to recognize that, while the wireless component of the national ICT strategy will most certainly include a variety of models to reach out to communities, the mid and long-term strategic goals need to be taken into consideration, in order to avoid implementing short-term solutions that could result in unnecessary costs socially and economically in the long-term. It is then a matter of public policy to ensure an effective spectrum regulatory framework that nurtures harmonization; as well as balancing innovation and scalability of ICT ecosystems. Initiatives striving to make more efficient use of the spectrum resource through spectrum sharing, dynamic access and cognitive radio are supported and encouraged within ITU-R technical studies, with the expectation that they will provide a valuable contribution in the future of wireless. However planning of the finite spectrum resource requires all-encompassing frameworks (technical, legal, economic and social) which need to be sufficiently versatile and adaptable to industry and regulatory changes, as well as capable of providing choices (through incentivized competition) and avoiding the formation of infrastructure monopolies (with its consequent costs and inefficiency issues). Comprehensive spectrum strategies and policies need to be developed towards sustainable mid and long terms, considering the international regulatory developments; or else spectrum bottlenecks will arise as demand continues to grow. TVWS utilization needs to be assessed within such strategies.

THE ROLE OF TV WHITE SPACES AND DYNAMIC SPECTRUM IN HELPING TO IMPROVE INTERNET ACCESS IN AFRICA AND OTHER DEVELOPING REGIONS

8

Mike Jensen
Association for Progressive Communications
lankamike@gmail.com

Many people may ask, why do we need new connectivity technologies in Africa? Isn't WiFi, DSL and mobile Internet enough? However we still have a long way to go in providing ubiquitous affordable and reliable Internet access in Africa and other developing countries. At the household level Internet penetration is estimated at 77% in Europe by the ITU, compared with 7% in Africa. With regard to broadband access, the divide follows similar patterns, but inequalities are even more accentuated, with less than 10% of the world's population having broadband access. Average broadband speeds vary by a factor of more than 40, from 256 kbps to more than 10 Mbps. Access inequalities are even more visible when disaggregated by disadvantaged groups, especially in developing countries - particularly the rural population, women, oppressed cultural groups, people living in remote small island nations, and in the least developed countries generally.

The two major reasons for these inequalities are the limited distribution in many areas of basic Internet infrastructure (international and national backbones and last mile/local networks), and the high cost of access, which makes services largely unaffordable in regions such as Africa, where the price of a computer-based broadband plan with 1 GB of data volume represents on average more than 50% of GNI per capita (by comparison the figure is 2% in Europe) [1].

The impact of this is that without affordable Internet, the high proportion of people who have low incomes in developing countries will not be able to participate fully in the digital revolution - to find new ways of making a living, to make more efficient use of available resources, to

1. http://www.itu.int/en/ITU-D/Statistics/Documents/facts/ICTFactsFigures2013.pdf

access online learning materials, gain knowledge of health issues and use online government services, and to maintain regular contact with friends, peers and family.

Without ubiquitous Internet, those in more isolated and rural areas (the majority of people in Africa and other developing regions) will continue to remain cut-off from the benefits described above. People living in rural areas are particularly disadvantaged because they cannot take advantage of the 'death of distance' that the Internet provides, spending much time and their limited incomes travelling to urban centres for simple transactions. Outside main centres throughout Africa, schools, small businesses, local government offices, NGOs, libraries, clinics, colleges and many institutions that are fundamental to day to day social and economic development, still don't have affordable, reliable and fast internet access.

Without dependable access, the institutions and the public will not be confident about relying on the services provided over the Internet - as we come to depend more on connectivity for carrying out many day-to-day activities, service interruptions need to be minimised through having at least two physically independent connections to the Internet.

Use of TVWS and other innovative uses of spectrum for fixed wireless access can help meet these goals in the following ways:

1. **Reducing Internet access costs** - Internet service providers able to make innovative use of radio spectrum can help to create more competition in markets for Internet access. This will put pressure on the existing/incumbent carriers which rely on their market dominance to maintain high profit margins or inefficient business practices. Mobile operators in particular, have become the 'new incumbents', often operating in cartel-like fashion even if there is nominal competition. These 'monopolistic' practices do not only keep prices high, they also limit network neutrality and innovation.

2. **Providing more ubiquitous access** - the lower radio frequencies used by TVWS can help by reaching greater distances than higher frequency systems which are less cost-effective. In addition, greater competitive pressure provided by new fixed wireless providers will also increase the incentive for carriers to make more infrastructure investments in unserved areas.

3. **Providing more reliable access** - in the developed world 'permanent' connectivity would most often be provided by a DSL or cable-TV service, complemented by a mobile broadband service. In Africa and other developing regions, a fixed wireless solution such as TVWS could be complemented by a WiFi or mobile broadband connection. In this way TVWS can provide an alternative physical path to the Internet, ensuring that vital services continue in the event of a service interruption on one of the links.

8.1 THE POTENTIAL FOR INNOVATIVE SPECTRUM USE

With the growth in use of wireless technologies generally, radio spectrum has become a particularly vital part of the Internet ecosystem. The use of TVWS and other dynamic spectrum-uses are particularly appropriate for developing countries - where there is plenty of unused broadcast spectrum, bitrate expectations are lower and there are large numbers of people living in areas unserved by existing infrastructure. The explosive growth of mobile access has tended to draw attention away from the provision of fixed access (which offers higher speeds and lower subscription costs), and as a result fixed last-mile infrastructure has tended to take a lower priority in public policy, and current policy and regulatory practice has not responded to the problem with much creativity.

Rural communities are especially vulnerable to poorly managed spectrum because they are less likely to have any fixed line alternatives. But although there is also more spectrum available in rural areas because there are much fewer existing spectrum users, this has not translated into better spectrum access.

Lack of awareness by national policy makers of the need for low cost spectrum for wireless operators is a key factor, along with lack of capacity to update spectrum plans as new technologies emerge, as well as resource constraints in spectrum regulation enforcement. Among the most visible of these problems is linked to the slow move from analogue to digital TV in developing regions, delaying the availability of the important 700-800 MHz wavebands [2], which are particularly suitable for high-speed wireless broadband services. Allocation of the 2.6 GHz waveband is important for broadband in urban areas and is also subject to allocation delays in many countries. Use of dynamic shared and unlicensed spectrum technologies such as TVWS and WiFi could have a major role to play in meeting connectivity needs immediately, without having to wait for the analogue to digital switchover, which now appears that it will not take place in many developed countries before the 2015 deadline proposed by the ITU.

Currently the high cost of spectrum licenses is a major constraint on deploying new wireless services, limiting the deployment of wireless Internet services, and increasing end-user costs. High spectrum prices are also linked to the continued dominance of the mobile operators. Having paid millions of dollars to the state for these licenses, the mobile operators are able to convince governments to limit the entry of other new wireless players in the market. Many mobile operators have claimed that the license fees were paid on the basis of a limited number of market players and that the market size is insufficient to support more operators. This has been reinforced by the fact that different approaches to spectrum management for increasing access are usually overlooked

2. Often called the 'Digital Dividend'.

by most regulators and smaller and local ISPs.

Of particular importance is that the dynamic spectrum-use model can also be applied to other frequencies to increase efficiency of spectrum-use more generally, and help reduce the burden on regulators for spectrum management. The few TVWS trials that have taken place have already demonstrated that very large portions of the allocated spectrum bands are not actually in use, and this has thrown into question the whole premise of 'spectrum scarcity', upon which current allocation models are based. Hopefully, as more on the ground spectrum-use information becomes available from more developing countries, and from more sources than just the (often poorly resourced) national ICT regulator, such as through crowd sourcing, there will be better awareness of the increased potential of the radio spectrum resource.

In this respect TVWS is a point of entry for highlighting issues of spectrum management generally, and can bring together a wide range of stakeholders to work together on solutions to the access problem. As highlighted by the history of TVWS support in the US where NGOs first pushed for its use, civil society has an important role to play in bringing attention to dynamic spectrum use. With a technology-neutral agenda, civil society groups are not biased toward a particular access solution and can be a trusted partner in helping to guide the adoption of the most effective mix of technologies.

8.2 MAXIMISING THE IMPACT OF INNOVATIVE SPECTRUM USE

It is important to note that TVWS and other dynamic spectrum technologies are part of a larger 'connectivity ecosystem' and will not reach their full potential unless other needs for the access ecosystem are also addressed at the same time. In developing countries these needs are many but the most important of these are:

- **Low barriers to entry for new Internet providers (licensing)** - as noted above, aside from the existing ISM/WiFi spectrum bands, high licensing costs for spectrum usually exclude smaller players who may wish to enter the market, and mobile operators are often resistant to any new applicants. Even more of a constraint in some countries is that new licenses to operate Internet services are simply not available, leaving the market to the incumbent and the existing mobile operators.

- **Efficient Interconnection** - without good interconnection with existing networks, the level of service that smaller dynamic spectrum providers can offer their customers will not be on par with those of the existing larger players. At a minimum this requires efficient exchange of local traffic with other Internet providers &

Content Distribution Networks (CDNs) by ensuring the presence of well run Internet Exchange Points (IXPs) with participation from all the major Internet providers. Ideally this should also include interconnection mechanisms with the traditional voice operators for carrying out Voice over IP (VoIP) calls. In some countries VoIP and voice services generally are not sanctioned except for use by the existing incumbent fixed and mobile networks.

- **National fibre backbones** - without good national fibre backbone infrastructure, the more remote areas which are most likely to benefit from TVWS and other wireless technologies will not be able to connect affordably and with sufficient capacity. Governments need to encourage more investment in this infrastructure by encouraging competition and also ensuring cost-based access to existing fibre optic cabling, ducts and rights of way of energy, transport, water and sanitation networks. This may need the adoption of new regulations to allow third party access to this infrastructure and to limit prices charged. Some good examples include: West African Power Pool (WAPP), Tanzania water distribution control network, the Brazilian public national fibre backbone (Telebras), Broadband Infraco public national backbone in South Africa. At the same time this also requires implementing infrastructure sharing regulation for existing providers. This usually applies to provisioning of ducts or conduit for optic fibre in new transport or energy networks, but also applies to water and sanitation pipes in municipal areas, and to wireless base-station masts. Up to 80% of the cost of laying fibre lies in the civil works - the trenching, ducting, permitting and obtaining the rights-of-way. These costs are avoided by using the energy grids, thereby making it much more economic to deploy fibre. In addition, many electricity distribution grids already have fibre installed on them (to control power distribution sub-stations) and can provide excess fibre pairs at very little cost. Unfortunately, the level of awareness of the potential of this 'alternative infrastructure' is low in most developing countries and where it exists, the energy operator often does not understand the market dynamics for telecom capacity and wishes to charge excessive amounts for access.

- **Low cost access devices.** Low income groups are particularly constrained in being able to afford the necessary equipment to access the full potential. To support better access for these communities, public financing schemes may need to be adopted with low interest loans or guarantees, and by minimising import duties on equipment.

- **Public support for extension of connectivity** to remote and rural areas. The use of universal service funds which take a proportion of revenues from existing operators to support network deploy-

ment in underserved areas has become a well accepted vehicle for this. However, few examples of good practice in this area have emerged. One good example is in a developed country, France, where operators must provide a quote in response to a request for service in any part of the country. The regulator deducts the national average cost of providing a connection (determined by the regulator's own benchmarks) and gives the difference to the operator who must install the connection within a specified time period. A reverse auction for provision of service in under-serviced areas is another such mechanism.

- **Public access facilities are needed** for those who cannot afford access in the home or at work. This can often be achieved by equipping libraries and community centres with the necessary equipment.

- **Online payment systems.** Without widely available electronic payment systems for the unbanked, those in rural areas will not be able to take advantage of one of the most desirable features of the Internet - e-commerce. Unfortunately most of the payment systems adopted to date rely on mobile networks - other alternatives need to be made available.

- **Local content development** - support is needed for building relevant local applications in order to maximise the demand for networks, such as for e-Governance and civil-service networking.

- **Effective consumer protection** - to reduce the risks of accessing the Internet, effective protection will be needed against such as aspects as spam, fraud, and hate speech, especially against women and minority groups.

- **Improved electricity distribution and renewable energy policies.** Energy dynamics are becoming increasingly linked with Internet connectivity at many different levels. The impact of energy supply and energy costs on Internet access is a well-recognised issue for disadvantaged communities, most of which suffer from high energy prices and lack of, or unreliable and/or poor quality grid power. This even includes capital cities and other major urban areas in many developing countries. These energy constraints not only affect end-users needing to provide power to their access devices and run them reliably, but they also have a deep impact on operator costs to deploy and maintain their networks. One of the reasons why mobile access charges are higher in many developing countries is the need to install generators for base stations, and to operate an entire supply chain to replenish them with diesel, often over difficult and remote terrain. Even when power is there but is unreliable, operators have much higher capital costs for

network deployment just to install backup power facilities which may be only infrequently used. Fortunately, renewable energy options for powering network operator and end-user equipment are beginning to see greater use, most especially where countries have adopted Independent Power Producer Policies (IPPPs) which allow the cost of renewable power generation facilities to be defrayed by selling any excess power generated back to the grid. New models for supplying energy in disadvantaged communities are also emerging. In many developing countries, energy kiosks are now available where people pay to have their phones recharged with an adapted car battery or solar panel. Energy distribution grids (high voltage pylons, local electricity distribution poles, and oil/gas pipelines) are a vital resource for minimising the cost of backbone optic fibre deployment.

PART II

TECHNOLOGY

WHITE SPACE BROADBAND ON THE ISLE OF BUTE, SCOTLAND

9

David Crawford
Centre for White Space Communications
University of Strathclyde
United Kingdom
david.crawford@strath.ac.uk

9.1 INTRODUCTION

In April 2011, a six-partner consortium, with support from the UK government's Technology Strategy Board, started work on a rural broadband trial network that would use white space radio spectrum to provide broadband connectivity to a small community on the south part of the Isle of Bute, Scotland (see Figure 9.1). A key aim was to investigate and demonstrate the potential of white space spectrum for providing broadband access to remote, difficult-to-reach rural areas in challenging terrain. The 18-month project involved the planning and installation of white space radio links from the local telephone exchange to eight premises in the surrounding area, as well as backhaul connectivity from the telephone exchange to the mainland and then on to BT's IP backbone for access to the Internet.

As well as assessing the technical ability of the network to provide broadband access, a further aim was to investigate the extent to which the white space broadband transmissions would be able to co-exist with Digital Terrestrial Television (DTT) transmissions without adversely affecting TV reception, and to what extent theoretical predictions would match measurements made in the field. This, it is hoped, would help to inform a number of decisions being considered by Ofcom with regard to regulation of white space access in the UK.

9.1.1 The Project Partners

Six partners formed the consortium that was set up to carry out the project:

Figure 9.1: High-level illustration of trial white space network on Bute.

- **Steepest Ascent, Ltd** - a privately owned SME with its head office in Glasgow, UK and an office in Los Angeles, USA. Steepest Ascent was the lead partner in the consortium, responsible for managing the project and providing engineering expertise in RF planning and installation.

- **BT** - one of the world's leading communications services companies, operating in more than 170 countries worldwide. Representatives from BT Innovate and Design and from Openreach were part of the project consortium. Openreach led the installation of infrastructure equipment in the local telephone exchange and the provision of backhaul connectivity to the mainland and the backbone IP network. BT Innovate and Design provided engineering expertise and prototype WiMAX-based white space radio equipment for the project.

- **BBC Research and Development** - BBC R&D is at the core of the BBC's efforts to be at the cutting edge of media technology, and drives the exploration of exciting new production tools and distribution technologies. The BBC led the RF test and measurement activities on Bute, and provided technical expertise on DTT coverage predictions and interference modelling.

- **Berg Design, Ltd** - industrial design engineers who provide unique, tailor-made solutions from initial product design to full manufacturing support. Berg provided consultancy and mechanical design support for a first-generation extended-reach UHF/GHz base station mast.

- **Netpropagate Systems, Ltd**- UK operating subsidiary of Netpropagate Corporation, based in Los Angeles, USA. Netpropagate's core product is a next-generation video conferencing and collaboration solution for mass deployment using standard PCs and standard broadband. This formed one of the user applications used in the project.

- **University of Strathclyde**- the University of Strathclyde's Department of Electronic and Electrical Engineering is one the largest in the UK. Staff from the Department's Centre for White Space Communications provided prototype WiFi-based white space radio equipment for the test bed on Bute, and were heavily involved in the practicalities of installing and configuring the radio network.

9.1.2 Implementing the Plan

The project was implemented in four work packages:

1. **Installation and commissioning of the network.** TV-band white space transceivers were installed at eight trialists' premises and the aerials were pointed in the direction of the telephone exchange, where a white space base station mast was erected. The telephone exchange was equipped with a dedicated 18 GHz backhaul microwave link (not white space) to the mainland, where an IP connection to the BT backbone was made. After testing, the network was activated and the trialists were encouraged to use it normally.

2. **Modelling, laboratory testing, and field measurements.** Field measurements were made (during a 10-day period in June 2012) in order to characterize the performance of the network and evaluate the impact on DTT reception. Comparisons were made with predictions obtained from theoretical models and laboratory tests.

3. **Assessment of network operation and user experience.** The operation of the network was monitored while video-streaming took place, and trialists took part in video-conferencing sessions to test the network's ability to support broadband applications. A user survey was also carried out towards the end of the trial period, in order to gain insight into the trialists' experiences and their views on the connectivity provided to them during the trial and on broadband in general.

4. **Technical R&D and development of self-powered masts.** Technical R&D activities were carried out in relation to self-powered radio communications masts (using wind and solar energy).

9.2 INSTALLING AND CONFIGURING THE NETWORK

Figure 9.2 shows a high-level diagram of the network. A high-capacity 18 GHz microwave backhaul link was set up between the telephone exchange at Kilchattan Bay on Bute and West Kilbride on the mainland, where a connection to BT's IP backbone was made in order to provide Internet connectivity for the trialists. Point-to-Multipoint white space radio links operating in the TV band were set up between the Kilchattan Bay telephone exchange and trialists' premises. This involved the installation of white space Customer Premises Equipment (CPE) at trialists' premises and the construction of a white space base station mast in the grounds of the telephone exchange. The eight trialists' locations were split into two groups of four: Trialists in Group 1 were equipped with white space radios based on WiFi technology which was modified to operate within a single UHF TV channel; trialists in Group 2 were equipped with white space radios based on WiMAX, operating in a different TV channel from that which was used for Group 1.

9.2.1 *White Space Radio Equipment*

Two types of white space radio equipment were used in the trial:

- Prototype equipment from the University of Strathclyde's Centre for White Space Communications, based on XR7 WiFi technology from Ubiquiti Networks. A number of modifications were made, including scaling of the bandwidth down to 5 MHz so that transmissions would fit within a single, 8 MHz-wide TV channel. This equipment was used for trialists in Group 1.

- Equipment from Airspan Networks, based on WiMAX (IEEE 802.16e), configured to operate within a single, 8 MHz-wide TV channel, using 2x2 MIMO with antenna polarizations of ±45°. This equipment was used for trialists in Group 2.

In each group, uplink and downlink radio transmissions between the base station and trialists' CPEs took place using Time Division Duplexing (TDD). The non-operational test licence issued by Ofcom allowed for three 8 MHz channels to be used if required, but at any one time, only two were utilized in the network: one for the trialists in Group 1, and another for the trialists in Group 2.

96
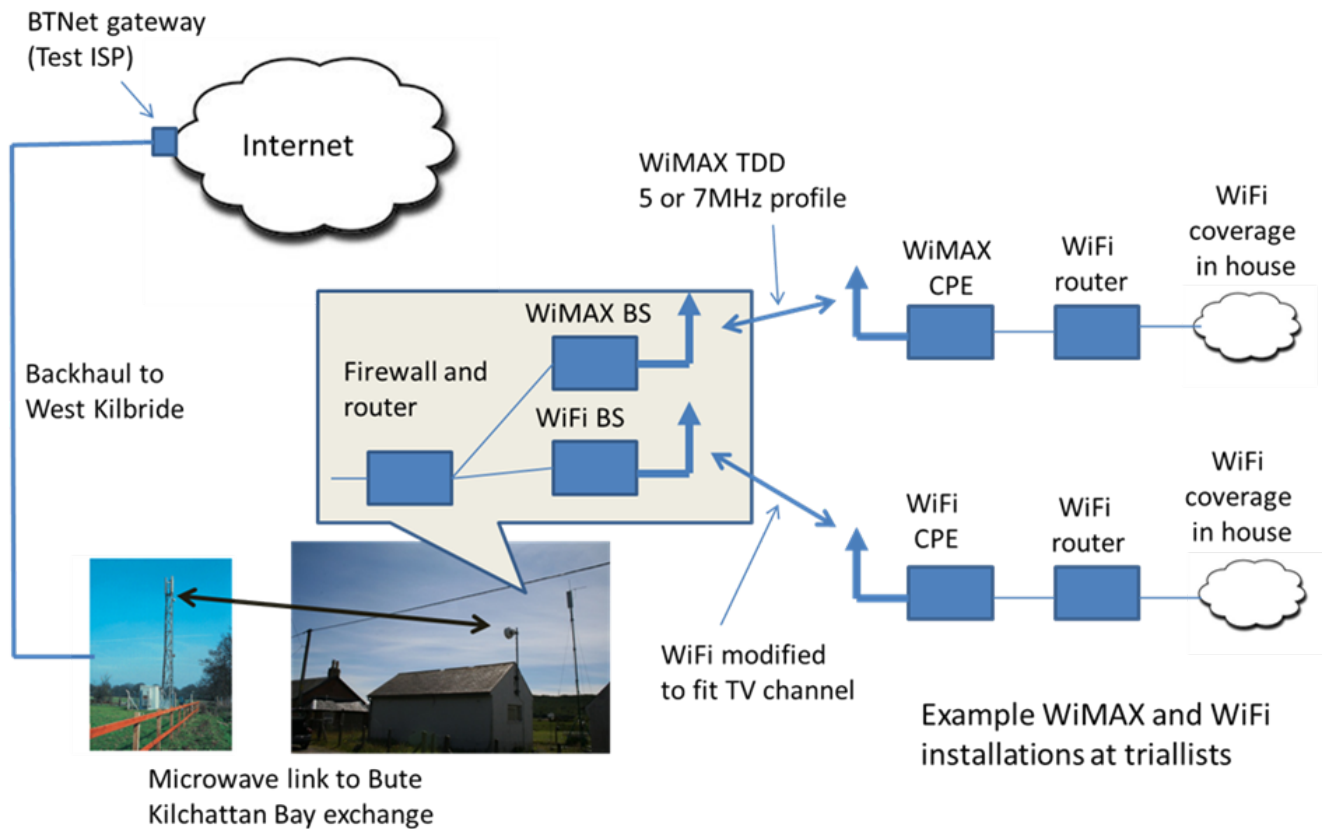
Figure 9.2: High-level illustration of trial white space network on Bute.

Customer Premises Equipment (CPE)

CPE units comprising a white space transceiver and aerial were installed at trialists' premises, as shown in Figure 9.2 and 9.3. The white space transceivers were mounted externally and connected to an Ethernet cable which was fed into the premises.

Inside the premises, a small Ethernet/WiFi router was supplied and configured to allow a number of devices within the home to be connected to it. (The provision of a pre-configured router allowed trialists to easily add end-user devices within the home without there being any need to modify the address space of the master firewall.)

The Ethernet cable was also used to deliver electrical power to the externally-mounted white space transceivers, using Power-Over-Ethernet (POE).

Base Stations

A mast was built at the local telephone exchange and fitted with a white space base station pointing roughly westwards for the trialists in Group 1 and one pointing roughly northwards for the trialists in Group 2. The set-up is shown in Figure 9.4.

Figure 9.3: CPE installations at trialists' premises.
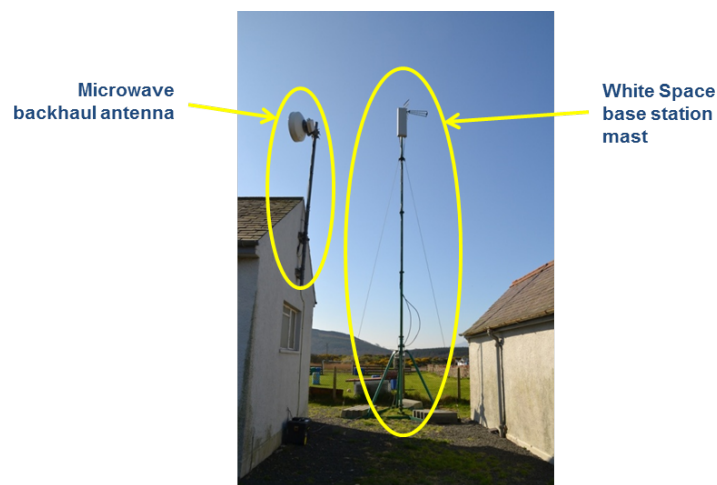
Figure 9.4: White space base station mast at local telephone exchange. (The 18 GHz backhaul dish antenna is also visible.)

Backhaul to the Mainland

Backhaul was provided using standard products from BT Global Services, BT Wholesale, and Openreach. Internet access was provided by a BT Net connection. An 18 GHz microwave link was installed between the island and the mainland - a distance of 12 km. (The microwave antenna at the exchange can be seen in Figure 9.4.)

9.3 DATA THROUGHPUT MEASUREMENTS

Data throughput on the network was measured and analysed in a number of ways, including:

- Laboratory measurements, aimed at characterizing the equipment 'on the bench' in controlled conditions;

Prototype TVWS Technology	Connection Protocol	Maximum Uplink Throughput	Maximum Downlink Throughput
WiMAX (5 MHz B/W) (36 dBm EIRP in total, i.e. 33 dBm per port)	TCP	3.5 Mbit/s	8.9 Mbit/s
	UDP	3.4 Mbit/s	16.4 Mbit/s
Wi-Fi (35 dBm EIRP)	TCP	7.6 Mbit/s	3.8 Mbit/s
	UDP	8.0 Mbit/s	5.2 Mbit/s

Figure 9.5: Summary of data throughput measurements taken at selected test points on Bute.

- Vehicle-based measurements made at various locations in and around the trial area;

- Measurements made at trialists' premises using the previously-installed white space CPEs.

Figure 9.5 shows the maximum data rates that were achieved from the mobile measurements. With the WiMAX system operating in its 5 MHz bandwidth mode, and the base station transmitting at 36 dBm total EIRP (i.e. 33 dBm per MIMO port), UDP data throughput rates of about 6-16 Mbit/s (downlink) and 1-3 Mbit/s (uplink) were observed, depending on the location. TCP throughput rates were lower than expected, given the good UDP throughput. A problem by which the traffic source and destination fail to co-ordinate and adjust the TCP window size in certain test configurations was subsequently discovered, and it is thought that this might be responsible for the lower-than-expected TCP throughput values.

The WiFi system was configured to use a 5 MHz channel width and a maximum base station transmit power of 35 dBm EIRP. Data throughputs of 1-5 Mbit/s (downlink) and 2-8 Mbit/s (uplink) were observed. As was also observed in the laboratory experiments, the WiFi equipment, as configured, favours the uplink; this is a limitation of the firmware used to drive the prototype radio equipment used in the trial.

It is worth noting that at distances of about 5 km, the mobile antenna was lowered to approximately 2.5 metres rather than fully extended to 10 metres. This seems counter-intuitive as far as normal radio planning practice is concerned, but a white space antenna positioned at a height of 10 m will pick up more DTT signal power than one at 2.5 m. Reducing the height of the antenna helps to reduce interference from DTT transmissions, although this needs to be balanced with the need to maintain adequate antenna height in order that a sufficient level of white space signal power is received in the first place.

Figure 9.6 shows the rates achieved from measurements at selected trialists' premises. The measurements were scheduled to run during the night in order to minimize the likelihood of conflicting with trialists'

routine use of the broadband links, and they involved the transfer of data from a PC at the telephone exchange to laptops connected to the modems in the trialists' premises. Measurements were run for several minutes, with multiple connections simultaneously active in order to investigate how well the radio systems can share the bearers among users.

The throughput of the WiMAX system was greater than that of the WiFi system, but it should be borne in mind that:

- The WiMAX radios were configured to operate in a 7 MHz bandwidth mode and to make use of MIMO techniques;

- The WiMAX trialists' premises were closer to the exchange than those of the WiFi trialists, and therefore the WiMAX CPEs were each operating with good carrier-to-noise ratios, facilitating operation in the 64-QAM modes;

- The WiFi kit used for this project was modified for use on Bute without any optimization.

It is worth noting that beyond about 2 km from the telephone exchange, the performance of the WiMAX equipment was found to decrease to the point where it fell below that of the WiFi equipment. This is contrary to predictions derived from the laboratory measurements, and possible explanations include: unwanted downtilt on the WiMAX BS antenna; poor performance of the CPE; interference on the uplink; poor ACS on the uplink receiver; other installation issues. Further work is required to understand why the WiMAX equipment behaves in this way at present.

9.4 COVERAGE AND INTERFERENCE ANALYSIS

White space devices will be permitted to use white space spectrum on a licence-exempt basis only if they do not cause harmful interference to licensed transmissions such as DTT broadcasts or properly-licensed PMSE transmissions. Therefore, a key aim of the trial on Bute was to assess the impact of the white space transmissions on DTT reception in the vicinity of the trial. To this end, several activities were carried out:

Several DTT receivers were tested in the laboratory to assess their sensitivity to co-channel and adjacent-channel interference. DTT and white space coverage predictions for the trial area on Bute were made, using the UK Planning Model (UKPM), and corresponding predictions of co-channel interference to DTT by white space transmissions were made. Field measurements of actual DTT and white space signal strengths in the trial area were made, along with a corresponding assessment of co-channel interference to DTT transmissions. In addition, measurements

Prototype TVWS Technology	Connection Protocol	Number of Simultaneous Links	Total (Aggregate) Downlink Throughput on Bearer
WiMAX (7 MHz B/W) (36 dBm EIRP in total, i.e. 33 dBm per port)	TCP	1	14 Mbit/s
		2	22 Mbit/s
		3	23 Mbit/s
	UDP	1	23 Mbit/s
		2	24 Mbit/s
		3	25 Mbit/s
Wi-Fi (35 dBm EIRP)	TCP	1	2 – 4 Mbit/s
		2	3.5 – 4.5 Mbit/s
		3	3.8 Mbit/s
	UDP	1	3.3 – 4.5 Mbit/s
		2	4.0 – 4.5 Mbit/s
		3	4.4 Mbit/s

Figure 9.6: Summary of total (aggregate) downlink throughput on radio bearer, measured while downloading data to selected trialists' premises simultaneously.

of DTT signal strength were made at various test points distributed across Bute, and these were compared with predictions obtained from the UKPM. The aim of this activity was to confirm the validity of the UKPM itself, as the UKPM is likely to form the basis for constructing the UK's geo-location database for white space.

9.4.1 Laboratory Testing of DTT Protection Ratios

Laboratory tests were carried out on fourteen DTT receivers, using various candidate white space technologies as interferers. The DTT receivers were a varied mix of devices which included set-top boxes (STBs), integrated digital televisions (IDTVs), and personal video recorders (PVRs). Seven of them used can-type tuners; the other seven used silicon tuners. A wide variation in performance was observed among the fourteen receivers. The performance of certain receivers was also found to depend on the nature of the white space interference; certain white space transmissions tend to cause more severe problems than others, although this depends upon the architecture of the DTT receiver's RF tuner. Figure 9.7
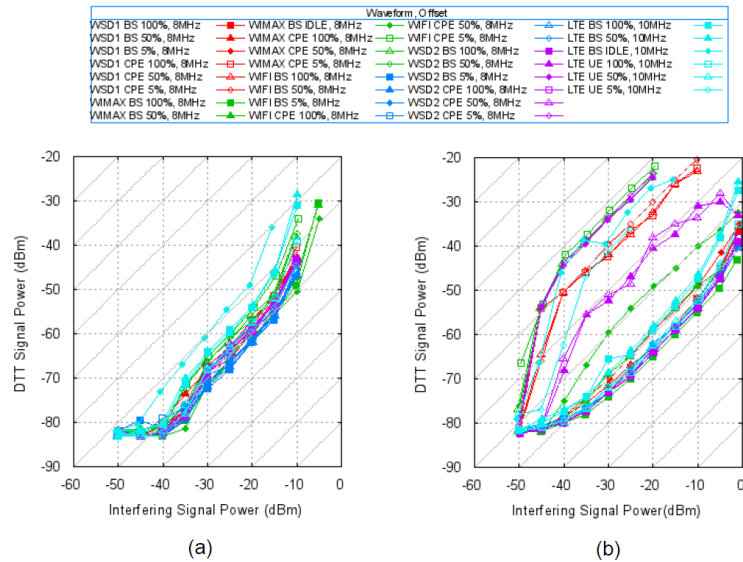
Figure 9.7: DTT receiver performance in the presence of various types of white space interference. (a) A 'typical' receiver; (b) A 'poor' receiver.

shows the performance of two DTT receivers in the presence of various types of adjacent-channel white space interference (the graphs show the points at which the picture just starts to break up). The performance of the receiver in Figure 9.7(a) is relatively consistent for various types of white space interference. The receiver in Figure 9.7(b), however, shows wide variation in performance in the presence of different types of white space interference. Of the fourteen receivers tested, three exhibited problems due to non-linearity caused by the presence of pulsed white space transmissions.

9.4.2 Quality of White Space Channels

When considering the issue of co-existence between WSDs and DTT, much of the attention to date has focused on the extent to which the transmissions of WSDs might affect DTT reception. However, potential users of white space spectrum are likely to be interested in the extent to which DTT signals from TV transmitters might impinge upon white space channels that are available for use in a particular location. (When a WSD is given permission to use a white space channel in a particular location, there is no guarantee that the channel will be free of DTT signals that could potentially interfere with the white space transmissions.)

From the numerous DTT signal strength measurements that were taken across Bute, estimates of white space channel availability were made for each test location, and the residual DTT signal strength in each of those channels was calculated. This gives a rough indication of the quality of each white space channel at each test location. Figure 9.8 shows the resulting Cumulative Distribution Function (CDF), from which it can be seen that at least 75% of locations have a residual DTT
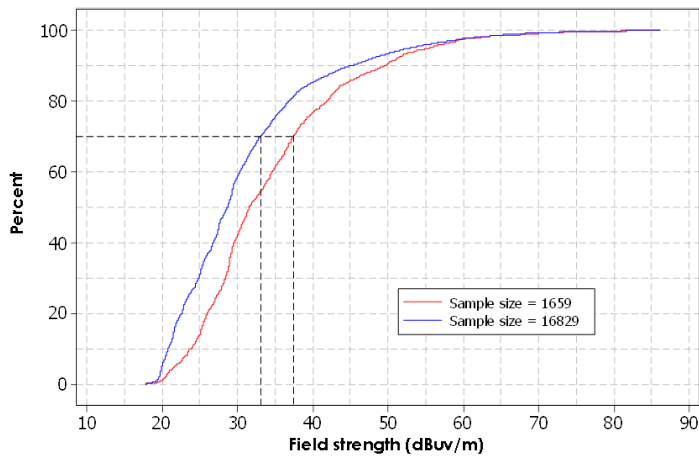
Figure 9.8: Cumulative Distribution Function (CDF) for residual DTT signal strength in white space channels on Bute.

field strength of less than 40 dBμV/m. This implies, therefore, that some 75% of white space channels on Bute would be usable in practice.

9.4.3   WSD-to-DTT Coupling Measurements

Any coupling from a white space device to a TV aerial creates an opportunity for interference to be injected into the DTT receiver. The effects of WSD-to-DTT coupling depend on the relative positions and orientations of the antennas. In order to assess WSD-to-DTT coupling in the field, measurements were made at various premises - mainly those of trialists but also those of a few non-trialists. The measurements involved the taking of power readings from the output of the TV aerial downlead, which represents the signal that would normally be entering the DTT receiver.

Figure 9.9 and 9.10 shows two CPE installations on Bute. In Figure 9.9, the TV aerial and white space CPE antenna are 14 metres apart and their boresights are offset from one another by 80°. This is considered to be an example of a 'good' installation: the antennas are sufficiently far apart and their boresights sufficiently misaligned to result in a high WSD-to-DTT coupling loss. (The coupling loss was 82 dB.) In Figure 9.10, the TV aerial and white space CPE antenna are mounted on the same pole, with a separation of approximately 1 metre in the vertical direction. Their boresights are offset from one another by 30°. The WSD-to-DTT coupling loss was only 22 dB, and although all of the property's TV sets were functioning without any apparent problems, this is nevertheless considered to be a 'poor' installation.

In order to minimize WSD-to-DTT coupling, factors such as physical separation and boresight offset of the DTT and TVWS aerials at the customer premises are clearly important. In addition, several of the trialists' installations included amplifiers of unknown gain and TV aerials of unknown quality, thus adding to the complexity of installation.
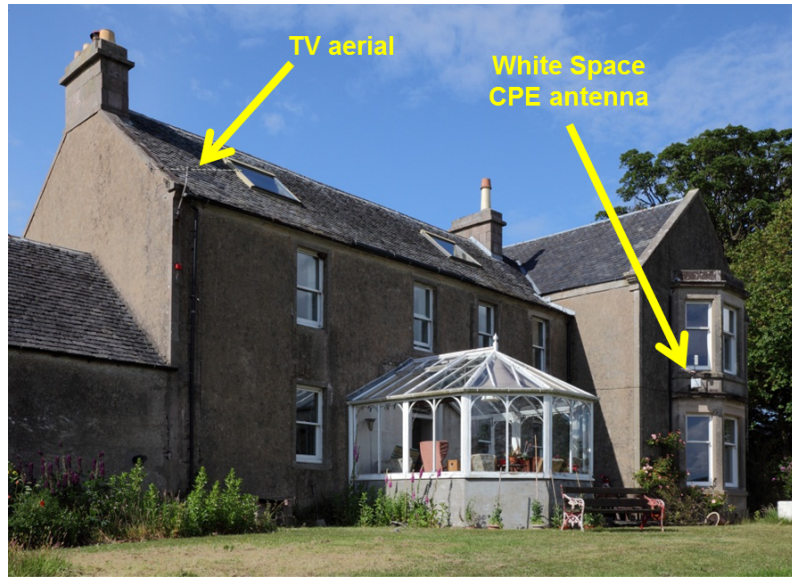
Figure 9.9: As far as WSD-to-DTT coupling is concerned, this is considered to be a 'good' installation.
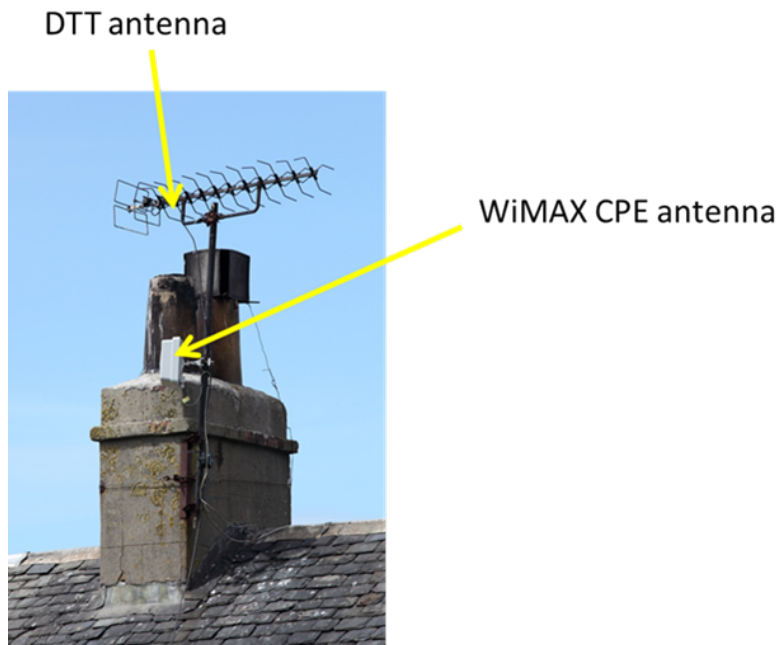
Figure 9.10: As far as WSD-to-DTT coupling is concerned, this is considered to be a 'poor' installation.
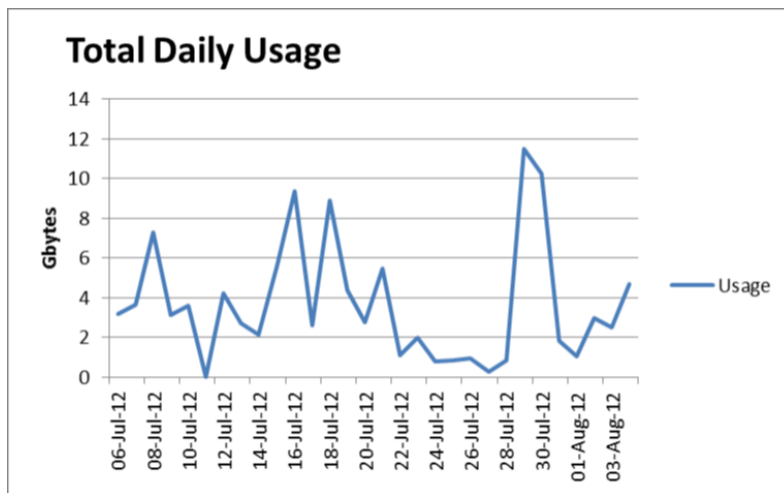
Figure 9.11: Daily usage statistics for the whole network over a one-month period.

9.5 NETWORK OPERATION AND USER EXPERIENCE

Many of the residents in the trial area are farmers, and there is increasing pressure on them nowadays to carry out various administrative tasks on line rather than by paper or telephone. The same is true of hotel owners, and fast, reliable access to the internet is becoming an essential tool for many businesses.

The white space trial on Bute involves a real network with trialists making real use of the broadband services provided to them via white space spectrum. Figure 9.11, for example, shows the total daily usage measured over a one-month period during the summer of 2012. The trialists have spoken very positively about the broadband connectivity that they have been receiving as part of the trial, and the value that it has brought to their personal and business lives. When asked if expectations had been met as a result of the white space trial, one trialist responded: *"Very much so —compared with what we had before, this is excellent."*

9.6 FURTHER EXTENDING BROADBAND REACH

A proposed method of further extending the reach of broadband provision involves the use of self-powered 'relay' masts located at suitable locations such as a hilltop, and connected wirelessly to the local telephone exchange or some other kind of aggregation point. Self-powered masts have the advantage of not requiring an electricity supply, making them ideally suited to locations where such an electricity supply does not exist.

This concept has been considered as part of the project, and prototypes have been developed and manufactured (see Figure 9.12). Initial

Figure 9.12: Prototype 'Wind-Fi' mast.

tests suggest that the concept is viable, and further test and development activities are being planned.

9.7 SUMMARY AND CONCLUSION

The white space rural broadband trial on the Isle of Bute has been extremely useful for gaining insight into the viability of using white space spectrum for rural broadband provision, and has successfully demonstrated the potential of white space technology through the use of real-world applications such as video streaming and video conferencing. The trialists have embraced the network for a wide range of uses related to working life, social life, leisure and recreation, online shopping, education, etc. They speak very positively about the broadband connectivity they have been receiving as part of the trial, and the value that it has brought to their personal and business lives. The provision of adequate

broadband connectivity in rural areas is clearly very important in today's society, and the benefits of using white space spectrum are applicable not only to remote parts of Scotland but also to remote areas in many other parts of the world.

9.8 ACKNOWLEDGEMENTS

The author expresses thanks and acknowledgements to the Technology Strategy Board for its support throughout the project, and to colleagues in each of the partner organizations for their contributions to the main project report, from which this case study is derived. Particular thanks are due to Mark Waddell (BBC), Shyamalie Thilakawardana (BBC), Tim Harrold (BBC), Michael Fitch (BT Innovate Design), Andrew Garrett (BT Innovate Design), Chris Gibbs (Openreach), Malcolm Starke (Openreach), Malcom Brew (Steepest Ascent), and Faisal Darbari (Centre for White Space Communications, University of Strathclyde).

9.9 FURTHER INFORMATION

Further information regarding the Isle of Bute White Space Trial can be found at: http://www.wirelesswhitespace.org/projects/white-space-trial-on-the-isle-of-bute.aspx

COGNITIVE RADIO AND AFRICA

Linda E. Doyle
Trinity College
University of Dublin
Ireland
Linda.Doyle@tcd.ie

10

The focus of this chapter is on cognitive radio and Africa. There are many questions abut the long term viability and commercial success of cognitive radio. These questions are amplified when set in the context of Africa and other more resource constrained environments. This chapter looks at the general motivations for cognitive radio and questions whether these hold in the African context before going on to suggest a range of key areas in which cognitive radio could play a role on the African continent. This chapter seeks to look beyond the focus on TV white spaces and speculate about the longer-term future of for cognitive radio.

10.1 INTRODUCTION

The purpose of this chapter is to look at the potential for cognitive radio in Africa. The chapter begins with a brief reminder of the varied definitions that are in use for cognitive radio as well as looking at the traditional factors driving cognitive radio. The chapter then goes on to pose the question whether these drivers are valid in the African context. Following this the outlook for cognitive radio in Africa is explored and the issue of cost is discussed.

10.2 THE MEANING OF COGNITIVE RADIO

As cognitive radio is over a decade old, it might seem unnecessary to provide a definition. However, given the wealth of the meaning that is encompassed in the term cognitive radio, it is worth repeating a few definitions as the purpose of this chapter is to focus on the future of this technology in Africa, and hence the definition in use matters. The term
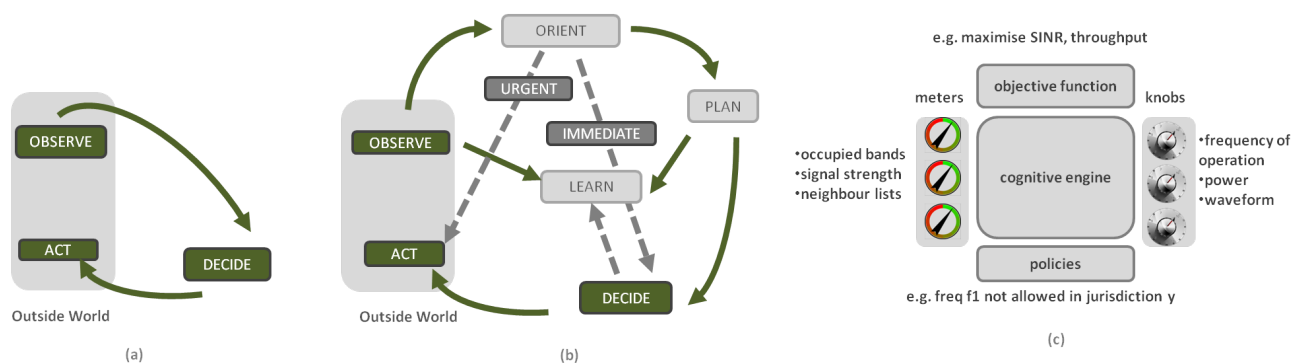
Figure 10.1: Many Ways to View a Cognitive Radio

1. J. Mitola and G. Maguire, Cognitive radio: Making software radios more personal, IEEE Personal Communications, 37:10 (1999), 1318.

2. Doyle, L.E., The Essentials of Cognitive Radio, Cambridge University Press, The Cambridge Wireless Essentials Series, April 2009, pp240.

3. Clancy, C.; Hecker, J.; Stuntebeck, E.; O'Shea, T., "Applications of Machine Learning to Cognitive Radio Networks," Wireless Communications, IEEE , vol.14, no.4, pp.47,52, August 2007

4. I. Macaluso, D. Finn, B. Ozgul, and L. A. DaSilva, Complexity of Spectrum Activity and Benefits of Learning for Dynamic Channel Selection, IEEE Journal on Selected Areas in Communications (JSAC), Cognitive Radio Series, 2013 (to appear).

5. Gavrilovska, L.; Atanasovski, V.; Macaluso, I.; DaSilva, L., "Learning and Reasoning in Cognitive Radio Networks," Communications Surveys & Tutorials, IEEE , vol.PP, no.99, pp.1,17

cognitive radio was coined by Mitola in an article he wrote with Maguire in 1999 [1]. In that article, Mitola and Maguire describe a cognitive radio as a radio that understands the context in which it finds itself and as a result can tailor the communication process in line with that understanding. Over the years the cognitive cycle has been used to define cognitive radio functionality. Using the cycle, a cognitive radio is a radio that can make observations about its environment, take decisions about how to respond to the environment and act by configuring itself appropriately as in Figure 10.1 (a). The type of cognitive radio associated with the use of the TV bands is one that follows this cycle. It makes observations about spectrum availability through reading from a database, decides which frequency to use and acts by configuring the frequency and power of operation of the white space device. However, much more advanced definitions of cognitive radio have also been conceived [2]. For example, some definitions focus on learning and a cognitive radio is often defined as a radio that has the ability to learn from its actions and from this learning to feed into any future actions it may take. In line with this, more complex versions of the cognitive cycle have been used to include this level of functionality as depicted in Figure 10.1 (b). A body of research does exist in which learning algorithms are explored in the context of cognitive radio [3] [4] [5] though it is probably fair to say that no compelling applications yet exist that undisputedly require learning.

The decision-making part of the radio is often referred to as a cognitive engine and some definitions of cognitive radio focus more on this engine. Figure 10.1 (c), for example, places it at the centre of a system and views a cognitive radio as a device that has a set of 'meters' which feed into a cognitive engine that outputs the settings for the 'knobs' on the radio. The meters are the various different sensing and observation mechanisms, the knobs correspond to the parameters of the radio system that can be configured. The engine strives to achieve an objective or set of objectives given the state of the environment and the options for configuration (i.e., range of settings of the knobs). As can be seen in Figure 10.1 (c) there is also a possibility for policy-level input, i.e., for policies to drive the output of the system. Cognitive radios can also,

therefore, be associated with the ability to process policies [6]. The coining of the phrase cognitive radio is generally considered both a help and hindrance. It has unlocked ideas around the notion of a radio with a brain and led to an embracing of multi-disciplinary investigations in the field [7]. On the other hand it has conjured up notions of radios with emergent properties that will, if left untamed, wreak havoc on incumbent systems. It is against the multiple definitions of cognitive radio and with an acknowledgement that cognitive radio is still an emerging technology that the role of cognitive radio in Africa is now explored.

10.3 DRIVERS OF COGNITIVE RADIO

To determine whether there is a role for cognitive radio, the drivers of the technology need to be identified. Cognitive radio can generally be seen as:

1. a means of enabling new modes of spectrum access

2. a technology for supporting autonomous/self-configuring/self-planning networks.

Broadly speaking, whether considering commercial, military or public safety applications, cognitive radio will play a part if spectrum needs to be accessed in some form of dynamic or shared manner, or if there are requirements for complex autonomous decisions to be made.

10.3.1 Cognitive radio as a Means of Enabling New Modes of Spectrum Access

Traditionally, access to spectrum has been managed in a limited number of ways. Most spectrum has been organised on the basis of some form of exclusive access. Typically, licenses are granted to licensees by a variety of mechanisms (beauty contents, auction, administrative incentive pricing schemes, etc.) and only the licensee can use the specific spectrum. In contrast to this approach, a commons-like approach in which access to the spectrum is open to all (on the proviso that certain rules are followed) has also been in operation. The best known example of this is the ISM band. In the ISM band all devices wishing to transmit can do so provided a certain power level is not exceeded. Cognitive radio has long been seen as an enabler of many more varied and nuanced forms of spectrum access. More specifically, it has been seen as a key technology in the drive towards dynamic forms of spectrum access and spectrum sharing. The term dynamic spectrum access (DSA) can be used to encompass all kinds of spectrum access regimes that do not involve static assignments of access rights but call for the identification of opportunities for using spectrum either that others (i.e.,primary users) are not occupying or through some sort of regime that allows spectrum

6. Wilkins,D.; Denker,G.; Stehr,M.O.; Elenius,D.; Senanayake,R.; Talcott,C., "Policy Based Cognitive Radios,"WirelessCommunications, IEEE , vol.14, no.4, pp.41,46, August 2007

7. S. Haykin, Cognitive Radio: Brain-empowered wireless communications, IEEE Journal on Selected Areas in Communications, Special Issue on Cognitive Networks, vol. 23, pp. 201-220, February 2007

8. Note DSA does not necessarily imply unlicensed access.

9. In exclusively shared systems, a network will dynamically get a spectrum assignment for a given period of time for its own exclusive use.

10. President's Council of Advisors on Science and Technology. Realizing the Full Potential of Government-Held Spectrum to Spur Economic Growth. July 2012.

11. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committe of the Regions, Promoting the shared use of radio spectrum resources in the internal market. September, 2012.

to be assigned when needed and subsequently relinquished.[8] The use of the TV white spaces can be seen as a very slow form of dynamic spectrum access. The TVWS device ascertains what spectrum is available in a given area and uses that spectrum - i.e., the TVWS devices do not have static assignments of spectrum. Additionally the TVWS device shares with all other TVWS devices that choose to use the same spectrum. Hence, it is a non-exclusive shared flavour of dynamic spectrum access.[9] In this case the primary user/incumbent is afforded a specific level of protection.

Over the past number of years more nuanced forms of sharing have come to the front. The 2012 PCAST report [10] from the FCC suggests a broad framework for a tiered model of shared-access of Federal spectrum. In this spectrum management model there are three tiers of access; Federal Primary Access, Secondary Access and General Authorised Access (GAA). The Federal Primary Access users register their actual deployments within a database. These Federal Primary Access users enjoy full exclusive use of their assigned spectrum but do not have the right to block others from using it, if they themselves are not using it. Secondary Access (SA) users are issued with short-term access rights and must also register in the database. These rights give them certain guarantees of levels of service and assure them protection from interference from the lowest users in the tiered access model. The final and lowest layer of the hierarchy is the General Authorised Access (GAA) tier. GAA usage is purely opportunistic, and hence this tier of users only gets assigned whatever frequencies are left over at any given time and in any given location. It is clear that there is a role for cognitive radio if any of these ideas were to become reality. Currently, the PCAST report remains a set of aspirations though the FCC has released as "notice for proposed rule making" for the 3.5 GHz bands in the USA which embrace a lot of the PCAST concepts.

In resonance with some of the approaches in the PCAST report, concepts such as Licensed Shared Access (LSA) have also been gaining traction. This approach to sharing spectrum was initially proposed by an industry consortium under the name Authorised Shared Access (ASA) and currently the term ASA tends to be used in the USA and LSA in Europe. The LSA framework sees the initial licensed user or users, i.e., the incumbents, sharing their spectrum with one or more new users who may be offering the same service or a different one, according to conditions imposed on both the incumbent and new user. It can be seen as a type of highly controlled sharing and not hugely different in concept from some of the concepts mentioned in the PCAST report. The EU's approved Radio Spectrum Policy Programme endorsed the LSA concept and CEPT is fleshing out the details of how such a system would work in practice, both within the confines of technology and with the confines of the European Treaties [11].

It can be reasonably argued that the main motivation for dynamic spectrum access and spectrum sharing has always been the so-called *spectrum crunch*. The term spectrum crunch is used to emphasise the scarcity

of the spectrum resource. There are numerous graphs forecasting the explosive growth of future mobile data [12]. A plethora of measurements exist to highlight the fact that assigned spectrum is not always used efficiently and effectively by the licensee and hence (exclusive or non-exclusive) sharing can alleviate the pressure on the resources. A second and also very powerful motivation for sharing comes from a more political *open spectrum* perspective. Open spectrum advocates promote freer and easier access to spectrum and believe that much like in the ISM band new forms of innovation will follow and most importantly opportunity for new players, including smaller entities, will emerge. In this context, sharing is seen as a means of gaining access to a resource that is central to any wireless communication system and gaining access to a resources that is typically limited to a number of powerful controlling entities. A third motivation is the fact that *sharing is the new clearing*. Clearing refers to the moving of incumbents out of specific bands and in most cases this is done to allow the emptied bands to be auctioned for exclusive usage. Clearing can be a costly and slow process. In some cases incumbents must be paid to move to other bands. And typically nothing happens in a band until all the incumbents have moved. The times involved can vary from years to decades. Sharing can be seen as a dynamic form of clearing. Figure 10.2 explains how. Initially a strong vibrant service is in operation in a band. As the need for this service wanes or because of the existence of large amounts of idle capacity within the band, sharing can be permitted (on a hierarchical basis, for example). Over time it may be the case that the incumbent needs increasingly less spectrum - either as mentioned already because the needs for the service reduces, or as for example in the case of Digital TV, more effective use of the spectrum is made. Roles may then be reversed. Using the terminology of primary and secondary user, the primary incumbent starts as a primary and exclusive user, subsequently permits sharing with a secondary system on some kind of hierarchical basis, over time both become equal sharers of the band and finally the secondary becomes the new primary as its services gain popularity and the old primary assumes secondary status as its popularity decreases until it finally dies out. Taking this approach means that there is a constant recycling of bands.

12. http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/whitepaperc11-520862.pdf

10.3.2   Cognitive Radio as an Enabler of Autonomous System Configuration and Management

A cognitive radio, or possibly more correctly a network of cognitive radios, can be considered to be a self-organising system. The network can understand the context it finds itself in and can configure itself in response to a given set of requirements, in an autonomous fashion. The configuration need not just focus on frequency issues, such as dynamic spectrum access, and can involve many other features of the network such as power, beam pattern, routing algorithm in use, cod-

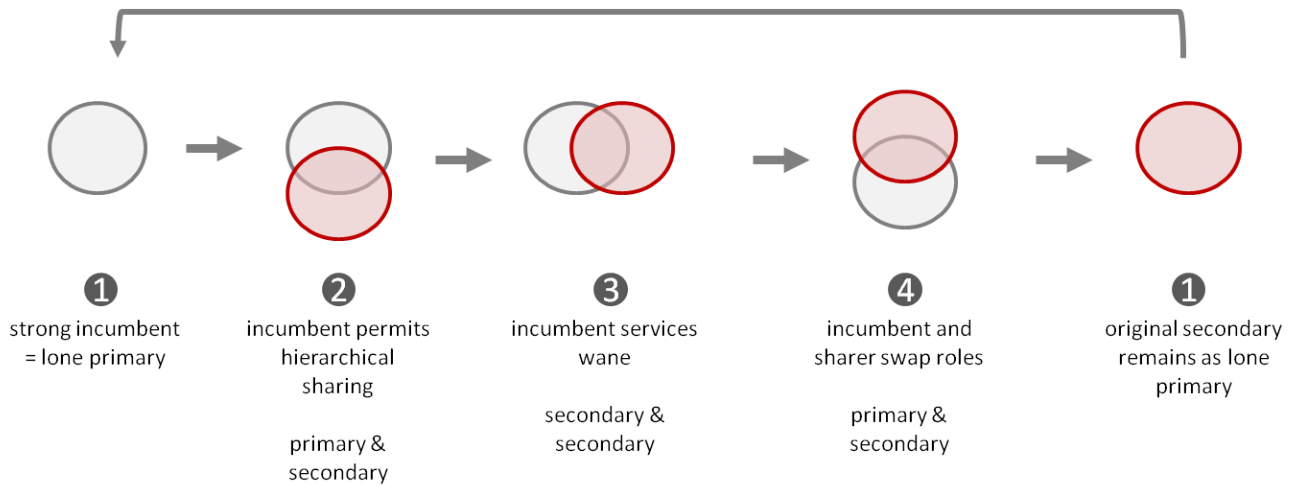| ❶	❷	❸	❹	❶
strong incumbent = lone primary	incumbent permits hierarchical sharing	incumbent services wane	incumbent and sharer swap roles	original secondary remains as lone primary
	primary & secondary	secondary & secondary	primary & secondary	

Figure 10.2: Sharing is Clearing

ing techniques, filtering techniques, etc. However, an element of spectrum management is likely to feature in many configuration processes. Looked at from this self-organising point of view, we can say that any communication application that requires a radio or network of radios to self-organise can justifiably make use of a cognitive radio. We can consider the need for autonomous self-configuration within more traditional communication systems. Consider for example an LTE-A system. The reality is that the number of parameters (knobs) which can be set in such a system is vast. Variable parameters include numbers of antennas in use, multiple-input, multiple-output (MIMO) mode, modulation, power, frequency, scheduling options, number of frequency bands that are aggregated, spatial configuration of primary and serving cells associated with the aggregated spectrum among many others. It seems infeasible that the true potential of LTE-A networks can be achieved without some advanced decision-making and optimization based on contextual information. Hence, it is possible to argue that the realization of LTE-A systems, whether explicitly labelled as such or not, will need some elements of cognition to function. Context will have to be determined through observation of the environment (meters) and the many parameters (knobs) configured (with the help of a cognitive engine) to suit the context, as per Figure 10.1 (c). Taken from this perspective cognitive radio is a natural part of the roadmap for future mobile communication systems. The same argument can be made in the context of the self-organisation of large numbers of small cells and other user deployed infrastructure that cannot depend on centrally coordinated human intervention. We can also consider autonomous system configuration in the context of any system using spectrum dynamically. It naturally goes hand-in-hand with the requirement to seek out spectrum opportunities and configure appropriately to exploit those opportunities. In addition, cognitive networks sharing the same spectrum must act like autonomous interference management systems to co-exist with one and

another.

10.4 ARE THE DRIVERS OF COGNITIVE RADIO DIFFERENT FOR AFRICA?

We return now to focus on the specifics of Africa. The key question that arises is whether the drivers for cognitive radio remain the same or whether there are others that might be relevant or even if there is an absence of drivers in the African context.

10.4.1 Africa and New Modes of Spectrum Access

In terms of an enabler of new modes of access to spectrum the question firstly arises as to whether there is or will be a spectrum crunch in Africa. On the grand scale of things, the simple answer must be no, as a large proportion of the population remains unconnected. There is much to be done in Africa to enable basic connectivity for large percentages of the population. In addition, it could be argued that there are many other techniques that can be exploited before cognitive radio is called on to squeeze more efficiency out of the spectrum. To build a counter argument to this we should focus on the fact that in the developed world spectrum has been managed into scarcity. In other words its scarcity is more due to how it is managed than anything else. The many measurements which show vast tracts of idle spectrum substantiate this point. The highly static nature of the spectrum management regimes and the historical tendency to regulate for 'how technologies work now' rather than 'how technologies could work in the future' are at fault. Rather than wait for a similar situation to eventually build in Africa, it could make sense to proactively regulate for more dynamic forms of spectrum access and sharing for when these approaches are eventually needed. Africa is the most rapidly urbanizing region on the planet. Though the vast bulk of the mobile technology in Africa is based on GSM with movement to 3G continuing, there are LTE deployments planned for 14 countries in Africa.[13] There are around 8 networks in service. While the deployment of LTE is highly limited it does at least flag that there is an increase in pace in the take-up of new technologies. Around 350 000 Huawei IDEOs Android handsets were sold in the first six months in Kenya since its launching in January 2011. While the smart phone is beyond the means of the vast majority of Africans this number is a large number for a country where 40% of the population live on less than $2 a day, and indicates an appetite for data and new services. Reiterating the point about regulating for the future, there is no reason not to plan and regulate for the kinds of dynamic and sharing situations that cognitive radio enables rather than wait to respond when it becomes necessary. In addition, as mentioned in section III-A, the facilitation of sharing ultimately supports clearing. It may of course seem extravagant to be discussing long

13. These numbers are based on http://ltemaps.org/home/ as of July 2013.

14. Michael Jenson, Chapter 2: Technical Access Issues, in Accelerating Development Using the Web: Empowering Poor and Marginalized, George Sadowsky, ed. Published by the World Web Foundation, May 2012 http://public.webfoundation.org/publications/accelerating-development/

term regulation plans when there are so many pressing challenges in enabling connectivity in Africa. Jensen provides an excellent summary of the many challenges in Chapter 2 of the book Accelerating Development Using the Web: Empowering Poor and Marginalized [14]. The challenges range from regulatory to practical such as the lack of internet interconnection points or to challenges relating to power supply and off-grid issues to the lack of content in specific languages and education. In that chapter Jenson also points out that, '*The decline of the small Internet provider continues, especially in developing countries where mobile providers are taking most of the consumer market share. When combined with the ongoing consolidation of fixed and mobile operators, their massive economies of scale and ownership of the delivery media leaves fewer niches for small providers, who have been largely relegated to countries where local-loop unbundling has taken place.*' He also provides a set of ten points for action that should be taken to address the technical challenges around access. These include (a) increase competition in the market, (b) implement infrastructure sharing for providers and (c) liberate more radio spectrum for broadband. These suggestions resonate strongly with the more open approaches to spectrum sharing (enabled through cognitive radio) which can provide a means of gaining access to, as stated earlier, a resource that is central to any wireless communication system and that is traditionally monopolised by a number of powerful controlling entities. To set the wider context Safari.com has 78% of the mobile market in Kenya and 18% of the country's GDP flows through that company. It is vital that alternative forces can come into play, in Kenya and elsewhere in Africa. The wide deployment of WiFi is largely because of the fact that it uses unlicensed spectrum and its low cost. This has spurred many schemes and innovative approaches in Africa. However, ultimately a mix of frequencies are needed (lower for longer distances) and more generally there is a need for increased access to spectrum. And while Jenson's call to implement infrastructure sharing was meant mainly in the context of cellular networks, cognitive approaches can enable much more advanced forms of sharing, and cognitive networks can lend themselves very well to virtualisation, which can be the basis of extreme forms of sharing.

10.4.2   Africa and the need for Autonomous System Configuration and Management

The second key driver for cognitive radio, as described in section III-B, is based on the fact that cognitive radio facilitates the making of autonomous decisions, of self-configuration etc. This kind of functionality bodes well for scenarios in which operational costs (OPEX) need to be kept to a minimum. In addition, returning to Figure 10.1 (c) for a moment, the objective function of the cognitive system can be one that takes power consumption as well as communication related issues into

account. Hence cognitive radio can be exploited to make best use of scarce energy as well as spectral resources. Depending of the sophistication of the cognitive system, behavioural patterns can be learned and the network can be adjusted to take these into account. It is already the case that existing systems perform 'semi-cognitive' like functions. For example, there are communication systems such as those from Altobridge, which recognise when traffic is local and do not waste resources by directing the traffic back to the core network only to have to re-emerge it again locally. Using cognitive radio language, these systems can be described as making observations about traffic, making decisions on how to respond and subsequently taking actions regarding the redirection of the traffic. While a simple example, it is illustrative of the trends that are emerging and the opportunities for increasingly cognitive capabilities. Perhaps the most potent area in which the autonomous, self-configuring functionality of a cognitive radio might bear fruit is in the context of backhaul. This links with the previous section, section 10.4.1, on new modes of spectrum access as it is predicated on the notion that access to spectrum becomes easier and more plentiful. In the last decade there has been improved connectivity in terms of fibre connections being brought to Africa. There are huge challenges in connecting users with these fibre backbones. There is still very limited fibre within the continent. There is also the usual problem of urban centres being much better catered for than suburban and rural areas. Wireless backhaul has to be a key enabler of connectivity - i.e., a means of connecting users to the fibre infrastructure. It is more competitive from a price perspective as it does not incur the costs associated with trenching etc. There is no reason why large tracts of spectrum could not be made available to provide wireless backhaul services. Suppose for a moment, as a thought experiment, that all and any spectrum were deemed usable for backhaul (except for argument's sake the spectrum belonging to mobile operators) BUT on a dynamic basis and of course on the premise that no harmful interference is experienced by legacy systems. In other words the balance would be tipped from a world in which the status quo is about exclusive rights to one in which the vast majority of access is non-static or dynamic. It is possible to envisage a series of dynamic links, criss-crossing Africa, that self-configure while managing interference to protects incumbents, making the most of any spectral assets that can be used. There are whole areas in Africa in which there may be no incumbents to avoid in the first place and in the longer term a dynamic system will allow for much flexibility should assigned but unused spectrum made available. In summary, the autonomous self-configuring functionality of a cognitive system could, in theory, be ideally suited to solving key challenges in Africa provided that regulations are put in place to exploit the opportunity.

10.5 THE ISSUES OF COST

It is not possible to tackle the issue of cognitive radio and Africa without addressing the issue of cost. Most people will reasonably argue that cognitive radios are expensive radios. Typically, these radios are frequency agile and hence have more sophisticated RF frontends. In addition, they can have complex processing capabilities, especially if learning is included. Many of the sharing paradigms envisage the requirement for some sort of database, typically an advanced version of what is needed for TV white space databases. In fact, cognitive radio is considered expensive in the developed world even before developing world incomes and other challenges are considered. While progress is being made on the reduction in cost of smart phones, for example, which would bode well for the future of cognitive radio, there are still many challenges. Again, even before considering cognitive radio, LTE is seen as hugely expensive technology whose cost of deployment is not warranted in many places in Africa. Hence it seems reasonable to assume that even if cognitive radio can facilitate spectrum sharing and perhaps reduce barriers to entry for new players or provide the kinds of autonomous behaviour that could be essential in remote areas of Africa, it would remain prohibitively expensive for the long-term future. There are some dissenting voices however, and it is worth airing these to provide a fuller picture. Marhsall has long contended that *cognitive radio can be a cheaper radio*. In [15] and [16] he argues that a new business case is possible. His main argument is built around the notion that linearity and filtering in the RF front ends are the drivers of cost. Typically, linearity is essential for high dynamic range. His work shows that non-cognitive radio systems have significant 3rd Order Intermodulation noise increase, even for high performance filters. Cognitive radios, which use dynamic spectrum access techniques and can therefore have a choice about the spectrum bands they use, can operate in a manner that ensure that intermodulation products do not become an issue. Marshall has shown that cognitive radio can enable a 30 dB reduction in required IIP3 performance, while creating a lower noise floor simultaneously, even for moderate filter selectivity (20%) therefore saving on costs. An unrelated work, but relevant in terms of explaining the concepts that underpin this approach is [17]. In essence Marshall argues to re-think RF design, leveraging the smarts of the radio to make a low cost front end. Fettweis and his team take a somewhat connected approach under the heading *Dirty RF*[18]. They point out that building compact and low-cost but flexible and reconfigurable radios for future wireless systems is generally a challenging task. The trade-offs between using flexible hardware and at the same time trying to keep radios as small and power efficient as possible while at the same time exploiting multiple antenna techniques means that various imperfections and impairments surface in the radio transceivers, especially in the radio frequency (RF) analogue electronics. Examples of the imperfections are, e.g., mirror-frequency interference due to I/Q imbalance,

15. Marshall,P.F.,"Dynamic Spectrum Management of Front End Linearity and Dynamic Range, "New Frontiers in Dynamic Spectrum Access Networks", 2008. DySPAN 2008. 3rd IEEE Symposium on , vol., no., pp.1,12, 14-17 Oct. 2008

16. Marshall, P.F.,Quantitative Analysis of Cognitive Radio and Network Performance (Mobile Communications) (Artech House Mobile Communications), June 2012

17. Marshall, P.F., Scalability, Density, and Decision Making in Cognitive Wireless Networks, Cambridge University Press, December 2012.

18. Fettweis, G.; Lohning, M.; Petrovic, D.; Windisch, Marcus; Zillmann, P.; Rave, W., "Dirty RF: a new paradigm," Personal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005. IEEE 16th International Symposium on , vol.4, no., pp.2347,2355 Vol. 4, 11-14 Sept. 2005

non-linear distortion due to mixer and amplifier nonlinearities, timing jitter and non-linearities in sampling and analogue-to- digital (A/D) converter circuits, and oscillator phase noise. Fettweis et al, stress that if these impairments are not properly understood and taken into account, they can easily become a limiting factor to the quality and performance of the radio device and thereon of the whole wireless link. Their approach is to use baseband processing algorithms to compensate for the impairments. They show that by knowing the statistical properties of impairments in the analogue front-end and using powerful digital baseband processing, future wireless communications systems may be able to cope with dirty RF. They extend the transmission rate by joint optimization of RF components and baseband processing - opening the path for high performance devices at reasonable cost. While this work does not explicitly reference cognitive radio it implicitly does - a radio can self-profile, have an in-depth awareness of its own flaws and can correct those flaws through appropriate techniques. Without a doubt the term low-cost and reasonable-cost are relative. However, the work described here does challenge conventional wisdom and at least postulate that there are different ways of doing things. This work shifts the perspective. Rather than build systems that are highly tuned to certain bands, with strict filtering requirements and high-level performance that pushes the cost up, it is possible to use lower cost entities and compensate for their performance in different ways. It is an entirely different mindset but one that could ultimately unlock new possibilities.

10.6 CONCLUSIONS

Cognitive radio is an area in which much academic work has taken place in the past decade. It can be seen as part of the natural progression of radios, i.e., they simply get smarter and therefore a natural part of a future roadmap for LTE-A for example. Seen in this manner cognitive technologies will eventually become part and parcel of many future communications systems and eventually be deployed in Africa as much as anywhere else. However, as a key enabler of dynamic spectrum access and new forms of spectrum sharing, cognitive radio may also have a more powerful role to play in underpinning communication systems that are outside the traditional domain of the large operators and provide opportunities for different players. They also have a role to play in providing the level of robust autonomous behaviour that is needed in remote areas. The cost, as for most technologies, remains a significant factor. However, there is work which can contribute to the creation of lower cost systems. While the challenges of cost matter more in Africa, there is no reason why Africa cannot be a role model or take a leadership position in at least regulating for a dynamic future. Whatever the timescale for deployment of more flexible, cognitive and dynamic systems elsewhere in the world or within Africa, it is worth bearing the

longer term in mind when regulating.

THE WEIGHTLESS STANDARD

11

Alan Woolhouse
Weightless, United Kingdom
alan.woolhouse@weightless.org

I love my smart phone - it's brilliant. It does everything that I want it to do and plenty more that I didn't know I wanted to do before I bought it. And it does what it does so well because it's connected. Network connectivity is the secret sauce - it's where the magic happens and value is leveraged from remote devices. And so it is with the Internet of Things - tens of billions of things, connected to the internet. The value comes from being able to turn data into actionable information and for that we need to capture and transmit tens of billions of seemingly unrelated snippets of data to a network where it can be collected, analyzed, processed, stored and used to make intelligent decisions. And now we're straying into Big Data so let's take a step back and look at a critical jigsaw piece in this architecture - connectivity.

In theory we have everything that we need with our current systems - widely deployed 3G and LTE networks - indeed in developing economies cellular technology investments have been ongoing for years and we now have well established infrastructures to connect people to the Internet. In Malawi earlier this year I was talking and emailing and surfing the web in villages where some children do not even have shoes - cellular technology is truly approaching worldwide ubiquity. Great - we already have the critical connectivity solution to enable the Internet of Things to thrive and there is no further need for debate. Unfortunately, commercial reality is not so unequivocally realized and we are not yet enjoying the utopian Shangri-La of universal connectivity for some compelling reasons.

Current wireless connectivity technologies fall into two categories - short range - local and personal area networks like Bluetooth, ZigBee and WiFi, and long range telephony based architectures - 2G, 3G and LTE. And for wide scale global deployment these technologies all bring something valuable to the table. Current LAN architectures offer low price points and excellent low power consumption characteristics to enable long battery life - but with a range measured in meters. 3G and 4G offers excellent long range reach measured in kilometers but at high cost and with a battery life measured in hours - or at absolute best in

an optimized system, weeks. If we could cherry pick the performance characteristics of these different technologies - cost, battery life and range - then we'd have the building blocks for a new Internet of Things architecture. Enter Weightless...

11.1 WEIGHTLESS TECHNOLOGY

Why has the long forecasted M2M market not reached its potential? The commercial opportunity is substantial - an order of magnitude greater than that of cellular technologies with tens of billions of devices projected to be potentially worth more than a trillion dollars by 2020.

Conventionally M2M solutions have been developed around cellular technologies but for most applications they are not optimal. Cellular technologies do provide sufficiently good coverage for some applications but the hardware costs can be $ 20 or more depending on the generation of cellular used and the subscription costs are often closer to $10 per month than $ 10 per year. Battery life cannot be extended much beyond a month. Cellular networks are often ill-suited to the short message sizes in machine communications resulting in extremely significant overheads associated with signaling in order to move terminals from passive to active states, report on status and more. So while cellular can capture a small percentage of the market which can tolerate the high costs and where devices have external power, it cannot meet the requirements of the 50 billion plus device market. Indeed, if it could, it would have done so already and there would be no further debate about the need for new standards.

There are many short-range technologies that come closer to the price points. These include WiFi, Bluetooth, ZigBee and others. However, being short range these cannot provide the coverage needed for applications such as automotive, sensors, asset tracking, healthcare and many more. Instead, they are restricted to machines connected within the home or office environments. Even in these environments there are many good reasons why a wide-area solution is preferable. For example, an electricity supply company is unlikely to accept that their meter is only connected via, e.g. WiFi, into a home network, which in turn connects to the home broadband. Were the homeowner to turn this network off, fail to renew their broadband subscription or even just change the password on their home router, then connectivity could be lost. Restoring it might require a visit from a technician with associated cost. Maintaining security across such a network might also be very difficult. Short range technologies are not the solution.

Finally, it is critical that the technology is an open global standard rather than a proprietary technology. With a wide range of applications there will need to be a vibrant eco-system delivering chips, terminals, base stations, applications and more. The manufacturer of a device such as a temperature sensor will need to be able to procure chips from

multiple sources and to be sure that any of them will interoperate with any wireless network across the globe.

Without a wide-area machine communications network that meets all of the sector requirements it is unsurprising that forecasts for connected machines have remained consistently optimistic.

While the needs of the machine sector have long been understood, the key problem to date has been a lack of insight as to how they could be met. Ubiquitous coverage requires the deployment of a nationwide network, and such networks are extremely expensive. For example, a UK-wide cellular network would cost more than $ 2 billion with costs of spectrum adding another $ 1-2 billion. Such investments are not justifiable and would result in an overall network cost that would not allow the sub $ 10/year subscription fees needed to meet requirements.

The key to unlocking this problem is free, plentiful, globally harmonized low-frequency spectrum. It needs to be free, or at least very low cost, to keep the investment cost low. It needs to be plentiful to provide the capacity to service billions of devices. It needs to be globally harmonized in order to allow devices to roam across countries and to enable the economies of scale needed to deliver cost effective networks and terminals.

The lack of spectrum that meets all these requirements has meant that up until now the only option for wide-area machine communications has been to make use of existing networks, predominantly cellular.

11.2 WHITE SPACE IS THE PARADIGM SHIFT

A new option has emerged for spectrum access. This is the use of the "white space" spectrum - the unused portions of the spectrum band in and around TV transmissions. White space meets all of the requirements for M2M communications. It is unlicensed and so access to it is free. It is plentiful with estimates of around 150MHz of spectrum available in most locations - more than the entire 3G cellular frequency band. It is globally harmonized since the same band is used for TV transmissions around the world. Finally, it is in a low frequency band which enables excellent propagation without needing inconveniently large antennas in the devices. This is why white space is the paradigm shift. Access to white space provides the key input needed to make the deployment of a wide-area machine network economically feasible.

It is clear that white space access will require devices that have the following characteristics:

1. Relatively low output power. The FCC has specified 4W EIRP for base stations and 100 mW EIRP for terminals. These are an order of magnitude lower than cellular technologies.

2. Stringent adjacent channel emissions. White space devices must not interfere with existing users of the spectrum, predominantly TVs. Hence, the energy that they transmit must remain almost entirely within the channels they are allowed to use. The FCC has specified that adjacent channel emission need to be 55 dB lower than in-band emission, a specification much tighter than most of today's wireless technologies.

3. The need to frequently consult a database to gain channel allocation. Devices may need to rapidly vacate a channel if it is needed by a licensed user. They must consult a database to be informed as to the channels they can use and must quickly move off these channels as required.

Interference can be problematic in white space. Many channels have residual signals from TV transmissions. These can either be in-band emissions from distant, powerful TV masts that are too weak for useful TV reception but still significantly above the noise floor. Alternatively, they can be adjacent channel emissions from nearby TV transmitters some of which are transmitting in excess of 100 kW. In addition, since the band is unlicensed, other users might deploy equipment and transmit on the same channels as the machine network, causing local interference problems.

These are not insurmountable issues. But no current technology has been designed to operate in such an environment and so would be sub-optimal at best. For example, we have shown that in the UK an optimized technology could access around 90 MHz of white space after all the interference issues are taken into account, whereas an existing technology such as WiFi or WiMAX could only access around 20 MHz.

So white space spectrum provides the key to unlock the machine network problem. But it comes at the cost of needing to design a new standard. Fortunately, that new standard has been developed. It is called Weightless.

11.3   DESIGN RULES FOR M2M

There are many benefits to the design of a standard specifically for machine communications. Machines are very different from people; typically, their requirements vary in the following manner:

1. Much shorter message size than most human communications (with the exception of SMS text messages). Most machines only send a few bytes of information whereas a person may download megabytes of information.

2. More tolerant of delay. Most machine communication is relatively unaffected by a few seconds of delay whereas people quickly find this frustrating.

3. Generally predictable communication patterns. Machines often send data at regular intervals and so can be "pooled" on these occasions. People's communication needs are typically unpredictable and so contended access for resources is needed.

Taking advantage of these differences allows the design of a system that is much more efficient, providing greater capacity than would otherwise be the case and hence having low cost. The predictability of most communications allows a very high level of scheduled communications as opposed to unscheduled, or contended, communications. The difference is akin to pre-booking passengers on flights so that each flight is full, but not over-crowded, rather than just letting passengers turn up, as with most trains, and suffering the crowding problems that occur. By telling terminals when their next communications is scheduled, future frames of information can be packed very efficiently and terminals can be sent to sleep for extended periods extending battery life.

Scheduling brings many other advantages. The first is efficiency. Contended access schemes can only operate up to about 35% channel usage - above this level the probability of access messages clashing becomes so high that very little information gets through. By comparison, scheduled access can achieve close to 100% efficiency. Scheduling can be enhanced by complex algorithms in the network that prevent terminals close together in neighboring cells transmitting simultaneously, that ensures that terminals suffering local interference are scheduled on frequency transmissions where interference is minimized, and much, much more.

Another design rule for M2M is that coverage is typically more important than data rate. For example, it is more critical that all smart meters can be read than what the data rate of transmission is - as long as it is sufficient to transfer data regularly. In fact, most machine communications can be measured in bit/s rather than kbit/s or Mbit/s. As an example, a smart meter will typically send around 20-40 bytes of information perhaps once every 30 minutes. This equates to an average of 240 bits per 30 minutes or 8 bits/minute. There are applications that will require higher data rates, but speed is rarely critical. Hence, a good M2M system design will trade off data rate against range. This can be achieved by spreading the data to be transmitted. Spreading involves multiplying the data by a pre-defined codeword such that one bit of transmitted data becomes multiple bits of codeword. The receiver can then use correlation to recover the codeword at lower signal levels than would otherwise be possible. Codewords are selected to have particular correlation properties and typically have length 2n (e.g. 16, 32, 64). So, for example, multiplying the transmitted data by a codeword of 64 results in an improvement in link budget of some 18 dB but reduces the data rate by a factor of 64. Most buildings have a penetration loss for signals entering them of around 15 dB so spreading by this factor would provide indoor coverage to machines where only outdoor coverage previously

existed. Some M2M solutions have spreading factors extending as far as 8192, providing great range, but very low capacity. Large spreading factors do add complexity to the system design since they extend the time duration of important system control messages that all devices must hear, which in turn requires long frame durations. These design decisions make M2M networks radically different in many respects from cellular solutions.

Another requirement, at least at this embryonic stage of the market, is flexibility. Many diverse M2M applications will emerge that will benefit from this ability to configure the performance characteristics. Even the balance between uplink and downlink may benefit from this flexibility: for example smart meters will likely generate predominantly uplink traffic while software updates, perhaps for car engine management systems, will generate large downlink messages. This suggests that systems should be time division duplex (TDD) in order that the balance between downlink and uplink can be changed dynamically.

M2M systems should make the terminal as simple as possible, keeping complexity within the network. This is contrary to the trend in cellular communications where handsets have been becoming ever more powerful and complex. There are two key reasons to keep M2M terminals simple. The first is to keep the cost as low as possible - as mentioned earlier many applications require chips with costs of the order $ 1 - $ 2. The second is to minimize power consumption for terminals that are expected to run off batteries for 10+ years. This means that, for example, complex multi-antenna solutions should be avoided and that terminals should not be expected to make complex calculations to decode their messages. Even an apparently simple decision, such as requiring a terminal to respond on the uplink of a frame where it receives a message on the downlink could require it to process the downlink message much more rapidly, needing a more powerful processor. Careful design throughout is needed to achieve minimal terminal complexity.

Finally, there is likely to be an imbalance within an M2M network where the base station has much more power and processing at its disposal and so can have a greater range than the terminals. This is of no value since the terminals need to be able to signal back and so the link budget must be balanced. With base stations transmitting often around 4 W (36 dBm) but battery powered terminals restricted to 40 mW (16 dBm) there is a 20 dB difference. This can be balanced by using greater spreading factors in the uplink, which will improve the power budget at the cost of decreasing the bandwidth in that direction. Designing M2M solutions does not require any technological break-through. But it does require great care in understanding the implications of each decision and it needs a system design that is radically different from a cellular network, with design decisions often appearing contrary to the conventional wisdom of the day.

11.4 DESIGN RULES FOR WHITE SPACE

White space is unique spectrum. It is the first band where unlicensed users are allowed to mix with licensed users as long as they do not cause any interference to those users. This brings the benefit of free access to highly valuable spectrum but also a need to operate in an uncertain environment. Any system operating in white space should adhere to the following design rules.

Firstly it needs very low levels of out-of-band emissions. This minimizes interference caused to licensed users and so maximizes spectrum availability. Achieving such low emission levels means that modulation schemes such as Orthogonal Frequency-Division Multiplexing (OFDM) should be avoided as these tend to have relatively large adjacent channel emissions.

Next it needs to avoid interference caused by other unlicensed users which can be random and sporadic. Classic techniques for doing this include frequency hopping to rapidly move off compromised channels. However, hopping in a network requires central planning to avoid neighboring cells using the same frequencies. Optimal planning where different frequencies may be available in different cells and the sequence may need to dynamically adapt to interference is complex and requires new algorithms.

Where interference cannot be avoided the system needs to be able to continue to operate. Spreading, as discussed above, can also be useful to work in channels with interference, again trading off range (or tolerance to interference) against data rate. Base stations can often experience significant interference from distant TV transmissions and require mechanisms such as interference cancellation to reduce its impact.

Finally, where there are few white space channels available, it can often be possible to increase availability by transmitting with lower power and hence causing less interference. Power control is therefore critical, again coupled with spreading where needed to regain the range lost from the lower power.

11.5 WEIGHTLESS - THE STANDARD DESIGNED FOR M2M IN WHITE SPACE

Designing the standard for M2M in white space requires many trade-offs and iterations. A key starting point is the conflict between excellent coverage requirements and yet low-power constraints both due to white space regulation and the need for long battery life in terminals. The only way to achieve long range with low power is to spread the transmitted signal. Hence, variable spreading factors from 1 (no spreading) to 1024-fold are a core part of the Weightless Specification. Spreading is essentially a mechanism to trade range against throughput using high spreading factors to achieve significant range extension without increasing power

output but at the cost of lower data rates. There is sufficient bandwidth in the white space frequencies and M2M data rates are sufficiently low that more than adequate capacity and throughput can be achieved even with high levels of spreading.

Use of the white space spectrum does not provide guaranteed spectrum to allow for uplink and downlink pairing, so Time Division Duplex (TDD) operation is essential. This in turn leads to a frame-structure with a downlink part and then an uplink part which repeats periodically. The maximum spreading factor controls what this repetition should be since the header information at the start of the frame needs to be spread by the maximum factor in order that all terminals in the cell can decode it. If this header takes up more than around 10% of the frame length then the system starts to become inefficient as signaling becomes a significant percentage of the total traffic. Simple calculations show frame lengths of around 2 s are optimal. This would be overly long for person-to-person communications, but is not an issue for M2M communications.

The need for stringent adjacent channel emission levels suggest the use of single-carrier modulation (SCM) rather than OFDM as the latter cannot be filtered tightly without distorting the transmitted signals. OFDM also has a high peak to average power ratio which does not fit well with very low powered devices. Because the terminals typically have very low power output, 40 mW, compared to base stations, which can be up to 4 W, the link budget needs to be balanced. This is achieved with a narrower band uplink such that the noise floor is lower. Using around 24 uplink channels for each downlink has the effect of balancing the link budget.

Operation in white space requires good interference tolerance. This is achieved primarily using frequency hopping at the frame rate (2 s) so that the impact of any interference is restricted to a single hop rather than degrading the entire transmission. Frequencies with persistent interference can be removed from the cell hopping sequence. Other mechanisms to remove interference include the base station directing antenna nulls towards strong sources of interference, careful scheduling of transmissions to terminals to avoid the frequencies where they perceive the strongest interference and the use of spreading to make the signal more resistant to interference when all these other techniques are insufficient.

Finally, M2M traffic is often characterized by very short messages, for example a 30-byte smart meter reading. The MAC protocol is designed to add minimal signaling overhead to such messages to avoid highly inefficient transmission. This is done through flexible small packets with highly optimized header information.

A global standards body - the Weightless SIG - has been established to take Weightless technology and deliver a royalty-free fully open standard - a goal achieved in April 2013.

11.6 CONCLUSIONS

The value in machines having wireless communications has long been understood and a large market predicted for many years. That this has not transpired has been because of the difficulty of meeting all the requirements within the constraints of the available radio spectrum. These constraints changed significantly with the advent of white space which provides near-perfect spectrum with free access. However, the combination of the unique and unusual nature of that access and the very different characteristics of machine traffic compared to human traffic means that using any existing standard is far from optimal. Hence, the need for a standard designed specifically for machine communications within whitespace. The Weightless standard was completed to version 1.0 in April 2013. Be part of the future of M2M and IoT with the only standard optimized to bring the 50 billion device and $ 1 trillion opportunity to life. More information is available on weightless.org where visitors can register for membership of the Weightless SIG and download the comprehensive 630 page Standard document.

OVERVIEW OF WHITE SPACE STANDARDS

12

Ermanno Pietrosemoli
The Abdus Salam
International Centre for Theoretical Physics
Italy
ermanno@ictp.it

Standards are very important for the success of any technology. A good example is Spread Spectrum technology. Although the idea first appeared in a 1941 patent application submitted by Hedy Lamarr (Hedy Kiesler Markey) and George Antheil for a "Secret Communication System" [1], it was not until the publication of the IEEE 802.11 Standard in 1997 that the technology took off and became the basis of the enormous success story known as WiFi.

IEEE is an international institute based in U.S., but with worldwide membership. Although it is not an official standards body like the ITU (International Telecommunications Union) or the ISO (International Standards Organization) it is very respected and very often the IEEE standards are later incorporated into official standards. For instance the IEEE 802.3 has been adopted by ISO as ISO/IEC 8802-3, the *de jure* standard for Ethernet.

It also happens that products that enjoy considerable market success can become a *de facto* standard, even without any international organization's backing. Standards are generally very advantageous for customers, since they lead to competition among different manufacturers, which drives prices down, benefitting also from economy of scale, protects the investment in case of a manufacturer going out of the market, and avoid vendor's lock in, the dependence from a single manufacturer that can take advantage from their dominant position.

For the vendors, it is a mixed blessing, since driving the price down is not an objective for the incumbent (although it is for other manufacturers who aspire to get a piece of the market), and also sometime standards stifle innovation. That is why many vendors offer additional features, extensions of the standard, which are proprietary, that is, exclusive to a single vendor. So it is frequent to find a product that complies with a certain standard, but in top of that a particular vendor has added additional capabilities, that, when used, inhibit the interoperability with equipment

1. http://www.hedylamarr.org/hedystory1.html

131

Figure 12.1: Photograph of Hedy Lamarr, movie star and inventor of Spread Spectrum http://www.uh.edu/engines/epi435.htm

from other vendors. For example, standard WiFi radios are not well suited for long distance point to point links, because the medium access protocol was designed for short distance point to multipoint links. Many manufacturers have addressed the issue by offering, alongside CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance), the standard WiFi medium access protocol, alternatives based on TDM (Time Division Multiple Access), which can significantly enhance the throughput at long distances at the sacrifice of interoperability

12.1 EXAMPLES OF WIRELESS STANDARDS

Official standards take a long way to be ready for publication, since very often they affect vested interests and compromises must be reached among the different stakeholders in order to reach consensus. Figure 12.2 shows some of the wireless standards with respect to geographic coverage, spanning from WPAN (Wireless Personal Area Networks) with reach of less than 15 m, to WLAN (Wireless Local Area Networks) extending to some 150 m, going to WMAN (Wireless Metropolitan Area
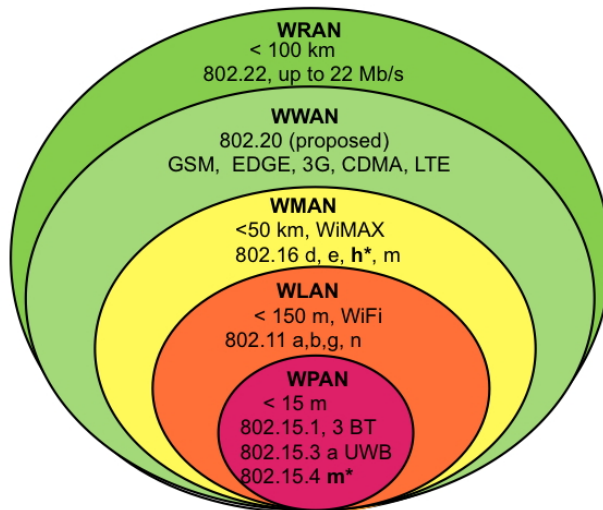
Wireless Standards Coverage

Figure 12.2: Geographical range for some wireless standards.

Networks) covering about 50 km. A special case is that of WWAN (Wireless Wide Area Networks), the cellular networks, in which each base station defines a cell of few kilometers of radius, but the cells are interconnected with backhaul links that can extend the coverage indefinitely. WRAN (Wireless Regional Area Networks can extend up to 100 km from a single base station.

12.2   WHITE SPACES STANDARDS

In general, all the standards specify fixed and mobile stations with different capabilities, and further differentiate between stations that can operate independently and those that need to be enabled by a primary station before attempting to use the channel.

Spectrum sensing is another common feature, which consists of the scanning of the RF energy in a given channel to detect the presence of incumbents. This can be augmented (at the cost of added complexity) by processing the received signal plus noise in order to obtain statistical features that help to discriminate between the signal and the accompanying noise (without prior knowledge of the signal or the propagation channel). Further signal detection precision can be obtained when either the propagation features of the channel or the type of signal to be detected are known, at the cost of more complexity, detection time and loss of generality [2].

Spectrum occupancy is also determined by compiling a database of all known primary users, with precise geographical coordinates, transmitted power, frequency and antenna pattern. This information is used to produce estimates of coverage area for each using detailed terrain elevation maps and/or RF propagation models. A White Space device

2. Yucek, T., Arslan, H., "A Survey of Spectrum Sensing Algorithms for Cognitive Radio Applications", IEEE Commun. Surveys & Tutorials, vol. 11, No 1, 1st qtr.2009, pp. 116-130. http://xanthippi.ceid.upatras.gr/courses/mobile/2009_10/cognitive.pdf

must query such database to obtain information about which channels are available in its location at a given time, to avoid interfering with incumbents. In the following we give an overview of some wireless standards in TV white spaces.

12.2.1 IEEE 802.22

3. C. Cordeiro, K. Challapali and D. Birru, IEEE 802.22: An Introduction to the First Wireless Standard based on Cognitive Radios, Journal of Communications, VOL. 1, NO. 1, April 2006

The IEEE 802.22 is the first world wide effort to define a standardized air interface based on Cognitive Radio (CR) techniques for the opportunistic use of TV bands on a non-interfering basis [3]. Cognitive Radio is a device capable of adjusting its operating parameters accordingly with the environment in which it is currently deployed. The standard covers the whole TV spectrum from 54 MHz to 862 MHz, although its application in different countries will use only portions of this range which is also used by many other services besides TV, like emergency and aeronautical communications, radioastronomy (RAS, 608-614 MHz), aeronautical radionavigation (ARNS, 645-790 MHz), trunking and so on. The primary target of IEEE 802.22 is to use Cognitive Radio techniques to enable sharing of geographically unused spectrum allocated to TV broadcast services to build Wireless Regional Area Networks (WRAN), to deliver wireless broadband access to rural and remote areas. Numerous other crucial markets for this standard include single family residential, multi-dwelling units, small office/home office (SOHO), small businesses, multi-tenant buildings as well as public and private campuses. In terms of service coverage, the standard is capable of facilitating access ranging from a minimum of 10 km to a maximum of 100 km, if enough transmitted power is allowed and propagation characteristics are exceptional, but to accommodate the longer distances will require adjustments in the timing protocol. With the current EIRP (Equivalent Isotropic Radiated Power, the actual power transmitted after taking in consideration the transmitting antenna gain) of 4 W in the US, the maximum range is about 30 km with reasonable CPE antenna gains, and without any change to the basic timing protocol. This enhanced coverage range offers unique technical challenges regarding interference as well as opportunities for offering cost effective services in sparsely populated areas.

The topology is the same as that of a typical cell phone operator, point to multi-point with a Base station (BS) and several clients, the CPEs (Consumer Premise Equipment). The BS can serve up to 512 fixed or portable CPE units equipped with outdoor directional antennas. Target service capacity is to deliver to a CPE at the edge of coverage a minimum throughput, 1.5 Mb/s in the downstream direction and 354 kb/s in the upstream direction, comparable to DSL services. Closer CPEs might enjoy higher throughput, and the total capacity of the Base Station is up to 22 Mbit/s per channel. IEEE 802.22 requires two separate antennas at each CPE: one directional and one omni-directional. The directional antenna is pointed towards the base station and is used for communication

purposes, while the omni-directional antenna is required for sensing purposes. The advanced radio capabilities include dynamic spectrum access, incumbent database access, accurate geolocation techniques, spectrum sensing, regulatory domain dependent policies, spectrum etiquette, and coexistence for optimal use of the available spectrum [4].

Currently, there are 3 active standards in this family officially approved: 802.22 for physical and media access layer, 80.22.1 for Interference Protection and 802.22.2 covering Installation and Deployment, issued in 2012 [5]. The standards are available from the IEEE page, at no cost for the ones that are older than 6 months.

In an IEEE 802.22 cell, multiple CPEs are managed by a single BS that controls the medium access. The downstream is TDM (Time Division Multiple Access) where the BS transmits and the CPE receives. The upstream transmissions, where the CPEs transmit and the BS receives, are shared by CPEs on a demand basis, according to a DAMA/OFDMA (Demand Assigned Multiple Access/Orthogonal Frequency Diversity Multiple Access) scheme. The MAC (Media Access Control) implements a combination of access schemes that efficiently control contention among CPEs while at the same time attempting to meet the latency and bandwidth requirements of each user application. This is accomplished through four different types of upstream scheduling mechanisms: unsolicited bandwidth grants, polling, and two contention procedures; one based on MAC header and another based on CDMA (Code Division Multiple Access). This provides flexibility to accommodate different types of traffic, while preventing interference to the incumbent and also managing the access to the shared channel among different secondary users, in what is called self-coexistence mode. The sharing of the channel is accomplished by dividing the frame in two parts: a downstream subframe (DS) and an upstream (US) subframe. The boundary between the two subframes is adaptive to better accommodate traffic asymmetries. Time division duplexing (TDD) is the only mode currently supported by the standard. The difference between propagation times of far away and close CPEs is taken care of by time buffers inside the frame.

Incumbent Protection

Understandably, this has been the focal point for White Spaces viability. It is accomplished mainly by two mechanisms: database query and channel occupancy sensing. A third mechanism, using beacons to signify channel occupancy is also part of the standard, but it is not normally used since it entails modifications of incumbent's transmission protocols. Neither the BS nor the clients shall operate on the same channel or on the first adjacent channels of a TV operation within the TV protected contour, as defined in the respective coverage database (if one exists). However, they may operate on co-channels or adjacent channels outside this protected contour as long as they are located at sufficient separation distances beyond this protected contour. The parameter used to quantify

4. http://standards.ieee.org/news/2011/802.22.html

5. http://standards.ieee.org/develop/wg/WG802.22.html

this aspect is the Adjacent Channel Leakage Ratio (ACLR). The protected contour corresponds to the geographical area potentially served by a given TV transmitter, which is derived from its coordinates, transmitted power and antenna radiation pattern using some propagation model like the Longley-Rice, Hata, or any other indicated by the corresponding administration.

The BS must perform incumbent detection by means of spectrum sensing in each of the channels listed on the available channel list and also each adjacent channel if its EIRP (Equivalent Isotropic Radiated Power) exceeds the limit specified by the corresponding regulatory domain. This is done by means of an omnidirectional antenna independent of the one used for actual communication that can be directional.

Main Features

The main features of IEEE 802.22 are:

- Spectrum Sensing

- Spectrum Sharing (by agreement or compulsory)

- Location Identification by the Mobile

- Network/System/Service Discovery

- Frequency Agility

- Dynamic Frequency Selection

- Avoidance of co-channel operation

- Adaptive Modulation/Coding

- Transmit Power control

- Dynamic System/Network Access

- Mobility and Connection Management

- Security Management

The major challenges facing the deployment of IEEE 802.22 in developed countries are the self coexistence and the hidden incumbent problem. The self coexistence issue is associated with challenges raised by other cognitive radio systems in the same geographical area. This led the creation of the IEEE 802 committee project 802.19.1 to develop standards for TV white space coexistence methods in 2009. The hidden incumbent refers to the fact that a WS device assessing channel occupancy with its low gain omni-directional antenna might not be able to detect an incumbent signal that could on the other hand be detected by

136

a high gain TV antenna. This aspect is analyzed in the Bute case study described in this booklet.

Recently, the IEEE 802.22.b working group (WG) is specifying an amendment standard for supporting the smart grid network using WRAN.

12.2.2   IEEE 802.11af

The IEEE 820.11af study group was formed in January 2010 to adopt 802.11 for TV band operation. The concept behind 802.11af is to leverage the success of WiFi while addressing the limitations due to propagation characteristics and unlicensed spectrum congestion, implementing wireless broadband networks in the bandwidth allocated to TV broadcasts stations, and has been called super WiFi and also White-FI. The advantages of IEEE 802.11af are:

Propagation characteristics 802.11af systems operate at frequencies below 1 GHz, which would allow coverage of greater distance. Current WiFi systems use frequencies in the ISM bands, at 2.4 GHz and 5 GHz, where signals are more absorbed by walls and suffer greater free space and obstacle losses.

New Spectrum Availability The greatest challenge of current WiFi implementations is that the 2.4 GHz band is very crowded and the 5 GHz one is also approaching saturation, hence the need to make use of other frequencies. However, it will be necessary to aggregate several TV channels to reach the 20 MHz bandwidth currently employed in WiFi and thus match the throughput at the higher frequency. Nevertheless there are many applications that can make do with lower data rates and can be accommodated in the bandwidth of a single TV channel which can be 6 or 8 MHz, depending on the country allocation. In the IEEE 802.11af draft standard, four bandwidths: 5 MHz, 10 MHz, 20 MHz and 40 MHz are defined regardless of regulatory domain. It means that channel bandwidth can be adaptively changed when several adjacent TV channels are available, which is often the case in developing countries.

802.11af includes three different stations types: fixed, enabling, and dependent [6].

Fixed and enabling STAs are stations that broadcast its registered location. The enabling STA controls the operation of unregistered STAs, i.e. dependent STAs. The enabling STA gets the available channel information from the TV WS database, and transmits the Contact Verification Signal (CVS). The CVS is used for establishing that the dependent STAs are still within the range of enabling STAs, as well as for checking the list of available channels. In addition, Channel Power Management (CPM) is also used to update the list of available channels for work in a Basic

6. D. Lekomtcev and R. Maršálek, Comparison of 802.11af and 802.22 standards - physical layer and cognitive functionality, Electrorevue, vol.3, No.2, June 2012

Service Set (BSS), change the maximum transmission power or change the channel frequency and bandwidth. Unlike 802.22, which is aimed at outdoors operation, 802.11af also addresses the indoor scenario, in which the new spectrum available and reduced wall absorption can be an advantage. The use of CSMA/CA (Carrier Sense Multiple Access/ Collision Avoidance) is also an advantage here, but at longer distances the TDM (Time Division Multiplexing) used in 802.22 achieves higher throughput while solving the well known hidden node problem of WiFi. On the other hand, WiFi's "listening to the channel before transmitting" protocol provides a mechanism of protection for other secondary users which is lacking in 802.22. Both standards require geolocation accuracy of 50 meters, obtained by GPS, but 802.22 also has an option of terrestrial based position determination.

802.11af has not been approved, currently is still a draft Standard [7].

12.2.3   IEEE 802.15.4m

7. "IEEE P802.11afTM/D1.02 Draft Standard for Information Technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 3: TV White Spaces OperationU.S.", June 2011.

The IEEE 802.15 Task Group 4m (TG4m) is chartered to specify a physical layer for 802.15.4 and to enhance and add functionality to the existing standard 802.15.4-2006 MAC, meeting TV white space regulatory requirements. The amendment enables operation in the available TV white space, supporting typical data rates in the 40 kb/s to 2 Mb/s per second range, to realize optimal and power efficient device command and control applications. Eight proposals for baselines for standard drafting were submitted and presented in July 2012 [8].

The 802.15.4m design inherits the two physical layers specified in 802.15.4g Smart Utilities Networks (SUN), frequency shifting and OFDM, and adds a narrowband OFDM to accommodate different requirements. It also introduces peer-to-peer mesh network architecture in the White Spaces arena, allowing range extension and increased network reliability [9].

8. http://www.ieee802.org/15/pub/TG4m.html

12.2.4   IEEE P1900.4a

The "Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks" was published in February 2009. The IEEE draft standard P1900.4a for "Architecture and interfaces for dynamic spectrum access networks in white space frequency bands" defines additional entities and interfaces to enable efficient operation of white space wireless systems [10].

9. C.-S. Sum, G. Porto Villardi, M. Azizur Rahman, T. Baykas, H. Nguyen Tran, Z. Lan, C. Sun, Y. Alemseged, J. Wang, C. Song, C.-W. Pyo, S. Filin and H. Harada "Cognitive Communication in TV White Spaces: An Overview of Regulations, Standards, and Technology", IEEE Communications Magazine, pp 138-145, July 2013

12.2.5   IEEE P1900.7

This standard is a result of the DYSPAN (Dynamic Spectrum Access Networks) Standards Committee Working Group, the successor of IEEE P1900 Standard Committee. They are developing standards related to

10. S. Filin, K. Ishizu and H. Harada, "IEEE draft standard P1900.4a for architecture and interfaces for dynamic spectrum access networks in white space frequency bands: Technical overview and feasibility study", 2010 IEEE 21st International Symposium on Personal, Indoor and Mobile Radio Communications Workshops (PIMRC Workshops), pp 15 - 20, September 2010

dynamic spectrum access with a focus on improved spectrum usage and addressing the 'Radio Interface for White Space Dynamic Spectrum Access Radio Systems Supporting Fixed and Mobile Operation'. The goal is to facilitate a variety of applications, including support of high mobility, both low-power and high-power, short, medium, and long-range, and a variety of network topologies while avoiding causing harmful interference to incumbent users [11].

11. http://standards.ieee.org/develop/wg/DYSPAN-1900.7.html

12.2.6 ECMA392

ECMA International is the successor of the European Computer Manufacturers Association. Founded in 1961, it has promoted almost 400 standards, most of which have been approved as international standards.

ECMA 392 is a standard that specifies a physical layer and a medium access sub-layer for wireless devices that operate in the TV frequency bands. It was originally published in 2009 with a second edition in June 2012, fully aligned with the 1st edition of ISO/IEC 16504:2011. It is mainly directed at personal and portable wireless devices. The standard aspires to serve a broad range of applications, including multimedia distribution and Internet access. Applications include high speed video streaming and Internet access on personal/portable electronics, home electronics equipment, and computers and peripherals. ECMA 392 also designates a MUX (a session management protocol) sublayer for higher layer protocols and numerous incumbent protection strategies that may be used for protecting the primary spectrum user.

The standard supports flexible network architecture with three types of devices: master, peer and slave, originating different networks topologies including master-slave, peer-to-peer and even mesh. Although in a master slave configuration the master controls the communication, a slave device may also directly communicate with another slave device under the coordination of the master. On the other hand, a peer device can access the channel by distributed reservation without the intervention of the master and therefore can construct a self organizing and self healing ad-hoc network. Two or more networks can share the same channel and may also communicate with each other in a coordinated way. It also opens the possibility to form a large scale network in a mesh topology.

Its target applications are wireless home network and wireless Internet access at campus, park, hotspot and so on. Ecma-392 additionally supports the spectrum sensing functionality to periodically check the existence of incumbent signals on current operating channel. It supports operation in only a single TV channel of 6 MHz, 7 MHz, or 8 MHz according to the regulatory domain.

The medium Access (MAC) design is based on a hybrid medium access architecture which allows reservation based channel access and contention based access. Medium access slots may assume reserved or unreserved form, the former may be invoked periodically for QoS-

demanding audio/video stream. The latter may be invoked in prioritized contention (PCA), based on four access schemes, including background (BC), best effort (BE), Video (VO) and voice (VI). Highly efficient data transmission is supported by numerous frame processing mechanisms encompassing Frame Aggregation, burst transmission and block acknowledgement (B-ACK). Self coexistence and mitigation of interference between near-located networks is taken care of by additional mechanisms. The standard is freely available [12].

12.2.7 IEEE 802.16h

This amendment of the 802.16 standard was ratified in July 2010 as "Air Interface for Broadband Wireless Access Systems Amendment 2: Improved Coexistence Mechanisms for License-Exempt Operation" and describes the mechanism for implementing the protocol over which WiMAX (Wireless Microwave Access) is based in uncoordinated operation, licensed or license exempt applications. Although most deployments have been in the 5 GHz band, it can also be applied to lower frequencies and specifically in the TV bands. In general, interference can be caused by licensed user or by other unlicensed users. It is now superseded and its content is part of IEEE Std 802.16-2012 [13].

12.2.8 ETSI EN 301 598

This draft of the Harmonized European Standard "White Space Devices (WSD); Wireless Access Systems operating in the 470 MHz to 790 MHz frequency band; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive" was issued in July 2013 and applies to TVWS devices controlled by a geolocation database that operate between 470 MHz and 790 MHz.

The document is freely downloadable [14].

It specifies two types of devices; type A, that can have any type of antenna, and type B which can have only integral or dedicated antenna, precluding the use of other antennas. There are also two device categories, master and slave. The master cannot transmit in absence of communications with the approved database (TVWSDB) and the slave cannot transmit in absence of communications with its master. The slave must communicate to its master the corresponding Device Parameters, which will then communicate them along with its own to the corresponding TVWSDB which will use them to compile the Operational Parameters allowed. The master will use this information to produce a list of Channel Usage Parameters to be used for transmission, both for itself and the slaves. This information will be forwarded to the TVWSDB. Equipment must comply with one of the five Device Emission Classes according with the level of emission leakage on adjacent channels. A detailed list of tests to be performed in the devices is described in the document.

12. http://www.ecma-international.org/publications/files/ECMA-ST/ECMA-392.pdf

13. http://standards.ieee.org/findstds/standard/802.16h-2010.html

14. http://www.etsi.org/deliver/etsi_en/301500_301599/301598/01.00.00_20/en_301598v010000a.pdf

140

12.3 CONCLUSIONS

Although the idea of using TV White spaces has been around for more than a decade, it was only in June 2011 that the IEEE officially approved IEEE 802.22 for long range "Wireless Regional Area Networks". The IEEE 802.11af for short range transmission is still being debated, as is the IEEE 802.15.4m for device control and command applications.

Still pending are the IEEE 802.19 for coexistence among multiple TV white space networks and the IEEE DySPAN aimed at Dynamic Spectrum Access Networks. On the other hand, the IEEE 802.16h, originally meant for the 3650-3700 MHz contention band is now also specified for the TV bands.

The European Computer Manufacturers Association is still working on the ECMA 392 directed at personal and portable wireless devices. Likewise, the IETF (Internet Engineering Task Force) submitted in April 2013 a proposal for "Accessing a Radio White Space Database" for publication as a Proposed standard named Protocol to Access WS database (PAWS) [15].

15. https://datatracker.ietf.org/wg/paws/charter/

Weigthless, described elsewhere in this booklet, is mainly focused at Machine-to-Machine interactions at low speed.

It is worth noting that, to the best of our knowledge, none of the vendors that offer WS equipment comply with the only officially approved standard. Although IEEE 802.11af is still in draft, its specifications are less stringent and easier to be met by manufacturers in the near future.

GREEN POWER FOR RURAL COMMUNICATIONS

Sebastian Büttrich
Network Startup Resource Center
USA
IT University of Copenhagen
Denmark
sebastian@nsrc.org

13

13.1 DEFINITIONS AND BACKGROUND

Power - in the sense of electrical power - remains one of the key challenges in improving living conditions in rural and remote parts of the planet. In 2012, "nearly 1.3 billion people remain without access to electricity and 2.6 billion do not have access to clean cooking facilities. Ten countries - four in developing Asia and six in sub-Saharan Africa - account for two-thirds of those people without electricity"[1]. In sub-saharan Africa, 57% of the population have no access to electricity[2]. Lack of electricity affects many areas, some of these arguably even more fundamental than communications - light, cooking, cooling/heating, water purification, to name a few.

For the scope of this article, we will define green or sustainable energy as *any form of electrical energy not based on fossil or nuclear fuel, but on fully renewable resources such as hydroelectricity, solar energy, wind energy, wave power, geothermal energy, artificial photosynthesis, and tidal power* (see [3] for alternative definitions).

A key characteristic of sustainable energy is abundance rather than scarcity:

- Fossil energy draws on limited resources, resources that will be depleted within the foreseeable future and that surge in price as more people demand access to them.

- While estimates about oil and coal reserves are well outside the scope of this paper, current best estimates assume about 1,500 billion barrels of proven sources left, which would make for about

1. IEA World Energy Outlook http://www.worldenergyoutlook.org/publications/weo-2012/

2. IEA World Energy Outlook http://www.worldenergyoutlook.org/resources/energydevelopment/globalstatusofmodernenergyaccess/

3. https://en.wikipedia.org/wiki/Sustainable_energy

4. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm

50 years of oil even if consumption could be frozen at its current level [4].

- The primary sources of green energy however are unlimited within timeframes of human imagination, and access to them becomes more affordable rather than more expensive with growing demand, due to mainstreaming and growth in production capacity.

5. https://en.wikipedia.org/wiki/Sun_energy#Energy_from_the_Sun

6. http://phys.org/news/2012-01-earth-energy-unusually-solar.html

7. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm

There are of course limits to this simplified view - one river will not be able to host an unlimited number of hydroelectricity dams. The principle of abundance is particularly strong in solar energy. The total solar energy absorbed in the earth's atmosphere in one hour is larger than the whole world's energy consumption in one year. [5] The total solar irradiance, measured in watts per sqm, to the earth's atmosphere is around 1365 W/m^2 [6]. With the surface of the earth's disk as seen from the sun being 128 million square kilometers, the earth receives a total of about 174 petawatts, about 80,000 times its current total electricity consumption (18,466.459 billion kWh/year in 2010) [7]. About a quarter of this energy gets absorbed or reflected by the atmosphere. Each square meter of earth surface, facing directly in the sun's direction, thus receives an average 1000 W per square meter. The details of what part of this energy can be successfully harvested depend on many factors to be discussed later - but the key finding is: *even with today's soaring energy hunger, the sun supplies tens of thousands of times the total human consumption.* Access to solar energy is essentially limited only by access to a receiving surface, i.e. land or building mass, and the availability of technology to convert sunlight into electricity. This technology, called photovoltaics, is available and currently realistically reaches conversion efficiencies of about 20%.

In what follows, we will focus mainly on solar power as our choice of sustainable energy.

While the term "developing countries" should not be mistaken as a synonym for "southern countries", the global statistics for rural population and access to electricity cited above put special focus on developing Asia, Sub-Sahara Africa and South America, all of which are among the truly rich regions on this planet, when it comes to solar light. Looking at the second part of Green Power for Rural Communications, we will define rural communications as any form of data transmission - whether these data are text, numbers, moving or still pictures - between humans or machines, and we will not define rural any more precisely than denoting the absence of typically urban infrastructure. A defintion based on population density, as typically used to define rural, is less meaningful in the context of our topic. Already at this point, it is worth noting that there are significant differences in requirements and approaches to communication technology, depending on whether one is looking at human communications or machine-to-machine communications. In what follows, we will narrow down the term communications to de-

note digital communications via networks, or more specifically, TCP/IP networks.

13.2   THE CASE FOR SOLAR POWERED ICT

Electrical power or its absence or instability remains one of the main challenges in building communication networks. Significant progress has been made in the energy efficiency of end user devices such as laptops, pads and tablets, which today can run on battery for 5, 10, even 20 hours without depending on any external backup. However, these devices to a growing extent depend on network connectivity, requiring extra energy to power the additional infrastructure. Most network infrastructure depends on grid electricity, often complemented by backup mechanisms such as grid charged UPS (uninterrupted power supply) or diesel generators. However, in most places in e.g. developing Asia and sub-saharan Africa, a stable grid is nothing but an assumption, a myth rather than a reality. Even where utility grids exist, these are often unstable or subject to brown outs and load shedding.

Even in highly developed regions with grid power currently seen as stable, this might change as fossil fuel in all its forms will become more and more difficult to source and to pay for. Unstable grid power not only causes services disruptions, it also destroys equipment and thereby investments. Strangely though, and partly explainable by the fact that ICT capacity and knowledge is driven by those in privileged environments, network professionals keep working with a base assumption of stable grid electricity, which only is complemented with backup or UPS solutions, often based on diesel generators or grid charged batteries, in case of grid failure.

While obviously, solar power - and other forms of sustainable power - offer suitable alternatives in this field, they are not just a backup solution for the time period until conventional large scale grids reach stability. In developing as well as highly developed regions, such as the strong economies of Asia, the USA, or Europe, conventional large scale grids are entering a phase of transformation - transformation of conventional centralized demand-driven grids towards decentralized grid fabrics, driven by complex negotiation of demand, opportunity and production, and consisting of micro-grids of all sizes and sources. Solar, wind and hydro power generation become part of these decentralized structures that will replace the conventional large scale grids, in the post-fossil-fuel era. It is thus more likely that today's grids will develop in the direction of the decentralized autonomous structures that we are proposing for wireless networks, rather than centralized in the foreseeable future growing to offer the reliability that our networks require.

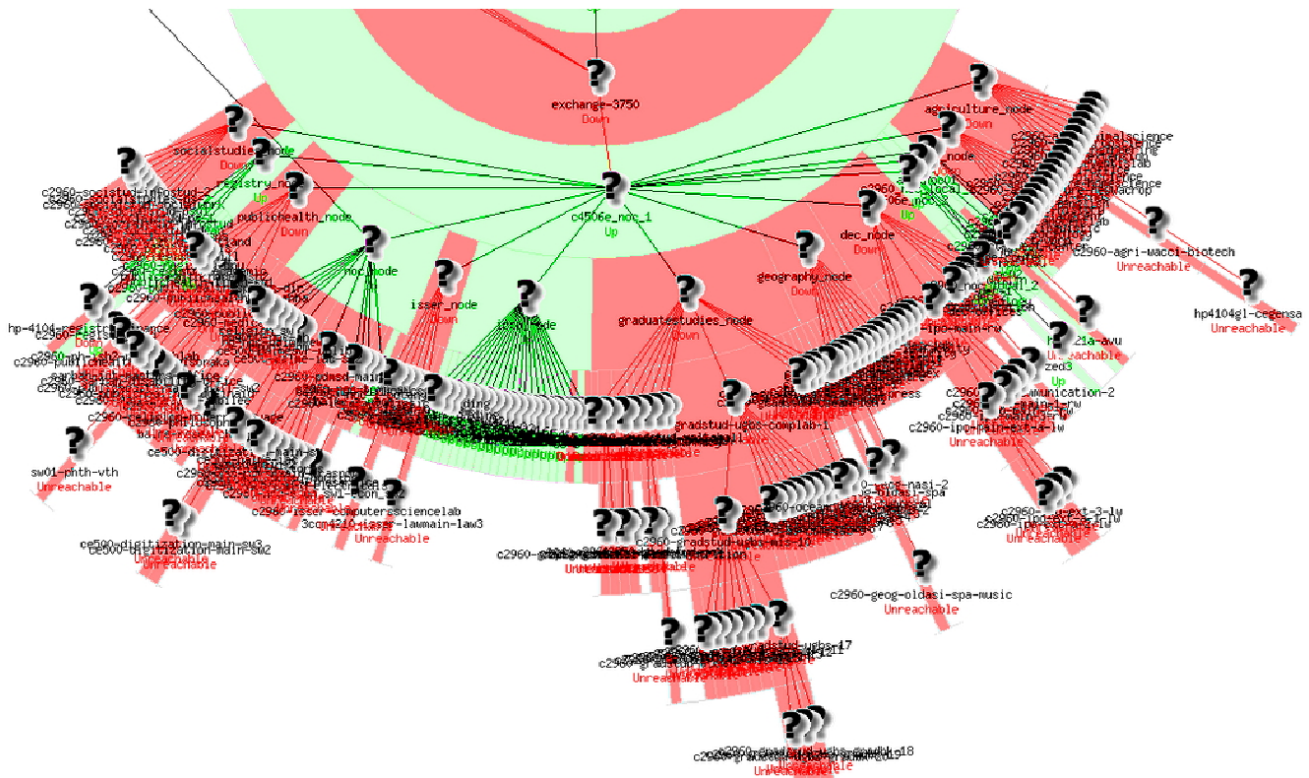The benefits of getting started with solar power for networks and other infrastructure include:

Figure 13.1: Power failure as seen by a typical network management tool (Nagios network monitoring at the University of Ghana).

- Stability

- Protection against hardware failure caused by grid instability

- Price

- Independence from political, financial changes, e.g. changes in grid energy or fuel pricing

- Sustainability

- Future readiness

- Local ownership and control

Leading technology companies have begun to understand these benefits, and like most other businesses in the developed world are establishing their own, partly grid-independent power generation: Google's current solar allocation is about 1.6 MW and Apple is planning for about 5 MW at their new headquarters in Cupertino [8].
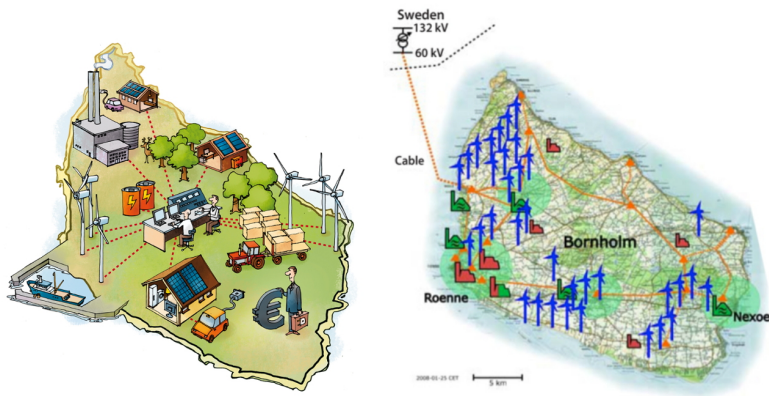
146

Figure 13.2: Smart Grid Bornholm, source: EcoGrid EU.

13.3   THE CASE FOR SOLAR POWERED NETWORKS

Having narrowed down communications to digital network communications earlier, we will now look at wireless networking, and at TVWS in particular. With the emergence of 802.11 WiFi networking and its huge success in infrastructure over the last 15 years, solar powering has been a popular choice from day one, both for networks and general IT infrastructure.

Likewise, mobile networks (GSM, GPRS, etc) especially in rural areas, often depend on solar powering. For basics of solar powering of IT infrastructures, see [9] and [10].

One needs to be very careful not to compare technologies beyond what they are comparable in: 802.11 WiFi is different from mobile in both its purposes and underlying technology, and the same is true for any other pair of technologies we are mentioning here. While it is tempting to work towards a "performance per power consumption" rating, such a rating does not make a lot of sense: the requirements for different kinds of networking are too different from one another. Speed, reach/coverage, availability, ease of roaming, energy efficiency - all of these and more are valid performance parameters.

When looking at networks for rural communications, however, we can isolate a few key requirements:

- long distance reach and NLOS is more important than ultra high bandwidth - despite sometimes being coined "super WiFi", TVWS will not be able to compete with 802.11n, 802.11ac and proprietary TDMA extensions at 2.4/5 GHz, in terms of bandwidth

- availability and stability are more important than seamless roaming

TVWS lends itself very well to reaching both of these, at low input and output power, for two main reasons:

9. Wireless Networking in the Developing World, http://WNDW.net

10. Amos Nungu, Robert Olsson, Björn Pehrson, "Powering Communication Networks in Developing Regions", 16th IEEE International Symposium on Computers and Communications (ISCC 2011), Corfu, Greece, June 2011.

147

Figure 13.3: Powering teachers' computer room at the Kopan monastery school, Nepal.

11. http://www.newamerica.net/files/nafmigration/Rural_Broadband_and_TV_WhiteSpace.pdf

- Working at low frequencies (470-860 MHz, depending on region), compared to WiFi's 2.4 and 5 GHz and mobile networks 1.8 GHz, TVWS is better suited for long distance and non-line-of-sight (NLOS) links. A first order estimate leads to the result that TVWS will cover an area four times larger than WiFi at 2.4 GHz, at the same output power [11].

- Emerging TVWS protocols put a lot of focus on minimizing protocol overhead, so that energy efficient operations become feasible.

At this point we need to remind ourselves that, within TVWS proponents there are radically different ideas of how it is going to be used. The potential for extreme low power TVWS is significant especially for sensor networks, devices, rather than human communications, as sleep modes can come into full effect [12].

12. http://www.weightless.org/benefits-battery

13.4 ELEMENTS OF A PHOTOVOLTAIC SYSTEM

While a full introduction to photovoltaics is beyond the scope of this booklet (see [13] and links therein for this), we introduce the main elements of a photovoltaic system:

13. Wireless Networking in the Developing World, http://WNDW.net

- Solar panel, the heart of the system, turning light intro DC electricity, typically at 5 or 12 volts or multiples thereof

- Battery (of a type suitable for solar operations)

148

Figure 13.4: Solar powered WiFi networks in Guam.

- Charge controller

- Inverter, if conversion to AC and/ or connection to an AC grid is
  needed.

plus cabling and mechanical installation

13.5   TYPES AND EFFICIENCIES OF SOLAR PANELS

The main types of commercially available solar cells are:

- mono- and polychrystalline silicon

- amorphous silicon

- thin film cells, made from Cadmium telluride (CdTe), copper
  indium gallium selenide (CIGS) and amorphous silicon (A-Si)
  have significantly lower efficiency, but allow for the production of
  flexible bendable panels, which are well suited for mobile applica-
  tions, solar tents, solar wrappings on existing building structures
  and so forth, and are considerable cheaper in production than
  silicon cells

There are numerous other approaches, e.g. based on organic poly-
mers, (organic) dyes or advanced quantum structures. While most of
these have not reached market maturity yet, the diversity of technologies
promises access to the principal abundance of solar energy, even if one
or the other of the raw materials should become short in supply. In

most cases, we will look to maximize efficiency, and at this point in time, monochrystalline SI cells remain unrivalled in this regard. Commercially available monochrystalline panels are available with about 15% (-20%) efficiency, and a 25-30 year guarantee on 80% of that rating.

13.6 DIMENSIONING OF PHOTOVOLTAIC SYSTEMS

The dimensioning of a photovoltaic powering system depends on three key input parameters:

1. insolation or peak sun hours at the given location

2. total power consumption or load

3. maximum time of autonomy (i.e. time of operation without recharge, time without sun)

plus a number of supportive system parameters, such as area available, panel efficiencies, etc.

Based on these three input parameters, different views and approaches may be chosen in order to calculate solar panel and battery sizes. The solar panels of course are the source of all energy within the system. For the sake of dimensioning, however, it is helpful to look at the battery system as the primary entity: the batteries are powering the load constantly, while the input power from the panels varies, e.g. in day/night cycles. The accumulated input from the panels obviously needs to be in balance with the overall energy consumption, and capable of keeping the batteries at a high charge state. Batteries should never to be discharged to below 50% of their capacity. Ultimately, regardless of what view one chooses, the model has to be critically tested against real life experience, and adjusted where necessary.

But first of all, let us look at where to get the input parameters from:

- Insolation or peak sun hours at the given location may be looked up from databases and tools [14], [15], [16].

- Total power consumption or load may be derived from data sheets or trusted technical information. Measuring and confirming these under realistic operation conditions is always recommended.

- Autonomy expectations ultimately depend on the network engineers' and users' educated opinion. While it might be acceptable for a computer classroom to run out of power during the night or on weekends, for networks we should generally design for near 100% uptime.

14. http://www.wunderground.com/calculators/solar.html

15. http://www.altestore.com/howto/Solar-Electric-Power/Reference-Materials/Solar-Insolation-Map-World/a43/
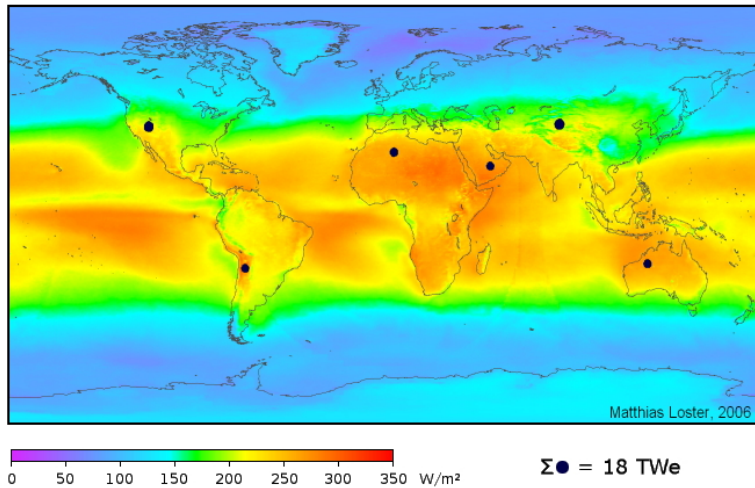
16. Photovoltaic Geographical Information System (PVGIS) http://re.jrc.ec.europa.eu/pvgis/

Figure 13.5: World insolation map.[17]

17. http://commons.wikimedia. org/wiki/File:Solar_land_area. png

13.7 INSOLATION DATA AND PEAK SUN HOURS

We will be using the concept of Peak Sun Hours (PSH), which needs explaining. We mentioned earlier, that the earth's surface receives about 1 kW/sqm in full sunlight. Measuring the total insolation over one day, we can express the resulting value in its equivalent "hours of full sun". Peak Sun Hours thus is a measure of energy per surface area - the average daily solar insolation in units of kWh/m². A value of 6 PSH thus corresponds to an average power of 0.25 of the full 1 kW/sqm, i.e. 250 W/sqm.

While data on insolation or peak hours are readily available, the main challenge lies in taking into account all seasonal variations, or any variation that might occur at a given deployment site, whether it is due to special weather conditions (e.g. clouds, fog) or shading (by nearby trees or buildings) or, generally, anything that might have an impact on the amount of sun light that effectively reaches our solar panel. Seasonal variations of peak sun hours may be very strong, and it is clear that a system which is designed based on an all-year-average is very likely to run out of power in the worst part of the year. Even when choosing the worst-month approach, i.e. taking the month with the lowest PSH as base of our design, we might encounter particularly bad days where the total energy produced is not sufficient. In particular, the longest time without sun will be longer than simply assuming it to be 24 hours minus PSH. A more conservative approach - which we will call the battery approach - calculates the amount of energy the battery has to store to power the load during the period assumed to be the worst possible case, and then calculates the minimum size of the solar panels based on the requirement that the battery can be fully recharged during the peak sun hours. Note that this approach may lead to very high demands and thus

Photovoltaic Solar Electricity Potential in the Mediterranean Basin, Africa, and Southwest Asia
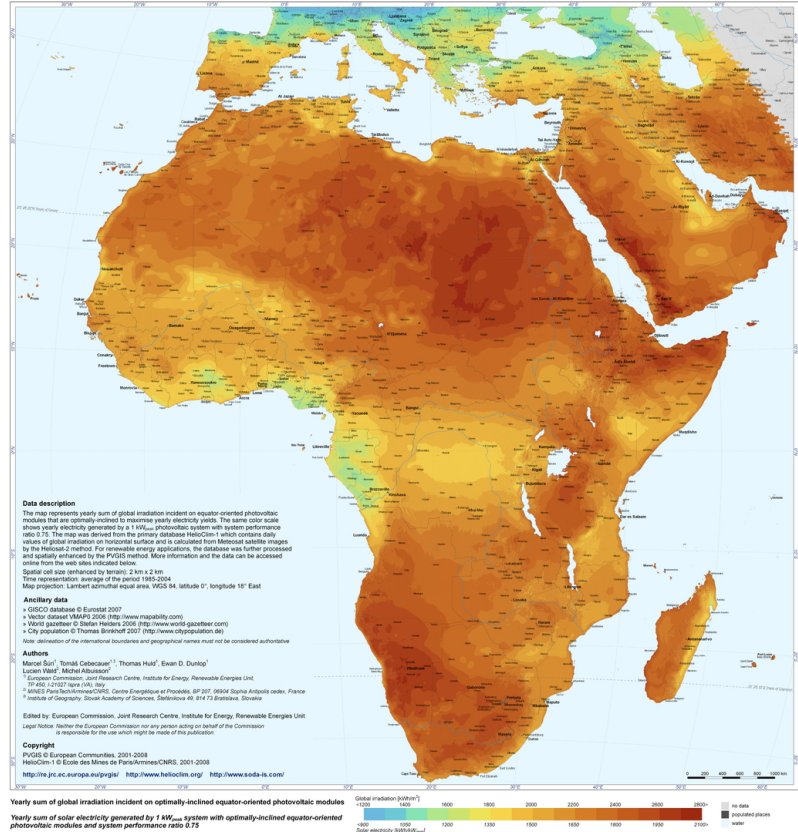

Figure 13.6: African insolation map.[18]

18. Solar Electricity Potential in Africa, South West Asia and the Mediterranean region , JRC's Institute for Energy and Transport - European Commission PVGIS http://re.jrc.ec.europa.eu/pvgis/

very expensive systems!

The differences between an all year average and a worst month model will naturally be small for places where seasonal variation is small, i.e. close to the equator. In the other extreme, both these PSH models become useless when working in the arctic or antarctic region, where polar nights might last for weeks and months. A battery approach is the only feasible model in these cases. There is no golden rule to solving this problem - ultimately we will have to make reasonable compromises between our expectations and the budgets available. The following formula provide the basis for dimensioning:

PSH peak sun hours (year average or worst month) [h]

P_l load [W]

W_p Power (watt peak) of solar panels [W]

E_p Energy produced by panels, in Wh/day.

E_{ff} Efficiency of solar panel [%]

C_b Capacity of battery [Wh], never be discharged to below 50%.

A Area of solar panel [sqm]

152

t$_O$ time of operations without recharge [h]. t$_O$ is at least (24 hrs - PSH), but likely significantly larger

t$_C$ charge time for batteries [h]

Energy produced by a panel, in Wh/day:

$$E_p = 1000\,W * E_{ff} * A * PSH = W_p * PSH$$

At an efficiency of 15%, about 7 sqm of panels are needed for 1kW peak (about 150 Wp / sqm).

13.8   YEAR AVERAGE APPROACH

Minimum panel size, in watts peak = P$_l$ * 24 / PSH (year average). The battery size in Wh may then (optimistically!) be deducted from:

$$C_b = 2 * P_l * (24 - PSH(year\ average))$$

Note the factor 2, due to the fact that batteries should never be discharged to below 50% of their capacity. This is a very optimistic calculation, that does not consider the power required to charge the battery, and by using the year average will fail to satisfy the demand those days in which the amount of sunlight is below average. It could be appropriate for non critical applications that can tolerate power outages.

13.9   WORST MONTH APPROACH

Minimum panel size = P$_l$ * 24 / PSH (worst month) The battery size may then be deducted from:

$$C_b = 2 * P_l * t_o$$

This is again an optimistic calculation, that does not consider the power required to charge the battery, but by using the worst month can provide a more realistic result.

13.10   BATTERY APPROACH

Starting with a more conservative assumption:

$$Battery Capacity C_b = 2 * P_l * t_o$$

we deduct optimistically, neglecting the power required to charge the battery:

$$Minimum Panel Size W_p = C_b / (2 * PSH)$$

Table 13.1: PSH in different locations.

Location	PSH Year Average [h]	PSH Worst Month [h]
Kenya, Nairobi	6.00	5.00
Germany, Berlin	3.00	1.00
South Africa, Cape Town	6.00	4.00
UK, Cambridge	3.00	1.00
Malawi, Lilongwe	6.00	5.00

Table 13.2: Minimum Panel Size in different locations.

Location	Minimum Panel Size Year Average Approach [W]	Minimum Panel Size Worst Month Approach [W]	Minimum Panel Size Battery Approach [W]
Kenya, Nairobi	400	480	380
Germany, Berlin	800	2400	2300
South Africa, Cape Town	400	600	500
UK, Cambridge	800	2400	2300
Malawi, Lilongwe	400	480	380

or more conservative, where we take into consideration the power required to charge the battery besides supping the load.

$$Minimum Panel Size\, W_p = C_b/(2 * t_c)$$

13.11 DIMENSIONING: AN EXAMPLE

With the preparation and examples above, let us look at an example task of powering a 100 watt load. This might for example be a TVWS base station plus some surrounding infrastructure, e.g. routers or switches, WiFi equipment. We make the following assumptions:

$$P_l = 100\,W$$

Note that for locations with moderate seasonal changes, the three different approaches give comparable results (which also are in good agreeent with real life experience). The stronger the variations over the year, the more difficult the planning becomes.

Table 13.3: Battery Capacity in different locations.

Location	Battery Capacity Minimum Year Average Approach [Wh]	Battery Capacity Minimum Worst Month Approach [Wh]	Battery Capacity Minimum For 3 Days Operation [Wh]
Kenya, Nairobi	3600	3800	7200
Germany, Berlin	4200	4600	7200
South Africa, Cape Town	3600	4000	7200
UK, Cambridge	4200	4600	7200
Malawi, Lilongwe	3600	3800	7200

13.12 POWER CONSUMPTION OF TVWS EQUIPMENT

Both the pilot in Malawi (started June 2013) and the trial in Cape Town, South Africa (started February 2013, [19]) are using TVWS equipment by Carlson. The Carlson RuralConnect Base Station is specified to have a power consumption of about 30 watts.

For a June 2013 Malawi pilot, a photovoltaic system with 150 W_p is tentatively planned to be powering this base station [20]. Note how this size is in accordance with the dimensioning example above.

The South African (Cape Town) pilot, being located in an urban area with privileged infrastructure, relies on grid power.

The Windfi pilot in Scotland uses a different approach, in that it combines solar and wind to take advantage of the varying seasons of a northern european country. A battery approach for dimensioning the combined wind and solar system is used to dimension for a total load of 50 W. A battery bank of 600Ah at 12 V allows the system to run for 3 days without recharge. Batteries are charged by the combination of solar panels with 480 watt peak, later reduced to 320 W), and a 200 watt wind turbine. Another significant difference to systems discussed above is the fact that a tracking system is used, i.e. the solar panels are motorized to follow the sun. While this wins another 20-35% in power, most photovoltaic systems deployed in remote areas avoid the use of tracking system, as moving parts are seen as potential source of failure, ot at least demanding regular maintenance.

Closeness to service personnel obviously is a key factor here - with people nearby, one can take the risk of using moving parts, which might be unacceptable in a truly isolated location, e.g. a repeater station.

19. http://www.tenet.ac.za/about-us/the-cape-town-tv-white-spaces-trial

20. Private communications, Ermanno Pietrosemoli
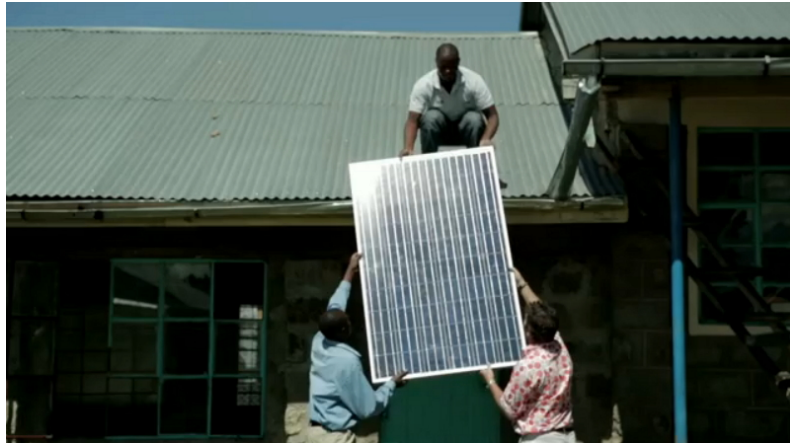
21. Mawingu project, http://www.
microsoft.com/africa/4afrika/
white_spaces_project.aspx

Figure 13.7: Deploying solar panels in the Kenya Mawingu project. [21]

22. HopScotch project, http:
//jwcn.eurasipjournals.
com/content/2012/1/112

Figure 13.8: TVWS project in Scotland. [22]

While environmental considerations strongly point at using solar power, the economic advantages of solar power are far less obvious.

At the time of writing, solar power still has the reputation of being relatively expensive - despite the fact that it has reached grid parity in many countries, i.e. it is cheaper than grid electricity. This reputation is largely due to the fact that capital expenses at startup are high, while the benefits of not having to buy fuel or pay any electricity bill only show over time. The life time of a photovoltaic system - indicated by solar panel performance warranties of 25 or 30 years - often are beyond the scope of day-to-day planning. This fact, in combination with a very limited availability of loans to finance the upfront expenses, still constitutes a major hurdle for solar power in developing countries. Network developers willing to look at sustainable power need to have arguments at hand to convince management and financial departments. In what follows, we will give these.

In order to understand that solar power is competitive, we need to calculate its price per unit of energy over time. Reliable statistics and calculations for the de-facto price of energy by source are not hard to find, but they often contain assumptions about tax subsidies or penalties, tariffs for grid integration, and local, national or regional market conditions. Therefore, we choose a very direct case study - the comparison of solar power vs diesel generator for an off-grid system, for the conditions of Kenya. We calculate the cost of a kWh, a common measure for energy produced and consumed, as produced by a solar power system, for systems of sizes in the range 1 kWp up to a few tens kWp. These are systems that a household, a network node, a university NOC or a small company realistically could require. We will be making very conservative assumptions, and we will allow enough budget for the calculation to be valid for a standalone system as well as for a grid-tie system.

At the time of writing (May 2013), the cost of quality solar panels is about \$500 to \$1000 per kWp. A price of \$3000 per kWp for a whole system, including controllers, cabling, batteries, inverters etc is realistic. Note that these are global market prices - some countries might put high taxes on imported systems. In many places, prices will be significantly lower. For a regularly updated list of solar price indices, see [23].

23. Solar price indices http://wire.less.dk/?page_id=103

How many kWh does a system of a size of one kWp produce in one year? This primarily depends on the amount of peak sun hours at the given location.

With

CAPEX initial capital expenses

PSH peak sun hours (year average) [h]

Y_{OP} years of operation

Table 13.4: Cost per kWh [$], in year of operation.

			1	5	10	20	30
Solar	PSH	Accumulated CAPEX	3000	4200	5700	8700	11700
DK	2	Cost/kWh	4.11	1.15	0.78	0.60	0.53
KE	5	Cost/kWh	1.64	0.46	0.31	0.24	0.21
Diesel	Price/Liter [$]	Accumulated CAPEX	500	700	950	1450	1950
DK	1.8	Cost/kWh	0.60	0.56	0.55	0.44	0.55
KE	1	Cost/kWh	0.36	0.32	0.31	0.31	0.31

MF annual maintenance factor for replacement of equipment, etc.

P$_D$ price of diesel per liter

H$_{OP}$ hours of operation per year (for Diesel generator)

C$_D$ Diesel consumption [Liter per kWh]

The total cost of a kWh produced is the total cost (capital and operational expenses) divided by the kWh produced. The price of a solar kWh is dominated by the initial capital expenses, while the "fuel" is free:

$$(CAPEX * (1 + (Y_{OP} - 1) * MF))/(PSH * 365 * Y_{OP})$$

The price of a diesel kWh is largely dominated by fuel cost:

$$(CAPEX * (1 + (Y_{OP} - 1) * MF) + Y_{OP} * H_{OP} * P_D * C_D)/(Y_{OP} * H_{OP})$$

The following results are based on the assumptions:

- 24 / 7 operations for both diesel and solar

- a diesel efficiency of 0.3 liters / kWh

- initial capital expenses of $3000 / kWh (solar) and $500 / kWh (diesel generator, a diesel friendly assumption taking the availability of used generators into account)

- a maintenance factor of 10% per year

In a simplified approach, assuming that both solar and diesel systems will require the same relative maintenance cost per year, and the diesel to run 24 / 7, we can calculate the year of operation in which solar power becomes cheaper than diesel power:

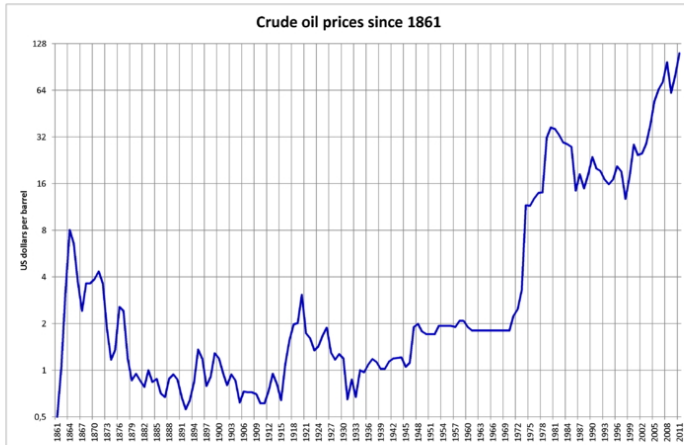The year of break-even for solar power vs diesel is:

Figure 13.9: Crude oil prices development.[27]

27. http://en.wikipedia.org/wiki/File:Crude_oil_prices_since_1861_(log).png

$$CAPEXSOLAR/((PSH * 365)(CAPEXDIESEL/8760 + P_D * C_D))$$

This formula is easy to transfer to the respective conditions in a country, but should only be seen as a rough guideline.

For Kenya, the solar kWh becomes cheaper than the Diesel kWh after approximately ten years.

Calculations for high insolation belt (with a PSH of 5.5 and above) of the US lead to similar result, putting prices at .15 - .30 $/kWh for small to industrial size installations, over a 20 year lifespan [24].
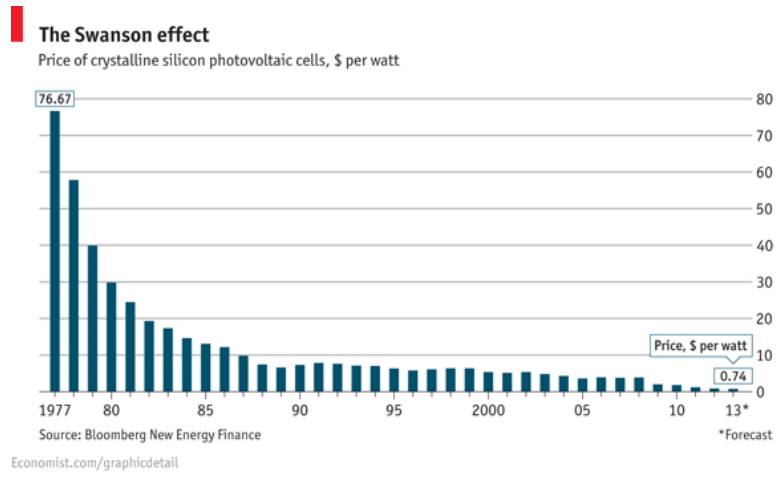
The strongest economical argument in support of solar power is difficult to quantify - it lies in the principle of abundance. While fossil fuel reserves are limited and prices bound to surge with growing demand and shrinking supply, more demand for solar power will lead to more panel production capacity, intensified research and continuous drop in prices. Swanson's Law - the observation that the price of solar photovoltaic cells tends to drop 20% for every doubling of industry capacity - so far seems to be valid: Crystalline silicon photovoltaic cell prices have fallen from $76.67/watt in 1977 to a forecast $0.74/watt for 2013 [25] [26].

Adding to all the economic reasons for a transition to solar power are the health and environmental damages caused by fossil fuels, with impact on human health especially when generators or stoves are used close to or inside homes and workplaces.

24. http://www.solarbuzz.com/facts-and-figures/retail-price-environment/solar-electricity-prices

25. http://www.economist.com/news/21566414-alternative-energy-will-no-longer-be-alternative-sunny-uplands

26. http://about.bnef.com/

The Swanson effect
Price of crystalline silicon photovoltaic cells, $ per watt

76.67

80
70
60
50
40
30
20

Price, $ per watt
10
0.74

1977 80   85   90   95   2000   05   10   13*
Source: Bloomberg New Energy Finance   *Forecast

Economist.com/graphicdetail

28. http://www.economist.com/
news/21566414-alternative-
energy-will-no-longer-be-
alternative-sunny-uplands

Figure 13.10: Swanson effect - price development for solar panel prices.[28]

LOW COST SPECTRUM MEASUREMENTS

Marco Zennaro and
Andrés Arcia-Moret
The Abdus Salam
International Centre for Theoretical Physics
Italy
mzennaro@ictp.it
aarcia_m@ictp.it

14

Recently a lot of attention has been given to the use of TV White Spaces for rural communications. Several monitoring campaigns have been carried out to measure spectrum occupancy worldwide, concluding that most of the spectrum is underutilized. In this chapter we present the design and implementation of two low cost systems to measure spectrum occupancy and to geo-tag the measurements to allow mobile measurement campaigns. The first system is based on the Raspberry Pi system on chip and on an affordable spectrum analyser. After calibrating the system against a professional spectrum analyser, we used it to measure the spectrum occupancy in urban and rural Venezuela, showing that there is plenty of vacant UHF TV spectrum. The second system is based on the popular Arduino board and has been used to measure spectrum occupancy in Malawi and Zambia. Then, we present a couple of representative results obtained from both devices during measurement campaigns. Finally, we conclude the chapter with some remarks about our experience on mobile spectrum measurements.

14.1 THE NEED FOR SPECTRUM MEASUREMENTS

Spectrum occupancy has become topical as the quest for efficient access to the spectrum continues. This is evidenced by empirical measurements of the radio environment in a bid to ascertain the spectrum usage by different wireless services.

Occupancy measurement campaigns efforts where initially carried out in USA using discone antennas, spectrum analyzers and a laptop[1].

1. D. Juyong, D.M. Akos and P.K. Enge, L and S bands spectrum survey in the San Francisco bay area, Position Location and Navigation Symposium, 2004, Pages 566-572

2. M. Lopez-Benitez et al., Evaluation of Spectrum Occupancy in Spain for Cognitive Radio Applications, in IEEE 69th Vehicular Technology Conference, 2009, Pages 1-5

3. V. Vaclav et al., Survey on Spectrum Utilization in Europe: Measurements, Analyses and Observations, in 5th International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications, 2010

4. A.Martian et al., "Perspectives on dynamic spectrum access procedures in TV White Spaces," Wireless Personal Multimedia Communications (WPMC) 2013, June 2013

5. M. H. Islam et al., Spectrum Survey in Singapore: Occupancy Measurements and Analyses, in Proc. 3rd International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CrownCom 2008), 2008, Pages 1-7

6. M.T. Masonta, D. Johnson and M. Mzyece, "The White Space Opportunity in Southern Africa: Measurements with Meraka Cognitive Radio Platform," Springer Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, Vol. 92, Part 1,pp. 64-73, 2012

7. L.Pedraza et al;, "Spectrum Occupancy Statistics in Bogota-Colombia", Proceedings of the IEEE Colombian Conference on Communications and Computing (COLCOM), 22-24 May 2013

8. Vo Nguyen Quoc Bao, Le Quoc Cuong, Le Quang Phu, Tran Dinh Thuan, Nguyen Thien Quy and Lam Minh Trung, Vietnam spectrum occupancy measurements and analysis for cognitive radio applications, in International Conference on Advanced Technologies for Communications (ATC), 2011, Pages 135-143

These occupancy measurements (as many others) showed information only about American spectrum regulation and utilization.

In Europe, a spectrum occupancy measurement was conducted in the frequency range from 75 MHz to 3 GHz in an outdoor environment in urban Barcelona, Spain [2]. Furthermore [3] takes a survey of Spectrum utilization in Europe and reports three major campaigns namely in the suburb of the city of Brno in the Czech Republic and in the suburb and the city of Paris in France during years 2008 and 2009 respectively. More recently, a Spectrum Occupancy measurement was carried out in Romania both in urban as in rural areas[4].

In Asia, researchers in Singapore[5] measured a 24 hour spectrum usage in 12 weekdays in the band 80 MHz-5850 MHz. The authors conclude from their measurements that their work is preliminary in its nature and, future long term studies need to be performed to determine any potential secondary usage on those channels that have low or no active utilization.

In Africa, measurements have been carried out in South Africa[6] by means of the Meraka Cognitive Radio Platform developed using the Universal Software Radio Peripheral hardware and the GNU Radio software. The authors present early results in rural and urban Southern Africa indicating that there are substantial white spaces available in both areas derived from digital dividend.

A measurement campaign carried out in Bogota is described in [7], using a high cost spectrum analyzer with a steep learning curve and sophisticated signal processing equipment.

The majority of researches reach a common conclusion on the necessity for further occupancy measurements at different locations over longer times. This thus motivates the need for more occupancy measurement. On concluding their investigations, some authors affirm that, to obtain local spectral pattern usage in multiple locations, the challenges for measurement-campaigns are not only cost (in equipment) but also the long time required to perform the measurements [8].

14.1.1   On Low cost Spectrum Monitoring

This chapter describes the design of a low-cost system to measure spectrum occupancy and geo-tag spectrum measurements. To make a monitoring system usable in Developing Countries (where TVWS have the highest potential) some design requirements have to be met. These design challenges include cost, power consumption, usability, data logging capabilities and availability of source code. Consequently, we propose a system considering the following design premises:

- **Low cost.** Commercial high-end spectrum analyzers are expensive (in the order of many thousand dollars), bulky, and are not typically available in University labs in Developing Countries. With a total cost of few hundred dollars, our system can be easily

acquired by Universities and civil society organizations worldwide. Similar systems cost one or two orders of magnitude more. We used the following low-cost parts to build up our systems:

– A Raspberry Pi[9] single-board computer. This credit-card-sized device was developed in the UK to promote the teaching of basic computer science in schools. It has a Broadcom BCM2835 system on a chip (SoC), which includes an ARM1176JZF-S 700 MHz processor, VideoCore IV GPU and 512 megabytes of RAM. It does not include a built-in hard disk or solid-state drive, using instead an SD card for booting and long-term storage. The B model with two USB sockets and an Ethernet connection sells for $35. The A model, with only one USB socket, sells for $25. The Raspberry Pi runs a Debian ARM distribution so it can use any Linux based software.

– A hand-held spectrum analyzer. Recently an affordable and easy to use device to make spectrum measurements has become available, the RF Explorer[10]. There are five RF Explorer models, covering the most-used bands below 2.5 GHz. In our system we use the Sub 1 GHz model, employing the Silicon Labs Si4431 receiver chip (covering 240 MHz to 960 MHz). The price of this model is 120 $ (as of November 2013).

– An embeddable computer. The Arduino[11] board is a low-cost micro controller platform, also considered as a small computer, capable of coordinating different sensors and actuators. The capabilities of this small computers are intended to solve lightweight problems while reducing the operational costs and space. The price of the model used is about 60 $.

- **Low power consumption.** Based on low power devices, the system must run for an entire working day with a small battery. In our case, both the Raspberry Pi and the Arduino board, power is provided via a micro USB connector, compatible with mobile phone chargers or any other 5 V supply (such as batteries, solar panels, etc). The Raspberry Pi B model requires about 5 W of power, while the A model requires 2 W[12]. For typical Arduino board, the energy requirements goes around the hundreds of milliwatts.

- **Ease of use.** Once switched on, the system has to run automatically without any human intervention. Non technical personnel can carry the system around and collect measurements. On the other hand, technical personnel can easily select the frequencies of interest with only a basic knowledge.

- **Data logging.** Weeks of measurements can be stored in the device's SD card with no need to download them on a PC. Collected

9. http://www.raspberrypi.org/

10. http://www.rfexplorer.com/

11. http://arduino.cc

12. Richard Heeks and Andrew Robinson. 2013. Ultra-low-cost computing and developing countries. Commun. ACM 56, 8 (August 2013), 22-24

measurements are stored in comma separated values (CSV) files for later processing.

- **Calibration.**

    To assess our set of measurements, we compared both systems against a professional Agilent N9344C recently calibrated spectrum analyser. A calibrated Agilent 8648C signal generator provided signals at 10 different power levels, i.e., from -95 dBm to -50 dBm, for the set of measured frequencies. From the calibration processes we can say that there are many characteristics to comply with a low-cost solution and it is quite challenging to balance the trade-offs. The calibration measurement show a systematic error lower than 4.5 dB over the range of interest. The measurements underestimate the true value of the signal, and the error is greater at higher frequencies, which in this case correspond to the cellular service.

- **Open Source.** The components of the system should be based on the open source concept. The system should be easily modified thanks to the availability of the source code.

Furthermore, the proposed systems, WhispPi and ASCII-32, are particularly suited to perform measurements while moving, either on foot or in a vehicle, thus facilitating the gathering of spectrum occupancy in relation with geographical position.

14.2   THE WHISPPI DEVICE

13. Arcia-Moret, A., Pietrosemoli, E., and Zennaro, M. Whisppi: White space monitoring with raspberry pi. In IEEE Global Information Infrastructure and Networking Symposium (GIIS 2013) (October 28-31. Trento, Italy 2013).

WhispPi [13] was designed on the principle that data from the spectrum analyzer have to be stored in a device with a battery backup for mobile measurements. In addition to spectrum, the position and the time of measurements are saved on the same device. Moreover, the Raspberry Pi allows fine tuning of the different components of the system through regular UNIX scripting.

The system is made out of four components:

1. A Raspberry Pi, used to control the data acquisition and geo-tagging of the data.

2. An RF Explorer, that has already proved its usefulness for spectrum efficiency advocacy in a previous measurement campaign[14].

14. M.Zennaro et al, "On the Relevance of Using Affordable Tools for White Spaces Identification", Proceedings of the IEEE CNBuB2012, Barcelona-Spain, 8-12 October 2012

3. A USB GPS, to collect the exact position and time of the measurement.

4. A small battery with micro USB output to power the Raspberry Pi which then powers the spectrum analyzer.

Figure 14.1: The WhispPi device

The spectrum analyzer, the GPS and the battery are connected to the Raspberry Pi via USB cables. To make the system easier to carry, an enclosure has been designed and printed with a 3D printer. The overall system is shown in Figure 14.1.

With the presented configuration, we were able to obtain 1 full measurement every 6 secs. A single measurement, essentially comprises a span of a 600 MHz geo-localized sample. Note that the full processing of the spectrum sample was completely delegated to the RF Explorer, which in our experience consumed most of the time per sample. Moreover, we sampled in the fastest possible configuration, i.e., with the widest span (of 600 MHz) for a reasonable bin (of 5.6 MHz) to detect a TV channel.

14.2.1   Specifics of Spectrum Monitoring for WhispPi

Mobile monitoring the RF spectrum requires a portable spectrum analyzer. High-end spectrum analyzers are traditionally expensive and bulky, so they are not suited for nomadic use. Some portable Spectrum Analyzers have a GPS on board, but are out of reach for most Universities. New affordable devices such as the ones listed below enabled us to develop a low cost solution for spectrum monitoring.

The main features of the RF Explorer are:

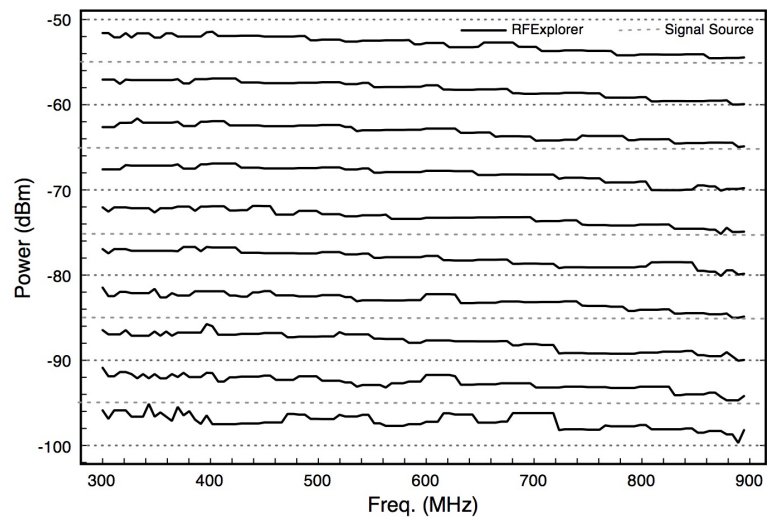- Spectrum Analyzer measurements with Peak Max and Hold, Normal, Overwrite and Averaging modes

Figure 14.2: Calibration of the RF Explorer.

- High capacity Lipo battery for 16 hours of continuous run, rechargeable through USB port

- SMA antenna connector (50 ohms)

- Dynamic range: -115 dBm to 0 dBm

- Absolute Max input power: +5 dBm

- Can be fitted with internal Expansion Modules for additional band and functionality (signal generator)

It has an LCD display (128x64 pixels) that offers great visibility outdoors. While it is fully functional as an independent unit, optionally can be connected to a PC via USB for additional features.

14.2.2 Calibration of WhispPi

A calibrated signal generator provided signals at 10 different power levels, i.e., from -95 dBm to -50 dBm in 5 dB steps, for each of the 113 measured frequencies. From the results displayed in Fig. 14.2, we can infer that in the frequency range from 300 MHz to 900 MHz, the RF Explorer displayed value is consistently slightly less than the power applied to its input, with a maximum discrepancy of 4.5 dB. In the UHF TV spectrum range that extends up to 806 MHz the under estimation is bounded to 2.8 dB.

14.3 THE ASCII-32 DEVICE

ASCII-32, shown in Figure 14.3, is a low-cost device to identify and geo-tag RF spectrum in the sub 1-GHz band. The name ASCII-32 is derived
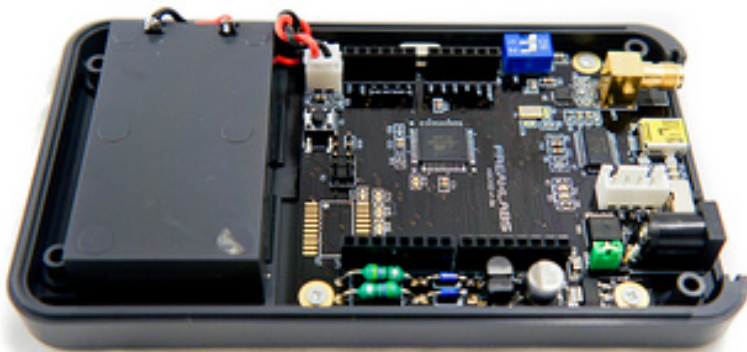
Figure 14.3: Low-cost ASCII-32 device

from the ASCII character set, where the number 32 corresponds to a white space. Selling for $ 110, ASCII-32 is affordable for universities and civil society organizations in Developing Countries.

The main component of the design is the SI4313 low cost wideband receiver IC. It covers a frequency range from 240 to 960 MHz which adequately spans the spectrum of TVWS. Although this IC has the circuitry to decode multiple wireless signalling protocols, in this application the main function used is the energy detection. After tuning to a certain frequency, one function of the IC is to sense the amount of energy, recording the value in dBm on the RSSI (Received Signal Strength Indicator) register. This is the same function as a standard spectrum analyzer, however at a vastly different cost scale.

The essential part of the design is to use a micro-controller to tune the IC to each frequency in pre-determined bandwidth intervals and measure the amount of energy at each frequency. By doing this quickly enough, it's possible to build up a plot of the occupied spectrum within the 240 to 960 MHz frequency range. This implements the spectrum analyzer functionality of the device.

Besides the spectrum analyzer functions, there are other requirements specific to white space identification. Two of those are GPS location and local storage. By adding a GPS to the device, it is possible to tag the occupied spectrum for a specific location. Bulk local storage, in the form of inexpensive micro SD cards, allows vast amounts of data to be stored for later processing and visualization. This combination allows the geographic variance of spectrum occupation to be measured, recorded, and visualized and automates the task of doing wide area site surveys for white space identification.

Finally, the manufacturer [15] added small details on to the design in the form of battery and power management and a ruggedized enclosure. This improves the portability of the device and allows it to be taken around
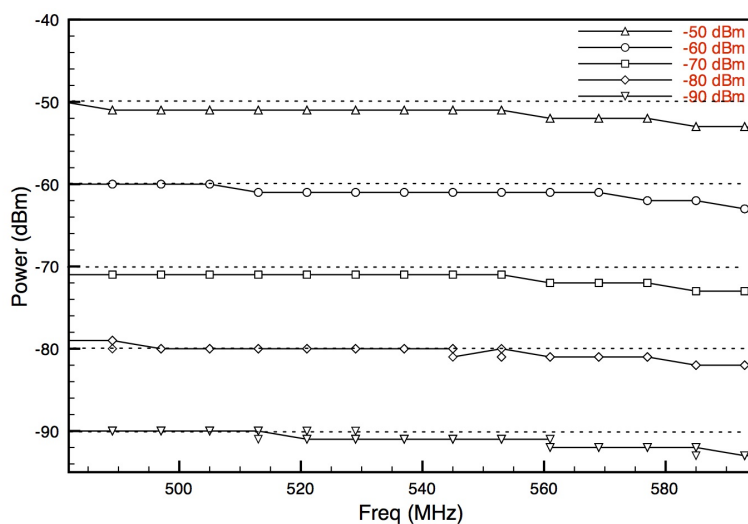
15. http://www.freaklabs.org

167

Figure 14.4: Measured power by ASCII-32 when input with pre-calibrated values

Table 14.1: Comparison of ASCII-32 and WhispPi

	Cost	Observable Bandwidth	Sampling Frequency	Processing Flexibility
ASCII-32	110$	100 MHz	High	Low
WhispPi	180$	600 MHz	Low	High

easily and unintrusively. Conventional spectrum analyzers are often subject to import duties (even for temporary usage) in many countries significantly encumbering the logistic of measurement campaigns.

14.3.1 Calibration of ASCII-32

Figure 14.4 shows the calibration results, the Y axis shows power in dBm. The reference calibrated power from the signal generator is represented as dotted horizontal lines, while the corresponding readings from the ASCII-32 device are represented by different symbols (upward triangle for -50 dBm, circle for -60 dBm, and so on). From the figure, we can infer that in the frequency range of interest, from 482 MHz to 554 MHz, the device is providing accurate results with a maximum difference of ±2 dB from the calibrated value.

Discussion

Table 14.1 shows the comparison of the two designed systems. Here we point out the salient characteristics that defined their usability. Remark that, although ASCII-32 is more portable and provides a better sampling frequency, WhispPi is capable of observing a broader portion of the spectrum for a single sample. The data processing becomes easier since Raspberry Pi board provides provides higher computing capabilities.
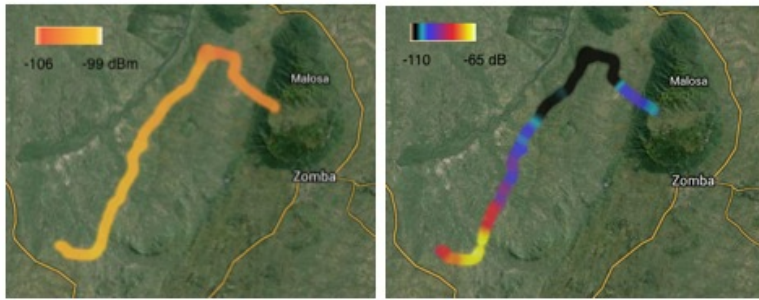
Figure 14.5: Heatmaps of Frequencies 498 MHz (on the left) and 546 MHz (on the right) in Malawi's Measurement Campaign.
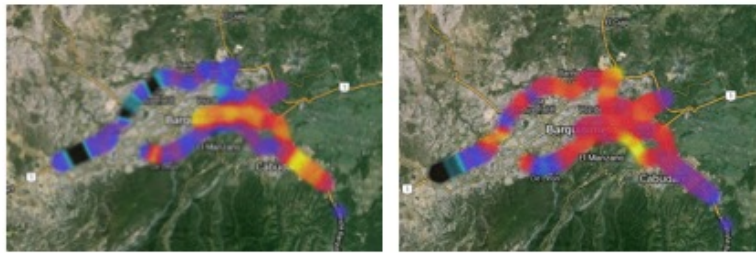

Figure 14.6: Heatmaps of UHF Channel 62 (on the left) and Channel 24 (on the right) in Venezuela's Measurement Campaign.

Moreover, it provides a network interface that allows adding automatic uploading of collected data. On the other hand, ASCII-32 provides higher sampling frequency suitable for higher heat-mapping resolution during vehicular measurement campaigns.

14.4 UHF BAND ACTIVITY AND WHITE SPACES

In this section we provide some examples of the possible graphical displays obtained from the collected data. The rendering stage is mainly independent from the device, however, the resolution of a heatmap depends on the sampling frequency.

Fig. 14.5 shows a heatmap of two representative channels during a journey in Malawi in June 2013. During this measurement campaign we travelled 130 km observing the spectrum with ASCII-32. The figure shows the contrast of a busy channel versus a free channel along the trajectory. The figure on the left shows that there is a free TV channel at the central frequency of 498 MHz. Observe that power levels during the whole path range from -106 dBm to -99 dBm. This contrast with the figure on the right that shows a busy channel on 546 MHz. During this journey we could collect more than 25000 samples for the 130 km route, i.e., one sample every 5 meters in a high speed highway.

Site	Leg Length (km)	White Spaces (%)
Mérida city	20	75
Ejido	10	86
Lagunillas	85	92
El Vigia	20	92
Santa Cruz de Mora	9	87
Mucuchies	10	96
Barinitas	20	90
Barinas	23	84
Guanare	41	86
Acarigua	50	87
Barquisimeto	20	66

Table 14.2: Summary of White Spaces in Venezuela Western Region as of June 2013.

Fig. 14.6 shows part of the result of a measurement campaign carried out in Venezuela in June 2013 recorded with WhispPi. This figure shows a heatmap for two types of busy channels. The figure on the left shows spectrum activity corresponding to channel 24 (530 MHz to 536 MHz), on one of the biggest cities of Venezuela, Barquisimeto, of about 1.600.000 inhabitants. The figure on the right shows the activity in Channel 24 in urban and suburban areas of Barquisimeto.

In Table 14.2 we summarize the white spaces findings during the measurement campaign carried out in western Venezuela. We observed that in urban and suburban areas the amount of white spaces (expressed as number of available channels) goes from 66% to 75% and in suburban and rural areas the amount of white spaces goes from 86% to 96%. It is worth noting that this quantity of White Spaces corresponds to a region in which the TV service is still analogue, and so we can expect an increase of spectrum availability after the transition to digital TV broadcasting.

14.5   LESSONS LEARNED

In this chapter we have presented the construction and use of affordable tools and techniques to assess the amount of white spaces in developing regions. The designed systems are easy to set up and well suited to long term mobile spectrum measurements. With these tools we were able to account for white spaces on the UHF TV band.

There is a trade off to consider when performing measurements with low cost equipments, namely the sampling frequency versus the observable bandwidth. So far, we have noticed that higher sampling frequency implies less observable bandwidth. Moreover, by exploring different trade-offs of these parameters, one can obtain valuable information about not only current activity in the channel but also what-if scenarios for future deployments.

BIOGRAPHIES

ROBERT HORVITZ

A graduate of Yale University, Robert Horvitz has been involved in the analysis and reform of radio spectrum policy for over 30 years. He currently heads the Open Spectrum Foundation (OSF), a not-for-profit research project registered in the Netherlands. OSF was an Associate Member of the International Telecommunication Union's radio sector in 2010 and 2011, enabling Horvitz to participate in the work of ITU-R Study Group 1 (spectrum management). In 2009 he co-founded the Open Spectrum Alliance, which has branches in Europe and South Africa. From 2000 to 2004 he was manager of the Global Internet Policy Initiative whose aim was to expand public access to the Internet in developing countries. Before that, he was international coordinator of the Open Society Institute's Internet Programme. In the 1990s he worked for the Open Society Institute as their radio specialist for the post-communist countries, helping new radio stations to get licensed and on the air. He is the author of "The Local Radio Handbook for East and Central Europe" (Internews, 1991) which has been translated into 6 languages. In the 1990s he also co-founded the Transnational News Agency, a daily satellite-based video newsclip exchange for TV networks in Eastern Europe. Before moving to Prague in 1991, he was executive secretary of the Association of North American Radio Clubs.

RYSZARD STRUŻAK

Ryszard Strużak, a Full Professor at National Institute of Telecommunications, (NIT Poland), is also the Co-Director of ICTP winter schools on wireless networking (Italy) and former V-Chair of Radio Regulations Board, ITU. He founded the Electromagnetic Compatibility (EMC) Laboratories at NIT and co-founded the International Wroclaw Symposium on EMC. He was with the ITU/CCIR, Wroclaw University of Technology, and Rzeszow

University of Information Technology and Management. He delivered lectures in all continents, except Australia. He worked as an independent consultant to international organizations, governmental agencies and industry in several countries. He served as the Editor-in-Chief and the Chair of Editorial Board, Global Communications. He authored or co-authored some 200 papers, 10 patents and numerous analyses and drafts included later in national and international documents in the areas of radio communications, spectrum management, and electromagnetic compatibility. He was active in international organizations of ITU, URSI, IEC, CISPR and CEI, where he was elected to leading positions. He received the ITU Silver Medal, two international awards at EMC symposia (Montreux and Rotterdam), highest national awards and decorations and six Prize Paper Awards in competitions organized by the Polish Society of Theoretical and Applied Electrical Sciences, Wroclaw. He was elected a member of New York Academy of Science and an Academician of the International Telecommunication Academy. He is a Life Fellow of IEEE and was awarded the IEEE EMCS Acknowledgment of Gratitude and Special Recognition award in 2010.

DARIUSZ WIĘCEK

Dariusz Więcek received the M.Sc. and Ph.D. degrees in Telecommunications Engineering from Wroclaw University of Technology, in 1992 and 2006, respectively. He joined National Institute of Telecommunications (NIT) in Poland in 1993 where currently he is Head of Spectrum Engineering and Management Section. His research areas include radio systems networks planning and optimization, broadcasting systems, compatibility analysis of different radio systems, cognitive radio, opportunistic and white space spectrum radio, dynamic spectrum access as well as spectrum engineering and management on national and international (CEPT, ITU, WRC, IEEE) levels. He was involved in preparation of the digital broadcasting switchover strategy in Croatia and digital plans in Poland. Dr. Więcekis is member of Management Committee COST IC0905 (TERRA - Techno-Economy and Regulatory Aspects of Cognitive Radio Systems). He manages many projects for companies from telecommunications industry sector. He was official delegate of the Republic of Poland to the various ITU and CEPT conferences (e.g. WRC's). He is member of Section of Electromagnetic Compatibility of Electronic and Telecommunications Committee of the Polish Academy of Science (PAN), Senior Member of IEEE and v-Chair of Polish Chapter of the IEEE EMC Society. He takes part in reviewing and evaluation process of EU and national founding research projects. He is author or co-author of more than 50 scientific papers in journals

and conference proceedings and more than 200 commercial as well as more than 100 scientific Reports of the NIT. Dr. Więcek received Bronze Medal for Long Standing Service from President of the Republic of Poland.

STEVE SONG

Steve Song is an advocate for cheaper, more pervasive access to communication infrastructure in Africa. He is the founder of Village Telco, a social enterprise that builds low-cost WiFi mesh VoIP technologies to deliver affordable voice and Internet service in underserviced areas. Steve also works with the Network Startup Resource Center (NSRC) to develop strategies for expanding the utilization of wireless technologies through shared spectrum strategies to enable more Internet access in Africa and other emerging market regions. Previously, Steve worked at the International Development Research Centre (IDRC), where he led the organization's Information and Communication Technology for Development program in Africa, funding research into the transformational potential of ICTs across the continent.

CARLOS ALBERTO AFONSO

Currently is executive director of the Nupef Institute (www.nupef.org.br), a research, policy advocacy and learning center focused on leveraging ICTs for sustainable human development. Studied naval engineering at the Polytechnical School of the University of São Paulo, Brazil. Master in Economics, York University, Toronto, Canada, with doctoral studies in Social and Political Thought at the same university. Works in human development fields since the early 1970s, when he worked with Chile's National Planning Office under Salvador Allende's government. Has been active as a consultant for UNDP, IDRC (Canada), Kellogg Foundation, Friedrich Ebert Foundation and other international organizations, on themes related to communications, ICTs and human development, in Angola, Argentina, Brazil, Cambodia, Colombia, Honduras, Mozambique, Nicaragua, São Tome and Principe, among other countries. Co-founder of the Brazilian Institute of Social and Economic Analyses, Ibase (1981), Rio de Janeiro, where he conceived and led the first Internet services provider project in the country (Alternex, 1989). Co-founder of the Association for Progressive Communications, APC (1990), an international

consortium of NGOs with the overall mission of promoting universal access and democratization of information and communication. Proposed and coordinated the Eco '92 Internet project in Rio de Janeiro in association with APC and the UN. Board member of Brazil's Internet Steering Committee (CGI.br), 1995-1997/2003-2014. Member of the UN's Working Group on Internet Governance (WGIG) - 2004-2005. Member of ICANN's GNSO (Generic Domain Names Supporting Organization) - 2003-2004 - on behalf of the Non-Commercial Users Constituency (NCUC). Chairperson of NCUC - 2005-2006. Coorganizer of the II Latin American and Caribbean Preparatory Meeting for the IGF, Rio de Janeiro, August 12-13, 2009. Special advisor to the Brazilian co-chair of the Internet Governance Forum (IGF), 2007. Special advisor to the chair of IGF's secretariat - 2008-2009. From 2009 to 2011 was a member of UNCTAD Expert Group on ICT and Poverty Alleviation. Board member of Telebras (Brazil's state company in charge of the National Broadband Plan) – 2010-2012. Current chair of the Brazilian chapter of Internet Society.

TIM X BROWN

Timothy X Brown is a Visiting Professor in Electrical and Computer Engineering at Carnegie Mellon University in Rwanda. Since 1995 he has held faculty appointments at the University of Colorado at Boulder, most recently as Director of the Interdisciplinary Telecommunications Program. He received his B.S. in physics from Pennsylvania State University and his Ph.D. in electrical engineering from California Institute of Technology in 1990. His research interests include adaptive network control, machine learning, and wireless communication systems. His current research funding includes NSF, DOE, and industry. Projects include the role of mobility in network control of unmanned aircraft, denial of service vulnerabilities in wireless protocols, spectrum policy frameworks for cognitive radios, and indoor wireless network performance. He is a recipient of the NSF CAREER Award, and the GWEC Wireless Educator of the Year Award.

JON PEHA

Jon Peha is a Full Professor at Carnegie Mellon University where he addresses both technical and policy issues of information networks, in the U.S. and in developing countries around the world. He has served in the US Government, as Chief Technologist of the Federal Communications Commis-

sion (FCC), at the White House as Assistant Director of the Office of Science & Technology Policy where he focused on telecommunications and research, on legislative staff in Congress where he addressed telecommunications and e-commerce legislation, and at the U.S. Agency for International Development (USAID) where he helped launch and lead a U.S. interagency program to assist developing countries with information infrastructure. He has served in industry as Chief Technical Officer for three high-tech start-up companies, and a member of technical staff at SRI International, AT&T Bell Laboratories, and Microsoft. At Carnegie Mellon, he is a Professor in the Dept. of Engineering & Public Policy and the Dept. of Electrical & Computer Engineering, and former Associate Director of the university's Center for Wireless & Broadband Networking. Dr. Peha's research spans technical and policy issues of information networks, including spectrum management, broadband Internet, wireless networks, video and voice over IP, communications for emergency responders, universal service, privacy, secure Internet payment systems, online dissemination of copyrighted material, and network security. Dr. Peha holds a PhD in electrical engineering from Stanford, and a BS from Brown. He is an IEEE Fellow, an AAAS Fellow, and a winner of the FCC's "Excellence in Engineering Award," the IEEE Communications Society TCCN Publication Award for career contributions, and the Brown Engineering Medal.

CRISTIAN GOMEZ

Mr Cristian Gomez graduated from electronics and telecommunications engineering, carrying out his studies in Chile and New Zealand. In the latter country, he also earned his MBA, specializing in Corporate Strategy, and has further graduate studies in the area of Public Policy at University of London. Mr Gomez is a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE), and Professional Member of the Institute of Engineering and Technology (IET). He has held various positions across the ICT industry, including R&D of wireless technologies in the private sector, defense industry and government sector. Before taking up his current position at ITU, Mr Gomez spent over 7 years as senior specialist on spectrum policy and planning at the spectrum regulator of New Zealand, leading important spectrum planning projects and providing advice on spectrum matters to the Minister of ICT of that country, as well as working at regional inter-governmental level in Asia Pacific (Asia Pacific Telecommunity, APT).

MIKE JENSEN

Mike Jensen is a South African who has assisted in the establishment of Internet-based communication systems in more than 45 developing countries over the last 25 years, mainly in Africa. He provides advice in the formulation, management and evaluation of Internet and telecommunication projects, ranging from national ICT policy development to international submarine fibre and rural wireless telecommunication feasibility studies. After receiving his MSc in rural planning and development in Canada, he returned to South Africa to work as a journalist on the leading national newspaper in Johannesburg, the Rand Daily Mail. When the paper closed in 1983, with little sign of improvement in the political situation, he moved back to Canada, and in 1987 he co-founded the country's national Internet service provider for NGOs, called coincidentally, The Web (web.ca). He returned to South Africa to support the growth of the Internet in developing countries in the early 1990s, and as a member of the African Conference of Ministers' High Level Working Group he helped develop the African Information Society Initiative (AISI) in 1996. Mike is currently the Association for Progressive Communication's Internet Access Specialist. His recent projects include strategic advice on cross-border fibre provision in Africa, a case study of national broadband deployment in Brazil and formulation of national analog-to-digital TV migration strategies.

DAVID CRAWFORD

David Crawford has over fifteen years' experience in the consumer electronics industry, working mostly in the area of signal processing and wireless communications. He currently runs the Centre for White Space Communications, an industry-focused R&D centre set up by the University of Strathclyde to investigate techniques and applications for the efficient utilization of White Space radio spectrum. He previously ran Epson's semiconductor design centre in Livingston, Scotland, and has held positions with Motorola and Ensigma.

He was the Project Manager for the Isle of Bute White Space Trial.

Dr Crawford has a PhD in Electronic Engineering from the University of Strathclyde, and an MBA from the University of Strathclyde Business School.

LINDA DOYLE

Prof. Linda Doyle is director of CTVR / The Telecommunications Research Centre and a faculty member in the School of Engineering in Trinity College, University of Dublin, Ireland. CTVR is the national telecommunications research in Ireland, headquartered in Trinity College and involving six other academic institutions and over 120 researchers. The centre focuses on research in the area of optical and wireless networks and works closely with industry.

Linda's areas of expertise are in the domains of cognitive radio, reconfigurable networks, spectrum management and art & technology. Linda is a member of the Ofcom Spectrum Advisory Board. She is a Fellow of Trinity College Dublin. She is a Director of Xcelerit and SRS, two recent CTVR spin-outs.

ERMANNO PIETROSEMOLI
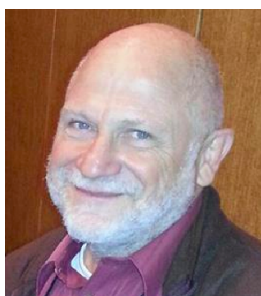
Ermanno started collaborating with the wireless networking efforts at the International Centre for Theoretical Physics (ICTP), in Trieste, Italy, in 1995 and from May 2010 has been a full time researcher at the Telecommunications/ICT for Development Lab (http://wireless.ictp.it) of this institution. He is also president of Fundación Escuela Latinoamericana de Redes "EsLaRed" (http://www.eslared.net), a non-profit organization that promotes ICT in Latin America through training and development projects since 1992. These accomplishments were recognized by the Internet Society that awarded to EsLaRed the 2008 Jonathan B. Postel Service Award.

After 30 years of teaching Telecommunications at Universidad de los Andes in Venezuela, Ermanno has focused in the planning and deployment of wireless data communication networks with low cost technology in Argentina, Colombia, Ecuador, Italy, Lesotho, Malawi, Mexico, Morocco, Nicaragua, Peru, Spain, Trinidad, USA, Zambia and Venezuela. He has presented in many conferences and published several papers related to wireless data communication and is coauthor and technical reviewer of the book "Wireless Networking for the Developing World" freely available from http://wndw.net.

SEBASTIAN BÜTTRICH

Sebastian, Research Lab Manager at the IT University of Copenhagen, works with (low-cost) wireless technology, open source software and solar energy to build networks, systems, skills and capacity - as a manager, developer, architect, consultant and teacher. This work is focused on (but not limited to) developing countries and communities, especially in Asia and Africa. One current focus is to help develop campus networks for research and education, with emphasis on global integration and sustainability.

His current affiliations are:

- the IT University of Copenhagen (http://www.itu.dk), where he runs the Research Lab
- the Network Startup Resource Center (http://www.nsrc.org)
- wire.less.dk - NGO and company co-founded with Tomas Krag (http://wire.less.dk)
- wirelessU - a group of dedicated professionals working towards a world-wide, people-centered, inclusive Information Society (http://wirelessU.org)
- Wireless Networking in the Developing World - Co-author of the Wireless Networking in the Developing World book (http://wndw.net/)

Sebastian holds a Ph.D. in quantum physics from the Technical University of Berlin in Germany, with a focus on optics, radio spectroscopy, photovoltaic systems and scientific programming. He loves and plays music, is fascinated and engaged with text, language and poetry in many forms.

MARCO ZENNARO

Marco received his M.Sc. Degree in Electronic Engineering from University of Trieste in Italy and his PhD in Telecommunications from KTH-Royal Institute of Technology, Stockholm, Sweden, with a thesis on "Wireless Sensor Networks for Development: Potentials and Open Issues". He is a Research Officer at the Abdus Salam International Centre for Theoretical Physics, where he coordinates the Marconi Laboratory. Marco is a Sensemaking Senior Research Fellow of MIT.

His research interest is in ICT4D, the use of ICT for Development. In particular, he is interested in Wireless Networks and in Wireless Sensor

Networks. He has been giving lectures on Wireless technologies in more than 25 countries, both on Wireless Networks and on Wireless Sensors.

Marco is coauthor of the book "Wireless Networking for the Developing World" (http://wndw.net), translated in 7 languages and downloaded more than 3 million times from the Internet.

ANDRÉS ARCIA-MORET

Andrés Arcia-Moret is an associate professor at University of Los Andes, Mérida, Venezuela, in the Computer Science department since 2002. He received his B.Sc. (with honours) and M.Sc. in Systems Engineering and Computer Science respectively at University of Los Andes, Mérida, Venezuela. He holds a PhD degree in Computer Science from the Institute Mines-Telecom, Telecom Bretagne, France. He has been a visiting scientist at IRISA/CNRS in Rennes, France and at the Marconi Lab in the International Centre for Theoretical Physics, Trieste, Italy. His research interests include: transport protocols, wireless networks and network simulation.

ALAN WOOLHOUSE

A Marketing graduate with over twenty five years experience in technology marketing from large blue chip semiconductor companies to emerging start-up organisations. In 2000 Alan Woolhouse joined Bluetooth silicon pioneer Cambridge Silicon Radio (CSR) as Vice President of Communications, architecting and managing the entire function and helping to establish the start-up as the premier fabless chip company in Europe and leading Bluetooth silicon vendor worldwide in less than six years. In 2004 he provided the communications expertise to support the successful Initial Public Offering as CSR floated on the London Stock Exchange. In 2009 he left CSR to establish his own company specialising in technology marketing with particular focus on emerging technologies and companies. He is now founder and CEO of Cambridge Start-Up Limited, a full service Marketing Communications Agency and parent company of Weightless Marketing Limited. The subsidiary company is contracted to provide the marketing communications services to the Weightless SIG - a global organisation dedicated to the development, licensing and marketing of a fundamentally new regime for the Internet of Things.