Innovations in Spectrum Management

Enabling community networks and small operators to connect the unconnected

Internet Society

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Contents

Executive Summary

The value of being connected to a communication network is steadily rising. And yet, half of the world population remains unconnected to the Internet. Traditional solutions are showing signs of having reached their limits. Attempts to address this problem whether through universal service strategies/funds, private sector initiatives or philanthropy have met with limited success. This presents a conundrum for policy-makers and regulators where value continues to accrue to those with affordable access to communication infrastructure while the unconnected fall further and further behind by simply staying in the same place.

In order to address this issue, fresh thinking is required. There are changes in the telecommunication landscape that represent genuine cause for optimism that it is possible for everyone on the planet to have affordable access to communications. This is particularly true if these opportunities are used for the unconnected to connect themselves via small operators or community networks. However, in order for that to happen, changes in access policy and regulation are required, in particular with regard to spectrum management, as they are largely rooted in analogue paradigms. This report is intended as a resource for regulators and policy makers interested in driving this change. First, it provides new lenses to understand the vocabulary, the framework, and the current landscape for spectrum management. In particular, these sections address the following issues:

- Make the vocabulary and concepts of spectrum management more approachable. By using analogies and examples, the different factors involved in communicating using radio waves are described. Similarly, new metaphors are introduced in order to deconstruct the current narrative of spectrum management based on property rights, which blinds us to innovations in wireless technology that could help connect the unserved. Managing spectrum using this metaphors shows that we could easily move from the current "spectrum scarcity" debate, to one of abundance, particularly in the places where the unconnected live.
- The fact that organisations using the same frequency at the same time in the same location resulted in communication failure, leads to a complex dance among regulatory agencies, standards bodies, equipment manufacturers, and network operators, all of which influence the evolution and uptake of wireless technologies.
- The accelerating pace of technological change is challenging the traditional pace of spectrum allocation and assignment. This is compounded by the increasing demand for wireless spectrum from operators in order to be able to meet growing demand for broadband services.

Then, it includes a detailed survey of the current status of spectrum management in frequency-bands used to provide connectivity in a selection of representative countries around the world (Argentina, Brazil, Canada, India, Mexico, South Africa, and the United States) and outlines the basis for an evolving spectrum management ecosystem where complementary approaches can be used to remove the barriers and provide support to community networks and small operators. In particular, regulators and policy makers are recommended to consider evidence of innovative spectrum management in the following topics:

- The rapid spread of license-exempt spectrum use in the form of Wi-Fi is an important lesson about the power of frictionless innovation and about the pent-up demand for affordable Internet access. It makes sense for regulators to leverage this success by **expanding access to license-exempt spectrum** and further reducing costs associated with its use.
- The reduced harmful interference from antennas that can focus wireless communication along very narrow beams/paths has led some regulators to extend the use of some bands, like the 11 GHz band for **fixed PtP backhaul links**. Regulators should consider the market availability of low-cost microwave solutions in 11 GHz and other frequencies and adapt regulation to encourage their uptake. This could take the form of a **light-licensing** scenario for the cooperative assignment of geo-located frequency assignments.
- Rising costs for exclusive-use, licensed spectrum, stands in stark contrast to license-exempt spectrum that is available at no cost. **Dynamic spectrum** offers the opportunity to establish a middle ground between both. While TV White Space regulation has been implemented in a few countries, its real potential may yet to be realised as an affordable access technology in developing countries where UHF spectrum is largely unoccupied. Regulators should accelerate the adoption of TVWS regulation and explore the application of these management approaches to other frequency bands.
- While demand for spectrum often exceeds its administrative availability in urban areas, large amount of licensed spectrum lies unused in sparsely-populated, economically poor regions. A variety of low-cost 2G and 4G manufacturers have emerged in recent years that offer the potential to dramatically change the cost model for sustainable rural mobile network deployment. Regulators should consider allocations of small parts of the **spectrum for mobile network services** that may not have value for incumbent operators, but will have a significant impact for small operators and community

networks, together with an economic study to understand the economic cost of unused spectrum and approaches to incentivize its use.

- Spectrum auctions should be reviewed in terms of their role in increasing affordable access in underserved regions. **Wholesale approaches to spectrum** assignment targeted at difficult to serve regions should be explored.
- The rise of spectrum as a critical resource in the delivery of affordable access has led to the need for a more inclusive public debate. This places an obligation on regulators to increase **transparency and communication** with regard to spectrum management issues and telecommunication infrastructure in general.

As the evidence of the impact of remaining unconnected has grown, regulators throughout the world have shown the interest in becoming more familiar with these innovative approaches to spectrum management and the ways to implement them. The Internet Society, the Association for Progressive Communications and their partners, including industry body associations, are willing to provide support in different areas to make this a reality.

1 Introduction

The value of being connected to a communication network is steadily rising. More than a decade ago researchers established that simple proximity to a communication network was directly correlated[1] with a reduction in the probability of dying from malaria. Today, with smartphones delivering powerful generic services like group and personal messaging and more specific apps aimed at critical sectors such as education, agriculture, and others, communication networks are approaching the status of essential infrastructure for a modern economy. And yet, over half of the world population does not have access to the Internet[2]. Traditional solutions are showing signs of having reached their limits. Mobile subscriber growth is slowing[3] as the current economics of mobile network operators struggle to find viability in markets with subsistence level incomes and/or sparsely populated regions. It is also noteworthy that the same situation is being mirrored in the number of Internet users, whose growth has slowed from 12% in 2016 to only 7% in 2017[4]. Varied attempts to address this problem, through universal service strategies/funds, private sector initiatives or philanthropy have met with limited success.

This presents a conundrum for policy-makers and regulators where value continues to accrue to those with affordable access to communication infrastructure while the unconnected fall further and further behind by simply staying in the same place. Those who most desperately need support are cut off from access to opportunity, to social and health safety nets, to education, to information that can improve lives and to platforms to demand change. It is ironic, or perhaps tragic, that the voice of the unconnected are not heard on this issue for the very reason that they are unconnected.

In order to address this issue, fresh thinking is required. Previously, solving connectivity challenges could only be tackled by entire governments investing vast resources in state-owned networks. The mobile phone revolution opened the door to private sector investment in telecoms and new business models such as pay-as-you-go services which extended sustainable communication services further than anyone could have imagined. Yet becoming a mobile network operator still involves millions of dollars, creating a high barrier to market entry.

There are a number of factors that suggest that the telecommunications landscape is shifting once again.

- The value chain of telecommunications networks is becoming disaggregated. Previously in order to enter a market, an operator needed to invest in international, national, middle mile, and last mile infrastructure. Now we are beginning to see competition in each of those segments.
- The spread of fibre optic infrastructure, both undersea and terrestrial is changing the access market. While there is no question that fibre optic networks are increasing the ability of existing operators to deliver broadband, those same networks are opening up possibilities for new players who can now deliver more targeted, localised, affordable solutions to unserved populations.
- Changes in last mile technology are also opening up new possibilities. The spread of Wi-Fi as an access technology is empowering both commercial, government, and community access initiatives to offer local services. Dynamic spectrum technology also shows promise as an alternative access technology.
- Finally, the meteoric growth of access combined with mass manufacturing has brought down the cost of access technologies to the point where they are within the reach of small scale operators. For example, low-cost solar-powered Open Source GSM base stations can be deployed for a fraction of the cost models of existing mobile network operators.

All of these changes represent genuine cause for optimism that it is possible for everyone on the planet to have affordable access to communications. This is particularly true if these opportunities are used to enable the unconnected to connect themselves via small operators or community networks. However, in order for that to happen, changes in access policy and regulation are required, in particular with regard to spectrum management. As the International Telecommunication Union (ITU) Development Bureau (BDT) recommends: it is *"important that administrations, in their radio-spectrum planning and licensing activities, consider mechanisms to facilitate the deployment of broadband services in rural and remote areas by small and non-profit community operators"*[5].

The recommendation above is based in the increasingly vital role that wireless communication systems have in connecting society. However current models of radio spectrum management are still largely rooted in analogue paradigms, and have yet to adapt to the growing diversity of connectivity provision models and the latest technology developments, such as software-defined radio and dynamic spectrum assignment, which have the potential to help provide more universal and affordable communications, especially in areas lacking connectivity. This report, part of an ISOC series in the topic[6], is intended as a resource for regulators and policy makers interested in driving this change. It surveys the current status of spectrum management in frequency-bands used to provide connectivity in a selection of representative countries around the world[7] and outlines the basis for an evolving spectrum management ecosystem where complementary approaches can be used to remove the barriers and provide support to community networks and small operators.

2 Spectrum Basics

Wireless spectrum is a challenging topic to discuss - even finding the right vocabulary is complicated. Terms such as wireless spectrum, radio frequencies, radio communication, or even simply the "airwaves" all generally refer to the same thing, which is the transmission of information (voice or data) via electromagnetic radiation, or what we know more commonly as radio waves[8].

The distance from crest to crest of a radio wave is known as its wavelength and that distance determines the number of waves per second or frequency of the radio wave. Historically, different frequencies have been allocated to different functions[9]. Thus, for example, FM and AM frequencies have been dedicated to radio broadcasting and GSM frequencies to mobile communications. These have been the basic conventions for the operation of radio equipment at different frequencies ever since the use of radio communication technology was developed.

2.1 Factors involved in the success of wireless communications

We communicate by encoding information in radio waves. Historically it was analogue information such as voice or music that was encoded, but increasingly all types of communication are converted to digital format before being encoded for radio communication. There are four key factors involved in the process of this communication:

- The originator of the communication or "transmitter";
- The recipient of the communication or "receiver";
- The media and distance through which the radio waves must travel - usually the atmosphere, which can include rainfall, trees or buildings, etc.; and,
- Other radio transmissions.

For transmitter and receiver, this is like a conversation between two people. How loudly and how clearly the speaker communicates is a factor, but equally the ability of the listener to hear effectively is as significant in successful communication. In broadcasting systems, whether analogue or digital, there is a clearly identified transmitter and several receivers. Successful communication is a team effort between transmitter and receiver; the loudness and clarity of the former combined with the sensitivity of the latter determines the robustness and quality of the communication. However, in many contemporary communication systems, both sides act as both transmitter and receiver. Mobile telephony, Wi-Fi, etc, operate this way. For the communication to be successful, both have to have good enough "speaking and listening abilities" to reach the other end. That is why in most cases successful communication is determined by the device with "worst abilities".

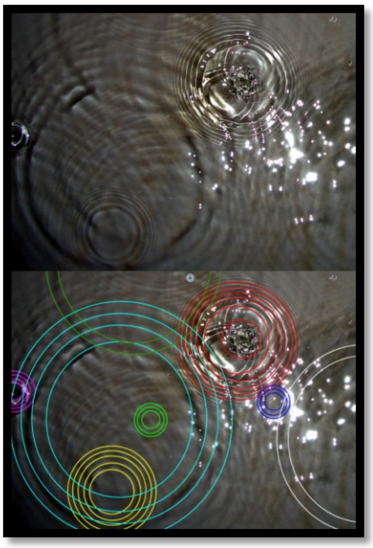


Figure 1 Representation of interference

What physically exists between the transmitter and receiver is a factor as well. The length of a radio wave or its frequency determines how it is affected by the media it encounters between transmission and reception. Longer radio waves tend to be less impeded by physical obstacles like trees and buildings although even long radio waves are impeded by mountains. Higher frequency (shorter) radio waves are more inclined to bounce off or be absorbed by physical obstacles. This is why shortwave radios, which have quite a long wavelength (in spite of their misleading name in this context), can communicate over hundreds of kilometres whereas Wi-Fi may be impeded by a single cement wall. That is also why satellite communication is possible, as the media outside the atmosphere has other characteristics that allow the signal to propagate without much interference.

Finally, other radio transmissions play an important factor in radio communication. If there is more than one radio transmission on a given frequency, then it can be difficult for the receiver to discern which radio transmission was intended for it. Radio waves, though, do not interfere with each other in the way that a grove of trees or a wall might impede a radio transmission. In radio physics, interference simply refers to the overlaying of one wave over another. Think of a still pond. If a stone is dropped in at one end and a person drops a stone in at the other end; the waves generated by those stones will eventually meet, but they don't impede each other, they pass through each other. If we could somehow colour the waves from one stone yellow and the other blue (see Figure 1), we would see each set of waves clearly pass from one side of the pond to the other.

The inability of radio receivers to distinguish between multiple transmissions in the same frequency is the reason radio spectrum is regulated - to prevent harmful interference - and has led to the allocation of specific frequencies to specific purposes and to specific organisations. The unique assignment of specific frequencies to specific organisations, when enforced, effectively guarantees that there is no radio interference, but, as we will discuss in this paper, it may not be the most efficient strategy to enable affordable access for the unconnected.
As a combination of the factors above, information will reach its destination with a given energy level. The clearer that one side is able to receive the signal from the other side i.e. the higher the signal is above the background noise level, the more information is able to be conveyed. Think about a conversation in a quiet place, no matter how fast a person is speaking that you will be able to make sense of what the person is saying. However, in a noisy place, such as a bar or a restaurant, that same person would have to speak more slowly for you to follow the conversation. As a result, it will take longer to convey the same amount of information. In wireless communication, because the two endpoints can be far apart, noise levels can be different for each of the parties, and so one side will be able to convey more information per unit of time than the other one. The same happens with the data rates that can be exchanged between two devices. The clearer the channel between the devices in each direction the more megabits per second (Mbps) will reach the other end, but the flow will not necessarily be symmetrical. There is a limit to how much data can be conveyed per unit of time, which we will explore this in the next section.

2.2 The Limits of Spectrum

The development of radio communication technology over the last few decades has seen the continuous improvement of radio transmitters that can speak ever more efficiently and clearly, and receivers that are more sensitive and less prone to be distracted by interference. We also have steadily increased our ability to encode more and more information into the same radio waves, especially when the signal received is clear. However, there are limits to this progress. The Shannon Bound[10] describes a maximum threshold for the amount of data that can be communicated over a frequency channel. It is derived from Shannon's Law, developed by mathematician Claude Shannon in 1948, which proved that maximum data-rate is a function of bandwidth and signal-to-noise ratio. What this means is that there is a fixed limit[11] to the amount of data we can send through a given frequency range. Thus the size of the frequency band is proportional to the amount of information it can carry. A practical example of this is that an operator of mobile data services with 20 MHz of spectrum assigned to them can offer higher capacity to their customers than a competitor with 10 MHz in the same frequency band.

However, even this seemingly immutable boundary needs to be re-interpreted in the light of technological change. Nothing has changed to disprove Shannon's Law, and yet by using multiple antennas, or what is known as MIMO (Multiple-Input / Multiple-Output), it is possible to exceed the Shannon Bound for a given frequency by transmitting the same frequency over different paths.

2.3 New metaphors for spectrum: moving from scarcity to abundance

The fact that radio waves are invisible and ubiquitous means that we are challenged to find ways to talk about the subject meaningfully and to establish effective regulations for their use. We are obliged to resort to metaphors. The current dominant metaphor is that of real estate in which the use of specific frequencies in a specific geographic area is treated in a similar way to a piece of physical real estate with property rights associated with it. This metaphor for spectrum was first conceptualised by economist Ronald Coase in 1959[12] and has gone on to become the dominant metaphor that underpins how high-demand spectrum[13] is made available today.

Operators are encouraged to bid for spectrum licenses which give them exclusive rights to specific frequencies, often in an entire country. These licenses typically extend over a 10, 15 or 20 year period. The theory behind this is that spectrum licenses should go to those who value the spectrum most and by extension have the strongest vested interest in making use of the spectrum. This model is based on an assumption that the market is the best means for the efficient disposition of natural resources but ignores other successful models. Managing natural resources as a common-pool resource is a proven alternative. Nobel prize laureate Elinor Ostrom's work on common-pool resource models[14] effectively dismantled the accepted wisdom of a "tragedy of the commons"[15] that occurs in absence of private property. In a market failure scenario, such as the one where most of the unconnected find themselves, it only makes sense to consider complementary strategies for managing natural resources, such as spectrum. Interesting enough, the ITU in their "Guidelines for for the establishment of a coherent system of radio-frequency usage fees"[16], consider one of the 8 principles for managing the commons[17]: "The establishment of a fee system should be based on a consensus among all the players, since this would make for a healthy collection rate." However, in practice, not all players have a saying on how these fees are established.

The metaphor of "property" and property rights has supported the current model of long-term, exclusive licenses for the operation of radio equipment in various frequencies. This has had utility in helping to find a practical way of managing spectrum; ensuring that spectrum goes to those who value it and that those with spectrum licenses do not experience interference. However, with the success of wireless technologies and the growth of the Internet, demand for spectrum has skyrocketed, leading to speculation that a looming "spectrum crunch[18]" will occur where operators will not have enough access to spectrum to meet consumer demand. However, others have described the spectrum crunch as a myth[19]. One of the answers to these contradictory claims lies in the metaphors that shape our thinking and ultimately our regulations.

If we explore the metaphor of property and property rights further, as it applies to the assignment of spectrum, we can begin to see some interesting and novel ways in which it might be applied and ways in which the metaphor starts to break down when we look at the nature of radio waves and how they behave.

Perhaps the most profound difference is the ability to re-use spectrum by shrinking the size or range of the transmission. Consider a single tower with a radio sending out a signal over a 12 kilometre (km) radius. It is possible to replace that tower with three towers of lower power and radius size that cover the same area, resulting in doubling or tripling the total spectrum capacity in the same spectrum frequency band in that area. At the same time, by both ends of the communication being closer, they will be able to transmit more information. If we pursue the property metaphor, you can think of this as building a high-rise apartment in the place of a mansion. With radio spectrum, there is no physical limit as to how high the apartment can be built. The practical limit is an economic one, as this would require higher investments. Wi-Fi access points are probably the best example of this with cells that are typically less than 100m allowing for massive re-use of the spectrum[20].

It is also possible to have radio transmissions operate in the same frequencies by implementing what might be best described as a "good manners" protocol. As a technology designed for license-exempt spectrum, Wi-Fi follows a "listen before talk" protocol which checks to see if the frequency is free before transmitting. While this may not be the most technologically efficient use of the spectrum, it has proven enormously successful in enabling the proliferation of billions of Wi-Fi devices around the world.

We can also take the property metaphor in another direction where it could be said that the management of licensed spectrum is like a large hotel where rooms can be booked out for years at a time whether or not they are actually occupied. If we consider how Airbnb has changed the hotel industry or Uber the taxi industry, the same potential exists to apply resource management software and business models to the process of spectrum assignments. Dynamic spectrum management, discussed later in this paper, is a great example of this. The technological development of dynamic resource allocation through software is now well-developed but, as yet, not widely applied in the realm of spectrum management. Early engagement from regulators on dynamic resource management can ensure that downsides seen in other sectors are mitigated.

There are also many ways in which radio waves behave that a property rights metaphor can blind us to. A simple example is that it is possible to have two independent radio transmissions operate successfully using the same frequency across a point-to-point connection through the implementation of antenna design that causes one transmission's radio waves to oscillate up and down while in the other radio waves oscillate from side to side. This property is known as polarity. If you have worn a pair of Polaroid sunglasses, you have experienced something like this phenomenon.

Yet another example is simply the orientation of the antenna that is used. Satellite antennas point upward toward the sky. Coastal weather radar antennas point out to sea. Even when two beams cross each other, this has no interfering effect as long as the "other" beam is not "heard" by the receiver. Think of two beams orthogonal to each other, for instance. The orientation of antennas due to the nature of the spectrum use can open up opportunities for the re-use of that spectrum in the same geographic area but oriented in a different direction.

Exploring yet another metaphor, perhaps you have been at a party where everyone is speaking English. In the cacophony of people talking, from across the room, you can pick out two people speaking your native language. If it were two people speaking English, you would not be able to understand them, but because they are speaking your native language, you can. This well-established phenomenon is known as the cocktail party effect[21]. This is a surprisingly good analogy for the development of what is known as cognitive radio[22]. Cognitive radio combines the ability to detect radio transmissions which could interfere, and to adapt effectively by teaching radio receivers to recognize specific transmitters by encoding radio transmissions in a way that makes them uniquely recognisable to a specific receiver. Radio technology like this (which requires a combination of antennas and software) is still at an early stage of development but the technology is steadily improving and one day we may be able to have multiple successful radio communications in the same frequency as a matter of course.

New metaphors can reveal other properties of radio waves that can prove powerful. Let us imagine you are at a rock concert and the band is blasting out your favourite tune and you are having a conversation with your best friend next to you about how much you love that tune. You are both using the same audio "spectrum" yet your conversation with your friend does not interfere with the band. This concept is known as the noise floor[23] and opens up new possibilities for co-existence of radio equipment in the same frequency.

Even the very radio interference that spectrum management has traditionally set out to avoid can be used in positive ways. Antennas for a radio transmitter can be combined in such a way that signals at particular angles experience constructive interference while others experience destructive interference, with the result that radio signals can be “directed” with increasing accuracy. This approach, known as beamforming, can be used at both the transmitting and receiving ends to improve communication where it is needed and reduce interference elsewhere.

In summary, thinking about spectrum **only** as long-term property blinds us to innovations in wireless technology that could help connect the unserved.

3 Regulatory and Standards Bodies

As wireless communication evolved from scientific experiment to commercial services in the early part of the 20th century, some obvious challenges emerged. In order for a wireless transmitter and receiver to speak to each other, they need to use the same wireless frequency and protocols. Independent development of wireless technologies around the world soon revealed this challenge because devices from one country were unable to communicate with devices from another country. As the use of wireless technology proliferated it also became evident that organisations using the same frequency at the same time in the same location resulted in communication failure as a result of harmful interference or the inability of radio receivers to distinguish the transmissions intended for it.

This problem has led to a complex dance among regulatory agencies, standards bodies, equipment manufacturers, and network operators, all of which influence the evolution and uptake of wireless technologies. The International Telecommunication Union (ITU) sits at the apex of this, facilitating agreements among countries on the use of spectrum frequencies as well as the development of standards for how radio frequencies are used. Yet, standards development happens through a number of different standards organisations and meta-organisations. The 3rd Generation Partnership Project (3GPP) is the standards body for mobile technologies while the Institute of Electrical and Electronic Engineers Standards Association (IEEE - SA) develops standards related to, among many others, data communications, including those for Wi-Fi and Television White Space (TVWS) technologies. The European Telecommunications Standards Institute (ETSI) also plays an important role in the development of technology standards for wireless systems. As the standards body for Europe, it wields significant influence on key factors such as allowed power output and spectral performance in wireless technologies. Standards set by ETSI are often adopted elsewhere in the world although the standards set by the Federal Communications Commission (FCC) in the United States can be equally influential depending on the region (see note on ITU Regions below)

The existence of standards which represent agreements among manufacturers influences international agreements on the allocation of frequencies. By choosing which standards to invest in, large multinational manufacturers have tremendous influence on the standards that are developed. By extension, large network operators, through their purchasing power, influence both manufacturing choices and standards evolution. WiMax, for example, was a very promising technology standard that failed as a result of choices made by operators and manufacturers[24]. National regulators must take all of this into account as they develop regulations which must avoid interference with other countries, exploit manufacturing trends while embracing standards which promote competition and address the specific communication needs of their country.

Understanding regulation is complicated by the fact that national regulation is implemented in different ways in different countries. All countries have an entity or entities responsible for communication regulation in general, and for spectrum regulation in particular, but how that is implemented varies widely. In some cases responsibility for spectrum management lies with the independent communication regulator and sometimes that function is retained within government. In some cases, the independent communication regulator is not autonomous and is hard to distinguish from a government department. In addition regulators may be overly influenced by the concerns of the operators that have paid them millions of dollars for their spectrum licenses. For historical reasons, sometimes the use of spectrum for broadcast is managed by a different organisation to that managing spectrum for telecommunications. In other cases, management of spectrum for use by government agencies is distinct from management of commercial spectrum use.

Table 1 - Spectrum Regulation responsibility in each country under study

Country	Spectrum Regulation
Argentina	Radio spectrum is managed by the communication regulator (http://www.enacom.gob.ar/)
Brazil	Radio spectrum is managed by an independent communication regulator (http://www.anatel.gov.br/institucional/) The Ministry of Science, Technology, Innovation, and Communication (http://www.mctic.gov.br/portal) is responsible for broadcast spectrum.
Canada	While an independent communications regulator exists (https://crtc.gc.ca), the allocation and assignment of all radio spectrum is managed within a government department (http://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/home)
India	Radio spectrum for telecommunications is managed by the independent communications regulatory agency (http://www.trai.gov.in/). The auction of high-demand spectrum is directed by the Ministry of Communications (http://www.dot.gov.in/spectrum) while broadcast spectrum is handled by by the MInistry of Information and Broadcasting (http://www.mib.gov.in/)
Mexico	Spectrum is managed by an independent communication regulator (http://www.ift.org.mx/) although policies regarding high-demand spectrum are directed by the government
South Africa	All radio spectrum is nominally managed by the independent regulator (http://icasa.org.za/) but the government exerts strong direction over the disposition of high-demand spectrum.

United States	Spectrum for commercial use is managed by the independent communications regulator (https://www.fcc.gov/) but spectrum for government use is managed by a separate government agency (https://www.ntia.doc.gov/category/spectrum-management)

In all of the above cases, radio spectrum used by the Ministry of Defence remains independent of other regulatory processes.

3.1 International Telecommunication Union (ITU)

The roots of the International Telecommunication Union (ITU) date back as far as 1865 as a venue for consensus-building on standards for wireless communications which addressed both devices and frequency use. In 1947, a decision was made to bring the ITU into the newly created United Nations, recognising it as the specialized agency for telecommunications[25]. As of 2016, the ITU Constitution and Convention has 193 state parties, which includes 192 United Nations member states plus the Holy See. The ITU also has over 700 Sector Members and Associates from industry, international and regional organizations, as well as academia. While sector member do not have voting privileges, the larger sector members from industry do wield considerable influence.

The ITU is divided into three sectors:

- Radiocommunication (ITU-R)
  ITU-R exists to broker consensus and develop standards in the use of space and terrestrial wireless communication. It works to achieve agreement among all UN Member States on the allocation of radio-frequency spectrum for specific uses and in satellite orbital slots, dealing with a range of services including fixed, mobile, broadcasting, amateur, space research, meteorology, GPS, monitoring and communication.
- Development (ITU-D)
  ITU-D's mission is to foster international cooperation on telecommunication and ICT development issues as well as to build human and institutional capacity. ITU-D works to expand telecommunications infrastructure in developing nations throughout the world which make up the majority of member countries.
- Standards (ITU-T)
  ITU-T works to broker consensus in non-wireless telecommunications standards which

range from video and audio compression standards to fibre optic infrastructure protocols. It collaborates with a range of other standards bodies around the world.

ITU Conferences

The ITU organises a number of global and regional decision-making conferences and it can be confusing to understand what decisions are taken at what events. The ITU Plenipotentiary Conference is the top policy-making event of the ITU, meeting every four years in order to set the Union's general policies.

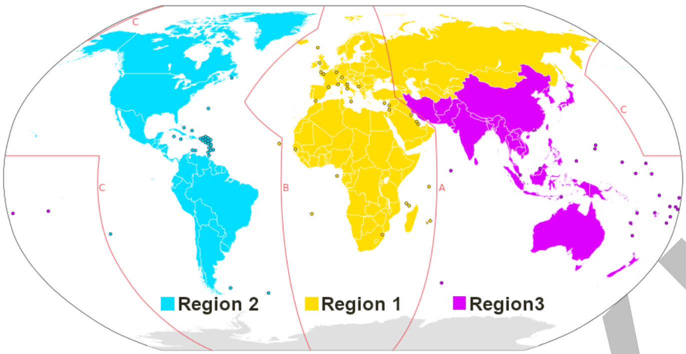
From the point of view of spectrum management, the World Radio Conference (WRC) which is organised by ITU-R and which also happens every four years, is the principal decision-making event related to the allocation of radio spectrum frequencies to specific purposes and use. The outcome of the WRC is the ITU Radio Regulations which is a binding international treaty governing the use of the radio spectrum. Preparations for WRCs typically begin years before the event, with countries working through study groups to develop positions to be agreed on specific issues at the event. Most countries and regions hold their own preparatory process to prepare for each WRC. This is a political process that requires significant investment of time and resources to engage in.

The treaty nature of the Radio Regulations is complex, as the ITU constitution also recognises "the sovereign right of each State to regulate its telecommunication[26]". Ultimately countries can do what they like with radio spectrum but mostly they find it useful to agree on international standards, especially given the dependence on multinational manufacturers. It is relevant to note that many countries also coordinate their border communications in order to avoid interference with their neighbours.

While the issue of wireless spectrum has always been clearly centred within ITU-R, recommendations adopted[27] at the World Telecommunication Development Conference (WTDC), the main ITU-D conference, suggest that the boundaries may not be as clear as they used to be. Recommendation 19 advises regulators "in their radio-spectrum planning and licensing activities, [to] consider mechanisms to facilitate the deployment of broadband services in rural and remote areas by small and non-profit community operators". As the need to address the digital divide in developing countries becomes an increasing priority, spectrum regulations may evolve differently to address development challenges, particularly in rural areas.

Historically, geographically and economically, large countries such as the United States have felt free at times to pursue their own interests with regard to spectrum management. This has presented a challenge for spectrum harmonisation and has, in part, led to the emergence of three separate regions which have their own agreements on spectrum allocations:

- *Region 1* comprises Europe, Africa, the former Soviet Union, Mongolia, and the Middle East west of the Persian Gulf, including Iraq.
- *Region 2* covers the Americas including Greenland, and some of the eastern Pacific Islands.
- *Region 3* contains most of Asia (that wasn't part of the former Soviet Union) east of and including Iran, and most of Oceania.



3.2 International Standards Bodies

3rd Generation Partnership Project (3GPP)

The 3rd Generation Partnership Project[28] (3GPP) is a collaboration between groups of telecommunications standards associations to develop standards relating to mobile telephony. 3GPP mobile telecommunications network technologies include radio access, the core transport network, and service capabilities, as well as work on codecs, security, and quality of service. 3GPP is a venue for the development of standards for existing 2G, 3G, and 4G technologies as well as emerging standards such as 5G.

Institute of Electrical and Electronic Engineers Standards Association (IEEE - SA)

The Institute of Electrical and Electronic Engineers[29] (IEEE) is an international body that specifies industry standards for power, consumer electronics, and computers, including computer communications. The IEEE Standards Association (IEEE-SA) is an organization within IEEE that develops global standards through a consensus building process in a range of technology industries, including information and communication technologies and telecommunications. In contrast to the ITU, IEEE-SA is not a body formally authorized by any government, but rather a community. IEEE-SA came to prominence in the wireless world through its development of the 802.11 wireless standards which has enabled the growth of Wi-Fi technologies by establishing standards for interoperability.

European Telecommunications Standards Institute (ETSI)

The European Telecommunications Standards Institute[30] (ETSI) is a European body that specifies standards used by telecommunications networks operating within European countries. ETSI produces globally applicable standards for Information and Communications Technologies (ICTs), including fixed, mobile, radio, converged, aeronautical, broadcast and Internet technologies. ETSI is officially recognized by the European Union as a European Standards Organization. ETSI is an independent, not-for-profit association with members from 62 countries around the world. ETSI is also a member of 3GPP. From a wireless perspective, their standards work covers millimetre wave technology, emerging 5G standards, as well as standard for TV White Space technologies.

4 Current Landscape

One of the biggest issues facing spectrum regulators today is the accelerating pace of technological change, which is challenging the traditional pace of spectrum allocation and assignment. This is compounded by the increasing demand for wireless spectrum from operators in order to be able to meet growing demand for broadband services. The sections below explore the implications of these trends.

4.1 The Pace of Technological Change

This section explores the tensions that are emerging with the rapid evolution of technology, increased demand for spectrum, and the challenges that regulators face in making spectrum available. An apt illustration of how the pace of technological change is challenging spectrum regulation can be seen through the transition process from analogue to digital terrestrial broadcasting in African countries, which will free up spectrum in the ultra-high frequency (UHF) bands which are used for terrestrial television broadcast. This is because digital broadcasting needs only a fraction of the amount of wireless spectrum required by analogue broadcasting. In 2006, Sub-Saharan African countries agreed[31] to participate in a Digital Switchover (DSO) transition process that would, among other things, free up hundreds of megahertz of spectrum. The completion date was set for June 2015.

As of mid-2018, less than half of the countries in Sub-Saharan Africa[32] have completed the transition, with economic leaders such as Nigeria, South Africa, and Ghana only committing to complete by 2019 at the earliest[33]. The reasons for the delays are bound up in a combination of technological and standards challenges, financing problems and power politics. As spectrum regulation processes go, it is not unusual for deadlines like this to slip by. Traditional spectrum re-farming, which typically involves moving existing spectrum licence holders into new frequencies, can take years, with millions of consumers being affected by these changes.

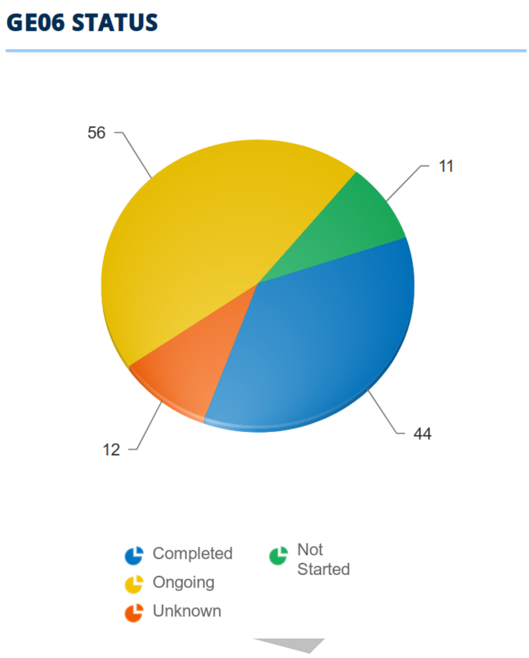


Figure 2 Status of Digital Switchover in Africa
Source: ITU – May 2018

What makes the DSO spectrum decision in Africa different from spectrum decisions in the past, is what has transpired since that decision was taken. In 2006, many technologies that are taken for granted today had yet to come to market. The first Apple iPhone, herald of the modern smartphone era, was only introduced in January 2007. Other technologies, such as tablets, arrived in 2010. Netflix, as an online service, began streaming movies over the Internet in 2007. Streaming music service Spotify, launched in 2008. As of 2018, a host of internet video distribution companies have emerged across a range of African countries, challenging the traditional distribution channels[34]. In the meantime, terrestrial television faces growing competition from satellite television services in African countries[35]. It is conceivable that digital terrestrial broadcasting could be largely overtaken by Internet and satellite services36 before the DSO is fully complete on the continent.

The lesson to be learned from this is that technological change is not slowing down and spectrum regulators need to adopt strategies that mitigate risks that result from the unexpected but inevitable market-changing innovations. Tying spectrum exclusively to specific technologies can result in missed opportunities to exploit new innovations as well as creating lost economic opportunities when valuable spectrum remains unused as a result of technological shifts.

4.2 Auctions and the assignment of high-demand spectrum

Auctions have become the dominant mechanism for making high-demand spectrum available and are widely regarded as “best practice” in the assignment of wireless frequencies where demand exceeds availability, typically in popular mobile frequencies[37]. Yet, many countries, especially in developing countries, have been slow to embrace spectrum auctions. This is perhaps not surprising as spectrum auctions are notoriously difficult to run well from the point of view of ensuring fair play and, even more so, from the point of view of ensuring the growth of competition[38].

For operators new and old, gaining access to spectrum frequencies is essential to success. For better or worse, long term, national, exclusive-use spectrum licenses are likely to continue to play a critical role in increasing affordable access to communication. As spectrum auctions emerge as an increasingly used mechanism for assigning spectrum, the large amounts of money associated with spectrum auctions and licensing have attracted a great deal of public attention. A closer look at the results of recent spectrum auctions, particularly in Africa, suggests that there their outcomes may be failing some of the basic goals that the auctions set out to address.

Lack of participation in spectrum auctions can often be attributed directly to the high reserve prices set in each country. There appears to be a conflict of interest for governments who may see spectrum auctions as a source of direct revenue as opposed to simply an effective means to fairly allocate resources. A recent study by NERA Economic Consulting[39] concluded that large amounts spent on spectrum acquisition resulted in lower quality networks, reduced network take-up, higher consumer prices, as well as lost consumer welfare. The GSMA have also published a report on spectrum pricing in developing countries that comes to similar conclusions[40]. Complete participation failures such as in Mozambique in 2013 where the high reserve price for a small amount of spectrum in the 800 MHz band saw zero participation in the auction[41], and in South Africa, where competing political agendas repeatedly stalled announced auctions since 2010[42], have resulted in valuable spectrum lying fallow for many years. Many operators have claimed[43] that this has directly impacted their ability to roll-out telecom infrastructure.

The lost opportunity cost of spectrum that is not successfully assigned does not appear to be a significant factor in auction planning. Examples such as the 2.3 GHz auction won for USD23 million by Bitflux in Nigeria[44] suggest there may also be a “winner's curse” associated with auctions that may inhibit investment in network roll-out. Another unintended consequence of spectrum auctions is their precedent-setting impact on future spectrum pricing where an initial price paid for spectrum must be matched by any subsequent auctions in that frequency, as may be seen in the case of the 800 MHz auction in Ghana[45],[46].

Lack of participation undermines the very purpose of an auction and all of the recent auctions profiled have revealed challenges in getting operators to participate, typically because the reserve price was higher than most operators were willing to pay. It seems likely that auction designers are being directed to prioritise an immediate and lucrative financial windfall from spectrum auctions instead of the longer term (and more diffuse) economic benefits that increased affordable access can bring.

In Egypt, the hard line taken by the Egyptian regulator may be an economic windfall for the Egyptian treasury[47] but time will tell whether it results in more affordable access in the country. The lack of willing participation of operators in spectrum auctions suggests that spectrum auction reserve prices need more careful evaluation.

The large amounts of money associated with spectrum assignments may be part of the problem, attracting the attention of governments and network operators alike. Civil society groups are often challenged both financially and technically to engage in national strategic debates on spectrum, although there are signs that this is beginning to change as spectrum is increasingly recognised as a critical roadblock to affordable access[48].

5 Innovations in Spectrum Management

The public focus on the topics described above is drawing attention away from several innovations in spectrum management that will enable a more conducive environment for community networks and small operators[49].

From a technological infrastructure perspective, we are seeing a shift to more pervasive availability of affordable backhaul infrastructure, both through the spread of fibre infrastructure as well as new generation satellite technology. Combined with dramatically less expensive wireless access technology, there is an opportunity for a more granular and dynamic approach to spectrum management as a complement to traditional long term license strategies. It is possible to envision a set of regulations that enable local access providers through the use of a combination of license-exempt, dynamic and traditional spectrum licensing aimed at increasing access in unserved regions.

In this section we explore some of these innovations in depth, looking into the regulations of seven countries: Argentina, Brazil, Canada, India, Mexico, South Africa and the United States.

5.1 License-exempt Spectrum

This section profiles the regulation of license-exempt spectrum. First we look into the more traditional Wi-Fi bands, then we look into the options that some countries are exploring to expand this successful approach into other bands. Finally, we look into the mmWave bands that are increasingly being made available for license-exempt operation in many countries.

5.1.1 Wi-Fi

The leading success story of license-exempt spectrum is its use in the 2.4 GHz and 5 GHz bands, particularly Wi-Fi communication. From its humble beginning connecting laptops in cafes, hotels, university campuses and airports, Wi-Fi access is now to be found in almost any commercial or public building, not to mention its default use in the home as the endpoint of a broadband connection. It is estimated that by 2021 there will be more than 540 million Wi-Fi hotspots worldwide[50]. We now see Wi-Fi in smartphones, tablets, cameras, printers, even refrigerators and weigh scales. It has become the default “last inch” technology. Unexpectedly it has now grown to play a critical role in mobile networks as well as a means of offloading the burgeoning demand for data on mobile devices. It is expected that by 2021, Wi-Fi will deliver 49% of global IP traffic[51].

There is often a tendency in valuing spectrum to emphasise the value generated through its sale or through the potential revenue generated by the network operator without considering the broader positive externalities that low-cost or free access to spectrum can generate. Researcher Richard Thanki has estimated the economic contribution of license-exempt spectrum, the results of which are summarised in the table below.[52] His work underscores the significant role that license-exempt spectrum, which comprises a tiny fraction of commercially usable spectrum, plays in the economy.

Table 2 - Economic contribution of license-exempt spectrum in countries under study

Country	Total fixed broadband connections (million)	Total fixed Wi-Fi Connections (million)	Evenly scaled annual economic value (USD million)
Argentina	3.85	3.27	726.70
Brazil	13.85	11.77	2613.70
Canada	10.35	8.80	1953.90
India	10.89	9.26	2055.30
Mexico	11.23	9.55	2119.80
South Africa	0.76	0.64	143.20
United Stated	82.38	70.02	15545.00

Whether commercial operators, government initiatives, or in community networks, Wi-Fi networks continue to grow at a rapid pace around the world. Both governments and network operators are realising that wherever they have high-speed backhaul networks, it is a small marginal cost to add Wi-Fi access points at key points on those networks. The combination of Wi-Fi's high performance and low-cost has made it an obvious access technology choice in countries where gaining access to licensed spectrum remains a challenge.

In South Africa, the municipal free Wi-Fi initiative, Project Isizwe[53], is evolving from a government-funded non-profit to an advertisement-driven model. Facebook is supporting Wi-Fi around the world with their Express Wi-Fi program. Express Wi-Fi is an agent platform for Wi-Fi operators that manages sign-up, revenue generation and sharing for Express Wi-Fi agents. Express Wi-Fi relies on an existing Wireless Internet Service Provider (WISP)'s network but it also brings investment to help the WISP expand its network. In India, a well-established rural wireless operator, AirJaldi[54], announced a partnership in 2017 with Facebook to roll out Express Wi-Fi hotspots. Google have also been investing in Wi-Fi in India with Google Station, an initiative to deploy Wi-Fi access at railway stations across the country. Launched in 2015, they now cover over 400 train stations with over 8 million monthly active users, offering limited free access as well as commercial services[55].

Most community networks are using the Wi-Fi bands in the countries under study to deploy their networks. To name a few, Colectivo Ik 'Ta Kop in Mexico[56], Zenzeleni Networks in South Africa[57], those facilitated by Coolab[58] and NUPEF in Brazil, and by Altermundi[59] in Argentina, most networks run by indigenous communities in the United States and Canada, including Tribal Digital Village[60] and K-NET[61], and the Digital Empowerment Foundation (DEF) in India[62] use Wi-Fi in their networks.

In most countries the use of Wi-Fi is license-exempt, which removes both spectrum fees and administrative overhead. Activity is regulated via the use of devices that are type-approved by the regulator, and the specification of the maximum power radiated in a given direction that each device can transmit in a given frequency. The latter is specified in most regulations as the Effective Isotropic Radiated Power[63] (EIRP) in decibel-milliwatts (dBm). The table below provides a description of the regulated output power in the bands used by Wi-Fi technologies in countries under study:

Table *3 - Regulated output power in bands used by Wi-Fi technology in the countries under study*

	2400 – 2483.5 MHz		**5150 – 5250 MHz**		**5250 – 5350 MHz**		**5470 – 5600 MHz**		**5600 – 5650 MHz**		**5650 – 5725 MHz**		**5725 – 5850 MHz**	
	EIRP	Tx Power	EIRP	Tx Power	EIRP	Tx Power	EIRP	Tx Power	EIRP	Tx Power	EIRP	Tx Power	EIRP	Tx Power
Mexico	33 dBm in PtP 30 dBM in PtMP	27 dBm in PtP 24 dBm in PtMP	23 dBm	17 dBm	30 dBm	24 dBm	30 dBm	24 dBm			30 dBm	24 dBm	36 dBm	30 dBm
South Africa	20 dBm		23 dBm		20 dBm		30 dBm				30 dBm		36 dBm (PtP 53 dBm)	30 dBm
Brazil	36 dBm	30 dBm	23 dBm		23 dBm		30 dBm	24 dBm			30 dBm	24 dBm	36 dBm	30 dBm
Argentina	36 dBm	30 dBm	23 dBm	17 dBm	36 dBm	30 dBm	36 dBm	30 dBm			3 6 dBm	30 dBm	36 dBm (53 dBm for PtP links up to 5.825 GHZ)	30 dBm

United States	36 dBm in PtMP. PtP of 1 dBm less in TxPower per 3 dBi increase in antenna gain above 6 dBm	30 dBm	36 dBm in PtP & 53 in PtMP	30 dBM	30 dBm	24 dBm	30 dBm	24 dBm	30 dBm	24 dBm	30 dBm	24 dBm	36 dBm in PtMP and no limit in the Antenna Gain in PtP	30 dBm
India	36dBm	30 dBm	20 dBm		20dBm								20 dBm & 36 dBm (5.825 to 5.875 GHz)	30 dBm (5.825 to 5.875 GHz)
Canada	36 dBm in PtMP and no limit in the Gain in PtP	30dBm	23 dBm indoor only		30 dBm	24 dBm	30 dBm	24 dBm			30 dBm	24 dBm	36 dBm in PtMP and no limit in the Gain in PtP	30 dBm

The table above shows a great disparity between countries in the power levels allowed for the different bands where Wi-Fi devices operate. This disparity is based on the band being regulated for both fixed infrastructure (point to point - PtP- and point to multipoint - PtMP) and user access (hotspot) simultaneously, with most countries limiting the output levels as a way to reduce interference in user access mode. Few countries make this distinction obvious by having distinct regulation for PtP links, where the use of higher gain antennas and their narrower beam reduces by default the interference with adjacent devices. The impact of this approach for extending connectivity in rural areas cannot be underestimated. For instance, Canada's specific regulation in 2.4 GHz enables links above 30 km in PtP with existing hardware[64], whereas South Africa's regulations only allows links of about 2 km, and India, Argentina and Brazil links of about 10 km.

In the 5.8 GHz band, Canada, United States, South Africa and Argentina make the distinction between fixed infrastructure and user access mode. However, India, Mexico or Brazil do not make any distinction, limiting the maximum link distance to about 6 km compared to the 15 km in South Africa and Argentina, and even further (about 20 km) in the United States and Canada with existing hardware[65]. Note that the lower the frequency, the further it travels, as explained in the introduction, so making this allowance in 2.4 GHz has a greater impact than in 5.8 GHz.

Provided the narrow beam of directional antennas used in PtP links, regulators should review and increase their limitations to the power level in these bands, and make a distinction between the two ways Wi-Fi can be used.

5.1.2 Expanding the license-exempt bands

The success of Wi-Fi begs the question as to why more spectrum is not made available on a license-exempt basis. As highlighted in the section above, the United States is one the frontrunners in this space, having made 50 MHz available between 5600 and 5650 MHz for Wi-Fi, not available elsewhere. In addition, in February 2013 the FCC issued a Notice of Inquiry (NOI) to harmonize rules on the 5 GHz license-exempt band which could make the aggregation of channels in 5 GHz easier. This would make available the higher speeds that this enables and would assign another 75 MHz (from 5.85 to 5.925 GHz) that is currently assigned to the automobile industry where the likelihood of it being used is low[66].

Currently there is another on-going process in the United States that could expand the license-exempt band. In July 2017 the FCC issued an NOI entitled "Exploring Flexible Use in Mid-Band Spectrum Between 3.7 GHz and 24 GHz"[67]. On the particulars of the 5.925-6.425 GHz band the FCC sought comments on, among other things, the compatibility with adjacent band as "this would allow the devices to operate with wider channel bandwidths and higher data rates as well as increased flexibility for all types of unlicensed operations." Additionally, it made the question extensible to the 6.425-7.125 GHz band. Comments were received in October 2017, including a combined one from the major technology companies suggesting that the FCC amend "the existing Part 15 rules in the 6 GHz band to permit higher-power, more flexible unlicensed use, with robust protection for incumbents' current and future operations," as this "would advance these goals—driving rapid consumer adoption, maximizing economies of scale, and supporting forthcoming unlicensed wireless standards[68]".

It would be valuable to see other countries starting processes to evaluate the feasibility of expanding the spectrum that Wi-Fi currently uses.

5.1.3 License-exempt MMWave bands

In addition to the traditional Wi-Fi license-exempt bands, there are other bands that currently can be used without a spectrum license in many countries[69], provided that, as in the case of

Wi-Fi, devices receive type approval and do not transmit over certain maximum power output levels. Of particular interest are the 24 GHz and the 60 GHz bands, also known as mmWave as their wavelength in these higher frequencies is on the range of millimetres (mm). The table below describes how those bands have been regulated in the countries under study.

Table *4 - Regulated output power in bands used by mmWave technology in the countries under study*

	24.05 – 24.25 GHz		**57 -64 GHz**		**64 - 71 GHz**		**71 – 76 GHz**		**81-86 GHz**	
	EIRP	Tx Power	EIRP	Tx Power	EIRP	Tx Power	EIRP	Tx Power	EIRP	Tx Power
Mexico			82 dBm (if gain less than 51dBi, 2 dBm less TxPower per each dBi below)				85 dBm	35 dBm	85 dBm	35 dBm
South Africa			55 dBm (40dBm up to 66 GHz)	10 dBm						
Brazil										
Argentina			40 dBm							

United States	Gain must be at least 33 dBi	0 dBm	82 dBm (if gain less than 51dBi, 2 dBm less TxPower per each dBi below)		82 dBm (if gain less than 51dBi, 2 dBm less TxPower per each dBi below)					
India										
Canada	Gain must be at least 33 dBi	0 dBm								

With the most progressive of those regulations (Mexico and the United States), links of about 2 km are technically possible in 60 GHz[70], which could be used by some small operators to provide "fiber-like" experience to their customers. Still, similar to Wi-Fi, there is a wide range of values in the regulations. For instance, in Argentina this band can only be used indoors. Note that the situation in India may change in this band as the Department of Telecommunications (DOT) has expressed interest in following recommendations from Telecom Regulatory Authority of India (TRAI)[71] that propose license-exempt use of the 60 GHz band[72]. This band is particularly interesting as there is equipment becoming available that follows the 802.11ad standard[73], making Wi-Fi certification and interoperability possible.

In the 24 GHz band, the United States and Canada have harmonized their regulations and both countries allow license-exempt use of 200 MHz between 24.05 and 24.25 GHz for PtP links. This establishes another wireless alternative for fibre-like speeds for up to 5-6 km[74]. With the requirement of higher gain antennas in 60 GHz (51 vs 33 dBi), it is expected to see higher gain antennas appearing for 24 GHz equipment as well. These high gains result in extremely narrow beams that make interference with other devices extremely unlikely, making licensing unnecessary. In this regard, more regulators and policy makers should look at enabling the use of these bands on a license-exempt basis.

Similar to 60 GHz, low-cost hardware for 24 GHz is readily available in the market[75 76], although in this case there is currently no standard that will promote interoperability. In both cases, this hardware is at least an order of magnitude more expensive than devices operating in traditional Wi-Fi bands (2.4 and 5 GHz), but still considerably cheaper than traditional microwave equipment. It is expected that with more countries enabling the use of these bands in a license-exempt basis, expanding the target market for the manufacturers, their cost will go down.

5.2 Licensed Spectrum for backhaul links

The widespread adoption and low-cost of Wi-Fi devices make them the technology of choice for small wireless Internet service providers (WISPs) and community wireless networks. However, most of these operators serving areas outside urban centres still face the challenge of congestion (interference) in the Wi-Fi bands in the high sites that are used to relay the signal from the upstream points of presence in urban areas. The increase in availability of license-exempt spectrum in the mmWave bands brings some relief to this situation, but they do not provide the same distance of coverage that Wi-Fi does, which is critical for cost-savings by minimising the need for deploying additional intermediate infrastructure.

This congestion pushes small operators to obtain licensed spectrum for these PtP links. Licensed PtP links can be facilitated in many different bands depending on the country. Operators and regulators have tended to focus on the 7 GHz and 11 GHz bands. The latter, in particular, is attracting considerable interest, driven by a new generation of devices covering this band both from new microwave companies, such as Mimosa[77] and Cambium, as well as companies historically focused on license-exempt bands such as Ubiquiti[78] and Mikrotik. Similar to the equipment in the mmWave bands, it is still at least an order of magnitude more expensive than equipment in the traditional Wi-Fi bands, but still considerably cheaper than traditional microwave gear.

As licensed spectrum is protected from interference, the maximum radiated power allowed is usually higher in these bands[79], which helps to compensate for the greater free space loss that takes place at these higher frequencies.

As described in section 2, the orientation of the antenna is a factor that can be used to allow the reuse of spectrum bands. Countries like South Africa, the United States and Canada, are allowing the provision of fixed PtP backhaul links in a band traditionally used for fixed satellite services (10.7 - 11.7 GHz). The innovation in managing spectrum comes in ensuring coordination, not only among the different terrestrial licensees, but with satellite receiving Earth stations. This can become a lengthy process, because in many cases it is checked manually. To streamline this process, countries such as the United States have created a type of geo-location database - the Universal Licensing System database[80]. This database can be queried by operators in advance before submitting an application, to make sure they request a band that is empty in a given location.

Additionally, in some countries an automated process for applying for this spectrum is used, by which it is possible to have registered engineers certify coordination. In the countries under study, this is the case in the United States and Argentina[81], and it is very well established in New Zealand. This positive approach reduces the burden on regulators, who used to be the ones dealing with coordination. However, at the same time, the fees of those certified engineers may become an additional barrier for small operators and community networks to access these bands[82].

This type of automated approach also helps pave the way for the arrival of software-based national geo-location databases for frequency management, which is already occurring in TVWS frequencies (see below). Devices using this band are dynamically assigned spectrum by accessing a geo-location database. This approach may offer a means for regulators to reduce administrative and engineering overhead costs.

In Mexico, the case is different. Not only is operation in the 10.7 - 11.7 GHz frequency band not allowed, but the band allocated to microwave PtP links (10.15 - 10.3 / 10.5 - 10.65 GHz) was assigned regionally in 1998 via an auction. In Oaxaca, a region with a large rural population, 120 MHz of 10 GHz spectrum remains unassigned[83]. Sharing spectrum below the regional level in Mexico is not permitted in licensed bands[84].

It would be encouraging to see more countries explore co-existence with fixed satellite services to allow small operators and community networks to make use of state-of-the-art, low-cost equipment in this band, in the way South Africa, Canada and the United States are doing.

5.3 Dynamic Spectrum Management

Dynamic spectrum management refers to the opportunistic use of spectrum frequencies on a secondary basis where the frequency in question may be already be assigned on a primary basis to another organisation. Its roots lie in television broadcast frequencies. When radio spectrum was first allocated for television broadcast in the early part of the 20th century, broadcast and broadcast reception technology was crude by today's standards. In essence, broadband transmitters had to "shout" because the reception devices were a bit deaf. In order to cope with these loud services, regulators decided that gaps should be left in spectrum assignments as "guard" bands to prevent television signals from interfering with each other. These "guard" bands are also known as television white spaces because of the "white" noise signal that appears on a television in these unused bands. With the transition from analogue to digital broadcasting, the need for guard bands is disappearing and the DSO is also freeing up a lot of spectrum previously needed for broadcast. Thus the principle of opportunistic re-use of spectrum on a secondary basis is still very viable for television frequencies.

The nature of dynamic spectrum assignment is such that the users of that spectrum must always vacate any frequency the primary license holder chooses to use. Dynamic spectrum does not tolerate any form of interference to the activities of the primary license holder of the frequencies in question. As a strategy, it occupies a middle ground between traditional spectrum licensing and license-exempt spectrum. Dynamic spectrum management does not confer exclusivity in the way that licensed spectrum does, yet it offers the regulator some control over the use of the spectrum through a database approach to validating dynamic spectrum devices. Having a degree of control allows the regulator to move forward in making this spectrum available without the high risks entailed by completely re-allocating frequencies on a long-term basis to companies or technologies which may or may not prove a success.

Dynamic spectrum approaches such as Television White Space (TVWS) regulation and, more recently, Citizens Broadband Radio Service (CBRS) in the United States have emerged as an alternative approach to spectrum assignment.

5.3.1 TVWS

TVWS has particular attraction in regions like Sub-Saharan Africa because most countries in the region have few existing terrestrial broadcast channels. This means there are many channels in television broadcast frequencies currently lying fallow. In addition, (as indicated above) the lower frequencies allocated to TV broadcasting have much better propagation characteristics than the higher frequency license-exempt bands, and so are ideal for covering longer distances and non-line of site locations to reach dispersed rural populations. As a result Sub-Saharan Africa has more TVWS dynamic spectrum pilots underway than any other region in the world, with 12 pilots in 8[85] African countries. These pilots have provided convincing evidence that dynamic spectrum technologies can co-exist with broadcasters without interference, even in areas with relatively dense broadcast spectrum-use such as the city of Cape Town.

Around the world, with the notable exception of a few leading countries[86], adoption of TVWS regulation has been slow. A number of factors may have contributed to this. The lack of wide availability of low-cost mass-market TVWS/dynamic spectrum devices for purchase may be a factor and this may be a "Catch-22" as manufacturers may be waiting for formal dynamic spectrum regulation to be enacted to trigger larger scale manufacturing.

The middle ground between licensed and unlicensed spectrum that TVWS occupies highlights a growing tension between the economic success of license-exempt spectrum, for which no spectrum fees are incurred, and exclusive-use spectrum for mobile services which is often auctioned for millions of dollars. Traditional network operators have baulked at the notion that a significant amount of spectrum very close to emerging mobile bands in 700 MHz should be made available for free. Regulators are often caught between their desire to make more spectrum available and pressure from government to generate revenue from the sale of exclusive-use spectrum licenses. The case for the significant positive social and economic externalities generated through license-exempt spectrum has been well made by Richard Thanki (see table above) and others but this pushback from traditional operators also contributes to the slow progress of TVWS regulation.

United States

TVWS technology and regulation has its roots in the United States in the early 2000's where there was an emerging sense of the growing impact of wireless technologies designed for license-exempt bands use as well as a recognition that manufacturing costs were coming down substantially. Unoccupied guard bands in the VHF and UHF television frequencies showed great potential for the expansion of license-exempt approaches, with regulation encoded in the device itself rather than in legal license documents.

The original conception of TVWS was that it would operate on a spectrum-sensing basis, immediately vacating any band where television broadcasts were detected. However, that idea received a fair amount of pushback from incumbent broadcasters who were concerned about potential interference with television broadcasts. Even more strident in their objection to TVWS were the wireless microphone manufacturers and their consumer base. Wireless microphone manufacturers and popular religious ministries that used wireless microphones weighed in on the issue with the FCC.

Lobbying from anti-TVWS groups pushed the tolerances for spectrum-sensing to a point where it was going to be difficult to manufacture compliant TVWS equipment affordably. This led to a compromise scenario in which a database solution was proposed. A geo-location authentication database would map the existing use of spectrum by television broadcasters and each TVWS device would check in with the database before turning on its radio to ensure that it would not interfere with existing broadcasters. This was not the preferred outcome for TVWS advocates who wanted to enable the same kind of innovation in TVWS that the world has seen with Wi-Fi and Bluetooth. However it was a compromise that worked and the FCC enabled regulations in 2010 for TVWS devices based on their authentication against a geo-location database managed by regulator-sanctioned database service provider. Geo-location has now emerged as a global norm for TVWS regulations.

Canada

Canada has largely followed the blueprint for TVWS regulation set out by the United States. Canada launched consultations on television band frequencies in 2011[87]. In late 2012, it published a framework for TVWS regulation[88]. In 2015, access was "officially" enabled to this spectrum but commercial use was limited by the lack of a geo-location database service provider. In October 2017, the ministry for Innovation, Science and Economic Development (ISED) appointed Key Bridge Wireless as a designated white space database service administrator for Canada[89].

However, white space technology is *still* not yet commercially available as there is no equipment available that is fully approved and compatible with the database. Equipment manufacturers are in discussions with Key Bridge to enable their equipment to communicate with the database, at which point it will be become possible for the equipment to be certified by ISED for use in Canada.

South Africa

Advocacy for TVWS regulation in South Africa began in 2009[90] but it was not until October 2011 that the Association for Progressive Communications (APC) and the Wireless Access Providers Association (WAPA) organised a workshop to bring together international experts, regulators from the region, and South African government, industry and regulatory representatives to consider TVWS and its potential, that the discussion moved forward.

Following the workshop, a technology trial was organised to provide an evidence base for the regulator to confirm the technology would not cause harmful interference. A partnership emerged including Google as a sponsor, the Tertiary Education and Research Network of South Africa (TENET) as project manager, the Council for Scientific and Industrial Research (CSIR) as research partner, as well as WAPA, the eSchools Network as beneficiary partner and ISP Comsol as trial implementer[91]. The trial began in September 2012 with ICASA, the South African communications regulator, granting permission to CSIR and partners to establish a TVWS network in the Cape Town. The initial pilot ran for just over a year and was a resounding success. Evidence gathered in the trial has even been used to inform changes to the United States TVWS regulation[92]. Based on this positive outcome, ICASA has extended the experimental license so that the project might continue to provide access.

In March 2018, ICASA formally gazetted Regulations on the Use of TVWS spectrum[93]. This means that, subject to type approval and to authorisation through a geo-location database, TVWS wireless communication equipment can legally be used in South Africa. While this is a big leap forward from a regulatory perspective, it does not yet enable licensed operators to deploy TVWS technology as the regulator must also sanction a geo-location database service provider. The latter is expected sometime in 2018.

South Africa's TVWS regulation differs slightly from regulations elsewhere in that it requires all TVWS equipment to include a built-in GPS and it also requires installations to be carried out by an IEEE qualified engineer.

India

Gram Marg's rural broadband project[94] at the Department of Electrical Engineering, IIT Bombay, aimed to demonstrate the use of TVWS and other innovative wireless technologies to connect the unconnected in rural India. The trial initiative supports the provision of Wi-Fi access for villagers in a group of about 10 rural communities in the district of Palghar (Maharashtra state). Initially the backhaul links were implemented using TVWS equipment built by IIT, however, IIT was unable to obtain a renewal of the trial spectrum license. This has led to higher project costs as IIT was obliged to replicate backhaul links with 5 GHz Wi-Fi equipment which required much higher masts in order to gain line of site access to the communities. It was also observed that the TVWS deployment was faster and simpler because the antennae did not require accurate pointing, in contrast to the 5.8 GHz equipment which required accurate alignment.

IIT continue to lobby the regulator, TRAI, for access to the spectrum but the government's current position is that television frequencies may not be used for commercial TVWS services[95]. It is still possible to gain access to an experimental license for research purposes and the International Institute of Information Technology IIITB) in Bangalore has also experimented with TVWS[96].

Argentina, Brazil, Mexico

While there were announcements of TVWS trials in Brazil from Microsoft in 2014[97] and from the White Space Alliance in 2015[98], it does not appear that any trials have taken place to date in Brazil. Similarly in Argentina, Microsoft signed an MoU[99] with the regulator to conduct TVWS trials but nothing has taken place as of Q3 2018. Although the Mexican government has taken dynamic spectrum under consideration, it has not made any moves toward the introduction of TVWS regulations[100] .

5.3.2 Community Broadband Radio Service (CBRS)

Dynamic spectrum as an approach to spectrum regulation is in no way tied to the television broadcast frequencies. In the United States, another band to be considered for dynamic spectrum management is the 3.5 GHz band (150 MHz of spectrum between 3550 MHz and 3700 MHz). In 2015, the United States' FCC made this spectrum available for flexible use on a shared basis through a geo-location database system. Known as Citizen Broadband Radio Service (CBRS), it is three-tiered framework to coordinate shared use of the band. Within this framework, existing primary spectrum holders including United States' radar systems and fixed-satellite service Earth stations, make up the first tier and are protected from interference in the same way that a traditional spectrum license holder would be. This is followed by a second tier known as Priority Access Licences (PAL), which operators are entitled to bid for on a bi-annual basis. Finally there is General Authorized Access (GAA), the third tier, which operates more like conventional license-exempt equipment. Second-tier PALs will receive protection from third-tier GAA operations whereas GAA users must accept interference from all other users. CBRS is designed for LTE service delivery. The recent proliferation of low-cost LTE base stations may make this an attractive option for wireless ISPs seeking to branch out into mobile services.

To date the United States is unique in pursuing dynamic spectrum in this band. The same frequencies are also in demand for 5G services and, in the United Kingdom, were recently auctioned as part of the country's first 5G auction[101]. The Canadian spectrum regulator, ISED, has launched a consultation on the future of this band and is looking at both the U.K. and the United States approaches[102]. In Brazil, there are plans to auction this frequency in 2019[103]. India also seems to have earmarked this spectrum for 5G auctions[104]. For the time being, CBRS seems to be an approach that the United States will go it alone with. This may of course change as other countries observe how popular this novel spectrum management approach proves.

5.4 Mobile Network Services

Mobile telephony has transformed access to communication in developing countries. In 1994, there were more telephone lines in New York City than in the whole of Africa[105]. These days, about four fifths of the population in sub-Saharan Africa is covered by a mobile phone signal[106]. That's a remarkable and profound change yet, there are still millions of people who do not have access to mobile networks. Why is that? Typically, the reason boils down to the fact that a business case does not exist for mobile network operators to extend coverage to that area. That might be because it is sparsely populated, or in a hilly region that is expensive to cover, or because ability to pay is very low or some combination of the above.

Low-cost alternative GSM technologies have existed for some time and there are a variety of startups in this space including NuRAN[107], Fairwaves[108], Facebook's Open Cellular and others. Manufacturers like NuRan Wireless are producing low-cost radio systems that can serve as robust platforms for initiatives, such as Osmocom[109] which provide an Open Source alternative to the proprietary software for the management and operation of GSM networks. The result is that it is possible to put up a GSM base station for a few thousand dollars. Now, we are seeing this innovations coming to LTE (Parallel Wireless, Baicells) and as the user devices permeate in rural areas, this technology presents a great opportunity for small scale operators and community networks. What constrains small operators and community networks from taking advantage of these innovations is the fact that the popular GSM spectrum bands have largely been assigned to existing Mobile Network Operators (MNOs). However, regulatory innovations in some countries are beginning to change that reality.

5.4.1 Spectrum Allocations for Rural Mobile Operators

Mexico is the only country in the world where a fraction of the spectrum dedicated to mobile network services has been set aside specifically for the use of small operators and community networks in underserved regions. After a successful pilot by Rhizomatica in Oaxaca[110], the Mexican communication regulator (IFETEL) analysed the assignments in the 850 MHz band and concluded that there was a small amount of spectrum that remained unassigned. The modest amount of spectrum available meant that it was of little value to commercial operators. As a result, in IFETEL's Annual Program for the Use and Exploitation of Frequency Bands 2015[111], it assigned for "social use"[112] different slots per region[113]. In particular, 2x5 MHz of 850 MHz spectrum in 7 regions (excluding the urban areas occupied by Guadalajara and Monterrey) and 2 x 2.54 MHz of spectrum in another region, provided they meet the following criteria:

- It must be used in rural settlements with a population smaller than 2,500 people
- The regulator has the right to assign the spectrum for commercial use in the future.
-

Tecnologías Indígenas Comunitarias (TIC), a non-profit organisation based in Oaxaca, Mexico, holds a concession as a social telecommunications operator, and currently serves 3,350 active daily users spread across 63 villages and communities in the state of Oaxaca with 2G voice and data services. These users are served by 14 community-owned and operated cellular sites.
In Sub-Saharan Africa, small network operators focused on rural, low-cost, low population deployments have begun to emerge. In Rwanda, United States' telecoms start-up Vanu[114] has negotiated with the Rwandan regulator for access to GSM spectrum in order to roll out a wholesale, rural 2G network. Vanu does not offer any retail services, but generates revenue through existing operators paying fees for their customers to roam on Vanu's network.

5.4.2 Spectrum Sharing for Rural Mobile Operators

In Canada, communities are also providing mobile network services, but in this case it is through an agreement with one of the incumbent telecommunications operators holding a long-term, nation-wide, exclusive-use spectrum license. The Indigenous-people owned and controlled KMobile service began in 2008 in the Sioux Lookout region of north-western Ontario, in partnership with Keewaytinook Okimakanak, an organization that supports infrastructure development in its member communities. KMobile successfully obtained the right to use 2x5 MHz in the 850 MHz band from the national provider who had no plans to use it in this region because the Indigenous communities did not meet their population requirements[115]. Legally, KMobile is registered as a non-dominant carrier operating on a Subordinate Licensed (800 to 900 MHz) assigned to that operator. Currently 26 communities have 3G services, covering an estimated population of 22,000 across the indigenous region.

Another small-scale operator, Africa Mobile Networks, has partnered with multinational operators for access to their GSM spectrum to roll out low-cost GSM infrastructure in Benin, Cote d'Ivoire, Cameroun, DRC and Nigeria[116].

In South Africa, despite the debates around spectrum scarcity in the country, large amounts of spectrum bands dedicated for mobile communications are unoccupied in rural areas[117]. The figure below shows measurements of spectrum occupancy in the 1800 MHz band carried out in a rural part of the Eastern Cape of South Africa. At present, to use this unoccupied spectrum, a prior agreement needs to be reached with one of the license-holders of the spectrum. Additionally, an application to ICASA is required for approval of a spectrum sharing agreement in terms of the 2015 Radio Frequency Spectrum Regulations.

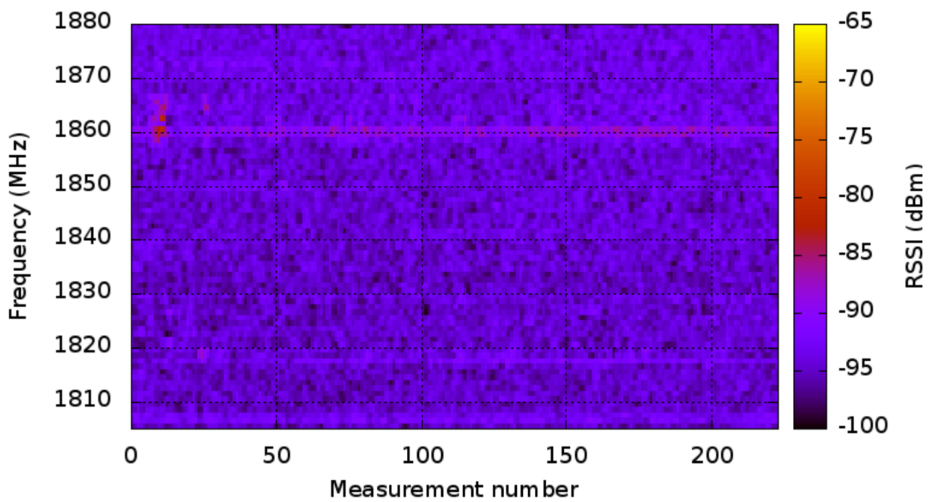


Figure 3 - Measurements of spectrum occupancy in the 1800 MHz band in a rural part of the Eastern Cape of South Africa

In Argentina, in the light of the recent policy development in the country, access to spectrum for underserved regions might become a possibility as the parliament is in the advanced stages of approving a law that will allow local operators to access spectrum for mobile telephony[118].

5.4.3 Experimental Licenses

In many countries, using experimental licenses can be a powerful way of demonstrating the potential of new technologies. For example, in Brazil and Argentina, where there are unassigned GSM frequencies in different states/provinces[119], experimental licenses can be awarded directly by the regulator. This is the process that CELCOM, a pilot project of the Federal University of Pará (UFPA)[120], followed in Brazil, in order to provide GSM services in rural areas.

That this process is possible does not mean it is easy. CELCOM started operations in 2016 in the state of Pará with an experimental license for 2x200 KHz with the aim of proving the viability of low-cost, Open Source-based, GSM services in the Amazon region. Currently, they are in the process of extending their operations into the states of Rio de Janeiro and Goiás, but this is process stalled, as in each state the range of available GSM frequencies are different. Follow-up on the matter has been conducted by multiple different Anatel staff, which does not facilitate the process.

As mentioned, in the case of Mexico, GSM trials were first run under an experimental license to prove that a social concession was not only feasible, but had large benefits for the otherwise unconnected population.

The extension and renewal of experimental licenses is also important. In India for instance, the length of an experimental license is 3 months, and can only be extended for another 3 months. In the first 3 months, the licensee is exempted of spectrum fees, but in the second, they are required[121]. In the case of Brazil, these licenses have a length of 2 years and are renewable[122], although spectrum fees must be paid for the duration of the experiment. In the case of South Africa, there is no fixed limit on the term of an experimental license. As a result, the Cape Town TVWS trial, mentioned in Section 5.3.1, which began in 2013, continues to provide valuable connectivity services to secondary schools in 2018.

In India, to the best of our knowledge, no pilot project involving the provision of mobile services by small operators and community networks has taken place to date. In Argentina, the Internet Society has discussed an experimental project for a LTE community-run initiative in Patagonia with Enacom, the Argentinian regulator.

5.4.4 Wholesale Wireless Networks

The challenge with spectrum auctions mentioned in Section 4.2 above has led some regulators to consider alternatives. A relatively new alternative is to define an entire spectrum band as a wholesale network, commission its construction, and make it available to all licensed operators to offer services on. In fibre optic networks, wholesale-only open access networks are fairly common, however, it is a relatively new concept for wireless spectrum and has not been implemented widely.

Rwanda was the first country to successfully implement a wholesale wireless network in the relatively new 800 MHz LTE band. It was commissioned as a partnership between the Rwandan government and Korea Telecom under the brand Olleh Networks (now KT Rwanda Networks). It was launched in 2014. As of Dec 2017, the Rwandan regulator has reported that the network has 84.7% geographical coverage in the country and 89% population coverage[123]. No other statistics appear to be published on its usage so it is hard to judge its success. In May 2018, Korea Telecom announced their plans to export the model to other countries[124].

Mexico has also launched a WOAN known as the Red Compartida with 90 MHz of spectrum in the 700 MHz band. Announced in 2014, it has taken some time to come to fruition but it finally went live in March 2018 offering coverage of 32% of the country[125]. In June 2018, it announced its first operator client[126]. It is too early to tell how well the network will fair.

In South Africa, the government announced the plan to create a WOAN using the 700 MHz, 800 Mhz and 2.6 GHz bands, plus potentially others that the operators had allocated but were not using[127]. This was as a result of a perceived failure of the current model to provide affordable universal access. Among strong African markets, South Africa remains one of the most expensive countries for mobile broadband[128]. Its implementation requires significant policy amendments, and the proposed bill[129], which created a heated debate in the country about the adequacy of this approach[130], is currently under review.

The industry association for mobile network operators, the GSMA, have produced a study that is critical of WOANs[131] arguing a lack of successful implementations of wholesale networks to justify it as a strategy. The counter argument is that it is early days and that, given some of the negative outcomes seen with spectrum auctions, alternatives need to be explored.

5.4.5. Fifth Generation Mobile (5G)

Mobile technologies have evolved generationally with new capacities and features being introduced with each generation. What we know now as the mobile network began in the 1990s with second generation (2G) technology; which was capable of voice and very limited data services. Third generation (3G) networks, introduced in 2001, offered the first mobile broadband services with speeds of a few megabits per second. 3G networks operate on a separate frequency from 2G networks and required both new network technology and new handsets to take advantage of the faster speeds. Mobile network operators needed to maintain both 2G and 3G services in order to offer both voice and broadband services to their customers. The arrival of fourth generation (4G), also known as Long Term Evolution (LTE), networks introduced efficiencies that optimised the use of available spectrum and increased upload and download speeds up to an order of magnitude faster than 3G. 4G represented a move to an all Internet protocol-based platform which offered the opportunity to delivery both voice (VoLTE) and data services on the same platform. The reality has been that most operators have preferred to continue to offer voice over 2G networks in order to guarantee quality of service. An additional complexity that 4G introduced was the ability to operate in a variety of different frequencies. There are over 40 4G spectrum bands available to manufacturers and operators[132]. Modern smartphones can support multiple spectrum bands but they are typically limited to a few 4G frequencies.

The innovations that each generation of mobile technology has brought to date are relatively easy to describe. However, Fifth Generation (5G) technology is not so easy to explain. 4G technology approaches what is achievable with radio spectral efficiency, coming close to the Shannon Bound. In order to improve on 4G, 5G must look elsewhere for its gains. What makes 5G different from its previous generations is that it relies on a wide variety of changes to achieve improvements in network performance133. These technological changes include the use of:

- mmWave radios which can transmit vast amounts of data but over much shorter distances than previous mobile network generations;
- small cells which increase spectral efficiency through frequency re-use;
- massive MIMO which groups large numbers of antennas at the transmitter and receiver to provide better throughput and better spectrum efficiency
- beamforming which leverages constructive interference to deliver more focused communication; and,
- full duplex technology which allows radios to receive and transmit information simultaneously.
-

Like 4G, 5G can operate in multiple spectrum bands but rather than a single frequency, 5G seeks to combine a range of frequencies to deliver ultra-fast, ultra-low-latency broadband. The fact that 5G will take advantage of a range of technological innovations and frequencies has an upside and a downside. The upside is that the combination will be able to deliver a range of services from ultra-low-latency narrowband network services to fibre-like speeds for high-capacity users. The ability to deliver network services with specific characteristics, latency, speed, capacity, etc is referred to as network slicing[134]. Network slicing creates a virtual network service with characteristics tailored to the needs of a specific industry. It is possible that this capacity may conflict with network neutrality principles but it is hard to say definitively as there are no commercial instances of this kind of network virtualisation in existence yet.

A potential downside of the 5G approach which embraces so many frequencies and technologies is that it may end up concentrating power and influence with existing operators. Also, the fact that most 5G frequencies are aimed at urban areas and increasing performance and capacity there may exacerbate the growing urban / rural digital divide. For developing countries, 5G may be some years away from being a practical technology choice for affordable access.

For community network operators, 5G is relevant in the implementation of license-exempt PtP technologies in the 60 GHz band which may offer high-capacity, short distance solution. It is also a technology that is important to pay attention to in terms of its potential encroachment into existing license-exempt frequencies. 4G has already seen the arrival of unlicensed LTE (LTE-U) in the 5 GHz band. It will be important to ensure that the benefits of license exempt spectrum are not eroded.

5.5 Spectrum Fees

Innovation in spectrum regulation has taken place through changes in the approach to calculating the fees or royalties operators need to pay for the right to use that portion of the spectrum.

5.5.1 ITU work on spectrum fees

Guidelines from the ITU make the difference between spectrum management fees, and spectrum usage fees[135]. The former are expected to be used to recover the cost of spectrum management, whereas the latter "to recover a spectrum resource rent for the government and to ensure that users of spectrum utilize the resource on an efficient basis". In addition, it is expected that spectrum usage fees, also contribute to achieve "the budgetary objective set by the authorities"[136]. In this section we will mainly focus on the innovations around the the spectrum usage fee. More on management fees can be found in section 5.7.

The ITU has developed guidelines to determine the spectrum usage fees resulting from the work of one of the Study Groups set up to operationalize Resolution 9 from WTDC 2006[137]. Although advocating for simplicity, the guidelines provide different formulas for each type of service. For the case of fixed point-to-point (PtP) assignments, the formula includes a bandwidth factor as well as factor that considers the location of the assignment in the frequency spectrum. As explained earlier, due to their varying performance characteristics, different parts of the spectrum are more useful / valuable than others. In a more recent guideline document the ITU introduced a "universal system performance pricing model" consisting of a formula that integrated a variety of factors.

Additionally, the study group created a database on how countries are applying pricing formulas[138]. From the countries under study, only information about Mexico was available, and only indicating the factors from the formulas that it considers, not how the fees are actually calculated, making very difficult the comparison among countries. Research on the mechanisms used in those countries has been carried out, and the results are presented in Section 5.5.2 below.

5.5.2 Spectrum usage fees for licensed backhaul links

In most cases under study, there is a formula that determines the amount to be paid by the operator. However, the parameters for the formula can vary greatly, which can have a significant impact on the fees requested from operators:

- Canada charges an annual fee plus an additional amount depending on the capacity of the link[139];
- In India the government considers only the bandwidth assigned as a percentage of the revenue the operator generates in the area[140];
- In South Africa[141], Argentina[142] and Brazil[143] a more complex formula, along the lines of "universal system performance pricing model" from ITU[144], introduces more granularity: the centre frequency, value of that band, a geographic factor[145], type of use (shared or exclusive), and population covered[146], among others.
- In the United States, FCC license fees include an Application Fee plus a Regulatory Fee. The latter is only paid once per location, whereas the former is paid every time an antenna is added[147]. The fee is independent of channel quantity, size or frequency.
- In Mexico, the 7 GHz and 11 GHz bands were auctioned, so they are not considered further in this section

As a result, the resulting fee structure in each country is fundamentally different for similar services. The chart below shows a comparison of the spectrum fees in the different countries under study of a 10 km link using 20 MHz at 10.65 GHz in a rural area[148]. Although Argentina shows the lowest fee[149], both there and in Brazil it is not permitted to use the 10.7 - 11.7 GHz frequencies, so operators cannot use the lower-cost equipment that is now available for those bands. As a result, South Africa has the cheapest viable framework for using this band.

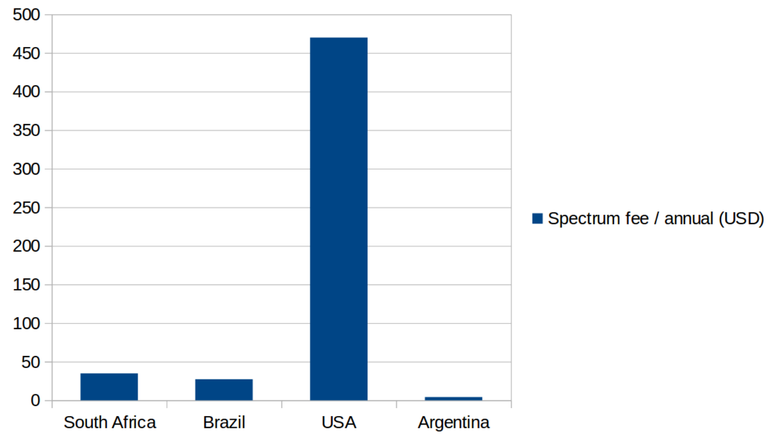


Figure 4- Comparison of the spectrum fees for licensed backhaul links

South Africa's current spectrum fee regulation came into force in 2012 and has "succeeded to an extent in placing a more accurate valuation on spectrum holdings and introduced greater efficiencies, particularly where spectrum allocated for access networks was being used for point-to-point links."[150]

In South Africa, Telkom, the historical incumbent, experienced significant fee increases. This was largely due to the fact that it was using PtMP spectrum for PtP links and would have to pay the PtMP fees under the new rules. This change led Telkom to begin relinquishing some of their licenses in these frequencies. Sentech, the public broadcaster, also returned spectrum for the same reason. The new arrangement imposed a use-it-or-lose-it requirement on operators that were not using spectrum efficiently. Although it is recognized as a success for the application of penalties for inefficient use, it has also been criticized for the current fees not giving "sufficient incentives to encourage efficient use of spectrum"[151].

Canada[152] and India[153] are not included as prices are respectively about 1,000 times, and 67,000 times higher than those in Argentina. In Canada a parliamentary process is required in order to change the structure of the spectrum fees, which is preventing changes in this regard. India's calculations are based on the formula proposed by TRAI[154]: fees are calculated on the basis of a percentage of the operator's revenue.

Spectrum fee strategies like the one used by South Africa that incentivize effective use of spectrum, can create opportunities for community networks and small operators to provide sustainable access in remote and rural areas. This could simultaneously meet the budgetary objectives required the government, while being "managed in the interests of the national community as a whole.", i.e. including the unconnected and those who cannot afford communications costs[155].

5.5.3 Spectrum usage fees for mobile telephony spectrum

Frequency bands for mobile telephony are licensed. For small operators and community networks wishing to provide mobile services, this means they must pay the corresponding spectrum usage fees. In most countries, these fees must be paid prior to gaining access to the spectrum. As in the case of licensed backhaul links above, a variety of approaches are used to calculate these spectrum usage fees.

In Brazil and South Africa the same formulas apply, with slight modifications. In Brazil a factor of the population covered is added, and in South Africa, the area covered instead of the distance of the hop is considered. This formula applies to all licensed spectrum regardless of the area. Hence, a national and a local operator in the case of South Africa, a regional operator in the case of Brazil, are subject to the same regime.

India also uses the same formula as in PtP, which is a factor of the revenue of the operator in a given service area. However, the Access Service (or the Unified License) are the only types of license that currently would apply to a mobile voice service provider, and they are intended for large scale operators only – e.g the minimum capital investment requirement is over USD2.2M 156. As a result of the requirements for this license category and the even more expensive Unified License, small-scale mobile networks are not a practical option for most community networks in India, and not considered further in this section.

Argentina uses a similar revenue-based formula for mobile services too. In Mexico, there is a formula that includes a regional factor depending on the band used, and the size of the assignment. In Canada there is a factor per frequency used for mobile communication that is corrected by the type of population (metro or not), and a fee is considered per each mobile station.

In order to compare the effect of these approaches in the case of small operators and community networks, consider the following example: a slot of 1.4 MHz[157] in 900 MHz to cover a rural community with 2000 potential users occupying an area of 20 square km[158].

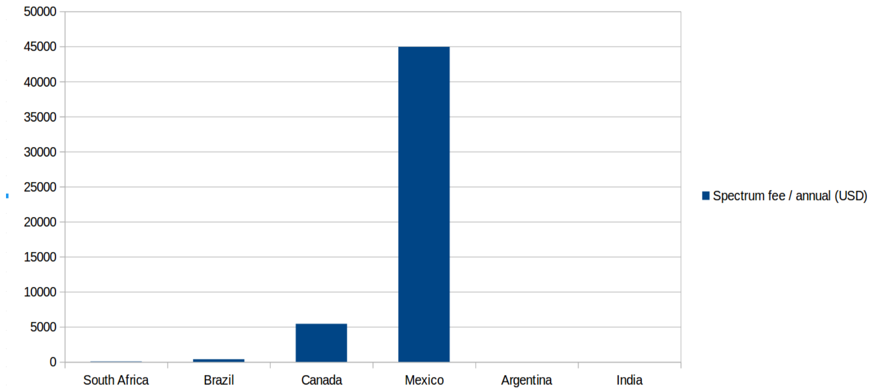


Figure 5 - Comparison of the spectrum fees for mobile networks

As the numbers for South Africa show (almost 7 times cheaper than Brazil, almost 100 times cheaper than Canada, and more than 800 times cheaper than Mexico), the more granular these factors are, the lower the cost per user. Note that this very same formula is the one to calculate the spectrum usage fees paid by large mobile network operators.

Calculations based on data from recent research[159], combined with pricing offered by existing voice-over-IP (VoIP) upstream providers, show that with this approach a community could reduce their cost of communications by more than half. In addition, this granular approach also allows the reuse of similar frequencies in communities in the same region, maximizing the social value of an assigned but unoccupied resource. Still, as critiqued in the ITU report, this fee is not enough of an incentive to promote efficient use of the spectrum as proven by the lack of usage of 1800 MHz in rural areas, as shown in Section 5.4.2.

In Mexico, there are some cases where some fees can be exempted. In particular, institutions that provide medical assistance, charity, or prevent accidents and disasters, are tax exempted[160]. TIC was recently requested to pay these fees[161], and it applied to IFT to be exempted from these payments based on the fact that they are exempted tax payers and their service contributes to accident prevention and disaster. This request was initially denied, but TIC won a case where the court ordered the IFT to re-examine their situation. The result was that TIC won an exemption based on their authorization to receive tax-deductible donations[162].

5.6 Innovations in spectrum management outside the regulatory framework

Not all the innovations about spectrum management come from national regulatory authorities and policy makers. As the two examples below demonstrate, spectrum users can create their own self-regulation mechanisms to maximize the use and socio-economic benefit of the radio spectrum.

5.6.1 Industry body Associations

In the United States, wireless ISPs are represented by WISPA, a registered advocacy organization, which serves its 800+ member organisations, consisting of wireless Internet service providers, municipal wireless internet providers, cooperative wireless Internet providers, and others. Cumulatively, they connect over 3 million users in the United States, often as a sole provider in rural areas. WISPA represents its member organisations in advocacy with the national regulator on access to spectrum for small operators.

In South Africa in 2006 most of the wireless ISPs established the Wireless Access service Providers Association (WAPA)[163], an industry body that has more than 200 members today, serving more than 164,000 users according to the last survey. This platform allows them to exchange information, coordinate deployments to avoid interference and share infrastructure. They use a large proportion of their fees for regulatory legal advice, which enables them not only to keep the pace of regulatory change in the country, but to contribute consistently to the public consultations from the South African government and the regulator. This collective advocacy in turn has led to the inclusion in the policy and regulatory frameworks of provisions enabling their work, such as the higher allowance of EIRP in PtP links in 5.8 GHz and the TVWS regulations. Additionally, their regulatory advisor maintains a clearly structured and up to date platform with the regulations that apply to the different activities of the wireless ISP[164], platform that is said to be used by the regulator itself.

Among the countries under study, such a platform would have been extremely helpful given the wide number of interconnected regulations that apply to wireless service provision, the inter-relationship of which is not obvious. There is much room for improvement in regulator websites, especially in the communication of wireless policy and regulation for small-scale operators.

5.6.2 Telecommunications infrastructure in "commons"

Another bottom-up spectrum management innovation comes from managing telecommunications infrastructure as a common-pool resource (CPR), adapting the works of Nobel Prize winner Elinor Ostrom on the collective management of natural resources introduced in section 2.3. This model considers the backhaul infrastructure contributed by the different participants as a stock resource (like a forest) that, if nurtured properly, can sustainably provide the connectivity required by all participants. For this to work, clear mechanisms to recognize and compensate investments made by participants, as well as clear guidelines for conflict resolution are required. Not only does this allow a more efficient way of managing the spectrum available for small operators and community networks, but brings economies of scale that enable the reduction of costs to the final user. In many ways, this model provides a good framework for managing the Wireless Open Access Networks described above.

Although many community networks use this model, the most notable example of its implementation is guifi.net, where more than 20 small operators have contributed over 8.5 million Euros to a CPR that is serving more than 100,000 users in Catalonia, Spain.
Given the benefits of this model, governments awarding resources through universal access funds to provide affordable connectivity in areas not profitable to traditional commercial operators might consider an economic model in which all infrastructure deployed with public funds is managed as a common pool resource, making it easy for others to contribute to and extend the resource.

5.7 Licensing

In most countries an operator license is a prerequisite to operating radio spectrum equipment, whether licensed or license-exempt. What this means varies from country to country and also depends on the service to be provided as well as the area to be covered. For instance, in India in order to provide VoIP services that interconnect with the Public Switched Telephone Network (PSTN), either an Access Service License or a Unified License is required. The table below outlines the license costs for operators in the smallest area permitted in the regulations.

Table 5 - License cost in countries under study to operate in the smallest area permitted by the regulations

	Mexico[165]	**South Africa[166]**	**Brazil[167]**	**Argentina[168]**	**United States**	**India[169]**	**Canada**
Fee[170] (USD/year)	1,482	1,848	108	764	N/A	1,350	N/A

Additionally, other annual fees, including contributions to the Universal Service Access Fund, or to the fund to support public broadcasting in the case of Brazil[171], may be required.
There are other fees depending on the country. In India, an operator needs to pay a fee for each high site on which it builds a tower. In Brazil, all equipment used in the network, including handsets incur fees[172]. These can be quite onerous. For instance, in Brazil the fees

levied of 3 Base Stations (BTSes) and 60 handsets is higher than the annual spectrum fees to operate in that band[173].

These fees can play the role of the administrative spectrum fees, recommended by the ITU. ITU guidelines recommend that these fees be established in a transparent manner and on a cost-recovery basis. Despite those guidelines, very few countries publish these fees. In the EU there is a directive enforcing this[174], which provides an indication of the cost of managing different services, as the table below from OFCOM shows.

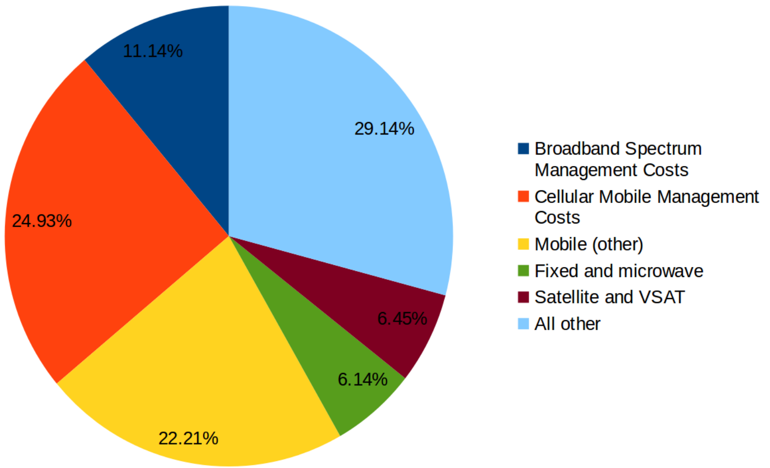


Figure 6 - Cost of managing different wireless services by OFCOM

In the countries under study, it is difficult to question the appropriation of the administrative fees, as there is no reference to those costs. It is noteworthy that in countries such as South Africa and Mexico there are exemptions for non-for-profit operators and in Brazil there are exemptions if operators have less than 5,000 subscribers and any of the frequencies mentioned in the regulations of equipment using restricted radiation[175].

On top of the licensing costs, the license application (and maintenance) requirements can be quite onerous as well. For instance, in Brazil and Argentina, a business plan and a technical plan signed by an engineer registered by a professional association is required. This is based on the entrenched idea among policy makers and regulators that only highly qualified professionals are capable of providing services of sufficient quality and at an affordable price. This view may have developed partly because of a lack of knowledge of existing alternatives but also because people living in rural areas lack the ability to voice their concerns over the poor quality of service provided by national operators where they live. In addition there may be data retention and regular reporting requirements that would be too onerous for many small operators.

Exploring the impact of licensing is outside the scope of this paper but these fees and administrative overhead factor into the overall costs for any entity, particularly community networks. The Internet Society recently published a paper on this topic[176], and a more in-depth follow-up would help identify the implications of these factors and shed more light on their impact on the economic feasibility of these models.

6 Transparency, Open Data and Spectrum

As the value of being connected to communication infrastructure grows, those without access are increasingly being left behind. In order to ensure everyone has affordable access to communication, more transparency in the telecommunications sector is required to better understand who is unconnected and what opportunities exist to solve connectivity challenges. Adopting Open Data policies and approaches in telecommunications ensures that a more constructive debate on access among civil society organisations, the broader Internet technical community, government, and industry takes place.

A simple first step would be to normalise transparency regarding the assignment of spectrum frequencies. It is impossible to have a public debate on innovations in spectrum management without a clear understanding of current spectrum assignments and their terms and conditions. The UK regulator, OFCOM, is a model of good practice[177] in this regard, as is the Mexican regulator, IFETEL[178].

Another important step in transparency is public information regarding network towers and their occupancy. As ensuring affordable access to all of the population becomes an increasingly important strategic priority, having a rigorous understanding of the limits of existing coverage becomes essential. Network operator coverage maps are useful tools, but require a mechanism for independent corroboration. Public access to information on tower location and occupancy is the simplest route to achieving that. As with spectrum assignments, good practice already exists. The Canadian regulator, ISED, publishes a downloadable database[179] of all towers and associated radios. In a great example of how useful Open Data practices can be, the data has been converted into a compelling and easy-to-use visual map by Steven Nikkel[180]. In India, commercial operator Airtel has published a map[181] of all of their tower infrastructure under the slogan "Because you have a lot to say. And we have nothing to hide."

Transparency in the deployment of terrestrial fibre-optic infrastructure is important too. Fibre-optic points of presence are the "deep water ports" of the Internet, meaning they can be very high capacity and very low-latency connections to the global Internet. Access to fibre for backhaul is often essential to fully take advantage of the innovations in spectrum management mentioned in this paper. Yet it is rare for operators to publish detailed fibre maps. With few exceptions, governments and regulators have been slow to push for transparency in this area. Good practice in this area can be seen in operators like Dark Fibre Africa in South Africa who have published a detailed fibre map[182] of their network since their formation over 10 years ago.

7 Conclusion and Recommendations

In the last 25 years, telecommunications has changed from monolithic, state-owned operators to a complex ecosystem of operators, technologies, manufacturers, and service providers. This new environment has opened the door to community network and small operators to fill access gaps that large operators are unlikely to address. Regulation which served well in predictable, slow-moving markets is no longer able to keep pace with the pace of technological change and is often failing to enable smaller, nimbler organisations that can address access challenges with new technologies and business models. Evidence is growing that existing access business models will not achieve affordable access for all. In order to meet this goal, innovation is required.

We recommend regulators to think more like forest stewards or gardeners who seek to deter negative behaviour while encouraging positive behaviour to flourish. Wi-Fi is a great example of a serendipitous success that could be reinforced and amplified with good regulation whereas the impact of excessive fees through spectrum auctions might be seen as a negative outcome to be mitigated. Recommendations concerning these and other strategies that are likely to yield positive outcomes are described below:

License-exempt Spectrum

The rapid spread of license-exempt spectrum use in the form of Wi-Fi is an important lesson about the power of frictionless innovation and about the pent-up demand for affordable Internet access. It makes sense for regulators to leverage this success by expanding access to license-exempt spectrum and further reducing costs associated with its use. Regulators should:

- ✓ Formally recognise that Wi-Fi has two important but separate purposes. Most people experience Wi-Fi as an access point to which they can connect to with their device of choice, but Wi-Fi has also grown dramatically as a technology that can create long-distance broadband PtP or PtMP links. These separate use cases can benefit from a more granular approach to regulation which recognises the need for higher power output levels for PtP links. This would amplify the impact of an already powerful access technology. Good practice example: Canada.

- ✓ Review power output levels for Wi-Fi. Allowed power output levels for Wi-Fi vary substantially across countries. Many developing countries have unnecessarily restrictive power limits for Wi-Fi. There is an opportunity for harmonisation of the regulation of Wi-Fi power output levels which would increase the potential of this technology to connect the unconnected.
- ✓ Expand license-exempt regulation to new frequency bands. The success of Wi-Fi suggests that more spectrum should be opened up on a license-exempt basis. Efforts to open 6 GHz for license-exempt use show great promise.
- ✓ Consider higher frequency bands for license-exempt use for PtP backhaul. Other frequency bands for backhaul links such as 24 GHz and 60 GHz should be examined for their potential to offer low-cost, high-capacity wireless infrastructure to community networks and small operators. Given their limited capacity to interfere with other links, extending the maximum power limits and reducing barriers to use should be considered.

Light Licensing for more backhaul spectrum

The reduced interference from antennas that can focus wireless communication along very narrow beams/paths has led some regulators to extend the use of some bands, like 11 GHz, traditionally assigned for satellite services, for PtP backhaul links. Additionally, powerful, low-cost microwave technology pioneered by Wi-Fi manufacturers can be used in almost any frequency band. Regulators should consider the market availability of low-cost microwave solutions in 11 GHz and other frequencies and adapt regulation to encourage their uptake. This could take the form of a light-licensing scenario such as is operated in the United States and in New Zealand for the cooperative assignment of geo-located frequency assignments. Regulators should:

- ✓ Expand the use of 11 GHz band and other frequencies for PtP backhaul links.
- ✓ Review spectrum fees for PtP backhaul links to ensure that fees are reduced to levels appropriate to the technology and solutions being implemented. Increase the granularity of regulation by recognising both geography and the likelihood of interference as factors.
- ✓ Explore administrative incentives to encourage license holders to relinquish spectrum that is not in use.

- ✓ Consider reverting exclusive-use licenses in bands such as 11 GHz to allow for the broader and more equitable uptake of the technology.

Dynamic Spectrum

Rising costs for exclusive-use, licensed spectrum, particularly through spectrum auctions, stands in stark contrast to license-exempt spectrum that is available at no cost. Dynamic spectrum offers the opportunity to establish a middle ground between both approaches. While TV White Space regulation has been implemented in the United States, the United Kingdom, Singapore and a few other counties, its real potential may yet to be realised as an affordable access technology in developing countries where UHF spectrum is largely unoccupied. South Africa is a pioneer in this regard. Regulators should:

- ✓ Accelerate the adoption of TVWS regulation and the promotion of standardised regulation, while reflecting the needs and priorities of developing countries
- ✓ Explore the application of dynamic spectrum management approaches to other frequency bands such as it is being done in the United States with the CBRS in the 3.5 GHz band.
- ✓ Consider dynamic spectrum management as an approach in new frequency band such as 3.7-4.2 GHz and others.
- ✓ Consider regional approaches to geo-location database services

Spectrum for mobile network services

While demand for spectrum often exceeds its administrative availability in urban areas, large amount of licensed spectrum lies unused in sparsely-populated, economically poor regions. A variety of low-cost 2G and 4G manufacturers have emerged in recent years that offer the potential to dramatically change the cost model for sustainable rural mobile network deployment. Incumbent operators often either do not have the incentives or the overhead structures to encourage the roll-out of these new technologies. Regulators should:

- ✓ Consider allocations of spectrum that may not have value for operators, but will have a significant impact for small operators and community networks.
- ✓ In countries where all the spectrum has been assigned but is not occupied in non-profitable areas, explore innovative ways of making that spectrum accessible to community networks and small operators.
- ✓ Establish spectrum fees to incentivize a more efficient use of the spectrum, and a more localized approach to where they are being used, enabling new entrants in areas non-profitable for operators.

- ✓ With the arrival of 5G, it will be important that regulators make sure that the benefits of license-exempt spectrum are not eroded, and consider special case in the use of the spectrum for small operators and community networks.
- ✓ Consider an economic study to understand the economic cost of unused spectrum.

Wholesale Approaches to Spectrum Assignment

The equitable assignment of spectrum in a manner that best serves national strategic interests remains a challenge. Spectrum auctions have proven difficult to execute well. High fees paid at auction may be a windfall for the exchequer but have been shown to result in lower consumer welfare through reduced network roll-out and higher consumer prices. Wholesale networks and common pool resources which establish a shared network infrastructure for all operators to provide services on, may be a practical alternative to spectrum auctions. It is too early to tell for sure as there are few examples and what examples exist are too new to evaluate effectively. Yet, wholesale models are common for fibre optic infrastructure, which suggests that this avenue merits further exploration.

Transparency & Open Data

Spectrum policy and regulation has traditionally been the domain of engineers, economists, and lawyers within the telecommunication sector. However, as spectrum has become an increasingly critical resource in the delivery of affordable access, the need for a more inclusive debate has grown commensurately. Recommendations on spectrum regulation tend to be dominated by input from large network operators and manufacturers. Although important to have the point of view of the industry, it misses the view of other important actors representing the broader public, such as civil society. Regulators can create more opportunities for civil society engagement through increased transparency and communication. Civil society's lack of participation in the processes that shape the telecommunications industry can be attributed, in many cases, to a lack of critical information being available to them. The authors of this report experienced numerous challenges in gaining access to basic information about spectrum frequency assignments, fees, and regulation in general. Regulators should:

- ✓ Ensure that all key spectrum assignments and regulations are publicly available on their website in an accessible and understandable manner[183].
- ✓ Work to promote standards for information sharing that will make it easier to compare regulations across countries and enable proactive discussion on harmonisation.

Capacity building and collaborations

As the evidence of the impact of remaining unconnected grown, regulators throughout the world have shown the interest on becoming more familiar with these innovative approaches to spectrum management and the ways to implement them. The Internet Society, the Association for Progressive Communications and their partners, including industry body associations, are willing to provide support in different areas to make this a reality, by:

- ✓ Providing training to national regulators, regional regulatory authorities and policy makers adapted to this evolving reality.
- ✓ Working together with regulators and policy makers to study the impact of the implementations of these innovations in their own policy and regulatory frameworks.
- ✓ Analysing other factors that influence the use of these innovations by small operators and community networks, such as licensing regimes where a license for the "social use" of spectrum is considered, among other factors.
- ✓ Developing guidelines for model websites, where information is clearly structured and available for consultation and analysis from a wide variety of stakeholders.
- ✓ Studying the impact of all networks deployed with public funding apply a common-pool resource model.

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1 https://malariajournal.biomedcentral.com/articles/10.1186/1475-2875-6-136

2 Connecting The Unconnected: Working together to achieve Connect 2020 Agenda Targets. A background paper to the special session of the Broadband Commission and the World Economic Forum at Davos Annual Meeting 2017 http://broadbandcommission.org/Documents/ITU_discussion-paper_Davos2017.pdf

3 https://www.gsmaintelligence.com/research/2018/02/unique-subscribers-and-mobile-internet-users-understanding-the-new-growth-story/653/

4 https://www.slideshare.net/kleinerperkins/internet-trends-report-2018-99574140

5 Recommendation ITU-D 19. WTDC 2017 report. https://www.itu.int/en/ITU-D/Conferences/WTDC/WTDC17/Documents/WTDC17_final_report_en.pdf

6 Resources are available at https://www.internetsociety.org/issues/community-networks/

7 Argentina, Brazil, Canada, India, Mexico, South Africa and United States of America.

8 The constantly evolving language and acronyms of spectrum manage are challenging for practitioners let alone non-experts.

9 As an example, a detailed map of frequency allocations for the United States can be found at https://www.ntia.doc.gov/files/ntia/publications/january_2016_spectrum_wall_chart.pdf

10 https://www.laroccasolutions.com/shannon-bound/

11 Spectral Efficiency http://www.cablefax.com/archives/spectral-efficiency Ron Hranac CableFax 1 October 2012. Accessed on 24 June 2018

12 Ronald H. Coase, "The Federal Communications Commission," 2 Journal of Law and Economics 1 (1959).

13 high demand spectrum refers to spectrum for which market demand exceeds the current administrative availability of spectrum, typically those spectrum bands used for mobile communication

14 Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press

15 Wikipedia entry on Tragedy of the Commons https://en.wikipedia.org/wiki/Tragedy_of_the_commons Original concept in Hardin, G (1968). "The Tragedy of the Commons" . Science. 162 (3859): 1243–1248.

16 https://www.itu.int/dms_pub/itu-d/opb/stg/D-STG-SG02.FEES-1-2010-PDF-E.pdf

17 Elinor Ostrom's 8 Principles for Managing A Commons 2 October 2011 On The Commons http://www.onthecommons.org/magazine/elinor-ostroms-8-principles-managing-commmons Accessed on 24 Jun 2018.

18 Example of many similar headlines. The Spectrum Crunch Cometh https://www.tvtechnology.com/news/the-spectrum-crunch-cometh TVTechnology, Steve Harvey, Oct 16, 2017. Accessed on 4 June 2018.

19 Cooper, Martin. The Myth of Spectrum Scarcity. 2010 (Position paper) http://dynallc.com/wp-content/uploads/2012/12/themythofspectrumscarcity.pdf Accessed on 18 June 2018

20 It is important to note that, with the use of directional antennas, WiFi can also be used for highly focused, line-of-sight, point-to-point broadband connections, often over 10s of kilometres.

21 How selective hearing works in the brain: 'Cocktail party effect' explained. 18 April 2012 Science Daily. https://www.sciencedaily.com/releases/2012/04/120418135045.htm Accessed on 24 Jun 2018

22 Wikipedia entry for Cognitive Radio https://en.wikipedia.org/wiki/Cognitive_radio

23 Wikipedia entry for Noise Floor https://en.wikipedia.org/wiki/Noise_floor

24 C. Rey-Moreno, J. Simo-Reigadas, and A. Martinez-Fernandez, “WiMAX-An Uncertain Promise for Bridging the Digital Divide,” IEEE Technology and Society Magazine, vol. 30, no. 4, pp. 26–33, Dec. 2011.

25 Overview of ITU’s History, ITU https://www.itu.int/en/history/documents/itu-history-overview.pdf Accessed on 10 June 2018

26 Constitution Of The International Telecommunication Union https://www.itu.int/council/pd/constitution.html Accessed on 2 July 2018

27 Final Report. World Telecommunication Development Conference (WTDC-14). Dubai, United Arab Emirates, 30 March to 10 April 2014

https://www.itu.int/en/ITU-D/Conferences/WTDC/Documents/D-TDC-WTDC-2014-PDF-E.pdf Recommendation 19 pg537

28 http://www.3gpp.org/

29 http://www.ieee.org/

30 http://www.etsi.org/

31 ITU Press Release: Digital broadcasting set to transform communication landscape by 2015 https://web.archive.org/web/20170318185816/http://www.itu.int/newsroom/press_releases/2006/11.html Original deleted from ITU website. Retrieved via Archive.org 24 June 2018

32 ITU - Status of the transition to Digital Terrestrial Television Broadcasting : Figures https://www.itu.int/en/ITU-D/Spectrum-Broadcasting/Pages/DSO/figures.aspx Accessed on 24 June 2018

33 Presentation to ITU Workshop on "Digital Broadcasting Technologies" for Sub-Saharan African Countries -- Nairobi, March 2018 Kezias MWALE https://www.itu.int/en/ITU-D/Regional-Presence/Africa/Documents/Nairobi%202018%20ITU%20Broadcast%20Workshop%20-%20DSO%20-%20Digital%20Migration%20Status%20%28Update%29%20in%20Africa.pdf

34 The rise of OTT and VOD services in Africa, ScreenAfrica, David Cornwell May 14, 2018 http://www.screenafrica.com/2018/05/14/digital/vod-ott/an-inside-look-at-the-meteoric-rise-of-ott-and-vod-services-in-africa/

35 African pay TV subscriber numbers to grow 74% by 2023, Andrew McDonald, 08 January 2018 https://www.digitaltveurope.com/2018/01/08/african-pay-tv-subscriber-numbers-to-grow-74-by-2023/

36 Cornwell, David. 14 May 2018. ScreenAfrica. The rise of OTT and VOD services in Africa http://www.screenafrica.com/2018/05/14/digital/vod-ott/an-inside-look-at-the-meteoric-rise-of-ott-and-vod-services-in-africa/

37 Friend, G. (2011, June 2). Best practice spectrum renewal and pricing (Rep.). http://documents.worldbank.org/curated/en/908691468210579972/pdf/832430WP0P122200Box379886B00PUBLIC0.pdf Retrieved 18 Jun 2018

38 Jochum, J., & Leonhard, M. (2015, November 23). Impact of Spectrum Auctions (Publication). http://www.detecon.com/en/Publications/impact-spectrum-auctions Retrieved 18 Jun 2018

39 Effective Spectrum Pricing: Supporting Better Quality and More Affordable Mobile Services. 22 February 2017

By Richard Marsden, Dr. Bruno Soria, and Hans-Martin Ihle

http://www.nera.com/publications/archive/2017/effective-spectrum-pricing--supporting-better-quality-and-more-a.html

40 Spectrum pricing in developing countries. Evidence to support better and more affordable mobile services. July 2018. https://www.gsmaintelligence.com/research/?file=5a8f746015d3c1f72e5c8257e4a9829a&download

41 The Failure of Spectrum Auctions in Africa, Steve Song, ManyPossibilities https://manypossibilities.net/2017/04/the-failure-of-spectrum-auctions-in-africa/ Accessed on 18 June 2018

42 Mawson, N. (2016, September 6). Spectrum meltdown. Brainstorm Magazine. http://www.brainstormmag.co.za/technology/12667-spectrum-meltdown Accessed on 18 June 2018

43 McLeod, D (2017, August 1). We have run out of spectrum: Vodacom. TechCentral. https://techcentral.co.za/run-spectrum-vodacom/76040/ Retrieved 18 Jun 2018

44 Despite massive investment, broadband plan totters. Punch Nigeria 21 Dec 2017 http://punchng.com/despite-massive-investment-broadband-plan-totters/ Accessed on 18 June 2018

45 Dowuona, S. (2017, January 12). 4G spectrum pricing: politics vrs industry, consumer interest. Ghana Business News. https://www.ghanabusinessnews.com/2017/01/12/4g-spectrum-pricing-politics-vrs-industry-consumer-interest/ Accessed on 18 June 2018

46 Adepoju, P. (2017, July 20). Ghana's govt rejects calls for 4G license price slash. ITWeb Africa. http://www.itwebafrica.com/networks/341-ghana/238882-ghanas-govt-rejects-calls-for-4g-license-price-slash Accessed on 18 June 2018

47 Egypt's Minister for ICT says 4G will launch this month. Telecom Review 23 Sept 2017. http://www.telecomreview.com/index.php/articles/reports-and-coverage/1614-egypt-s-minister-for-ict-says-4g-will-launch-this-month Accessed on 24 June 2018

48 Foditsch, N. (2017, April). The Power of Airwaves: The Role of Spectrum Management in Media Development . Center for International Media Assistance. http://www.cima.ned.org/publication/power-airwaves-role-spectrum-management-media-development/ Accessed on 18 June 2018

49 https://www.internetsociety.org/policybriefs/spectrum/

50 Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021 White Paper, 28 March 2017

https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html Accessed on 18 June 2018

51 Ibid

52 The Economic Significance of Licence-Exempt Spectrum to the Future of the Internet" by Richard Thanki, 2012. https://www.microsoft.com/en-us/research/wp-content/uploads/2016/02/spectrum-economic-significance-of-license-exempt-spectrum-report_thanki.pdf

53 Project Isizwe http://www.projectisizwe.org

54 AirJaldi https://airjaldi.com

55 Google says over 8 million people use its free WiFi service at railway stations in India, 7 June 2018, Jon Russell, TechCrunch. https://techcrunch.com/2018/06/07/google-says-over-8-million-people-use-its-free-wifi-service-at-railway-stations-in-india/ Accessed on 18 June 2018

56 Colectivo Ik' ta Kop http://www.iktakop.org/

57 Zenzeleni Networks, zenzeleni.net

58 Coolab http://www.coolab.org

59 Altermundi community wireless network http://altermundi.net

60 Tribal Digital Villeage https://sctdv.net/

61 KNET, http://knet.ca/

62 Wireless for Communities, India, http://defindia.org/access-infrastructure-2/#W4C

63 When setting transmission power limits, regulatory agencies generally use the Equivalent Isotropically Radiated Power (EIRP) as a measure of power. EIRP refers to the actual power radiated by the antenna element as opposed to simply the power output of the radio.

64 https://www.ubnt.com/airmax/rocketdish-antenna/

65 Combining https://dl.ubnt.com/datasheets/airfiber/airFiber_5XHD_DS.pdf and https://www.ubnt.com/airmax/rocketdish-antenna/, for instance.

66 https://transition.fcc.gov/Daily_Releases/Daily_Business/2013/db0220/FCC-13-22A1.pdf

67 https://transition.fcc.gov/Daily_Releases/Daily_Business/2017/db0713/DOC-345789A1.pdf.

68 https://ecfsapi.fcc.gov/file/10030766909973/Mid%20Band%20NOI%20Comments%20(10%202%2017).pdf

69 In most countries of the Americas the 900 MHz band is also license-exempt. In Mexico the slot between 1920 - 1930 MHz is licence free too. In South Africa 17.1 - 17.3 GHz is also license-exempt.

70 To the usual link budget calculations at these frequencies one need to consider vapour absorption, which bring loses of 20 dB/km http://frankrayal.com/2013/08/12/new-fcc-rules-give-60-ghz-a-boost/

71 https://www.trai.gov.in/sites/default/files/Consultation-Paper_Final%2028-3-14.pdf

72 https://telecom.economictimes.indiatimes.com/news/government-likely-to-allocate-backhaul-spectrum-without-auction/64556846

73 https://www.qualcomm.com/news/releases/2017/05/30/qualcomm-extends-benefits-80211ad-wi-fi-enterprises-and-outdoor

74 Although longer distances are possible in dry environments, heavy rain can render the link unstable or unusable, beyond the distances mentioned above: https://help.ubnt.com/hc/en-us/articles/204977614-airFiber-Rain-fade-effects-on-AF24-24HD-links

75 https://mimosa.co/products/specs/b24

76 https://dl.ubnt.com/datasheets/airfiber/airFiber_DS.pdf

77 https://mimosa.co/products/specs/b11

78 https://www.ubnt.com/airfiber/airfiber-11fx

79 Canada allows 85 dBm e.i.r.p. https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10414.html#s8

80 https://wireless.fcc.gov/uls/index.htm?job=transaction&page=weekly

81 https://www.entirety.biz/argentina-enacom-introduces-hertz-a-new-application-system-for-rf-approvals-%e2%80%a8/

82 https://www.balticnetworks.com/fcc-standard-coordination-ubiquiti.html

83 http://ucsweb.ift.org.mx/vrpc/

84 http://www.ift.org.mx/sites/default/files/contenidogeneral/espectro-

radioelectrico/tecnologiasdeaccesodinamicoyusocompartidodelespectro_0.pdf

85 The Dynamic Spectrum Alliance maintains a list of TV White Space pilots around the world at http://dynamicspectrumalliance.org/pilots/

86 United States, United Kingdom, and Singapore.

87 Consultation on a Policy and Technical Framework for the Use of Non-Broadcasting Applications in the Television Broadcasting Bands Below 698 MHz https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10058.html

88 Framework for the Use of Certain Non-broadcasting Applications in the Television Broadcasting Bands Below 698 MHz https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10493.html 30 October 2012

89 https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf10942.html

90 Tackling the spectrum question. Brainstorm Magazine. Samantha Perry. 1 April 2009 http://www.brainstormmag.co.za/features/11746-tackling-the-spectrum-question Access on 2 July 2018

91 The Cape Town TV White Spaces Trial. TENET website. https://www.tenet.ac.za/tvws Accessed on 2 July 2018

92 TV white space for South Africa. http://www.ee.co.za/article/tv-whitespace-south-africa.html by Chris Burger and Dr. Moshe Masonta. 13 Sept 2018. EE Publishers. Accessed on 2 July 2018

93 Regulations On The Use of Television White Spaces 2018. ICASA https://www.icasa.org.za/legislation-and-regulations/regulations-on-the-use-of-television-white-spaces-2018 Accessed on 2 July 2018

94 Gram Marg. IIT Bombay. http://grammarg.in/

95 DoT says no to releasing TV White Space spectrum, clarifies it is for experiments. The Hindu - Business Line. 16 June 2016. Varun Aggarwal. https://www.thehindubusinessline.com/info-tech/dot-says-no-to-releasing-tv-white-space-spectrum-clarifies-it-is-for-experiments/article8737575.ece Accessed on 2 July 2018

96 Techies tease out Internet from 'White Space'. The New Indian Express. Ramzauva Chhakchhuak. 9 March 2018 http://www.newindianexpress.com/cities/bengaluru/2018/mar/09/techies-tease-out-internet-from-white-space-1784600.html Accessed on 2 July 2018

97 Microsoft to Introduce "White Space" Broadband to Vast Areas of Brazil. NearShore Americas. Dan Tucker. 27 March 2014 http://www.nearshoreamericas.com/microsoft-introduce-white-space-broadband-brazil/ Accessed on 18 June 1028

98 LatAm: Alliance conducting white space trial for broadband in Brazil. RCRWireless. Roberta Prescott. January 22, 2015 https://www.rcrwireless.com/20150122/americas/latam-white-space-trial-brazil-tag5 Accessed on 18 June 2018

99 Enacom firmó un convenio con Microsoft https://www.enacom.gob.ar/institucional/enacom-firmo-un-convenio-con-microsoft_n1326

100 Presentation by IFT Commissioner, Adrian Labardini at Canadian Spectrum Summit 2017 http://www.ift.org.mx/sites/default/files/conocenos/pleno/presentaciones/adriana-sofia-labardini-inzunza-presidenta/spectrumsummit2017iftlabardinimexicooralfinale-170816174510.pdf

101 UK mobile operators pay close to £1.4bn for 5G spectrum. The Guardian Mark Sweney. 5 April 2018 https://www.theguardian.com/business/2018/apr/05/uk-mobile-operators-pay-close-to-14bn-for-5g-spectrum

102 Consultation on Revisions to the 3500 MHz Band to Accommodate Flexible Use and Preliminary Consultation on Changes to the 3800 MHz Band https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf11401.html June 2018

103 Challenges to Universal and Affordable Connectivity in Brazil. Leonardo Euler de Morais. Presentation at Dynamic Spectrum Alliance Summit. 3 May 2018 http://dynamicspectrumalliance.org/wp-content/uploads/2018/05/Day3-5-1_ChallengesToUniversalAndAffordableConnectivity_CommissionerLeonardo_Anatel.pdf

104 Indian Government harmonising spectrum for 5G services. OpenGov Asia. Priyankar Bhunia, 9 Mar 2018 https://www.opengovasia.com/articles/indian-government-harmonising-spectrum-for-5g-services

105 M'Bayo, Ritchard. 1997. "Africa and the Global Information Infrastructure." International Communication Gazette 59 (4): 345–64. doi:10.1177/0016549297059004007.

106 Ericsson Mobility Report – Sub-Saharan Africa. November 2015. https://www.ericsson.com/res/docs/2015/mobility-report/emr-nov-2015-regional-report-sub-saharan-africa.pdf

107 http://nuranwireless.com/

108 http://fairwaves.co/wp/

109 https://osmocom.org/

110 http://www.dof.gob.mx/nota_detalle.php?codigo=5387867&fecha=06/04/2015

111 http://www.ift.org.mx/industria/espectro-radioelectrico/programa-anual-de-uso-y-aprovechamiento/programa-2015

112 Social use gives rights to use and exploit frequency bands in the radioelectric spectrum to provide telecommunication services for cultural, scientific, educational community services on a non-for-profit basis.

113 Ibid

114 Vanu Rwanda http://www.vanurwanda.com/about/

115 http://firstmile.ca/wp-content/uploads/2015-Beaton-Burnard-Linden-ODonnell-Keewaytinook-Mobile.pdf

116 Can a for-profit company bring connectivity to ultra-remote villages? Devex. Sophie Edwards. 16 June 2017 https://www.devex.com/news/can-a-for-profit-company-bring-connectivity-to-ultra-remote-villages-90484 Accessed on 24 June 2018

117 Data collected with using RF Explorer 6G Combo http://rfexplorer.com/models/ and the GSM Track app (http://wireless.ictp.it/gsm/gsmtrack/GsmTrack.apk) created by ICTP, while driving in rural Eastern Cape, South Africa, between Mthatha and Mdumbi river mouths. More information can be found and results in http://wireless.ictp.it/gsm

118 http://www.aimdigital.com.ar/ley-corta-media-sancion-la-semana-proxima/

119 For instance in the state of Pará there is 2x2.5 MHz.

120 https://www.lasse.ufpa.br/2018/03/09/caravana-celcom-em-boa-vista-do-acara/

121 GSR.325(E). The Gazette of India. 14th May 2009.

122 http://www.anatel.gov.br/setorregulado/servico-especial-para-fins-cientificos-e-experimentais

123 RURA Statistics And Tariff Information In Telecom, Media And Postal Service As Of The Fourth Quarter 2017. http://www.rura.rw/uploads/media/Telecom_Statistics_Report_Fourth_Quarter_2017.pdf

124 KT Increases African Ambitions Following Rwanda LTE Success. Developing Telecoms. 29 May 2018 https://www.developingtelecoms.com/business/operator-news/7839-kt-increases-african-ambitions-following-rwanda-lte-success.html

125 Mexican wholesale 4G network opens for business. MobileWorldLive 23 March 2018 https://www.mobileworldlive.com/featured-content/top-three/mexican-wholesale-4g-network-opens-for-business/

126 Islim Telco first operator to join Mexico's Red Compartida. 18 June 2018 https://www.telecompaper.com/news/islim-telco-first-operator-to-join-mexicos-red-compartida--1248842

127 https://www.ellipsis.co.za/wp-content/uploads/2016/10/National-Integrated-ICT-Policy-White-Paper.pdf

128 Data pricing trends in South Africa. PPC presentation by Research ICT Africa. 31 October 2017 https://researchictafrica.net/wp/wp-content/uploads/2017/11/2017-presentation-to-the-PPC-on-the-cost-to-communicate-in-SA.pdf

129 https://www.ellipsis.co.za/wp-content/uploads/2017/11/gg41261-Invitation-to-provide-written-comments-on-Electronic-Communications-Amendment-Bill-1.pdf

130 https://www.ellipsis.co.za/electronic-communications-amendment-bill-2017/

131 GSMA Wholesale Open Access Networks. July 2017 https://www.gsma.com/spectrum/wp-content/uploads/2017/07/GSMA_SWN-8-pager_R3_Web_Singles.pdf

132 List of LTE Bands. Wikipedia https://en.wikipedia.org/wiki/LTE_frequency_bands

133 Everything You Need to Know About 5G, IEEE Spectrum, 6 Feb 2017, https://www.youtube.com/watch?v=GEx_d0SjvS0

134 An Introduction to Network Slicing. GSMA 2017. https://www.gsma.com/futurenetworks/wp-content/uploads/2017/11/GSMA-An-Introduction-to-Network-Slicing.pdf

135 https://www.itu.int/en/ITU-D/Spectrum-Broadcasting/Documents/Publications/Guidelines_SpectrumFees_Final_E.pdf

136 https://www.itu.int/dms_pub/itu-d/opb/stg/D-STG-SG02.FEES-1-2010-PDF-E.pdf

137 https://www.itu.int/dms_pub/itu-d/opb/stg/D-STG-SG02.FEES-1-2010-PDF-E.pdf

138 http://www.itu.int/net4/ITU-D/CDS/SF-Database/index.asp

139 https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf01027.html#aA

140

http://wpc.dot.gov.in/WriteReadData/Orders/Guidelines%20Dated%2016th%20October%202015%20for%20Interim%20allotment%20of%20MWA%20and%20MWB%20Carriers%20.pdf These guidelines stipulate a percentage of the revenue of the service provider in a given Service Area as a fee to use blocks 2x28 MHz, or parts thereof.

141 https://www.ellipsis.co.za/radio-frequency-spectrum-fees

142 http://servicios.infoleg.gob.ar/infolegInternet/anexos/270000-274999/270502/norma.htm

143 http://www.anatel.gov.br/legislacao/resolucoes/2004/326-resolucao-387

144 Guidelines For The Review Of Spectrum Pricing Methodologies And The Preparation Of Spectrum Fees Schedules. ITU-D. ITU 2016. https://www.itu.int/en/ITU-D/Spectrum-Broadcasting/Documents/Publications/Guidelines_SpectrumFees_Final_E.pdf Accessed on 3 July 2018.

145 Notes that Canada uses also this factor.

146 Note South Africa doesn't consider this factor.

147 https://www.fcc.gov/document/fee-filing-guide-0

148 Values provided in USD with a exchange rate from the 11th June 2018.

149 Exchange rate source xe.com on 22nd June 2018.

150 "Review of Policy and Formulation of Recommendations for the Department of Communications by BMI-TechKnowledge: As Is, Historical Review, Transformation & International Benchmarking Reports" Author: Denis Smit, Tertia Smit, Brian Neilson, Penny Smith, Tim Parle, Dominic Cull (Ellipsis), Dave Rogerson (Incyte), Harm Aben (Incyte)" dated August 2013

151 Guidelines For The Review Of Spectrum Pricing Methodologies And The Preparation Of Spectrum Fees Schedules. ITU-D. ITU 2016. https://www.itu.int/en/ITU-D/Spectrum-Broadcasting/Documents/Publications/Guidelines_SpectrumFees_Final_E.pdf Accessed on 3 July 2018

152 The maximum data rate of equipment operating in that band considered.

153 TRAI recommends to remove the presumptive revenue and to calculate the fees based on the formula provided in existing regulations that considers the distance and the channel width:http://www.trai.gov.in/sites/default/files/Recommendations_07032017.pdf .

154 TRAI recommends to remove the presumptive revenue and to calculate the fees based on the formula provided in existing regulations that considers the distance and the channel width:http://www.trai.gov.in/sites/default/files/Recommendations_07032017.pdf .

155 https://www.itu.int/dms_pub/itu-d/opb/stg/D-STG-SG02.FEES-1-2010-PDF-E.pdf

156 http://dot.gov.in/sites/default/files/2016_03_28%20ULG%20AS-I.pdf?download=1

157 A slot of this size allows for 4 non interfering channels in GSM.

158 In the case of Brazil, these allocations are regional, so the population and size of the state of Pará are considered. In the case of Mexico, the region of Oaxaca is considered for calculations.

159 Carlos Rey-Moreno, Renette Blignaut, William D. Tucker & Julian May (2016) An in-depth study of the ICT ecosystem in a South African rural community: unveiling expenditure and communication patterns, Information Technology for Development, 22:sup1, 101-120, https://www.tandfonline.com/doi/full/10.1080/02681102.2016.1155145

160 Article 76, Ley Federal de Derechos.

161 https://rising.globalvoices.org/blog/2018/01/24/the-first-mobile-phone-network-for-indigenous-communities-in-mexico-is-under-threat/

162 https://www.eleconomista.com.mx/opinion/Otorgan-amparo-a-las-telecomunicaciones-de-comunidades-indigenas-20180408-0004.html

163 http://www.wapa.org.za/

164 https://www.ellipsis.co.za/

165 http://www.diputados.gob.mx/LeyesBiblio/pdf/107_221217.pdf

166 https://www.ellipsis.co.za/icasa-fees/

167 www.anatel.gov.br/legislacao/resolucoes/2013/465-resolucao-614

168 https://www.enacom.gob.ar/multimedia/normativas/2017/res697MM.pdf

169 http://dot.gov.in/sites/default/files/2016_03_28%20ULG%20AS-I.pdf?download=1

170 Exchange rate source xe.com on 14th June 2018.

171 http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2008/lei/l11652.htm

172 http://www.wpc.dot.gov.in/static/a1.pdf

173 http://www.planalto.gov.br/ccivil_03/leis/L9691.htm

174 eur-lex.europa.eu/legal-content/EN/TXT/?uri=URISERV%3Al24164

175 http://www.anatel.gov.br/legislacao/resolucoes/2017/936-resolucao-680

176 https://www.internetsociety.org/resources/2018/unleashing-community-networks-innovative-licensing-approaches/

177 OFCOM Radiocommunications licences https://www.ofcom.org.uk/manage-your-licence/radiocommunication-licences

178 Instituto Federal de Telecomunicaciones: Registro Público de Concesiones http://ucsweb.ift.org.mx/vrpc/

179 Government of Canada: Spectrum Management System Data http://sms-sgs.ic.gc.ca/eic/site/sms-sgs-prod.nsf/eng/h_00010.html

180 Canadian Cellular Towers Map https://www.ertyu.org/steven_nikkel/cancellsites.html

181 Airtel Open Network https://www.airtel.in/opennetwork/

182 Dark Fibre Africa Coverage http://www.dfafrica.co.za/network/coverage/

183 While this report focuses on spectrum, the recommendation for more transparency can be equally applied to other kinds of telecommunications infrastructure such as fibre networks and towers.