Dynamic Spectrum Management in 5G: Lessons from Technological Breakthroughs in Unlicensed Bands Use

Fernando Beltrán[1(✉)], Sayan Kumar Ray[2], and Jairo Gutiérrez[3]

[1] University of Auckland, Auckland, New Zealand
f.beltran@auckland.ac.nz
[2] Manukau Institute of Technology, Auckland, New Zealand
sayan.ray@manukau.ac.nz
[3] Auckland University of Technology, Auckland, New Zealand
jairo.gutierrez@aut.ac.nz

Abstract. This paper discusses a number of issues associated with the increasing need to improve the utilization of unlicensed spectrum as a number of new technological advances provide an opportunity to share scarce resources in a dynamic fashion in the future 5G networks. The growth in connected devices via cellular and Wi-Fi networks is being complemented with a significant increase in networked "things" and this proliferation of devices presents a challenge to Spectrum Authorities. We propose that the ultimate purpose of Dynamic Spectrum Management (DSM) is to improve spectrum usage efficiency by fully exploiting spectrum sharing while assuring minimum undesired interference. Our aim is the identification of economic issues that impact the development of efficient markets for 5G networks that rely on dynamic spectrum technologies in the unlicensed spectrum. The paper covers how technological breakthroughs in spectrum access technologies challenge our current understanding of spectrum management. In each case, the contribution of the paper includes policy proposals or more focused regulatory instruments while the concluding section sums up the paper's key message about the interplay between technology and policy that helps lay out elements that regulators and policy-makers need to attend to when adopting practices that implement Dynamic Spectrum Management in the unlicensed spectrum.

Keywords: Dynamic Spectrum Management
Spectrum allocation and assignment · 5G networks · Unlicensed spectrum
Wi-Fi · LTE · IoT · TVWS · mmWave

1 Introduction

This discussion paper captures the most relevant aspects that need to be considered for regulation and policy to deliver socially optimal outcomes in a wireless service environment characterised by the dynamic use of the radio spectrum. As the utilisation of the radio spectrum evolves from exclusive band operation to shared, opportunistic, and intermittent usage, such new spectrum access modes demand a dynamic approach to

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access and interference control and so must spectrum policy and management, originally conceived as a command-and-control regime. Our aim is the identification of economic issues that impact the development of efficient markets for 5G networks that rely on dynamic spectrum technologies in the unlicensed spectrum.

After discussing the supporting policy principles of spectrum management in Sect. 2, the paper steers the discussion toward how technological breakthroughs in spectrum access technologies in the unlicensed spectrum challenge our current understanding of spectrum management. In particular, in Sect. 3 we analyse the impact that Long Term Evolution (LTE) may bring in as it is proposed to be deployed on Wi-Fi bands. Section 4 follows by discussing Internet of Things (IoT)'s need for new spectrum; then in Sect. 5 advances in opportunistic access and utilisation of TV White Spaces (TVWS) are presented. In Sect. 6 we discuss the irruption of Millimeter Wave technology. In each case, the contribution of the paper includes policy proposals or more focused regulatory instruments, all of which are intended to align with the issues the paper raises. Our concluding section sums up the paper's key message about the interplay between technology and policy that helps lay out elements that regulators and policy-makers need to attend to when adopting practices that implement Dynamic Spectrum Management in unlicensed spectrum for future 5G networks.

2 Spectrum Management

As radio spectrum is assigned as usage rights over ranges of frequencies called bands, undesired spill-over signals from using the spectrum in one band, known as interference, may negatively impact its usage in adjacent bands. Hence, the main reasons for spectrum management: band allocation and interference minimization. Rights to transmit are usually allocated to users in the form of a license, terms and conditions of which should not lead to excessive interference.

In light of technology and policy advancements Cave and Webb [1] discuss new features of spectrum management which, in addition to the conventional approach, the authors argue, needs to provide assurance that the value of spectrum to society is maximized. The latter calls for making a key objective of spectrum management that it allows as many users to gain efficient access to the spectrum as possible. Therefore, spectrum needs to be managed because, with current technology, maximizing its value to society can only be achieved by coordinating who can use which bands and over which geographical extensions.

A Spectrum Authority (SA) performs its spectrum management mandate by, first assessing all potential uses of a band and deciding about the type of use the band will be dedicated to; this is known as **spectrum allocation**. Then the SA provides a license to one or more operators for exploitation of the radio band; this is known as **spectrum assignment**.

Spectrum allocation and spectrum assignment are centrepieces of spectrum management. Spectrum users need assurance about the conditions under which spectrum is used; such conditions are paramount to achieving technical efficiency and minimization of interference. Long-term licenses provide the stability users seek and allow a SA to achieve other goals: conditions on service availability and coverage requirements imposed on the licensees. In a few cases SAs have decided specific bands do not require licensing but only the adherence to some basic technical requirements, typically enforced to minimize interference. The utilization of this type of unlicensed bands may be rather uncoordinated.

Technological innovation in wireless transmission is proving the static features of spectrum management need to be thought over. Policy decisions that respond to increasing pressure for competition in leading communication sectors such as cellular telephony and wireless broadband services are also causing spectrum management to evolve. When static features of spectrum management are changed or disrupted by technological innovations and policy changes, it is clear that managing the spectrum needs to cater for new challenges.

Technology changes and market interests exert pressure on SAs, demanding more spectrum and a more diverse approach to allocation and assignment. Leading SAs across the world have started a shift towards the inclusion of new elements and tools that promise to provide spectrum management with the ability to respond more dynamically to the changes technology brings in and users demand.

One of the techniques that spite being already allowed for quite a long time is retaking a central stage in spectrum management considerations is Spectrum Sharing (SS). A spectrum utilization scheme that allows two or more parties to utilize the same range of frequencies while no exclusivity is granted to any of them, SS is also a renewed tool for spectrum management. Techniques that facilitate spectrum sharing are divided into uncoordinated – radio systems adjust their operation to coexist with other radio systems with little information to share, and coordinated – techniques that require coexisting radio-frequency (RF) systems to exchange information to share the same frequency band. Examples of the former are dynamic channel selection and adaptive frequency hop to listen-before-talk, whereas examples of the latter include multiplexing techniques such as FDMA, TDMA or CDMA or channel-based control methods, such as CSMA/CA.

Thus, a renewed approach to spectrum management must acknowledge the most important changes in technology and policy, the economic importance of spectrum (value), changes in its utilization (innovation), and the need for efficient utilization in a market-driven way, all of which must be considered while managing the social role of spectrum. Allowing spectrum-sharing arrangements challenges the conventional regulatory approach to commercial use of the spectrum in particular for mobile telecommunications services.

Although spectrum sharing is favoured by many observers and seems to be finding a clear way as a policy tool of SAs, not all bands can or should be potential sources of sharing. The SCF Report [3] indicates that in Europe bands for distress calls, maritime navigation, and air traffic control must remain exclusive, deeming these bands as non-shareable. In spite those pockets, SCF concludes that "it is possible in many areas of the spectrum currently under commercial or administrative licensing regimes to use a shared regime without endangering those other services vital to safety of life".

The natural progression of spectrum management that aims to account for the features described and discussed above is called Dynamic Spectrum Management, DSM. The ultimate purpose of DSM is to improve spectrum usage efficiency by fully exploiting spectrum sharing while assuring minimum undesired interference. A number of current issues that demand spectrum management to be modified, changed or adapted for future 5G networks will next be discussed. In all cases the characteristics of those technology breakthroughs challenge aspects of the conventional approach to spectrum management, demanding a decidedly DSM-oriented context.

3 LTE vs WiFi in Unlicensed Spectrum

Telecommunications vendors and the cellular networks operators championing LTE are targeting the unlicensed 5 GHz bands, currently being used by Wi-Fi, Zigbee and few other communication systems, to expand the LTE capacity and meet traffic growth. Here we briefly discuss some relevant aspects of LTE's history in the unlicensed spectrum. In 2013 Qualcomm proposed the idea of deploying LTE in the unlicensed spectrum [4]. Two versions, LTE-U, which is the pre-standard proprietary version backed by the LTE-U Forum, and Licensed Assisted Access (LAA), which was developed by 3GPP, are the contenders.

Initial deployment of these LTE versions in the unlicensed bands is expected through small cells for DL only and then slowly for UL as well. Both LTE-U and LAA utilize carrier aggregation functionality using both the unlicensed bands and the licensed spectrum. While LAA complies with the different regulatory requirements for the usage of the unlicensed spectrum, LTE-U does not and instead uses the duty cycling-based system called Carrier Sensing Adaptive Transmission (CSAT). An LTE-U cell using CSAT does not sense the occupancy of a channel before transmitting and instead turns its signal on and off over small periods of time to, respectively, occupy the channel to transmit and vacate the channel for other technologies like Wi-Fi. LTE-U's focused deployment options are only in the non-LBT (Listen-Before-Talk) required regions in the world [5, 6].

The LTE-U Forum is progressing with developing the protocols for LTE-U operations in the 3.5 GHz band, while T-Mobile (US) is looking to adopt LAA for that same band. However, efficient operation in the 3.5 GHz band will set a strong requirement for low power RF equipment, e.g., low power small cell technologies for both LTE-U and LAA.

Additionally, improvements to the LTE standards, in Release 14, include enhanced LAA (eLAA), which among other functions provides full support for UL transmissions in the unlicensed spectrum. The issue becomes the potential overutilization of offloading and hence its impact on many Wi-Fi services. LTE-based networks can easily switch from unlicensed to licensed use, an ability that is not available to Wi-Fi networks and its many users.

The advances discussed above point towards mechanisms to enable the coexistence of LTE and Wi-Fi networks with convergence on both scheduled and ad-hoc wireless configurations. Regardless of the techniques available, the SAs need to address the issue of whether the co-existence scenario delivers more value than the existing unlicensed Wi-Fi scenario or not.

4 Internet of Things

The Internet of Things (IoT) refers to the widespread use of systems, heterogeneous technologies and the evolving paradigm of the interconnectedness of devices, using TCP/IP protocols, around our physical environments. IoT includes a new wave of sensor devices and interoperates with the growing cloud network infrastructure. On the long run it is envisioned that an IoT ecosystem will facilitate the interaction of devices (mobile or fixed), smart objects and other real world devices just as humans interact nowadays using internet-based applications. The IEEE is currently working on a reference architecture, which will define the basic IoT architectural building blocks and how they could be seamlessly combined into multi-tiered systems [7].

Currently spectrum allocations tend to be IoT application-specific and must satisfy the service requirements of individual applications. IoT allocations are particularly active in the Sub-6 GHz spectrum. Generally speaking, service requirements range from excellent and ubiquitous coverage, ultra-low power operations, provision of adequate bandwidth, to secured and low cost communication and guaranteed message delivery. While, from a spectrum allocation perspective, it is a challenge to meet these varied requirements, an initial step is making available globally harmonized low-frequency spectrum in the unlicensed bands, e.g., bands below 1 GHz like 870–876 MHz and 915–921 MHz along with the TV white spaces [8, 9]. In future, 700 MHz bands may also become available. All these bands allow extended coverage and support interconnection of a higher number of less complex and low-powered IoT devices. These are also beneficial to run IoT applications, which require in-building penetration. SigFox, LoRa (Long Range) and NB-IoT (Narrowband IoT) are examples of notable narrowband Low-power WAN (LPWAN) technologies operating in unlicensed spectrum. Low frequency bands are, however, scarce and high in demand, so there should be ways to find and free more such globally harmonized bands that can be made available for IoT applications. Another notable example is the Wi-SUN (Wireless Smart Ubiquitous Network) technology, which is based on the IEEE 802.15.4g standard. Traditionally SA's allocation and assignment processes have favoured exclusivity. With an inability to foresee the pathways of technological innovation a SA needs to reassess the importance of modifying the assignment stage to favour unlicensed or shared bands and hence alleviate scarcity.

Apart from these, some interests on shared bands over 2 GHz are also there, particularly for applications with higher bandwidth requirements, like video monitoring. Such bands include 2.3 GHz, 2.4 GHz, 2.6 GHz, 3.4–3.8 GHz, and 5 GHz. However, with multiple wide-ranged IoT technologies flocking the unlicensed spectrum, interference may always be an issue with the increase in the number of IoT devices even if the devices are low-powered. Recent research indicates that a license-exempt model, in fact a way of skipping the assignment phase in spectrum management, facilitates the rapid development of IoT devices as it eliminates the need for time-consuming negotiations about the spectra to be used. This could directly result in cheaper IoT nodes [10]. Another possibility could be setting a worldwide default frequency in the range of 915–928 MHz for IoT devices to facilitate compliancy and deployment. Other opinions have voiced the requirements for making the IoT devices themselves understand which country they are operating in and what are the available spectrum bands there and operate accordingly [11].

5 TV White Spaces

TVWS refers to frequencies allocated to licensed Digital Terrestrial TV (DTT) broadcasting services that are unused and freed up for unlicensed radio devices known as White Space Devices (WSD). These devices can dynamically share and opportunistically use TVWS on a secondary basis without interfering with each other or with the primary licensed service providers (digital TV broadcasters and wireless microphone users). TVWS, an important cognitive radio application, enables long-range services in broadband speeds. The first major implementation of the concept of Dynamic Spectrum Access (DSA) has been in the TVWS spectrum bands [12]. DTT broadcasting uses the VHF band (30 MHz to 300 MHz) and lower part of UHF spectrum bands (300 MHz to 1000 MHz) [13]. Table 1 lists some of the countries that have TVWS regulations in place [12, 13]. The TVWS spectrum market will experience the coexistence of WSDs and services of the different unlicensed technologies, including the IEEE 802.22 Wireless Regional Area Network (WRAN), IEEE 802.11af, IEEE 802.15.4m, ECMA-392 and Weightless, through dynamic sharing of the available spectrum bands. Trials and deployments of these are underway in multiple countries.

Table 1. Some of the countries with TVWS usage regulations.

Countries	Usage bands	Regulatory body
USA	VHF: 54–88 MHz and 174–216 MHz UHF: 470–698 MHz	Federal Communications Commission (FCC)
UK	UHF: 470–790 MHz	Ofcom
Singapore	VHF: 174–230 MHz UHF: 470–806 MHz	Info Communications Development Authority (IDA)
Canada	UHF: 470–698 MHz	Industry Canada
Europe	UHF: 470–790 MHz	European Communications Commission

Primarily, TVWS usage aims to enable secondary users using the bands without interfering with the primary incumbent users. Unlicensed Shared Access of spectrum is the possible approach to follow for DSM in this case. A strong need is there to protect the existing investments and users in the TV bands and calls for a globally coordinated and holistic approach to deal with key issues, like, identifying TVWS spectrum in different regions and countries, non-harmonized specifications for WSDs and lack of global standards or regulatory frameworks for TVWS usage. Geolocation databases are globally accepted as the most promising solution to identify and use TVWS spectrum for a variety of services. They store information regarding operating frequencies, schedules and locations of the licensed DTT providers and other users and devices sharing the TV bands. The WSDs can access the list of currently available TVWS channels in a region by providing their own geolocations to the geolocation databases in that region. Not having globally harmonized TVWS regulation for geolocation databases and WSDs, however, pose few challenges. It will not be possible to readily use an auto-configurable WSD from one region to work in another. For example, a WSD from UK (supporting only UHF TVWS bands) will not readily work everywhere in US, which supports both VHF and UHF bands. In addition, types of supported WSDs vary between countries. While US supports sensing-only WSDs, other countries do not support them. Moreover, to introduce new TVWS technologies or services that will not interfere with primary services or other coexisting services in a region, the databases used need to have common technical standards to identify and accommodate the new TVWS technologies or services and related WSDs introduced. Thus, for efficient DSM of TVWS bands in unlicensed bands, there needs to be standardised policies and regulations enabling the harmonization of geolocation databases and use of WSDs worldwide. Although there exists the European harmonized standard (ETSI Harmonized Standard) for WSDs, it is only a voluntary scheme [13].

6 Millimeter Wave (mmWave)

The millimetre wave (mmWave) refers to frequency spectrum above the 24 GHz bands that may range up to 300 GHz. It can cater for high broadband capacity and is emerging as one of the promising technologies for 5G communication offering a large pool of available spectrum for mobile users, satellite users, and other commercial users to share and coexist. The recent FCC mandate has opened up nearly 11 GHz of high frequency spectrum in the mmWave bands for fixed and mobile broadband usage of which 3.85 GHz is licensed and 7 GHz is unlicensed spectrum [14]. These 7 GHz of unlicensed bands combined with the already existing 57–64 GHz of unlicensed spectrum, will provide 14 GHz of contiguous spectrum for unlicensed usage in the mmWave bands, which will be nearly 15 times more than the WiFi unlicensed spectrum in lower bands. Moreover, in the US, there will be 600 MHz of spectrum for dynamic shared access in the 37–37.6 GHz bands for commercial and federal users [14]. The UK has made available 18.3 GHz of unlicensed spectrum in the 60–80 GHz bands, while in Europe the 57–64 GHz band is for licensed-exempt usage.

Harmonization of the mmWave bands worldwide in regards to usage models is crucial as opportunities exist for coexistence of different types of technologies sharing the bands. Sharing of the unlicensed spectrum in the mmWave bands should be done in a way to allow for substantial spectrum reuse while still keeping the interference to the lowest. Recent research on spectrum sharing in the mmWave bands has reported considerable performance enhancement utilizing concepts like uncoordinated spectrum sharing and hybrid spectrum access [15]. However, a consensus has neither been reached as of yet on a globally accepted coexistence model in the mmWave bands nor been reached on global usage policies in these bands. In addition, regulatory frameworks in the mmWave bands vary between regions and this may hinder spectrum sharing. For example, technical implementation specifications for antenna arrays can hugely vary between bands that are gigahertz apart and this will require user devices to not only just operate in multiple bands but also to self-identify the underlying operational band and to customize its configuration accordingly. This would require a global harmony or standardization of the technical specifications of the equipment and devices operating in the unlicensed parts of the mmWave bands.

Efficient utilization of available unlicensed spectrum in mmWave bands can enable the coexistence of heterogeneous deployments. Dynamic spectrum sharing will be important in such scenarios. It may be possible to adjust the amount of utilized spectrum in real-time depending on the service demand at any given moment, while still considering the geographical characteristics [14]. Thus, to enable coexistence of different technologies and services in the unlicensed mmWave bands, dynamic spectrum sharing is important and global harmony needs to be reached in terms of usage models, technical specifications of equipment, operational regulations, dynamic spectrum sharing mechanisms, and allocating priority access to services/operators depending on demand etc., before mmWave in the unlicensed bands can be successfully commercialized for future 5G networks.

7 Moving Towards DSM

The above sections discussed the different technological breakthroughs in spectrum access technologies in the unlicensed spectrum. Quite a number of issues associated with the increasing need to improve the utilization of the unlicensed spectrum are highlighted for regulators and policy-makers to consider when adopting practices to implement Dynamic Spectrum Management for future 5G networks.

As LTE-U and LAA seek to be deployed on the 5 GHz band, either as a mixed U/L implementation or fully unlicensed, such as eLAA, the question of fairness arises as the most critical coexistence issue for SAs. With 5 GHz not being a greenfield spectrum, its management needs to answer what policies are there to govern such fair sharing of spectrum. Clearly the initial allocation of the band is now being questioned, somehow, as new technology and commercial interests are pushing its way into the band. This situation exemplifies the threat that unlicensed bands face as the assignment problem was never really solved in terms of the definition of property rights; after all, 5 GHz as well as 2.4 GHz are conspicuous examples of spectrum commons, which foresees the high possibility of overuse in the unlicensed bands. Although preliminary research results have shown that Wi-Fi performance is not degraded in the presence of LTE-U and LAA, there are still some concerns about the potential dominance of LTE and Wi-Fi in the unlicensed bands.

One of the main concerns about the expansion of IoT technologies is how to effectively achieve worldwide default (preferably) unlicensed spectrum allocation for their operation. A rising challenge for SAs is the identification of internationally accepted mechanisms that allow IoT devices to understand which country they are operating in and self-switch to allocated (legal) IoT spectrum bands. The most likely scenario for a world of IoT is one in which multiple technologies use unlicensed spectrum in an uncoordinated manner. Assuming that the rise of universally accepted

LPWAN standard will include evolving into a support for M2M/IoT connections worldwide, any SA would need to be concerned with how interference between different wide-ranged LPWAN technologies will be handled. Foreseeing the complexity of yet another spectrum commons scenario, which might include default IoT frequencies allocated worldwide to facilitate global roaming and seamless connectivity on, for instance, the 915–928 MHz band, 'fair sharing' of such unlicensed spectrum among IoT technologies erects itself as a critical issue.

TVWS is intended to mitigate spectrum-sharing challenges. International experience indicates different countries maintain different compliancy regulations to assess the suitability and functioning of geolocation databases, which are regulated by national SAs but mostly provided and maintained by private providers. In such cases, DSA for TVWS bands would raise concerns that mostly deal with the provider, such as its suitability, the criteria it should fulfill, and the verification of its fair access and opportunity policies to use white bands on a temporary basis by opportunistic, second-tier operators. Also, when bands of choice in a region are not available to WSDs, band diversity may be a potential solution where the network and its WSDs are able to operate across multiple bands so that there are always bands available. This requires the geolocation database operators across regions to update their respective databases periodically with appropriate information and to share the updates amongst each other.

Additionally, the challenges associated with mmWave are characterized by the uncertainties linked to this newer technology. There are areas in common with the technologies discussed above: the global harmonization of bands, the search for an agreement on a coexistence model for the future use of these unlicensed bands by different technologies, and the appropriate role for the SAs. mmWave has some other concerns that are associated to its incipient nature, i.e., technical specifications of equipment, operational regulations, dynamic spectrum sharing mechanisms, and allocating priority access to services in the unlicensed spectrum depending on demand.

Finally, a preliminary proposal is to use some of the principles that have been successful in the provision of network management facilities using software defined networking [16]. As mentioned before one of the key areas in common is the search for an agreement on the use of the unlicensed bands (UB) by the different technologies surveyed. We propose a **Spectrum Controller** mechanism, akin to the Software Controller in software-defined networks (SDNs), which will coordinate UB requests within a given autonomous system (AS). Following the principles of SDNs, the requests are made via a control plane (or channel) and the associated allocation takes place in the assigned data channel. Upon termination of the connection, the SC will update the register of shared resources available for future requests. The SC is therefore the entity, which keeps track of the resources shared within an AS by a number of significantly different technologies which have in common a need to dynamically shared unlicensed spectrum. An area of future research is to work on the coordination of spectrum usage among cooperating autonomous systems.

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