Accelerating the Introduction of Spectrum Sharing Using Market-based Mechanisms

Fernando Beltrán[1]

ABSTRACT

Spectrum management needs to be effective, in that spectrum must be allocated to the right uses, and efficient, in that spectrum must be assigned to those that value it the most. Technological advances and demands for further spectrum availability from mobile broadband operators (among others) require spectrum management to timely and firmly incorporate schemes to increase the technical efficiency of spectrum utilisation. One such scheme is spectrum sharing which has the potential to result in higher spectrum utilization and greater spectrum value. In such context allocation and assignment, two critical functions to manage the spectrum, are also discussed. By means of tutorial-styled presentation of spectrum sharing techniques and policy decisions this paper argues that in the course of deciding about allocation and assignment of spectrum, a spectrum authority can and should include market-based mechanisms that incentivize incumbents to share spectrum needed by entrants.

Keywords— Spectrum management, spectrum sharing, licensed shared access, unlicensed spectrum.

1. INTRODUCTION

The unparalleled rise of the cell phone and the quiet revolution in data communications brought about by Wi-Fi and other wireless data technologies demand effective management of the spectrum, the foundation of robust wireless markets and innovative wireless services. Spectrum management is defined as the government function that organizes and regulates the utilization, allocation and assignment of blocks of frequencies to minimize interference between uses in neighboring bands. Spectrum management is instrumental in the way governments maximize the value of spectrum, its efficient utilization and its eventual benefits to society. When spectrum management creates opportunities for broader uses of the radio spectrum, it grants Wireless Information and Communications Technologies privileged access to a wider range of economic sectors, possibilities to boost complementary innovations and opportunities to generate important spillover effects.

Spectrum management has evolved from its early focus on interference avoidance [7] to a modern view whereby the SA seeks to maximize its value [6]. Under this view, a SA needs to establish who derives value from using the spectrum and what must be the right measurement of its value. However, spectrum is finite and therefore its management has become more prominent in the last decade. In order to address scarcity and underutilization of spectrum, spectrum sharing – the use of a frequency band by two or more parties - is taking high priority in the agenda of spectrum authorities (SAs) in many countries. Consequently, SAs have initiated reviews of their national guidelines for spectrum management in order to incorporate spectrum sharing into their regular processes of spectrum allocation and assignment. When applied to spectrum sharing the value maximization approach has the potential to enhance the SA's arsenal of policy tools and regulations to increase its effectiveness in allocating the spectrum and its efficiency in assigning it.

Using an economic policy lens and a tutorial-styled presentation, this paper aims to contribute to the discussion on spectrum management by (1) examining existing spectrum sharing schemes through an analysis of exclusivity of assignment and licensing, and (2) introducing a management tool that may address the challenges faced by SAs. Examples of market mechanisms that can be adopted by SAs to achieve increased effectiveness on allocations and effectiveness on assignments are provided to illustrate either adoption of proposed policy (such as a spectrum sharing framework) that empowers spectrum seekers to demand sharing; or band-specific regulations that enable sharing by multiple users, creating conditions for a rich wireless broadband ecosystem.

This paper first introduces and discusses the foundations of spectrum management in Section 2. Next, in Section 3, it defines spectrum sharing and describes particular aspects and modalities of spectrum sharing, including the adoption of renewed approaches to spectrum management that have made spectrum sharing prominent in a handful of countries. In Section 4 the paper argues that if effectiveness and efficiency of spectrum management are necessary conditions to achieve social benefits of spectrum deployment, market-based mechanisms can be used to respond to such challenge and deliver value to spectrum access seekers and end-users. Conclusions are drawn in the last section.

2. SPECTRUM MANAGEMENT

Since the times when radio spectrum was first used to guide ships on their Northern Atlantic routes and later commercially by early radio stations, the need for organizing it in channels without signal interference was

[1] *University of Auckland Business School.*

quickly acknowledged [8]. Minimizing interference and allocating bands to a handful of uses were therefore the focus of early spectrum management. Fast forward to the second decade of the 21st century and the scope, complexity and diversity of tasks associated with spectrum management are daunting. Its modern conception as stated by Cave et al is '*to maximize the value that society gains from the radio spectrum by allowing as many efficient users as possible while ensuring that the interference between different users remains manageable*' [6]. In other words, in addition to interference manageability, spectrum authorities (SAs) seek to allow more users to use spectrum and more value to be derived from it [2], [3].

Currently spectrum management is shifting away from a command-and-control approach to a market-based approach where users and applicants to spectrum licenses act within an incentive-based institutional framework expected to lead to efficient spectrum use. Spectrum management is not confined to policy enforcement, control and dispute settlement on spectrum matters that governments or their designated SAs perform. Private agents can and do manage spectrum as when spectrum managers, also called band managers, are allowed to coordinate spectrum access and utilization for a designated band [14]. Although, the emergence of such agents and other related schemes has been encouraged in a number of countries, this paper is only concerned with spectrum management as directly performed by national SAs. In [9] several private sharing schemes which are not directly managed by a SA are discussed.

When foreseeing the potential commercial use of a band, SAs have typically relied, first, on deciding the type of use the band will be given to, and then, providing a license to one or more operators for its exploitation. The former is known as *spectrum allocation* and the latter is known as *spectrum assignment* [6].

Every SA seeks to avoid excessive interference and therefore keep tight control on allocating spectrum in such a way that similar services tend to cluster in similar bands. The SA is also charged with assigning the spectrum to diverse users. In the early days when spectrum supply exceeded demand, assignment would occur with a straightforward process where the SA would simply fulfil a request to spectrum license by an applicant. As time went by and technological advances started to demand more and more spectrum, lotteries and other administrative processes were used to assign the spectrum. Soon the flaws of lotteries were evident and in a wide range of countries auctions became the mechanism of choice to assign radio frequencies supporting commercial communication services. Auctions became the spectrum management tool of choice for spectrum assignment of commercial communications frequencies; assignment entails licensing in order to protect the holder from undue interference from other spectrum users. Licenses are issued for relatively long periods of time, which assures the licensee stability and certainty about the main input to its commercial activity.

A range of services and applications have benefited from decisions to exempt users of certain bands from licensing. Cordless phones, remote controls and wireless Local Area Networks, for instance, operate without license thanks to those exemptions. The decision to allow for such commons, especially for Wi-Fi technology, opened unprecedented opportunities for innovation in wireless communications. Put simply, it reveals the significance of unconventional efforts to address spectrum utilization.

However, with the rapid growth in the number of wireless devices, especially wireless broadband-based devices, SAs face quite a number of challenges. A renewed approach to spectrum management must acknowledge the rapid pace of technological change, the economic value of spectrum, innovation in spectrum access, and the need for efficient spectrum utilization in a market-driven environment.

Spectrum value should guide decisions about alternative uses (allocation) of spectrum. In the UK a recent report [1] may turn out to be key to our understanding of spectrum value as it identifies three components of value: private user value, private external value and social value. Private user value, also known as the economic value of spectrum, is defined as the present value of the discounted future profits earned by way of using the spectrum [2], [3]. Value is affected by revenues, costs and uncertainty. Private external user value refers to the externalities that arise from the use of spectrum by other users. Social value of spectrum aggregates all expressions of value that are not directly attributable to economic activities that may profit from spectrum. Most social value resides in the spectrum allocated to defense, security and public affairs.

As technologies evolve to allow a more dynamic spectrum access, so must spectrum management evolve to respond to such changes. A key technological innovation that may help spectrum management with adopting a renewed perspective is spectrum sensing. Advances in spectrum sensing such as software-defined radio, and in particular one special type of it, cognitive radio technologies, are capable of providing dynamic access to the spectrum and optimizing spectrum usage by dynamically adjusting radio frequency parameters. Dynamic Spectrum Management is thus seen as the next stage in spectrum management that strives to improve spectrum usage efficiency by fully exploiting spectrum sharing while still attending to optimal uses and users of the spectrum.

Finally, as spectrum availability is low despite sustained progress in spectral efficiency, pressure builds on SAs to streamline access permit processes and authorizations that lead to efficient utilization of the radio spectrum. Allocation and assignment rules encounter information asymmetries between the SA and the parties requesting access to spectrum, calling for consideration of introducing incentive mechanisms. One of such mechanisms, auction, has proven superior to other methods of spectrum allocation and assignment and, although their use has drawn criticisms on grounds beyond those of economic efficiency, the principles underlying auctions should be guiding a modern perspective on spectrum management.

3. SPECTRUM SHARING

The preceding discussion pointed at the need for more spectrum management flexibility since the "command and control" approach has proven to favor a somewhat rigid, long-term exclusive use of the spectrum as demonstrated by the licensing of major cellular telephony services. We have argued elsewhere that such models have contributed to spectrum scarcity [17]. From a technical perspective, a more dynamic spectrum management is possible if and when new techniques that enable the redefinition of radio frequency parameters, such as frequency, modulation or output power are allowed to operate. The combination of new technology, improved radio transmission techniques, and flexible and innovative rules on the use of spectrum facilitate an increasingly alluring aspect of spectrum management: shared use of the spectrum. Spectrum sharing is a spectrum utilization scheme that allows two or more parties to utilize the same range of frequencies while avoiding granting exclusivity to any of them.

Spectrum sharing challenges conventional spectrum management [17] through new technologies or through purely administrative allowances that make it possible for several users to share a band therefore shifting the burden of agreeing to interference-free operation onto those users. As a management tool, in its beginnings spectrum sharing allowed several different uses of the spectrum to operate the same band with strong provisions against interference; eventually some spectrum bands were designated as unlicensed, allowing any device complying with technical parameters to use the band. More recently, technological progress has propelled the deployment of spectrum sharing techniques as described below.

3.1. ENABLERS OF SPECTRUM SHARING

Spectrum sharing is facilitated by both technological enablers and business/operations arrangements. In [12] techniques that enable spectrum sharing are primarily divided into coordinated, which require coexisting radio-frequency (RF) systems exchange information to share the same frequency band, and uncoordinated where RF systems adjust their operation to coexist with other RF systems that have little information to share. Coordinated techniques can be based on properties of the communications infrastructure – as in FDMA, TDMA or CDMA - or can use channel-based control methods, such as CSMA/CA. Uncoordinated techniques include: dynamic channel selection, adaptive frequency hop, listen-before-talk, distributed control power, and cognitive radio.

Business/operations arrangements among spectrum users that rely on standard or advanced technology can also be considered as coordinated or uncoordinated. Businesses that either share roaming or assets, or reach spatial agreements, or agree on usage priority schemes are examples of coordinated sharing. Uncoordinated sharing at the operational level where a multiplicity of broadband providers co-exist and provide access to broadband services is best exemplified by the utilization of the 2.4 GHz and 5.8 GHz bands for Wi-Fi networks and hotspots.

Spectrum sharing is not concerned with licensing per se; rather it is a spectrum utilization scheme that erodes exclusivity in spectrum access and utilization. A conspicuous example is IEEE 802.22, also known as Wireless Regional Area Network or WRAN, a technical standard that includes Cognitive Radio (CR) techniques able to use spectrum allocated to television broadcasters under direct coordination of a central database, which keeps up-to-date information about current band utilization. WRAN is meant to be deployed in rural, low-density geographical areas where broadband access is non-existent. WRAN was the first of its kind as it is meant for the opportunistic use of frequencies associated with TV bands – known as white spaces- while allowing no interference.

A report by SCF Associates for the European Commission analyses the impact of spectrum sharing for several variants that include license-exempt bands, bands shared by licensed and license-exempt applications and, licensed and light-licensed commons [18]. Unlicensed bands such as 2.4 GHz and 5.8 GHz which are used to provide access to Wi-Fi networks and hotspots illustrate a successful case of policy-making that deviated from conventional thinking at the time when exclusive rights to spectrum were strongly supported.

3.2. THE SPECTRUM SHARING LANDSCAPE

A rather simple, yet clear approach to understand spectrum sharing is to consider the two most important decisions facing any SA: does access to the band need to be licensed? And, should exclusive use be granted? The first question has overwhelmingly been answered in favor of issuing licenses for spectrum exploitation, whereas answering the second question has led to exclusive use of spectrum bands. In what follows several approaches to enhancing spectrum management via the adoption of sharing mechanisms are presented. Figure 1, which builds on a simple classification scheme first presented in [4], attempts to represent a view of the spectrum sharing landscape by positioning spectrum sharing techniques within the boundaries provided by the two above formulated questions.

As a prominent case of international experience, the European Commission has established two models for sharing frequencies [10]: CUS or Collective Use of Spectrum, and, LSA or Licensed Shared Access. CUS is a license-exempt mode that allows more than one user to use a spectrum simultaneously and with no requirement for a license; variants of the commons fit within the CUS approach. On the other hand, as stated in [18] LSA combines "*elements of traditional 'command-and-control' spectrum management with a market-friendly approach and innovative cognitive radio techniques*". In a LSA a limited number of parties are licensed to totally or partially use the band under sharing rules which have been approved by the SA and then included as terms in the license.

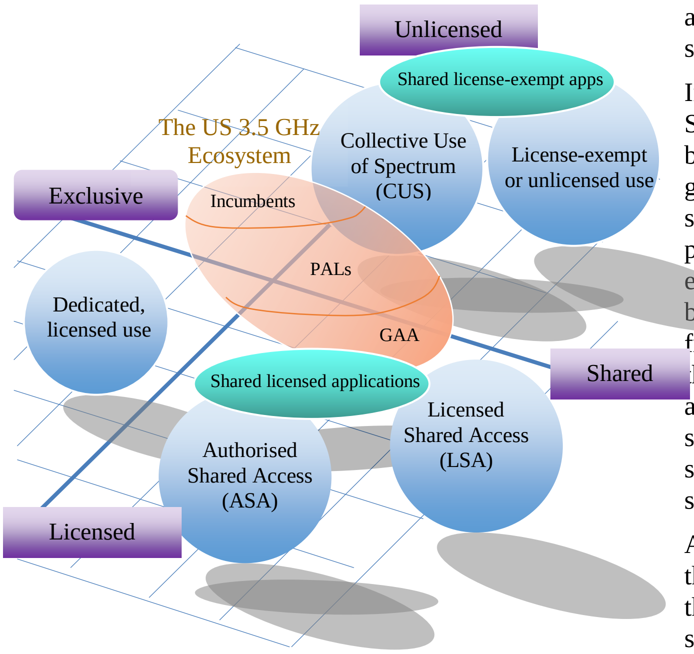

Figure 1: The spectrum sharing landscape

Authorized Shared Access (ASA), a special type of LSA promoted in the European Union, is a mechanism by which a new licensee is granted temporary access to the spectrum already assigned to an incumbent under the prescription that the incumbent does not use it [18]. ASA will allow any access seeker to deploy cognitive radio techniques that will allow it to learn about on-the-spot channel availability. Such scheme requires bilateral negotiations between the new licensee and the incumbent. ASA also allows multiple new licensees access to one or more incumbents' licensed spectrum. Figure 1 shows CUS on the unlicensed-shared domain whereas LSA and ASA lie licensed-shared side.

3.3. ADOPTION OF SPECTRUM SHARING

One of spectrum policy's longstanding questions when commercial use of the spectrum is involved is the identification of the most appropriate licensing mechanism for a new band. The question becomes even more challenging as advances in spectrum access technology reach scale and economic feasibility. With the irruption of spectrum sharing techniques, SAs need to broaden their perspective on spectrum management to enhance their practices on spectrum allocation and assignment. As described below, several SAs have adopted new frameworks that specifically address the spectrum sharing challenge or have issued regulations for spectrum access and use that break sharply with their old approach.

If policy makers and SAs are receptive to spectrum sharing, it may develop as a key spectrum management tool to use, allocate and assign spectrum to achieve the main management objectives discussed above of value maximization and interference minimization. Spectrum sharing has indeed recently found its place into regulatory frameworks promulgated by some SAs. Next we discuss a selected number of cases that, although not uniform in their approach or solutions offered, do reveal a trend towards smarter spectrum management.

In the UK Ofcom has recently released its Spectrum Sharing Framework [15] providing mobile and wireless broadband operators with legal room to initiate a request to gain access to share specific bands. In its framework Ofcom states the process by which a mobile operator or interested party initiate a request to gain access to share specific bands either licensed to incumbents or held by users who have been traditional holders of rights to their utilization. The framework involves three main aspects, namely, 1) stating the characteristics of use for prospective users who seek access to shared spectrum; 2) describing the nature and strength of barriers that may limit the future of spectrum sharing, and, 3) discussing regulatory tools and enablers of spectrum sharing, both at market and technology levels.

A common concern raised by potential new users to SAs is the efficiency with which government agencies use parts of the radio spectrum, indicating too that they would need shared access to such bands. Upon releasing its spectrum sharing framework [15], Ofcom outlined the request process as one by which a mobile operator or interested party initiate a request to gain access to a specific band that has been licensed to an incumbent or held by users such as government agencies, traditional holders of rights. The spectrum access seeker needs to go through two options that precede their sharing aspirations. First, it must have not found any suitable option among the currently available licenses (including license-exempt bands), or, second, found no trading or leasing opportunities. Then, and only then, Ofcom will consider looking into available information to determine whether the request is worth being further investigated [15]. Acknowledging that sharing may be detrimental to a licensee's interests, Ofcom will need to decide when spectrum sharing is economically and technically feasible and how it represents a beneficial alternative to the status quo; otherwise it must maintain the current allocation untouched.

In 2009 New Zealand introduced the Managed Spectrum Park (MSP), a special type of licensed commons that operates in the 2575-2620 MHz band. With such scheme the government has sought to encourage "*a flexible, cooperative, low cost and self-managed approach to allocation and use*" [14] of the spectrum. A MSP allows access to a number of users – usually operators of communication services such as wireless broadband- to the common band on a shared basis and is intended for local and regional services; applicants to a MSP only seek to cover small geographical areas and do not need or want a nationwide license. Sharing may take mainly two forms: it may be that two or three operators split the available bandwidth in such a way that the technical aspects are sorted out by private agreements, or it may consist of a geographical split within the license's region.

In the United States the FCC has designated Citizens Broadband Radio Service (CBRS) the 3.5 GHz band (3550 to 3700 MHz), arguing that it will "*meet the ever-increasing demands of wireless innovation.*" [10] The designation of this band is actually the culmination of a process to establish an ecosystem to propel wireless services in a three-tiered spectrum sharing space. At the highest tier incumbent users, mainly fixed satellite services and terrestrial wireless operations in the upper subsection (3650-3700 MHz), are protected from interference possibly generated by CBRS users. CBRS is actually implemented on the next two tiers and mediated by a Spectrum Access System (SAS). The middle tier, Priority Access, allows Priority Access Licenses (PALs) to use one or more 10-MHz channels for up to three years in the 3550-3650 MHz portion of the band. PALs are interference-protected from emissions from occupants of the third-tier, the General Authorized Access (GAA). Figure 1 displays the CBRS ecosystem as it spans the spectrum exclusivity domain through the licensed sharing and into the unlicensed mode, all of which is enclosed in the 3-tier structure. Old band rules for the 3650-3700 MHz band allowed access for rural broadband, small cell backhaul, and point-to-multipoint networks. The new band integrates 150 MHz of bandwidth, which means a three-fold increase in the available spectrum. In Figure 2 the US 3.5 GHz Ecosystem is shown as a layered framework that spans different domains, on the horizontal plane, as well as a "vertical" hierarchy representing the 3 tiers.

FCC relays ultimate responsibility for development of the CBRS band on to SAS administrators and potential licensees. It believes that the SAS approval process will facilitate interaction with stakeholders to develop such important band features as the bandplan. Figure 2 is an example of how a bandplan would develop. It reveals the composition of the tiered access in each of the two defined subbands.

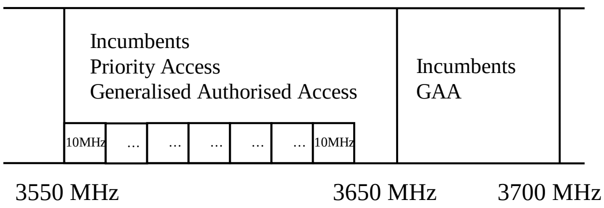

Figure 2**:** US FCC allocation in the 3.5 GHz band (adapted from [10])

For PALs a maximum of 70 MHz, that is seven 10-MHz channels, has been reserved in the band, with the remaining bandwidth available for GAA, or full availability of 150 MHz in areas where no PAL has applied. As FCC states it "*… fixed frequency reservations, coupled with opportunistic access to spectrum for GAA users across 150 megahertz, will increase band access, stability, and predictability for all CBRS users*" [10]. GAA users will access the band on opportunistic basis. Exact frequencies for PALs channels of GAA users are not fixed; instead, the SAS must assign and maintain appropriate frequency assignments, while assuring no interference from a lower tier user on a higher tier user is harmful. FCC's decisions reflect its need for endowing the band with flexibility and higher utility, in short, a higher value expectation for the 3.5 GHz band.

A major issue in the decision-making process, which included a lengthy public consultation, was the trade-off between flexible band management and the predictability and stability of spectrum availability. On one hand the SA opted for channel assignment to PALs with no fixed bands; on the other, it needed to set provisions so that channel assignment would remain stable and consistent within an area and contiguous geographical areas, should a PAL's usage span multiple areas.

The illustrations provided above indicate that SAs are engaging in reviews and/or straight adoption of spectrum sharing into spectrum management practices, even though such process threatens the highly attractive exclusivity of spectrum rights. And it is precisely the irruption of technological innovation that most urgently calls for changes in spectrum management and standardization. For instance, Internet of Things (IoT), the use of systems, and heterogeneous technologies to provide interconnectedness to disparate physical environments will enable the interaction of mobile as well as fixed devices using internet-based applications. While efforts are being developed to define a reference architecture – such as efforts by IoT standardization working group WG03 of the Alliance for Internet of Things Innovation, AIOTI, alongside other Standards Developing Organizations – that must support ubiquitous coverage, very low power operations, and adequate bandwidth, it has been suggested that a license-exempt model might facilitate the rapid development of IoT devices, as it would simplify negotiating access to spectrum.

4. EFFECTIVENESS OF SPECTRUM ALLOCATION AND EFFICIENCY OF SPECTRUM ASSIGNMENT

This section argues that spectrum sharing provides a renewed management tool to increase the effectiveness of allocations and the effectiveness of assignments, and that given market conditions such as the increasing demand for spectrum it will be more easily achieved if market mechanisms are adopted to implement decisions in key stages of the spectrum allocation and assignment processes.

In the context of organizational management, it is suggested in [13] that effectiveness means doing the right thing while efficiency is about doing the things right. A SA that puts spectrum to its best use will be improving, and hopefully maximizing the effectiveness of its decision about spectrum allocation. Likewise, a SA that puts the spectrum in the hands of those who value it most will be improving and hopefully maximizing the effectiveness of its spectrum allocation decision. It is clear, from the evolution of some of the ISM bands – such as 2.4 GHz and 5.8 GHz, originally conceived for applications non-related to telecommunications such as IEEE 802.11/Wi-Fi systems, that allowing non-licensed, open access use of the spectrum can create conditions that demonstrate the effectiveness of some spectrum management decisions.

The typical problem a SA faces is the following: what is the best use that can be given to a given frequency band and who should be entitled – or licensed – to use it? In other words, these questions address the SA's goal of effective allocation and efficient assignment.

As discussed above a SA allocates a spectrum band to a service or services that can occupy the band. International agreements and harmonization in the possible uses of the spectrum have led SAs to designate radio spectrum bands for their utilization by prescribed services, which in many cases must follow technical standards of transmission and interference management. Assignment of spectrum to users follows an administrative process that grants them rights over a number of bands. Spectrum auctions, a form of administrative process for spectrum allocation, are increasingly being accepted by many SAs for assigning spectrum in bands allocated to commercial communications and broadcasting operations.

In considering spectrum sharing a SA would need to ask itself how the introduction of sharing will affect its main spectrum management functions. In particular, it is adequate to wonder what the impact of spectrum sharing would be on allocation and assignment. In some cases, SAs are pressed from different directions to allow new users, particularly wireless broadband operators and other providers of newly developed services to access spectrum bands which are being cleared up from their previous licensees.

We now discuss several cases that provide specific applications of market mechanisms intended to help SAs to improve the quality of their spectrum management decisions that is, enhancing effectiveness of the allocation and increasing the efficiency of the assignment.

The US 3.5 GHz band: The three-tier framework adopted for accessing the 3.5 GHz band or Citizen Broadband Radio Service in the US is a hybrid approach that aims to optimize the utilization of spectrum based on local, instantaneous information about supply and demand. It seeks to balance competitive rivalry for spectrum access with pricing signals applied to the lowest two-tiers. The latter means that when competition for access is low the lowest tier, GAA, is practically an unlicensed band with low-cost entry. Alternatively, if competition is vigorous PALs will engage in an auction which will sort out winners for the geographic area in consideration. Furthermore, the mix of GAA and Priority Access is dynamically managed depending on the conditions of demand to access the spectrum; one major contributor to such flexibility is the fixed-term licensing imposed on the PAL. Not to be left to the market but in order to make it more efficient, the SAS serves as a frequency coordinator. Its main role is to provide higher tier users protection from lower tiers, also acting to optimize frequency use thus allowing maximum capacity and coexistence for both PAL and GAA users.

As competition for PALs is expected – a situation that the Telecommunications Act calls mutually exclusive applications to use a band – PALs will be assigned by competitive bidding, that is, auctions, only when the number of competing applications in a geographic area exceeds the available supply. The rules to be adopted will apply to competitive bidding in the 3550-3650 MHz band. Interestingly, if PAL applicants do not exceed the available supply, no PAL will be assigned. The preference in this case is for spectrum to remain available for GAA use, at least until the next application window for PALs. As the FCC states, "its approach would . . . properly incentivize targeted use of the Priority Access tier by a diverse group of users" [19]. In any case when there are n ($n > 1$) applicants for PALs, the SA will make n - 1 PALs available, up to a maximum of seven. It is the SA's intention to act in the public interest as such decision should promote easy and sufficient access to GAA by many applications while having PALs available for applications that need interference protection as congested environment would degrade their value.

Ofcom's 800 MHz and 2.6 GHz spectrum auction: Building provisions to endow spectrum sharing decisions with market-based mechanisms was attempted by Ofcom with its 800 MHz and 2.6 GHz spectrum auction in 2013. A previous 2012 Ofcom's consultation on the award of those bands gave ample consideration to auction rules that would lead bidders to reveal preferences for wining bands contiguous to bands won by other bidders with whom potential sharing agreements could be reached [16]. The proposal first explored the advantages and disadvantages of allowing bidders to express their preferences consistent with their goal to get blocks of spectrum contiguous to the blocks won by other bidders with whom they would be sharing the spectrum. Bidders would see benefits from pooling resources together, with higher speed and improved quality of service possibly achieved. However, bidders may be exposed to the risk involved in not being able to win the necessary blocks, hence the likelihood of an inefficient auction outcome. This is another instance of collective action that requires coordination between bidders over the course of the auction, an undesirable situation in the context of auction rules that protect anonymity of bidding. In its two-stage auction design Ofcom had proposed three ways to deal with coordination: a) to allow negotiations between winners of the first auction stage, b) to allow joint bidding on the second stage, and c) to allow bids in the second stage contingent on knowing the identity of potential neighbors (neighboring bands). Eventually for its 2013 auction, due to lack of support from respondents and no alternative provisions suggested, Ofcom decided not to facilitate joint bidding or spectrum sharing.

Plausible solution for jointly allocating and assigning spectrum: Back in 2007 several competing parties demanded that the Federal Communications Commission should designate the digital dividend, i.e., those bands left empty by the introduction of digital television in the US 700 MHz band, to their particular uses of interest. On one side, mobile telecommunications operators demanded that those bands be allocated to 4G services and an auction administered to assign extensive geographical licenses. On the other side, new comers – among them information and contents operators as well as some equipment manufactures - demanded that those bands should be designated unlicensed and opened for common exploitation by Wi-Fi services. A solution was explored using experimental work in an auction laboratory to investigate features of a market-based mechanism that would jointly decide allocation and assignment of a number of spectrum blocks. The auction, which was first proposed in [5], would allow both types of potential buyers to bid in an auction whose outcomes would determine who would use the spectrum, and in doing so also deciding the service, as well as the amounts to be paid for the licenses. Since such collective decision problem was expected to lead to free-riding by potential sharers therefore compromising the efficiency of the allocation, the experiments verified such possibility and, most important, quantified the extent to which free-riding occurred under several scenarios. Because of the possibility to freely use the spectrum by anyone after the auction was over in case sharers had won a slight change to the auction design could be introduced to restrict the use of those bands to a closed set of participants interested in operating the frequencies as licensed commons. With such approach a SA can shift the burden of spectrum allocation decision to a market-based mechanism that over the course of a clock ascending auction would simultaneously decide whether a band is to be shared or not, and the price to be paid for a shared license (if shared).

Centralized coordination for opportunistic access: Opportunistic use of a frequency band, as enabled by WRAN technology, requires a centralized database to allow CR-based devices to transmit on TV white spaces. Geolocation databases are accepted as the most promising solution to identify and use TV white spaces spectrum. Establishing and managing, or outsourcing, such a system requires that the SA covers the costs of equipment and administration. ASAs such as this would probably have to be funded, at least partially through license fees but most likely will need to be subsidized as the target population is usually sparse and remotely located from urban centers.

5. CONCLUSIONS

The modern role of spectrum managers has drastically become even more challenging as demand for spectrum has increased remarkably over recent years. Bandwidth-hungry applications and devices seek to get connected over the airwaves in vast numbers but the availability of spectrum is not keeping up with demand. This paper argues that since managerial decisions such as reallocation, clearing of low used bands and refarming are not enough, a renewed role for spectrum sharing needs to be embraced by spectrum authorities. In doing so, spectrum management is continuously expected to serve as the vehicle to maximize the value of spectrum, its efficient utilization and its benefits to society.

Several cases presented here have illustrated new directions for spectrum sharing at the regulatory level. First, SAs need to modernise their approach to spectrum sharing as suggested by the introduction of the spectrum sharing framework in the UK. In other cases, allowing market mechanisms to be deployed for the secondary use of the spectrum can lead to a more efficient deployment of sharing schemes. Also, experimenting with hybrid schemes such as the FCC's decision on a three-tier system for the 3.5 GHz band is a forward-looking decision that will allow enormous flexibility in using the scarce spectrum while protecting long-term users who are not to be reallocated to other bands.

In conclusion, spectrum sharing can enhance the spectrum authority's capabilities with a management scheme aimed to increase the effectiveness of allocations and the efficiency of assignments. Market-based mechanisms are not only conceivable but possibly efficient ways to decide about the best use and user of the spectrum. If spectrum management creates conditions for efficient allocation and assignment through spectrum sharing, it will stimulate the connection between policy and markets that make using the radio spectrum by wireless technologies a pervasive factor in a wide range of economic sectors, a booster for complementary innovations and a generator of important spillover effects.

Acknowledgements: The author wants to acknowledge funding for this work from the University of Auckland Faculty Research Development Fund, FRDF.

A previous version of this paper was presented at ITU Kaleidoscope 2016: ICTs for a sustainable world. Bangkok, Thailand.

REFERENCES

[1] P. Barwise *et al*., "Incorporating Social Value into Spectrum Allocation Decisions", *A report for UK Department for Culture, Media and Sport*, 2015.

[2] C. Bazelon, and G. McHenry, "Spectrum Sharing: Taxonomy and Economics", The Brattle Group, 2014.

[3] C. Bazelon, and G. McHenry, "Spectrum Value", *Telecommunications Policy*, vol. 37, no. 9, 2013, pp. 737-747.

[4] F. Beltrán, S.K. Ray, and J. and Gutiérrez, "Understanding the current operation and future roles of wireless networks: Co-existence, competition and co-operation in the unlicensed spectrum bands", *IEEE JSAC*, vol. 34, no. 11, 2017, pp. 2829-2837.

[5] M.M. Bykowsky, W.W. Sharkey, and M., Olson, "A Market-Based Approach to Establishing Licensing Rules: Licensed versus Unlicensed Use of Spectrum", *US Federal Communications Commission*, *OSP Paper 43*, 2008. https://www.fcc.gov/reports-research/working-papers/market-based-approach-establishing-licensing-rules-licensed-versus

[6] M. Cave, C. Doyle, and W. Webb, "Essentials of Modern Spectrum Management", Cambridge University Press, 2007.
[7] Cisco Systems Inc., "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update 2014-2019", Feb. 2015; http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networkingindex-vni/white_paper_c11-520862.pdf.
[8] R.H. Coase, "The Federal Communications", *Journal of Law and Economics*, 2, 1959, pp.1-40.
[9] L. Cui, M.M. Gomez, and M.B.H. Weiss, "Dimensions of cooperative spectrum sharing: Rights and enforcement", *2014 IEEE International Symposium on Dynamic Spectrum Access Networks*, 2014, pp. 416-26.
[10] European Commission, "Promoting the shared use of Europe's radio spectrum", Apr. 2016; https://ec.europa.eu/digital-single-market/en/promoting-shared-use-europes-radio-spectrum
[11] FCC, "Report and Order and Second Further Notice of Proposed Rulemaking", GN Docket 12-354, 2015.
[12] Y. Han *et al*., "Spectrum sharing methods for the coexistence of multiple RF systems: A survey", *Ad-Hoc Networks*, vol. 53, 2016, pp. 53-78.
[13] J. A. Larbi-Apau, and J. L. Moseley, "Performance-based measurement: Action for organizations and HPT accountability", *Perf. Improv.*, 49, 2010, pp. 7–17.
[14] MBIE Ministry of Business, Innovation and Employment New Zealand Government, "Managed Spectrum Parks Allocation Rules", 2010; http://www.rsm.govt.nz
[15] Ofcom, "A framework for spectrum sharing", Apr. 2016; http://stakeholders.ofcom.org.uk/binaries/consultations/spectrum-sharing-framework/statement/statement.pdf .
[16] Ofcom, "Second Consultation on assessment of future mobile competition and proposals for the award of 800 MHz and 2.6 GHz spectrum and related issues", May 2016; http://stakeholders.ofcom.org.uk/binaries/consultations/award-800mhz/summary/combined-award-2.pdf
[17] PCAST, "Report to the President: Realizing the Full Potential of Government-held spectrum to spur economic growth", 2012.
[18] SCF Associates, "Perspectives on the value of shared access: Final report for the European Commission", 2012.

Author’s biography

Fernando Beltrán received a bachelor’s degree in Electrical Engineering from the Universidad de Los Andes, Colombia, and a Ph.D. degree in Applied Mathematics from the Stony Brook University, The State University of New York, NY, USA. He is currently an Associate Professor with the Department of Information Systems and Operations Management, The University of Auckland, New Zealand. His current research on economics of broadband platforms, spectrum management, including spectrum sharing and spectrum auctions, and agent-based computational simulation has been published in *IEEE Comm Mag*, *IEEE JSAC*, *Telecommunications Policy*, *Journal of Information Policy*, *Springer LNCS*. Currently he is Associate Technical Editor of *IEEE Comm Mag*, Associate Editor of *Advances in Decision Sciences* and International Review Board Member of the *International Journal of Business Data Communications and Networking* (IJBDCN).