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Spectrum management for 5G: assignment methods for spectrum sharing

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Abstract

The current development of fifth generation of mobile communications technology, known as 5G, has triggered intense discussions about proper spectrum assignment procedures to accommodate 5G spectrum needs (LStelcom et al., 2017). In particular, spectrum scarcity and lengthy processes to remove and relocate low-intensity uses have led to a renewed interest in spectrum sharing (PCAST, 2012). Since access to radio spectrum for the provision of commercial mobile communications services, mostly cellular telephony and wireless broadband access, is generally granted by means of exclusive usage rights, a growing stream of research is recognising efficiency gains of allowing spectrum to be shared, questioning the primacy of exclusive access to spectrum (Beltran, 2017).

Against this background, this paper aims to discuss recent international attempts to introduce some forms of spectrum sharing for the assignment of spectrum rights for the fourth generation (4G) of mobile communications technology, in the light of current challenges posed by the fifth generation (5G). Recently, three cases have called or are calling for the award of rights to the shared use of the spectrum. These cases reveal the rationales supporting National Regulatory Authorities' (NRAs) decisions that led or will lead to the assignment of shared spectrum rights. Furthermore, they also reveal specific assignment methods – either proposed or not fully deployed, which this paper uses for its main contribution. The three cases considered for the analysis are: the 800 MHz and 2.6 GHz bands auction planned by the UK regulator in 2013; the Licensed Shared Access (LSA) approach defined by the European Union (EU); and the 3.5 GHz ecosystem developed in the United States (US).

Using an analytical framework for the identification of the adequate spectrum management approach, this paper undertakes a comparison of the abovementioned three cases to draw lessons applicable to the upcoming 5G services.

1. Introduction: renewed interest toward spectrum sharing

The current development of fifth generation of mobile communications technology, known as 5G, has triggered intense discussions about proper spectrum access arrangements to accommodate 5G spectrum needs (LStelcom et al., 2017). 5G is expected to be based on multiple frequency bands, both below 6 GHz, where the current spectrum for commercial mobile communications services is located, and above 6 GHz, in particular in the frequency range between 24-100 GHz (CEPT, 2017).

Traditionally, access to spectrum for the provision of mobile communications services has been granted by means of individual licenses. An individual license is an authorization assigned by a National Regulatory Agency (NRA) to a mobile operator to access, on an exclusive basis, a specific spectrum band, for a limited period of time, under specific conditions attached to the individual license. For instance, an operator may be granted a temporary license of 15 years, for the provision of services nationwide, with the obligation to serve 98% of the population.

The decision to grant individual licenses is grounded in the objective to ensure service providers protection from harmful interference. Exclusive access to a spectrum band ensures that the mobile operator can provide services with certain Quality of Service (QoS), having full control of the transmissions carried over that spectrum band. Notwithstanding the benefits for mobile operators in terms of interference protection, individual licensing has also generated a problem of spectrum scarcity (Peha, 2009).

Although discussions surrounding the potential benefits of spectrum sharing are not new (Peha, 1998), spectrum scarcity and lengthy processes of refarming have recently led to a renewed interest in spectrum sharing (PCAST, 2012). A growing stream of research is questioning the primacy of exclusive access to spectrum, highlighting efficiency gains by allowing spectrum to be shared (Beltran, 2017). In addition, several NRAs have recognised the importance of spectrum sharing to meet the growing demand for mobile communications (Ofcom, 2014; PTS, 2014). Attempts by national authorities to introduce spectrum sharing arrangements have led in the past few years to an increase in spectrum availability to be used for 4G.

Against this background, this paper aims to discuss whether past attempts to implement spectrum sharing for 4G may successfully find application in the context of 5G. In particular, this paper focuses on three cases which have called or are calling for the award of individual licenses for the shared use of the spectrum. The three cases

considered for the analysis are: the 800 MHz and 2.6 GHz bands auction run by the UK regulator in 2013; the Licensed Shared Access (LSA) approach defined by the European Union (EU); and the 3.5 GHz ecosystem established in the United States (US). Using a comparative framework that proposes four steps to the right spectrum management approach, namely, frequency harmonization, technology standardization, type of usage rights, and type of assignment procedure, this paper undertakes a comparison of the abovementioned three cases to draw lessons applicable to the upcoming 5G services.

The rest of this paper is organized as follows: section 2 briefly describes the four-step process to a suitable radio spectrum management approach. Section 3 presents three selected, recent cases that promote flexibility in the use of spectrum. The three cases exemplify many of the issues that surround current uncertainties in how best to manage the radio spectrum for 5G services. In Section 4, the paper brings the three cases into the four-step process presented in section 2 and discuss how each step has been dealt with in each case.

2. A brief introduction to radio spectrum management approaches: a four-step process

A spectrum management approach consists of a number of governing rules for the allocation of radio spectrum frequency bands to specific services and the assignment of radio spectrum usage rights to different spectrum users (Freyens, 2009). While decisions on spectrum allocation are generally taken at international level, spectrum assignment is a national responsibility. NRAs have the responsibility to design and enforce the rules governing spectrum assignment in their national territories (Freyens, 2009).

In 2007, a comprehensive set of criteria was proposed to guide regulators in the identification of the appropriate spectrum management approach (Pogorel, 2007). Building on Bauer (2002), Pogorel (2007) suggests that the decision-making process to identify the right spectrum management approach entails four steps related to frequency harmonization, technology standardization, type of usage right, and type of assignment procedure.

The first step regards the question of harmonization of frequencies. Frequencies are considered harmonized when they are allocated to specific services at international or regional levels. Harmonization is usually preferred as it helps reduce the risk of cross-border interference and facilitate coordination. In addition, harmonization can also be beneficial in terms of lower costs of network deployment and devices. Downsides connected to harmonization may include potential sub-optimal use of the spectrum resource in certain countries. Also, the innovation process may be negatively affected.

The second step requires to consider whether technology should be standardized. Technical standards make sure that the equipment and devices developed for a specific category of services comply with pre-defined technical requirements. Benefits generally associated with standardization includes economies of scale. On the other hand, standardization is said to be preventing the introduction of future technologies.

The third and fourth steps regard, respectively, the choice of the type of usage rights to be granted to service providers and the choice of the assignment mechanism for granting usage rights. With regard to the third step, a distinction is made between exclusive property rights, property rights with easements and collective use. At the assignment level, interference management, the key reason for spectrum management (Cave et al., 2007), has traditionally been carried out by conferring property rights to users, which guarantee a separation between the different users. Nevertheless, it has been suggested by several scholars that if technology can solve the interference problem without the need for exclusive spectrum access, property rights with easements and collective use should be promoted as this would guarantee a more efficient use of spectrum and higher consumer welfare (Noam, 1998; Benkler, 2002; Buck, 2002, Pogorel, 2007; Anker, 2010a).

Assignment mechanisms for granting usage rights are generally classified as administrative and market-based. The third and fourth steps are further described below.

2.1. The third step: deciding between property rights, property rights with easements and collective use

In the case of exclusive property rights, service providers obtain exclusive access to the spectrum resource, with certainty of protection from harmful interference. Several issues are associated with exclusive usage rights, including hoarding and foreclosure of new entrants. Property rights with easements would entail some forms of spectrum sharing between primary and secondary users, taking advantage of technology development. Examples are the underlay and overlay models which describe a situation where secondary unlicensed users are allowed to transmit simultaneously with primary licensed users, as long as no performance degradation of primary licensed users is caused. A basic difference between the two models is that, under the underlay approach, a noise threshold to protect primary users is set, which secondary users are obliged to comply with. An additional example

is the interweave model, also called opportunistic access model, where secondary users can dynamically access licensed spectrum, on an opportunistic basis, when the spectrum is not used by primary users. Secondary users would transmit over spectrum holes in licensed bands, in specific geographical or time domains.

The spectrum commons approach relies on technology to enable simultaneous spectrum use, where use is either self-regulated by its user community or subject to pre-defined rules set by the NRAs (Freyens, 2009). In the case of self-regulation, the concept of common property is also used (Buck, 2002). Common property confers common property rights to a limited number of users, which are in charge of co-managing spectrum usage. The regulator assigns and enforces such common property rights, but it is not responsible for managing the spectrum (Freyens, 2009). In the second case, the term open access (Noam, 1995) is usually used to describe a situation where access to spectrum is unrestricted, meaning that spectrum can be used by various types of services and applications. No usage rights are assigned to users. Nevertheless, users are required to comply with certain rules defined by the NRAs to guarantee equitable access and they may also be asked to pay an access fee (Freyens, 2009). Proponents of the spectrum commons approach claim that technologies such as cognitive radios would undermine the current practice to guarantee exclusive spectrum use (Faulhaber & Farber, 2002).

The major criticism against the spectrum commons approach is known as “the tragedy of the commons”, which describes a situation where a common resource will likely be destroyed if its use is rival and profitable and no one is excluded from its use (Hardin, 1968). Radio spectrum cannot be destroyed, nevertheless, excessive use may cause congestion and interference issues. In an open access approach, no protection from interference is guaranteed, which limits the usability of the spectrum. The tragedy of the commons may be less relevant in a situation of common property approach. Nevertheless, in such situation, potential conflicts may arise between common property owners, which would require resources for the definition of proper enforcement mechanisms (Freyens, 2009). The spectrum commons approach has never taken off as much as hoped for by its proponents, because of the difficulty associated with managing interference between different users (Ofcom, 2014). Although it is often claimed that the tragedy of the commons can be avoided thanks to advanced technologies which enable simultaneous spectrum use without the risk of producing interference, these technologies seem not to be ready for commercial deployment (Cave et al., 2007; Freyens, 2009; Anker, 2010b).

2.2. Deciding between administrative and market-based approaches

Assignment mechanisms are usually classified into two categories: administrative approaches, also known as command and control approaches, and market-based approaches. Since access to radio spectrum started to be managed in the 1930s, the command and control approach has been the conventional way of authorising radio spectrum access and use (Freyens, 2009). Market-based approaches, and in particular auctions, took over the administrative approach since the 1990s, as it was argued that assigning spectrum usage rights by means of market mechanisms would lead to more efficient uses of radio spectrum (Faulhaber & Farber, 2002).

2.2.1. Administrative approach

Under the administrative approach, NRAs grants spectrum usage rights to individual users, specifying portion of spectrum band, spectrum use, coverage areas and power limits, among other things (Freyens, 2009). Traditionally, usage rights were given for free or against a symbolic fee (Freyens, 2009).

When there is limited demand for access a spectrum band, usage rights is given on a first-come-first-served basis (Faulhaber & Farber, 2002). In case of spectrum demand exceeding supply, comparative hearings or beauty contests are held in order to identify the most suitable spectrum users, among competing applicants (Faulhaber & Farber, 2002). Users are selected based on a number of predefined criteria, including available financial resources of the applicants, proposed technical conditions for radio spectrum use and planned infrastructure development and service provision. An additional administrative approach includes the use of lotteries, awarding licences through random selection (Faulhaber & Farber, 2002).

Major flaws are attributed to the administrative approach, including lack of flexibility, political influence and lack of economic and social valuation of spectrum. First of all, the command and control approach lacks the flexibility necessary to respond to changes in market and technology conditions (Freyens, 2009). The administrative approach has also been harshly criticized because potentially subject to political preferences, while insufficient consideration is given to economic aspects of radio spectrum use, failing to make sure that licences are awarded to users who give the spectrum the highest value. Also, little attention is put to the social value of the radio spectrum and the services supplied (Freyens, 2009).

2.2.2. Market-based approach

The market-based approach usually entails the auctioning of exclusive usage rights to spectrum users and the trading of these usage rights in secondary spectrum markets (Freyens, 2009). The main benefit of employing an auction mechanism is to promote efficient spectrum use by allowing interested users to compete for obtaining spectrum usage rights (Madden et al, 2014). The price paid by auction winners for the usage rights is determined by the interaction between spectrum supply and spectrum demand (Faulhaber & Farber, 2002).

Relying on market-based mechanisms to assign spectrum licenses has been instrumental in overcoming flaws of administrative-based assignment procedures such as scarce flexibility to changing spectrum demands and technology advancements, long delays in the assignment of usage rights, and risk of political interference. Auction winners receive licences which authorise them to use a specific portion of a spectrum band, in a specific geographical area and for a limited period of time. By means of auctions, radio spectrum is readily made available to spectrum users, who give the spectrum the highest value. Political influence is considered less likely, because government intervention is limited, to give space to market mechanisms (Noam, 1995).

Notwithstanding successful outcomes in terms of assignment efficiency, spectrum auctions have revealed their limitations. Auctions have been misused by national regulators to pursue the goal of raising revenues. The goal of revenue maximisation may not represent a problem per se, if auction revenues were reinvested in network deployment. However, this has rarely been the case (Noam, 1995).

Unsatisfactory outcomes of spectrum auctions have also been caused by imperfections in the design itself of the assignment mechanism. Over time, regulatory and research efforts have led to a proliferation of auction designs, some of which have often become quite complex (Bichler & Goeree, 2017). Certain auctions have led to very high upfront spectrum fees, restricting the number of participants affording to pay, eventually preventing competition and innovations in services and technologies (Cramton et al., 2011). High auction prices represent a barrier to entry which impede new entrants to compete with incumbent users (Madden et al., 2014). Over time, high spectrum fees have contributed to create oligopoly situations (Noam, 1995). Also, high spectrum fees have been detrimental for investment in network deployment (Cramton, 2013; Madden et al., 2014).

An additional critical issue related to the use of usage rights is exposure to the so-called “tragedy of the anti-commons”. According to this concept, usage rights owners would impede new technologies and services to access the spectrum, even if that is underused by existing owners (Heller, 1998; Hazlett, 2005).

3. Three attempts to promote flexibility in radio spectrum use

Three selected attempts to promote flexibility in radio spectrum management are considered for this study: and the 800 MHz and 2.6 GHz bands auction planned by the UK regulator in 2013; the LSA approach; and the 3.5 GHz ecosystem.

In 2013, the UK’s NRA, Ofcom, attempted to introduce provisions for its two-stage 800 MHz and 2.6 GHz spectrum auction to account for bidding on shared spectrum rights. Ofcom explored the advantages and disadvantages of allowing bidders to express their preferences consistent with their aim to obtain blocks of spectrum contiguous to the blocks won by other bidders with whom they would be sharing the band.

The LSA approach allows two groups of users to share a spectrum band, based on pre-defined sharing conditions included in their individual spectrum rights of use. Currently, major opportunities of application of the LSA approach are envisaged in the case in which existing governmental users would share spectrum with new users providing mobile broadband services. Although trials have been carried out in several EU countries, the LSA approach has not been officially implemented yet. In particular, the discussion is still open as to how individual licences would be assigned to mobile operators. The current understanding is that incumbent users may lease part of their spectrum to new users, for a limited period of time, in exchange for a monetary compensation, based on sharing agreements approved by the respective NRAs (Massaro, 2017). Auctioning LSA has also been proposed (Marsden & Ihle, 2016).

The US 3.5 GHz ecosystem is a three-tiered spectrum sharing space (150 MHz in total) with incumbent users in the upper tier, including federal aeronautical uses, fixed satellite operations and terrestrial wireless services. The second tier features Priority Access Licensees (PALs) and the bottom tier, or General Authorised Access (GAA), allows the opportunistic use of the band by radio devices. A coordination mechanism, the Spectrum Access System (SAS) provides higher tier users with protection from interference caused by lower tier users. Auctions have been proposed as the assignment mechanism for PALs.

3.1. The UK 2.6 GHz band

In 2011, Ofcom proposed to award of the 2.6 GHz band, together with the 800 MHz band, for a total of 250 MHz, expected to be used for LTE technology (Ofcom, 2011). The 800 MHz band was considered ideal for wide-spread and indoor mobile coverage, while the 2.6 GHz band was recognised as a highly desirable band for providing high capacity services to many users in limited geographical areas (Ofcom, 2011). The 2.6 GHz band was considered particularly attractive, as its usage had been commonly identified for International Mobile Telecommunications (IMT) by the International Telecommunication Union (ITU) in all three ITU regions. Global harmonized bands allow to benefit from greater economies of scale (RealWireless, 2011).

Before conducting the award, Ofcom discussed the possibility to reserve part of the 2.6 GHz band for low-power shared use. This idea was justified by Ofcom’s intent to boost competition and innovation. In particular, Ofcom considered it to be particularly attractive to use a portion of the 2.6 GHz band on a shared basis for the provision of mobile services through small cells in limited geographical areas such as residential, indoor/outdoor public spaces and campuses or business parks. Reserving part of the 2.6 GHz band for low-power shared use was meant to facilitate the entry into the retail market of sub-national operators who would be able to coexist in the same spectrum (Ofcom, 2011). Ofcom had already implemented a form of concurrent low-power use amongst multiple operators with the award of the 1781.1-1785 MHz and 1876.7-1880 MHz bands, commonly known as the DECT guard band or low power GSM band. In May 2006, Ofcom awarded licenses to 12 operators which gained concurrent access to 2x3.3 MHz of spectrum. Although technology neutral, most use of this band has been for small area low-power GSM systems (RealWireless, 2011).

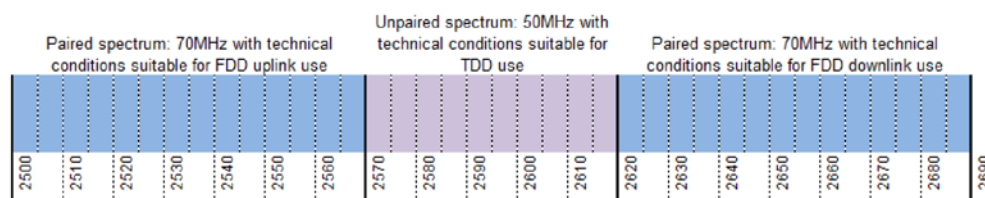
For the 2.6 GHz band, Ofcom decided that access to the 2.6 GHz band would be limited to a restricted number of operators. In addition, operators wishing to provide services in the same areas would be expected to coordinate their shared access to the spectrum (Ofcom, 2012a). According to a study conducted by Real Wireless Ltd for Ofcom, interference between shared access licensees in the 2.6 GHz band could be managed through appropriate technical conditions, including specific power limits; a code of practice licensees would agree upon; and other necessary arrangements, such as the use of information sharing databases (Ofcom, 2011; RealWireless, 2011). In addition, the use of consistent technologies would also contribute to avoid the risk of interference deriving from the use of dissimilar devices. In fact, the 2.6 GHz band was expected to be used for LTE technology although the principle of technology neutrality was in force (RealWireless, 2011).

3.1.1. Combinatorial clock auction for the assignment of rights of use

Ofcom decided to adopt the combinatorial clock auction format (CCA) to assign licenses for the use of the 800 MHz and 2.6 GHz bands (Ofcom, 2011). According to the CCA format, bidders make bids for packages of spectrum lots. A spectrum package can be either won or lost in its entirety. Separate elements of the spectrum package cannot be won (Myers, 2013). The “second-price” rule was adopted, whereby winners of spectrum packages do not pay their winning bids, but the second-placed bids. One characteristic of the CCA format regards the possibility to offer the same amount of spectrum in various mutually exclusive combinations (Ausubel and Baranov, 2017).

The 2.6 GHz band was arranged as 2500-2570 MHz (uplink) paired with 2620-2690 MHz (downlink) for frequency division duplex (FDD) use, as well as an unpaired portion between 2570-2620 MHz for Time Division Duplex (TDD) use, as shown in Figure 1.

Figure 1. The 2.6 GHz band plan (source: Ofcom (2011))



In accordance with the 2.6 GHz band plan, the auction included the following types of lots:

- 2.6 GHz individual frequency lots: 9 lots of 5 MHz each;
- 2.6 GHz paired frequency lots: 14 lots of 2x5 MHz each;
- 2.6 GHz concurrent low power 10 MHz lots;
- 2.6 GHz concurrent low power 20 MHz lots.

Four of the paired slots were planned to be made available either for low-power shared use or for high-power exclusive use (Ofcom, 2012b). In the case of low power use, bids could be placed to obtain licences for the non-exclusive access to a lot of either 10 MHz or 20 MHz (Ofcom, 2012a). Up to 10 different low power operators would be allowed to share this portion of the 2.6 GHz paired spectrum. In the case of high-power use, each licence would give exclusive access to the entire lot (UK Government, 2012).

Ofcom discussed two options to facilitate low-power shared use. The first option regarded the case where only low-power licensees would have access to 2x10 MHz of spectrum, on a reserved basis. The second option featured low-power licensees using a specific lot of 2x20 MHz, where 2x10 MHz would be used on a reserved basis, and 2x10 MHz on an underlay basis, sharing the spectrum with a high-power licensee (Ofcom, 2011: p 100); RealWireless, 2011). Eventually, Ofcom decided to guarantee low-power licensees reserved access to their portion of spectrum. That meant no sharing arrangement between high-power and low-power licensees was envisaged (UK Government, 2012).

Overall, bidders could not propose spectrum packages which included more than one 2.6 GHz concurrent low power lot, be it of 10 MHz or 20 MHz. The final decision between low-power and high-power usage was determined by comparing the sum of bids from bidders desiring low-power lots with the bids from bidders desiring high-power lots (Ausubel and Baranov, 2017).

The auction was held between January and February 2013. After more than 50 bidding rounds over five weeks, the CCA auction was concluded with the award of five national licences. No low-power licences were awarded at the auction (Ofcom, 2013a).

Licensee	Frequencies assigned	Base price	Additional prices	Licence fee paid
Everything Everywhere Limited	796 to 801 MHz and 837 to 842 MHz	£588,876,000	£0	£588,876,000
	2535 to 2570 MHz and 2655 to 2690 MHz		£0	
Hutchison 3G UK Limited	791 to 796 MHz and 832 to 837 MHz	£225,000,000	£0	£225,000,000
Niche Spectrum Ventures Limited	2520 to 2535 MHz and 2640 to 2655 MHz	£186,476,000	£15,061,179	£201,537,179
	2595 to 2620 MHz		£0	
Telefónica UK Limited	811 to 821 MHz and 852 to 862 MHz	£550,000,000	N/A	£550,000,000
Vodafone Limited	801 to 811 MHz and 842 to 852 MHz	£790,761,000	£8,060,020	£802,860,143
	2500 to 2520 MHz and 2620 to 2640 MHz		£4,039,123	
	2570 to 2595 MHz		£0	

Table 1. Award of the 800 MHz and 2.6 GHz bands: final results
(source: Ofcom (2013b))

3.2. The LSA case

The LSA is a regulatory approach aiming to facilitate the introduction in a frequency band of new users while maintaining existing incumbent services (CEPT, 2014a). A limited number of new users would be granted individual licenses to access a frequency band already assigned or expected to be assigned to one or more incumbent users (CEPT, 2014a). The case of bands expected to be assigned to one or more incumbent users refers to the case of vacant bands or bands with expired spectrum rights of use, in which the NRA has the opportunity to include in the licenses granted to the incumbents sharing conditions in order to facilitate the introduction of potential licensed users (RSPG, 2013).

Sharing between incumbent and new users would be enabled by the introduction in the LSA architecture of two functional blocks, called LSA repository and LSA controller (CEPT, 2014a). The LSA repository contains information on spectrum availability, taking into consideration the information provided by the incumbent users on their spectrum usage and requested level of protection. The LSA controller retrieves information on spectrum availability from the LSA repository and ensures that new users use the available spectrum accordingly (ETSI, 2013).

Both incumbents and new users would have exclusive access to a portion of spectrum at a given time and location (RSPG, 2013; CEPT, 2014). Geographical spectrum access sharing could be realized where incumbent users only operate equipment in certain geographic areas, opening up opportunities for additional users to access the same frequency bands in other geographic area. Time spectrum access sharing could take place where incumbents only use their assigned spectrum at certain times. In this case, there might be the possibility for additional users to use the available capacity at other times (RSPG, 2013). Users sharing frequencies on the basis of individual licenses can benefit from regulatory guarantee in terms of spectrum access and protection against harmful interference, thus allowing both the incumbents and new users to provide predictable QoS (CEPT, 2014; RSPG, 2013; EC, 2014). NRAs have to ensure that users abide by their license conditions, setting up clear enforcement procedures (RSPG, 2013).

3.2.1. Key stakeholders

The NRA, the incumbents and the new users are the key stakeholders which must cooperate closely together at national level in order to successfully implement the LSA approach. The incumbent is defined as a current holder of spectrum rights of use (RSPG, 2013). New users are the prospective additional licensees who will share the spectrum with incumbent users. The NRA has a leading role in setting the stage for the implementation and proper functioning of the LSA approach (RSPG, 2013). Taking into consideration international obligations and national policy objectives, the NRA is responsible for identifying those existing incumbent users which are to be kept in the long term (CEPT, 2014a). In addition, the NRA has also the duty to actively identify opportunities for the LSA approach to be introduced. These opportunities may also be identified thanks to contributions, proposals and technical studies from incumbents and/or new users (RSPG, 2013).

Successful implementation of the LSA approach depends on the interests of both incumbents and new users to take part in a sharing arrangement. In order to attract interests of both groups of users, the LSA approach has to provide users with tangible benefits (CEPT, 2014a). The LSA approach offers prospects for incumbents to share costs of investments and maintenance of the radiocommunication infrastructure with new users (RSPG, 2013). Incumbents who are either subject to spectrum pricing or need to deploy improved technologies to enable the use of the spectrum by additional users, may seek financial compensation, to be agreed between the parties (EC, 2012). In cases of incumbents being governmental entities, incentives to share the spectrum may be different as governmental users may not be subject to spectrum fees (RSPG, 2013).

New users can benefit from prompt access to radio spectrum on an exclusive basis, for a predictable timespan, at a given place and time. Predictable conditions of spectrum use are fundamental for new users to invest in network and equipment. In order to make investments, new users need to know exactly when and in which geographical areas a specific set of frequencies will be available, under the entire duration of the sharing agreement (CEPT, 2014a). Predictable conditions of spectrum use are also beneficial for the incumbents to know exactly which new user has access to the frequency band, at a specific time and location (CEPT, 2014a).

3.2.2. The sharing framework

Once an opportunity to implement the LSA approach is identified, the NRA is responsible for setting up a so-called sharing framework, which includes the sharing rules necessary for incumbents and new users to coexist in the same frequency band. The development of the sharing framework requires the involvement of all relevant stakeholders in order to take into account both the present and future spectrum requirements of the incumbents and the demand for alternative usage. Once the sharing framework is set up, existing incumbents' licenses are reviewed in order to identify the spectrum which can be made available for new users (RSPG, 2013). The sharing framework is established, for a given frequency band, taking into account national specificities. This means that the sharing framework for a given frequency band may vary from country to country.

The sharing framework includes coordination mechanisms, compatibility criteria, limitations in terms of timing and locations, spectrum masks, and so forth. The NRA is primarily responsible for defining technical and operational conditions which provide both incumbents and new users with legal certainty regarding spectrum access and protection against harmful interference. Incumbents and prospective new users can foster the development of such sharing framework through bilateral discussions (CEPT, 2014a). All relevant elements included in the sharing framework will depend on a case by case national decision (RSPG, 2013). One key element of the LSA approach is its voluntary character. Implementing the LSA approach translates into changes to the national table of frequency allocation. Therefore, it remains on the remit of each country to decide if and how the LSA approach can be implemented (CEPT, 2014a).

3.2.3. Assignment of licenses to new users

In accordance with the sharing framework established by the NRA, in collaboration with the incumbents and the prospective new users, the NRA sets up the authorization process for the assignment of individual licenses to the new users, taking into account national incumbent users and their necessities (CEPT, 2014a). Countries may look at their particular market structures and take into account desirable national specificities when granting individual spectrum rights of use (CEPT, 2014a; RSPG, 2013). Through the authorization process, a limited number of new users is granted individual licenses to use a frequency band under specified conditions in the sharing framework (RSPG, 2013).

Each country is responsible for designing the assignment process of individual licenses. EU member states are required to act in accordance with the EU regulatory framework for electronic communications, which disciplines that the authorization process has to be conducted in a fair, transparent, proportionate and non-discriminatory manner (RSPG, 2013, Authorization directive, Framework Directive). Nevertheless, each country designs its own authorization process and related features, including the number and duration of new licenses to be granted (CEPT, 2014a).

3.2.4. First practical application: the 2.3-2.4 GHz band for commercial mobile broadband services

Currently, major opportunities of application of the LSA approach are envisaged in the case in which incumbents and new users operate different applications and are subject to different regulatory requirements (CEPT, 2014a). In particular, discussions are ongoing to implement the LSA approach in frequency bands where the incumbent is a governmental user, and the new users provide commercial services (RSPG, 2013). More specifically, the first practical application of the LSA approach will regard the 2.3-2.4 GHz band, which will be used to provide access to additional spectrum for mobile broadband services, within specified geographical, time or technical limits (CEPT, 2014a).

One attractive characteristic of the 2.3-2.4 GHz band is that this band is allocated to mobile broadband services on a co-primary basis in all three ITU regions. Identifying additional harmonized spectrum for mobile broadband services is crucial to guarantee economies of scale, which are considered a key requirement by the mobile industry for the successful deployment of commercial services (RSPG, 2013; CEPT, 2014a). The allocation of the 2.3-2.4 GHz band to mobile broadband services was decided at WRC-07, however, after WRC-07 the spectrum could not be made available in Europe because of the need to maintain long-term incumbent uses (CEPT, 2014b). European countries currently use all or parts of the 2.3-2.4 GHz band for a variety of governmental applications including: telemetry (both terrestrial and aeronautical telemetry); other governmental use, such as Unmanned Aircraft Systems (UAS)); Programmed making and special events (PMSE) applications, specifically Services Ancillary to Broadcasting and Programme Making (SAB/SAP), closed-circuit television (CCTV) and also radio amateur services as a secondary service (CEPT, 2014b; RSPG, 2013). In the context of the LSA approach, the CEPT is currently developing harmonized conditions for the use of the band 2.3-2.4 MHz for mobile broadband services.

The LSA approach is not expected to replace traditional exclusive access. The LSA approach is seen as an additional instrument to be implemented in cases where re-farming of spectrum is impracticable due to incumbent use (CEPT, 2014a). Re-farming requires migration of incumbent systems to alternative frequency bands. The LSA approach gives the possibility to make available underutilized spectrum to other users while maintaining the existing ones (CEPT, 2014a). Under the current individual licensing regimes based on exclusive access, providers of mobile broadband services enjoy clear benefits such as guaranteed QoS and good interference management. Under certain conditions, LSA is expected to provide similar benefits as traditional exclusive access, ensuring that mobile operators have full control of their network performance (CEPT, 2014a).

3.3. The US 3.5 GHz ecosystem

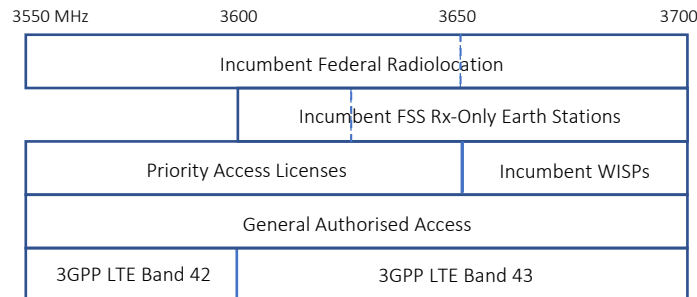
Following the President's Council of Advisors on Science and Technology (PCAST) report (PCAST, 2012) the Federal Communications Commission (FCC) designated the 3550-3700 MHz band as the Citizens Broadband Radio Service (CBRS), also known as the 3.5 GHz band. This decision sought to establish an innovative, sharing-based spectrum utilization environment whereby new services and technologies could find much needed wireless capacity.

3.3.1. Tiered sharing structure and access coordination

CBRS is a three-tiered spectrum sharing ecosystem. The first tier allows use of the band by incumbents: federal aeronautical users, non-federal fixed satellite services (FSS), and wireless internet service providers (WISPs). On the second tier, FCC ruling allows a new kind of actors, the Priority Access Licensees (PALs), which will be using up to 70 MHz in the 3550-3650 MHz band. Finally, the lowest tier consists of those devices which will

opportunistically use the spectrum conforming to the General Authorised Access (GAA) framework. Figure 2 shows the band sharing scheme in the 3.5 GHz ecosystem.

Figure 2. The US 3.5 GHz Ecosystem (source: Google)



The SAS mechanism coordinates such complex arrangement, determining the available frequencies at a given location to be assigned to CBRS devices and the maximum permissible radiated transmission power level (Senza Fili, 2017). The SAS registers and authenticates the identification information and location of CBRS devices, enforcing exclusion zones to protect incumbent operations. It also protects PAL licensees from GAA users' potential interference. In addition, users' transmissions are enabled by the Environmental Sensing Capability (ESC), a complementary module that needs to feed the SAS with accurate information regarding incumbent use of the band. It is also available at all times to answer any queries from the spectrum authority. Initially, a SAS is required when an area is sought for GAA use with an ESC to be introduced later. FCC ruling forbids PALs and GAA operations in areas where incumbents exist, but an ESC does not.

3.3.2. Recent regulatory developments

Satellite terrestrial stations and federal radiolocation stations have been traditionally using the lower part of the 3.5 GHz. As a response to demands from wireless Internet service providers, in 2007 the FCC allowed WISPs to register for the utilization of the 3650-3700 MHz band. Over the ten years after such allowance was decided, WISPs have grown steadily. The current landscape consists of a few large WISPs which can potentially cover very large portions of the US population and a long tail of small and very small wireless providers focused on a few customers on scattered areas.

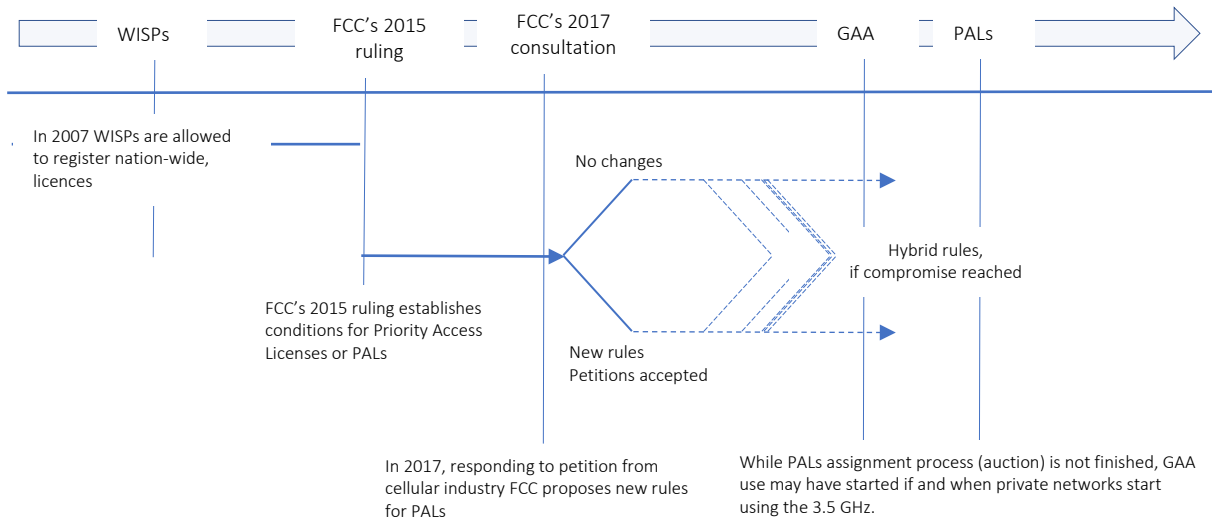
PAL applications are submitted to the FCC for particular geographical areas. Should applications exceed the block availability, the FCC is required to determine the allocation through competitive bidding. FCC 2015 has determined that when there are two or more applicants seeking to get PALs in a given area, the Commission will "force" an auction by making available one less PAL than the total number of PALs in the area. When only one applicant seeks to obtain some blocks, no PALs will be assigned in the area. The latter procedures seek to balance the idea that GAA should be easy to gain against the expectation that, when greater certainty in terms of interference protection is required, PAL blocks should be available. Figure 3 depicts the milestones in the build-up of the 3.5 GHz ecosystem.

As the FCC has ceased accepting applications for WISP registration in the 3650-3700 MHz band, it is expected that established WISPs trade their incumbency status for PALs or start operating under GAA. WISPs have also been further pressed by a recent filing to FCC (FCC 2017) that seeks to change the conditions for competitive bidding from potential PALs. The filing deals with three issues:

1. FCC agreed to consider a new 10-year term and stronger likelihood of renewal as opposed to the original three-year license term for PALs without any guarantee to be renewed. Understandably, the risk of ending up with stranded assets with a relatively short term and no assurances for renewal caused this petition. Not only that, the development of 5G has lately helped make a case for the US to harmonize the band term with a global trend that seeks the 3.5 GHz to be used by 5G services.
2. It has been proposed to replace the Census Tract, of which there are about 66,000 in the US, to Partial Economic Areas (PEA), which number 416 across the country, as the geographical service area that determines the extent of a licence.

- It is also proposed the elimination of the rule that limits the number of PALs made available for a service area. In addition, even if there is only one applicant in a given license area, PALs will be assigned. Originally, the FCC had decided that in areas with no incumbents and where no PAL operates, no PAL would be assigned, leaving the full 150 MHz available for GAA users (FCC 2015)

Figure 3. The road towards a fully shared US 3.5 GHz band (source: Beltran (2017))



The debate about the proposed new rules presents two major contenders. On one hand, the petitioners align with the expectations and aspirations of the large US mobile communications operators, which see in the 3.5 GHz, and particularly in the PALs, needed capacity to deploy 5G networks and services. The opposite side, led by WISPs, expects the FCC to keep its 2015 ruling on the characteristics of the PALs.

As of 2017's end, the FCC seeks views and comments on the proposed changes. It also seeks to learn the market reaction to a set of hybrid proposals that would establish license terms for PALs. The hybrid approach is meant as a trade-off between the two contending camps and it would be conceivable to think that a compromise may be reached whereby a hybrid set of rules applies, depending on the economic characteristics of a given geographical area.

4. A comparative analysis

In this section, the UK 2.6 GHz band case, the EU LSA approach and the US 3.5 GHz ecosystem are analysed based on the four-step decision criteria presented earlier in section 2, which comprises frequency harmonization, technology standardization, type of usage rights, and, type of assignment procedure. A comparison of these three country cases is conducted to draw lessons applicable to spectrum management for the upcoming 5G services.

4.1. Lessons from recent experiences

According to the decision-making process proposed by Pogorel (2007), the first step for the identification of the right spectrum management approach requires NRAs to understand whether spectrum should be harmonized. Spectrum harmonization has traditionally been considered fundamental for the provision of mobile broadband services, as it would reduce the costs of equipment and facilitate international roaming. This is reflected in the choice of the spectrum bands in the UK and LSA cases, respectively the 2.6 GHz and the 2.3-2.4 GHz bands. In fact, these bands are globally harmonized for IMT. Conversely, the 3550-3700 MHz band upon which the FCC created its 3.5 GHz ecosystem is not globally harmonized. Although not globally harmonized, the 3400-3600 MHz frequency band is allocated to IMT on a co-primary basis in almost all countries throughout the world (Huawei, N/A; Huawei, 2016).

For the next step the NRA decides whether technology should be standardized. In the matter of mobile cellular technology, there has been an increasing engagement in technology standardization processes. Technical standards are considered essential for guaranteeing reliability and interoperability, and for economies of scale. In

the UK and Europe’s LSA cases considered for this analysis, the objective was to facilitate the provision of mobile broadband services by means of LTE technology.

	HARMONISATION	STANDARDISATION	USAGE RIGHTS	ASSIGNMENT
UK 2.6 GHz band	Yes	Yes	Common Property	Market-based
LSA approach	Yes	Yes	Easements	Market-based Sharing agreement
US 3.5 GHz ecosystem	No	Yes	Easements	Market-based

Table 2. The four-step decision making process in the three selected cases

In the third step, a choice has to be made by the NRA with regard to the type of usage rights to be granted to service providers. In the three cases discussed in this paper, the respective NRAs made different choices with regards to the type of usage rights. In the UK case, Ofcom attempted to implement a common property model, whereby common property rights would be awarded to a limited number of users, which would be in charge of co-managing spectrum usage. In the LSA approach, individual usage rights would be awarded, including pre-defined sharing conditions. In the US case, the FCC envisions different forms of usage rights with easements, for PAL and GAA users.

Finally, the assignment mechanism for granting usage rights has to be chosen by the NRA. It is generally believed that market mechanisms should be implemented in cases where spectrum demand exceeds supply. In the UK, an auction was set up to assign usage rights for the collective use of certain spectrum lots in the 2.6 GHz band. This case is interesting because when collective use of spectrum is in place, assignment mechanisms are generally absent. A different case is that of the LSA, where there is still no clear understanding as to how usage rights should be awarded. Although the auction possibility is under consideration, there may also be the case that licences would be awarded by administrative means, based on a cooperative work between the NRA, the incumbents and the new users. In the US case, FCC has ruled that as long as more than one operator is interested in becoming a PAL the assignment procedure is based on auction. Currently, the FCC is reviewing the conditions established on its 2015 decision because of petitions from major telecommunications companies who would like to see changes in the pre-auction conditions; as expected, current incumbents, mostly WISPs, are opposed to such changes.

Table 2 summarizes the major findings of our analysis, whereby the four steps proposed in Pogorel (2007) have been assessed for each of the country cases.

4.2. How is 5G affecting the regulatory approach to spectrum management?

It is expected that 5G networks will provide a wider range of services, so diverse that a classification has been suggested to reduce the complexity associated with the rich environment 5G intends to provide. In particular services have been categorized into:

- Enhanced mobile broadband (eMMB);
- Mission-critical services (MCS);
- Massive machine-type communications (mMTC).

Figure 4 displays a scheme developed by ITU’s recommendation M2083 with the three service categories as three vertices of a triangular service map with a growing core of communications models. It also highlights map points characterized by low cost, low latency and very high-speed services.

As of mid-2018, the 3rd Generation Partnership Project (3GPP), a collaboration between groups of telecommunications standards associations, has not yet released their radio interface standards, which will be known as 5G New Radio or 5G NR. These standards are critical to the requirements demanded by emerging mobile broadband services such as streaming high-definition video and virtual/augmented reality, among others.

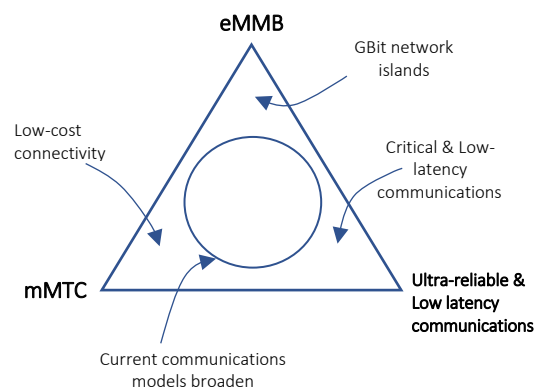
5G NR proposes the following array of bands vis-à-vis the expected services (Qualcomm, 2017):

- Low-bands below 1 GHz for mobile broadband and IoT: 600 MHz, 700 MHz, and 850/900 MHz
- Mid bands 1 GHz to 6 GHz: wider bandwidth for eMMB and MCS: 3.3/3.4 GHz, 3.6/3.8 GHz, 4.4 – 5 GHz
- High bands above 24 GHz: very high bandwidths: 24.25 – 27.5 GHz, 27.5 – 29.5 GHz, 37 – 42.5 GHz

Key allocation and assignment concerns clearly emerge from such generic array. For instance, the speed with which bands need to be cleared up for its furnishing to suit 5G demands, especially low frequency bands that are currently being occupied, is a clear point of contention. IoT devices vendors and operators need to get assurance of the band availability in a very short time, which may not sit well with the speed at which regulatory proceedings and decisions are carried out.

Experts, industry insiders, analysts and commenters all agree that a great deal of spectrum is needed for the upcoming 5G services: low-band spectrum below 1 GHz, mid-band from 1 to 6 GHz and high-band such as the spectrum above 24 GHz. These bands will need to support eMMB, mMTC, and MCS such as autonomous vehicles, critical infrastructure management, remote medical procedures and the like. What this means is that 5G services are indeed heterogeneous with vastly different requirements. In addition, given the scarcity of spectrum facing any new service demand, 5G will be required to use a broad and flexible array of spectrum opportunities not wedded to licensed spectrum but over a wider range of spectrum bands, possibly across opposite regulatory paradigms.

Figure 4. Diversity of application-specific requirements in 5G (source: ITU-R Rec. M2083)



Thus, not surprisingly, spectrum management needs to be understood as going beyond a single approach and instead it needs to consider, in ways that may have not been devised yet, licensed, shared and unlicensed spectrum arrangements. In recent years leading manufacturers have trialed and continue to trial spectrum sharing technologies which include LTE Unlicensed (LTE-U), LTE Wi-Fi Aggregation (LWA), Licensed-Assisted Access (LAA) and Licensed Shared Access (LSA). These technologies may contribute to alleviate the pressure built on spectrum supply and, at the same time, demand higher regulatory comprehension of the best approach to spectrum assignment for 5G.

With the main service types and band availability issues for 5G above identified, the paper now turns to identify the key questions that arise from considering the four steps in the decision-making process proposed by Pogorel (2007), towards a suitable spectrum management approach.

First of all, given the enormous efforts that needs to be put into the production of standards for 5G and because a final 5G NR draft has not been released yet, we put aside the issue of standardization. Thus, the ensuing analysis refers to harmonization, usage rights and assignment procedures.

Efforts to move faster with spectrum harmonization for 5G services seem to start with consideration for the 3400-3800 MHz band. In Europe, the Electronic Communications Committee, ECC, mandated a review for harmonization of technical conditions for spectrum use in the band. The result, drafted in the ECC Report 281, names the 3400-3800 MHz band as the primary spectrum band, in the 1 to 6 GHz range, for the introduction of 5G mobile/fixed communications networks. The report is an assessment of the existing frequency arrangements, in fact a regulatory framework, and presents the definition of the most appropriate frequency (unpaired) arrangement for 5G in the 3400-3800 MHz band. It does a thorough description of how interference will be handled based on TDD requirements, as coexistence in the band is a serious concern. Finally, from a regulatory perspective, ECC considers no need for separate frequency arrangements.

Determining the optimal usage rights for a given band is a very challenging issue. It is clear that cellular incumbents very much prefer a regime that awards exclusive rights, hence, the status quo represented by the administration

of auctions. However, it is yet unclear that a usage rights regime would apply only depending on whether the band is a low band, a mid-band or mmWave.

The US 3.5 GHz ecosystem is a spectrum sharing environment, whereby usage rights depend on the tier to which the spectrum user belongs. The mix allows tiered usage rights that protect higher tier users from interference originated in transmissions from lower tier users. As cellular operators seek to become tier-2 users or PALs in order to provide 5G services, the traditionally held spectrum exclusivity is no longer a characteristic. To be fair, largely extended parts of the continental US will pose no problem to a tier-2 user as tier-1 users are absent.

A recent theoretical result in (Gupta et al, 2016) about the use of mmWave for 5G service establishes the feasibility of uncoordinated sharing of spectrum among cellular mmWave operators due to the directionality of transmission and the short transmission distances mmWavelengths display. The scenario analysed in (Gupta et al, 2016) is a multi-operator mmWave system where every operator owns a spectrum license and has to share complete rights over the licensed band with other spectrum users.

What these situations illustrate is that regulation and technology are making progress towards facilitating spectrum sharing and with it moving the use of spectrum towards higher efficiency. In one case it is regulation by means of promoting and allowing spectrum use environments with centrally controlled coordination, and in the other, it is technology and the properties of transmission on a particular band, i.e., on mmWaves.

Perhaps the major question, once harmonization decisions have been reached and a set of frequency bands is then considered 5G-ready, is who is to obtain usage rights on those bands. Major telecommunications providers, in particular cellular giants, vie for auctions, mainly due to the experience already gained on previous assignment procedures of such kind, their financial muscle, and the fact that most auctions have assured exclusivity in the exploitation of the radio spectrum.

With all potential 5G bands being geared towards commercial services (eMBB, mMTC or MCS) NRAs and spectrum authorities will most likely administer auctions for the assignment of 5G bands, notwithstanding the fact that spectrum sharing high precedence as an effective, realizable spectrum utilization form. The cited UK case, although not seeing actual implementation in an auction mechanism, has shed light on a specific proposal for endogenizing the determination of who gets to share the spectrum. The key idea is to encourage bidders to reveal preferences for winning bands contiguous to bands won by other bidders with whom potential sharing agreements could be reached (Ofcom, 2012b). In essence the key proposal is to benefit bidders from pooling resources, so achieving higher speed and improved quality of service, while being aware of the risk they get exposed to in not possibly winning their preferred spectrum blocks (Beltran, 2017). In short, given the rising pressure exerted over existing spectrum in most countries, the adoption of a market mechanism able to remove the spectrum sharing question off the NRA's shoulders and pass it on to the market needs be seriously considered.

5. Conclusions

Using an analytical framework for the identification of the adequate spectrum management approach, this paper undertook a comparison of three spectrum management country cases that recently have allocated and assigned bands which either conferred shared rights for spectrum allocation or considered an assignment procedure that would have led to a shared spectrum arrangement. The cases were intended to draw lessons applicable to the upcoming 5G services.

They reveal varying degrees of consideration and assessment of the four steps in spectrum management. While it is observed that standardization is a commonly accepted ex-ante requirement for effective spectrum decisions, not all cases coincide on their approach to harmonization, usage rights and assignment procedures. However a trend seems to emerge towards easements in usage rights and market-based methods for spectrum assignment. The paper ends with a specific discussion on 5G that builds upon the preceding analysis.

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