Understanding the current operation and future roles of wireless networks: Co-existence, competition and co-operation in the unlicensed spectrum bands

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Abstract—Technology and policy are coming together to enable a paradigmatic change to the most widely used mechanism, exclusive rights, which allows mobile telecommunications operators to use the radio spectrum. Although spectrum sharing is not a new idea, the limited supply of spectrum and the enormous demand for mobile broadband services are forcing spectrum authorities to look more closely into a range of tools that might accelerate its adoption. This paper seeks to understand how co-existence and co-operation of Wi-Fi and cellular networks in the unlicensed spectrum can increase the overall capacity of heterogeneous wireless networks. It also reveals the challenges posed by new uses such as machine-to-machine communications and the Internet of Things. It also brings together two major proposed regulatory approaches, such as those by the UKs Ofcom and the European Commission, which currently represent leading efforts to provide spectrum authorities with robust spectrum sharing frameworks, to discuss policy tools likely to be implemented.

Index Terms—Spectrum sharing, Unlicensed spectrum, Wi-Fi, Cellular Networks, LTE, 5G, Spectrum auctions.

1 Introduction

WIFI and cellular networks have been the main technological developments employed to serve wireless users, having been supported by different groups and progressed through standardisation routes in different ways. The increasing limitations around licensed spectrum for cellular networks have motivated industry-based and academic researchers to look at the opportunities for co-existence, competition and co-operation in the unlicensed spectrum bands. As network densification, a consequence of cellular systems growth, results in an increase in interference, better use of underutilised spectrum is an attractive option. Research has shown that with the use of suitable mechanisms and interference avoidance schemes, heterogeneous and small cell networks can improve their capacity by sharing Wi-Fi spectrum without degrading the performance of those networks [1]. This type of work has included the bands that are currently being used by Zigbee and Wi-Fi networks. In 2014, average smart phone usage grew 45 percent worldwide, the number of mobile devices grew 72 percent, and global mobile data traffic grew 69 percent [2]. Demand for mobile data is expected to continue to rise as data intensive technologies and vehicular communications hit the market. Amongst both operators and vendors alike, small cells (pico cells and femto cells) have been considered as a promising solution to improve local capacity in traffic hotspots, thus relieving the burden on overloaded macro cells; however, additional solutions will be needed as the planned large-scale rollout of small cells is likely to encounter problems related to, potentially severe, co-channel interference between small cells and macro cells. By 2020, overall mobile data traffic is expected to increase by a factor of ten, demand in certain congested urban areas is expected to increase by a factor of 1000, and the number of connected mobile devices is expected to reach 50 billion. These trends will largely be driven by the Internet of Things (IoT) and Machine-to-Machine (M2M) technologies [3]. This demand increase must be met with an equal industry and government response because existing networks are not capable of providing the requisite capacity [2]. In view of all of this, the wireless industry is examining the efficient utilization of all possible spectrum resources including unlicensed spectrum bands to offer ubiquitous and seamless access to mobile users [4]. The unlicensed 2.4 GHz and 5 GHz bands, the latter with up to 500 MHz of available spectrum - that Wi-Fi systems operate in have been considered as important candidates to provide extra spectrum resources for cellular networks.

This paper unfolds as follows: section 2 reviews the main characteristics, recent evolution and technical highlights of two main contenders for spectrum: Wi-Fi and LTE. Section 3 discusses the main features of spectrum sharing, highlighting the importance of a suite of technologies and policy-based schemes that may facilitate its adoption; this section also presents approaches to regulatory decisions about ways to allow licensed or unlicensed use of spectrum sharing

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arrangements. In Section 4 the paper discusses co-existence and cooperation in the context of Wi-Fi, Zigbee, Bluetooth and cellular technologies sharing the spectrum. In section 5 recent technological advances in LTE, M2M technologies and IoT, which press for release of further spectrum bands to be shared with incumbent uses, are presented. Finally, Section 6 presents an analysis of the economics of spectrum sharing including spectrum value as a paramount economic concept upon which spectrum sharing decisions will be made, and illustrative examples of market-based mechanisms that would allow a market solution to spectrum sharing. In Section 7 conclusions are drawn.

2 Wireless Networks Technologies

Two main wireless technologies, originally conceived as two unrelated standards, Wi-Fi and LTE, are now becoming contenders as consumers regard them as substitutes, to some degree, and as competitors for spectrum, as advances in LTE currently target the 5 GHz unlicensed band, which has potentially up to 500 MHz of spectrum available. In most countries, the regulatory requirements of 'Listen Before Talk' in unlicensed spectrum mandate standard modifications, while in countries like the US, Korea and China, deploying LTE-A in unlicensed spectrum does not require changes to the existing LTE-A standards [1]. This section discusses current progress in Wi-Fi and LTE.

2.1 Wi-Fi

In the United States the FCC decided to make 100 MHz of spectrum in the 5 GHz band available for unlicensed Wi-Fi use, giving carriers and operators more opportunities to push data traffic to Wi-Fi networks. Wi-Fi access points have even been regarded as a distinct tier of small cells in the overall architecture of Telco-operated cellular networks. However, since Wi- Fi systems are wireless local area networks (WLANs) based on the IEEE 802.11 standards, they have usually been designed and deployed independently from the cellular networks. Now that diverse actors, including the 802.11 wireless industry, the telecommunications operators and the vendors of telecommunications gear are researching into the unlicensed spectrum currently used by Wi-Fi systems for LTE/LTE-A and future (e.g. 5G) cellular systems, the coexistence and inter-operation of Wi-Fi and cellular networks have become a distinct and active area of research and development while a thriving market for test-bed equipment is flourishing. These days, most mobile devices such as portable game systems, smartphones and tablets support Wi-Fi connectivity, while the proliferation of Wi-Fi access points continues unabated. The IEEE 802.11 standard has been extremely successful and it is widely adopted. From its beginnings in 1999 with the 802.11b version and with data rates up to 11 Mb/s, the standard has been evolving to support an increasing range of applications which demands higher data rates and improved security features (among a number of other developments). The 802.11g version was introduced in 2003 and it adopted OFDM as its modulation technique. This technology change upgraded the data rates to up to 54Mb/s. The 802.11n standard, published in 2009, is designed to support data rates of up to 600 Mb/s and it achieves that steep change by adopting multiple-input multiple-output (MIMO) antennas and by doubling the channel widths to 40MHz. The most recent version of the standard is the IEEE 802.11ac, which was published in 2013, and it supports data rates of up to 6.9 Gbps. 802.11ac uses the 5GHz band and this time the channel widths have been increased to 80 and 160 MHz. Finally, the ongoing work on the 802.11ah version is designed to support operations in the sub-1-GHz frequency spectrum for applications related to metering, sensors and the Internet of Things [5].

The Wi-Fi access point density in developed urban areas has reached over 1000 per square km and ubiquitous Wi-Fi networks are playing an increasingly important role in offloading data traffic from the heavily loaded cellular networks, especially in indoor traffic hotspots and in rural and other poor cellular coverage areas.

2.2 LTE

The proliferation of mobile devices and diverse applications worldwide has led to phenomenal growth of mobile data, a considerable chunk of which is carried by the LTE networks. According to recent reports from ABI Research, Global LTE subscribers are expected to exceed 3.5 billion by 2020. Qualcomm forecast says 65% of the worlds population is expected to have an LTE coverage by 2019.

Since its inception with 3GPP Release 8, LTE has evolved through multiple releases (Release 8-13) and has developed steadily over the years offering significant user capacity, unprecedented data rates and high standard quality of experience for services. Release 8 in 2008 introduced an all IP core system architecture for LTE along with a data rate of up to 300 Mbps DL and 75 Mbps UL. Release 9 followed in 2009 with multiple unique features like LTE femtocells, self-organizing networks, evolved multimedia broadcast and multicast services and location services. Release 10 in 2011, along with offering higher capacity and throughput, also introduced key features like the enhanced inter-cell interference coordination and carrier-aggregation (CA) to facilitate more efficient usage of the spectrum bands to increase capacity. From Release 10 onwards the technology is termed as LTE-Advanced. Release 11 in 2013 was mostly about refinements to existing LTE-Advanced capabilities, while Release 12 in 2014 offered salient features like enhanced LTE small cells for heterogeneous networks (HetNets), inter-site CA and interworking between LTE and Wi-Fi or HSDPA. All this vast array of features offered by the different 3GPP standards has not only enabled new services and bring greater efficiencies for networks and devices, but also paved the way for the future 5G era, where LTE is set to play a lead role.

From the current 3GPP Release 13 and beyond for LTE, it is known as 4.5G LTE Advanced Pro or just LTE-AP with a development timeframe between 2016-2020. Few of the key features of this release include enhanced CA to handle up to 32 carriers in UL and DL, enhanced signaling for inter-Evolved Node B Coordinated Multi-Point, enhanced device-to-device communication support for out-of-coverage and multi-carrier discovery, enhanced support for machine-type communication and License Assisted Access (LAA), which is the technique to combine licensed and available unlicensed spectrum to provide greater capacity for more user traffic as well improved data rates [6], [7].

Work on LTE Release 14 emphasizing on the future 5G technology has already started with an expected completion date around the middle of 2017 followed by the 5G focused Release 15 around 2020 or beyond [8]. Along with enhancing the current Release 13 capabilities, some of the key planned features of Release 14 include: enhanced LAA (eLAA); provision of full support for UL transmissions in unlicensed spectrum; support for V2X services for autonomous and safer driving; extending the development and testing of current Massive MIMO framework to include more than 16 antennas; achieving significantly lower latency for improved LTE end-user experience and enhancements for mission critical systems like multimedia broadcast supplement for public warning system and Mission Critical Video over LTE. LTE is driven by the ever growing need for a variety of data services that require high data rates, low latency and significant bandwidth to match the high streaming rates and QoS expectations from users. Being a mobile broadband system operating in the exclusive licensed spectrum has definitely been an advantage for LTE so far. However, availability of licensed spectrum is costly, limited and not enough to meet the requirements of the mammoth increase in mobile broadband traffic load. So, available spectrum in the unlicensed bands is currently considered for the growth of LTE.

3 Spectrum Sharing

Being a scarce resource spectrum needs to be managed so that its allocation and eventual assignment by telecommunications regulators and spectrum authorities across the world becomes a determinant factor for the success of wireless broadband services.

Assigning spectrum to interested parties has typically operated on an exclusive basis: use is granted to a single user who is conferred property rights for a limited number of years through a license issued by the respective spectrum authority. The license entitles its user to an interference-free operation of the allocated bands. It is common now that operators of wireless services compete for the right to gain spectrum licenses in spectrum auctions. Auction-based competitive spectrum allocation plays a definitive role in shaping the mobile telecommunications markets and, as it has become the conventional mode, may also be a factor that forecloses the emergence of alternative, plausibly more efficient, new modes of spectrum utilization.

Spectrum authorities have designated some bands as unlicensed, which means a license is not required to use them; in fact, those unlicensed bands can be freely used as long as the technology that uses them abides by approved standards.

A growing body of theory argues that a different approach, which combines licensed and unlicensed approaches to spectrum assignment, may lead to substantial gains in social welfare possibly brought about mainly by innovative uses.

One such innovation in the utilization of spectrum is to share the spectrum. Spectrum sharing is a concept that refers to an arrangement by which two or more parties utilize, or are authorized to utilize, the same range of frequencies. Using the frequencies does not confer exclusivity to any of the parties. Through spectrum sharing vast amounts of unused or little used and affordable communication spectrum can be made fast available to accommodate new users, new services and new infrastructures for businesses wherever needed.

In recent years several technologies have been developed to make shared use of the spectrum possible; technological progress in the field has consisted of providing transmitting sensing modules with more intelligent ways to decide when to use the spectrum. Thus, many spectrum sharing techniques rely on time-based usage. For example, Dynamic Spectrum Access (DSA) technologies enable devices to dynamically sense and detect a frequency or time slot to use without interfering with other devices sharing the same spectrum. Similarly, facilitated by the use of spectrum databases, geolocation database technologies enables devices to identify spectrum across different frequencies available for sharing without causing interference to other devices using the same spectrum. More intelligent transmission systems can also vary the transmission power depending on the information they obtain about other authorized transmitters sharing the frequency band. By changing the transmission power of the signal intelligent transmitters can avoid interfering with others.

While technological progress promises to overcome the many challenges posed by spectrum scarcity, in general, and spectrum sharing in particular, allowing different spectrum sharing arrangements challenges the conventional regulatory machinery currently in place in most countries, which has largely only able to conceive spectrum as a public good that must be licensed on an exclusive basis. Spectrum sharing has the potential to become a powerful alternative that may overturn the status quo in spectrum management. Accordingly, spectrum sharing embodies the potential to enhance spectrums efficient use in response to the increasing demand represented in a myriad of new end-user devices for person-to-person and machine-to-machine communications.

Spectrum sharing is now facilitated through the use of some technological advances in spectrum sensing such as software defined radio and cognitive radio technologies. Both are considered enablers of spectrum sharing. As software defined radio grows in popularity so does the need for geographical databases that would need to be deployed if opportunistic access on a secondary user kind of approach is allowed by a spectrum authority. But it is not only technology that may enable users to share the spectrum. Information about the current state of spectrum use in a geographical area is also regarded as an enabler [9]. In addition spectrum authorities may too deploy incentive schemes through market mechanisms to promote more efficient use of the spectrum.

Setting aside the dedicated, licensed mode of using the spectrum, which is favoured by the mobile telecommunications industry as it provides exclusive use of spectrum rights there are different ways, either being used or being proposed, of providing alternatives to exclusivity in accessing the radio spectrum.

According to a report hired by the European Commission [10] access to shared spectrum includes license-exempt bands, bands shared by licensed and license-exempt applications and, licensed and light-licensed commons.

Figure 1 displays a schematic relation between different ways of approaching unlicensed use of spectrum, which consequently allows shared use, as well as ways in which sharing is allowed through licensing. In this so-called spectrum access mode landscape two dimensions of the problem are considered: usage exclusivity and licensing. The resulting plane accommodates three main categories which are likely to co-exist if spectrum authorities commit to renovate their approach to spectrum utilization.

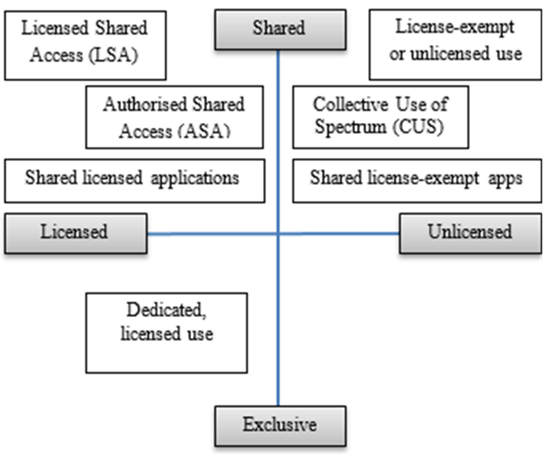

Fig. 1. The spectrum access mode landscape

In Europe, the European Commission has established two models for sharing frequencies:

1) CUS, Collective Use of Spectrum, and,
2) LSA, Licensed Shared Access

CUS is a mode that allows spectrum to be used by more than one user simultaneously without a license [11].

In LSA a limited number of parties interested in a frequency band are allowed to totally or partially use the band under sharing rules that have already been included in the rights of use granted to the licensees . In this case the rules must be first approved by the spectrum authority and then made part of the license conditions. LSA combines traditional command-and-control management with the need to share spectrum.

A variant of LSA is the Authorised Shared Access (ASA) that allows a new licensee temporary access to the spectrum already assigned to an incumbent under the prescription that the incumbent does not use it [10]. ASA prescribes using cognitive radio techniques that help the new licensee learn about channel availability and requires bilateral negotiations between the new licensee and the incumbent. In fact ASA is not restricted to a single licensee-incumbent pair, allowing multiple new licensees access to one or more incumbents licensed spectrum.

By allowing a spectrum band to be shared a SA seeks to increase the efficiency with which the band is used. Such decision needs to be assessed in order to obtain the evidence that will prove the solution to be beneficial. Several metrics can then be used, including utilisation, throughput, collision rate and access control delay (also called overhead). We argue that such metrics do not necessarily raise the same concerns to the involved parties and therefore they can be selectively used to evaluate policy and quality issues; for instance, a SA is concerned with the efficient use of the spectrum, thus, utilisation is of high concern to a SA. Throughput, on the other hand, would be a direct concern to the sharers in a particular band; in effect, while throughput of applications delivered by an operator will impact the quality of its services, the efficacy of the sharing regulatory framework is also dependent on such metric being acceptable to the sharers. Table 1 displays a proposal to defining metrics that assess sharing arrangements.

TABLE 1
A collection of metrics that help evaluate a sharing agreement and whose perspective is most directly involved

Spectrum authority	Spectrum Sharers
• Spectrum utilisation: use of spectrum (including prime/secondary spectrum sharing schemes) should be maximised as a result of allowing a spectrum band to be shared	• Throughput: each sharer expects it to be maximised • Collision rate: each sharer expects very low rate • Access control delay: this overhead in obtaining available capacity concerns users directly

4 Co-existence and cooperation

The co-existence and co-operation of Wi-Fi and cellular networks in the unlicensed spectrum can increase the overall capacity of heterogeneous wireless networks, provided that the mutual interference between Wi-Fi and cellular systems is addressed properly. This co-existence is also possible with Zigbee and Bluetooth networks as both technologies also rely on the Industrial, Scientific and Medical (ISM) bands. The advantages promised by the coexistence of Wi-Fi and cellular networks in the unlicensed spectrum have attracted considerable interest from the research community [4], [12], [13], [14], [15] and it is the circumstance that motivates this paper.

The pressing issue of finding ways to allow LTE-based systems to use spectrum besides the bands allocated by Spectrum Authorities (SA) via spectrum auctions is dealt with in [16], which studies the coexistence of Wi-Fi and LTE or in [17], which proposes a new access technique that takes advantage of unlicensed spectrum. Work in [16] identifies industry papers whereby experimental results of coexistence are presented. Their analysis show that, without changes to existing protocols Wi-Fi is significantly affected by LTE transmission, with a Wi-Fi transmitter spending a large amount of time in the listening mode. Its current proposal does not achieve a fair coexistence mechanism. In LAA is presented as a sharing method that allows LTE to use unlicensed bands. LAA uses carrier aggregation framework and aggregate carriers. As opposed to the previous work,

[17] is not concerned with coexistence with Wi-Fi and concludes with three scenarios. Its focus is on analysing LAA performance when it is used to provide additional downlink data capacity. Listen-before-talk techniques, not currently incorporated to LTE, are recommended for multi-operator deployments of LAA [17]. Another Wi-Fi - LTE coexistence study in [18] has reported the dismal performance of Wi-Fi in presence of LTE cells when both are deployed outdoors with no channel sensing-based adaptive mechanisms implemented. However, Wi-Fi performance is improved in an indoor/outdoor mixed deployment scenario when Wi-Fi is placed indoor and LTE outdoor. LTE signals suffered high penetration loss. A different approach on co-existence is attempted in [19]; an analytic model, partially validated through an experimental platform, found Wi-Fi and LTE to cause high levels of interference to each other; among the main factor of such occurrence are the power levels and the physical topology. An inter-network coordination mechanism with centralised radio resource management is proposed to improve co-existence of Wi-Fi and LTE systems.

5 New applications demanding spectrum sharing

LTE in the unlicensed spectrum, M2M communications and the IoT are among the range of new applications that are driving spectrum sharing initiatives. On the other hand, there is a healthy debate about the definitions used to describe the two latter growing technology trends. Back in 2010 M2M was defined as a generic concept that indicates the exchange of information in data format between two remote machines, through a mobile or fixed network, without human intervention [20] while IoT has recently been defined as the pervasive and global network which aids and provides a system for the monitoring and control of the physical world through the collection, processing and analysis of generated data by sensor devices [21]. Many publications used both terms interchangeably but there is an inclination, the authors have noticed, to refer to M2M configurations when this type of networks may be restricted to solutions or services offered by a network provider, say a cellular network provider, with connections restricted to users of that network. The concept of IoT almost always considers devices so connected to be part of the global internet infrastructure (notice the expression global network in our definition above). In the following sections well discuss the LTE spectrum sharing in the unlicensed bands and spectrum requirements of M2M and IoT networks in the context of new service offerings in New Zealand.

5.1 LTE: Spectrum Sharing

Cellular operators for LTE are targeting the unlicensed 5 GHz bands, currently been used by Wi-Fi, Zigbee and few other communication systems, to expand the LTE capacity and meet the traffic growth. The 3.5 GHz band (wherever it is unlicensed) is another option. The unlicensed or license-exempt bands are important for small cell deployments and will be a key in the 5G spectrum map. Here we provide a brief roadmap to LTEs evolution in the unlicensed spectrum.

LTE-Unlicensed and LAA -In 2013 Qualcomm proposed the idea of deploying LTE in the unlicensed spectrum [22]. There are two versions: LTE-U, which is the pre-standard proprietary version backed by the LTE-U Forum (a consortium of cellular operators and chipmakers) and LAA, which is developed by 3GPP. Initial deployment of these LTE versions in the unlicensed bands is expected through small cells for DL only and then slowly for UL as well. Both LTE-U and LAA utilise the carrier aggregation functionality to aggregate the carriers in the unlicensed bands with those in the licensed spectrum. While, LAA complies with the different regulatory requirements for the usage of the unlicensed spectrum, e.g., Listen-Before-Talk (LBT) schemes in which an LAA-LTE cell senses whether a channel is free to transmit, LTE-U does not and instead uses the duty cycling-based system called Carrier Sensing Adaptive Transmission (CSAT). Unlike LBT, an LTE-U cell using CSAT does not sense the occupancy of a channel before transmitting and instead turns its signal on and off over small periods of time to, respectively, occupy the channel to transmit and vacate the channel for other technologies, like Wi-Fi. LTE-Us focused deployment options are only the non-LBT required regions in the world [23]. Although LTE-U Forum wanted to go forward with the commercial deployment LTE-U soon, they are heavily opposed by the Wi-Fi operators and currently under the mandate of FCC and ETSI (European Telecommunications Standards Institute), LTE-U and LAA are going through a series of field trials to prove their transmission qualities and fair sharing (i.e., coexistence) of the unlicensed spectrum with the existing Wi-Fi systems. Preliminary results, although, have shown that presence of LTE-U or LAA does not hamper the performance of Wi-Fi, more rigorous trials are still needed.

Enhanced LAA (eLAA) -In line to planned 3GPP Rel 14 specifications, eLAA is defined as an enhancement to LAA. While LAA only supports DL, eLAA uses carrier aggregation in both UL and DL to collate licensed and unlicensed bands and thereby can support UL and DL LTE operations in the unlicensed spectrum [24].

MulteFire -While both LTE-U and LAA technologies need an anchor in the licensed spectrum, MulteFire can solely operate in unlicensed spectrum and does not need an anchor in the licensed spectrum. Although in its nascent stage, the technology has the potential to enable full-fledged LTE Unlicensed hotspots to operate even in the absence of anchor licensed spectrum [25]. Industry expects MulteFire to facilitate enhanced deployment of small cells in indoor locations and highly dense environments [26].

LTE Wi-Fi Link Aggregation (LWA) -This facilitates the offloading of LTE data traffic to Wi-Fi radio links in the unlicensed spectrum when needed. While DL traffic can be transmitted through both LTE and Wi-Fi links, UL is only through LTE.

LTE in 3.5 GHz -Since mid-2015, 150 MHz of spectrum in the unlicensed 3.5 GHz band has been made available by FCC for shared commercial usage. LTE-U Forum is currently progressing with developing the protocols for LTE-U operations in the 3.5 GHz (with an expected deployment around the third quarter of 2016), while T-Mobile US is looking to adopt LAA for the 3.5 GHz band. However, efficient operation in the 3.5 GHz will set a strong requirement for low power RF equipment, e.g., low power small cell technologies for both LTE-U and LAA.

5.2 M2M

M2M networks dont have a prescribed spectrum that needs to be used with the services offered. It all depends on the service requirements: both Wi-Fi and LTE frequencies, for instance, could be used to deploy the M2M services and of course unlicensed bands will provide a competitive option for many of those new links. In New Zealand the most consolidated example of an M2M network is that offered by Vodafone [27] with a focus on monitoring and control and experience in several application domains: healthcare, transportation and logistics, utilities and manufacturing. A typical configuration has a device (or sensor) using their mobile data network to link itself to a central management system. The central management system looks for anomalies or pre-specified threshold to trigger actions or communications. The M2M deployment could be quite complex with configurations that may start at the asset being monitored and include a communications device, a SIM card, a cellular network base station, a M2M platform (i.e. a server), cloud-based storage, and applications running somewhere remotely which take advantage of the M2M chain. Use of a mix of licensed and unlicensed spectrum as a possible component of a M2M service can then be envisioned. Companies with a multi-national footprint (such as Vodafone) could argue that the global characteristic of an IoT solution is being addressed by their M2M networks which could participate in roaming agreements and provide a multi-country deployment.

5.3 IoT

The Internet of Things (IoT) refers to the widespread use of systems, heterogeneous technologies and the evolving paradigm of the interconnectedness of devices, using TCP/IP protocols, around our physical environments. From an initial perspective IoT looks like M2M communications (the communication between system entities in a wired or wireless system that does not necessarily require direct human intervention) however, IoT encompasses not only M2M but also humans, home appliances, vehicles, machinery, pets, cattle in the field, animals in the wild, habitats, habitat occupants, even corporate organisations and how they interact with one another. IoT includes a new wave of sensor devices and it interoperates with the growing cloud network infrastructure. On the long run it is envisioned that an IoT ecosystem will evolve which will not be too different from the internet. It will facilitate the interaction of devices (mobile or fixed), smart objects and other real world devices just as humans interact nowadays using internet-based applications.

Examples of typical applications include remote meter reading implemented through smart metering solutions while the introduction of automatic meter reading applications will assist customers achieve better energy monitoring, usage and spending. The IEEE is currently working on reference architecture which will define the basic IoT architectural building blocks and how they could be seamlessly combined into multi-tiered systems [28].

IoT is an emerging area and a recent study has shown that the number of IoT connections is expected to surpass 360 million by 2022 [29]. Availability of spectrum is critical to support these connections. However, spectrum allocations will be IoT application-specific and must satisfy the service requirements of individual applications. Generally speaking, service requirements range from excellent and ubiquitous coverage, ultra-low power operations, provision of adequate bandwidth, to secured and low cost communication and guaranteed message delivery. While, from a spectrum allocation perspective, it is a challenge to meet these varied requirements, an initial step is making available globally harmonized low-frequency spectrum in the unlicensed bands, e.g., bands below 1 GHz like 870-876 MHz and 915-921 MHz along with the TV white spaces [29], [30]. In future 700 MHz bands may also become available. All these bands allow extended coverage and support interconnection of more number of less complex and low-powered IoT devices. These are also beneficial to run IoT applications, which require in-building penetration. SigFox and LoRa (Long Range) are examples of notable narrow-band Low-power WAN (LPWAN) technologies operating in unlicensed spectrum. Low frequency bands are, however, scarce and high in demand, so there should be ways to find and free more such globally harmonized bands that can be made available for IoT applications. Apart from these, some interests on shared bands over 2 GHz are also there, particularly for applications with higher bandwidth requirements, like video monitoring. Such bands include 2.3 GHz, 2.4 GHz, 2.6 GHz, 3.4-3.8 GHz, and 5 GHz. Ingenu offering its 2.4 GHz LPWAN technology fits this category [31]. However, with multiple wide-ranged IoT technologies flocking the unlicensed spectrum, interference may always be an issue with the increase in the number of IoT devices even if the devices are low-powered.

Recent research indicates that a licence-exempt model facilitates the rapid development of IoT devices as it eliminates the need for time-consuming negotiations about the spectra to be used. This directly results in cheaper IoT nodes. Another possibility could be setting a worldwide default frequency in the range of 915-928 MHz for IoT devices to facilitate compliancy and deployment. Other opinions have voiced the requirements for making the IoT devices themselves understand which country they are operating in and what are the available spectrum bands there and operate accordingly. On the flip side, fulfilling these requirements may require complex sensors fitted to IoT devices, which may then increase the cost [32]. Spectrum allocation for IoT devices is a wide open issue and still a long way to before a consensus can be reached.

IoT emphasises global reach. With that in mind attempts are started in order to provide genuine world-wide solutions. Network operators [1] deploying LPWAN, a wireless wide-area network that specializes in device interconnecting using with low-bandwidth connectivity, use free sections of the spectrum, in particular the ISM band, e.g., between 915 and 928 MHz in New Zealand, Australia and USA, and 868 MHz in Europe. Their network support both mono and bi-directional communication and because of using an ultra-narrowband technology interference is very low.

1. Recently Thinxtra the network operator of Sigfox for both Australia and New Zealand, has started operation in New Zealand. Sigfox has an IoT network, started in 2010, which now operates in 14 countries.

6 Economic issues in spectrum sharing

Widespread adoption of a spectrum sharing framework by an SA has the potential to disrupt the current stable conditions of spectrum usage. As SAs are under increasing pressure to provide access to spectrum by commercial operators planning to expand or start communications services, spectrum sharing will be an effective solution to the increasing demand only if rules, rights and technical conditions are rightly specified.

SAs, such as Ofcom in the UK, allow new entrants to initiate requests to share specific bands with incumbents who have been traditional holders of rights to their utilisation. In fact, Ofcoms approach to spectrum sharing includes defining a framework [9] that involves: stating the characteristics of use for prospective users who seek access to shared spectrum, the nature and strength of barriers that may limit the future of spectrum sharing, and the regulatory tools and enablers of spectrum sharing, both at market and technology levels.

The economics of spectrum sharing is associated with an inquiry by which the SA determines that spectrum sharing is economically and technically feasible and a beneficial alternative to the status quo. Thus, the main economic concern a SA needs to resolve in order to assess the convenience of allowing spectrum to be accessed on a shared basis is the issue of spectrum value. Valuing the spectrum provides the SA with a reference point that allows it to establish licensing fees, such as the administrative prices, or make decisions about the best use of a spectrum band, or set reserve prices when auctions are used to allocate spectrum.

When a decision about changing the access mode of a band from exclusive to shared needs to be made the termination of the value of such band relies on assessing the effects of a number of factors:

- **Benefits**: benefits derived from a yet-to-be-proven innovative service to be introduced by an operator requesting shared use of the band;
- **Opportunity costs**: where spectrum is scarce (demand exceeds supply) spectrum pricing should reflect the foregone opportunity of using it on its best alternative. Sharing, then, could be included into the calculation of opportunity costs.
- **Transaction costs**: whenever a licensee is required to incur in unforeseen costs to comply with an SAs request to provide information or execute an action in the process of determining whether the band can be shared, the calculation of value can be affected by such costs.
- **Externalities**: if the future operation of a band by a sharer causes interference with the licensees operations, such externality must be internalized by an estimation of the value of the potential harm.

In its decision a SA will need to weigh the foreseen benefits against any losses derived from the change of conditions. Potential new entrants and applicants are in a position to assess the benefits and make a case for innovation, if they plan to bring new services to the market. Licensees, on the other hand, would be in a position to assess any value losses. In such scenario parties have obvious incentives to exaggerate their claims. In addition, the SA would need to assess the transactional costs involved in the transition from exclusivity to sharing.

Ultimately it is the use of finely tuned mechanisms that will incite changes in the way spectrum is allocated. Market-based mechanisms, such as auctions, can illustrate instances in which concerned players can find an efficient allocation solution that may involve spectrum sharing. Two examples are now presented.

The US 700 MHz auction: back in the mid-2000s when the digital dividend the spectrum bands that would be left empty by the switch from analog TV channels to digital channels- a dispute arose between mobile telecommunications incumbents who demanded such bands would be allocated to 4G services followed by an auction that would grant exclusive rights to the winners, and new entrants such as information and contents operators, who demanded the bands would be designated as unlicensed spectrum so that they could be used by Wi-Fi services. In [33] an interesting proposal is presented whereby an auction of set of bands (or blocks) determines both the winners and their payments -, and the type of use that each band would be given. In its original design the auction in [33] would allow anyone to eventually use the unlicensed spectrum, if the set of unlicensed-type participants won. The latter means a free-riding problem may arise as an ex-post auction effect. Modifying the auction in such a way that shared use rights are allocated only to a winning coalition of participants, that is, those seeking shared access to the spectrum, would be a demonstration that a SA can indeed use a market-based mechanism that not only shifts the burden of deciding about spectrum allocation from the SA to the mechanism but also opens the way for sharers to compete on an equal-foot with seekers of exclusive rights.

UKs 2013, 800 MHz and 2.6 GHz spectrum auction: In 2012 UKs Ofcom attempted to build provisions to endow spectrum allocation decisions with a market-based mechanism that would have allowed spectrum sharing as an outcome of an auction. The 800 MHz and 2.6 GHz spectrum auction in 2013 was preceded by a consultation in 2012 on whether or not to include auction rules that would lead bidders to reveal preferences for bands contiguous to other bands won by bidders with whom potential sharing agreements could be reached [34]. On one hand, the mechanism would allow bidders to achieve benefits from pooling resources contiguous bands, possibly increasing the speed and quality of future services. On the other hand, the mechanism could expose bidders to not being able to win the necessary blocks, therefore, rendering inefficient the auction. The perceived high degree of bidding coordination between bidders and other potential downsides made Ofcom discard such provisions and the auction proceeded with no built-in spectrum sharing mechanism. Instead, later in 2016, Ofcom introduced a general spectrum sharing framework.

The examples above illustrate a feasible way forward for the inclusion of market-based mechanisms that would help SAs to effectively allocate bands to best uses and efficiently assign them to potential sharers of spectrum, among others.

7 Conclusions

It is clear that the co-existence and co-operation of Wi-Fi and cellular networks in the unlicensed spectrum can increase the overall capacity of heterogeneous wireless networks: a capacity that is being challenged by an ever growing demand from M2M and IoT users.

This co-existence and co-operation needs to be examined in the context of a competitive environment. For example, the use of exclusive licensed spectrum has been an advantage for LTE. Nevertheless, the availability of licensed spectrum is costly, limited and, by now, clearly not sufficient to meet the requirements triggered by the increase in mobile broadband traffic load. This has highlighted the fact that the available spectrum in the unlicensed bands is indeed an avenue for the growth of LTE. On the other hand, technological advances have been able to overcome the many challenges posed by spectrum scarcity, in general, and spectrum sharing in particular, allowing different spectrum sharing arrangements that now challenge the traditional regulatory frameworks operating in most countries. That traditional approach has relied on the concept of spectrum as a public good that must be licensed on an exclusive basis.

Spectrum sharing has the potential to become a powerful alternative that may overturn the status quo in spectrum management. Accordingly, spectrum sharing embodies the potential to enhance spectrums efficient use in response to the increasing demand represented in a myriad of new end-user devices for person-to-person and machine-to-machine communications.

An approach examined in this paper allows a prospective user to demand access to spectrum, when there is no suitable option among the currently available licenses or trading or leasing opportunities, or none of the license-exempt bands would be a good fit for his/her requirement. In such case the Spectrum Authority will need to look into the evidence to decide whether the users claim to spectrum sharing is worth being further investigated; but more importantly it is the role of the Authority to encourage the best social welfare outcome for the jurisdiction under its watch.

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