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Future Wireless Spectrum Below 6 GHz: A UK Perspective

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***Abstract*—Spectrum is a limited resource (especially below 6 GHz where most mobile and wireless systems currently operate) and optimizing its use is the target of national regulators in order to provide and deliver maximum benefit and services to the citizens. We present the UK perspective on the future wireless spectrum below 6 GHz, including plans and strategy of Ofcom (the UK telecommunications regulator) to make more spectrum available for wireless and mobile services. We identify capacity (especially indoors), coverage, machine-to-machine (M2M) and wireless backhaul as four major drivers that are expected to influence spectrum regulation in the coming future, and discuss the spectrum bands under consideration with respect to each. We then examine the amount and nature of future spectrum below 6 GHz. We find that, unlike currently allocated spectrum, most of the new spectrum (close to 80%) would be shared spectrum and it will be accessed via either licensed shared access (LSA) or opportunistic spectrum access (OSA) models. We outline a trend indicating that hybrid geolocation database plus sensing will be a dominant and more generally applicable spectrum access technique in the future when dealing with shared spectrum bands with incumbents not in the wireless services sector. On the other hand, some form of beacon signaling can enable efficient spectrum sharing among heterogeneous wireless systems assuming such signaling can be incorporated in a cost-effective manner. Finally we discuss 5G requirements under consideration and potential spectrum below 6 GHz to meet those requirements.**

I. INTRODUCTION

Wireless and mobile services are essential and integral part of daily life nowadays and different industries are based on wireless services now. Global mobile devices grew in 2014 to reach 7.4 billion devices compared to 6.9 billion in 2013 [1]. In addition, the global mobile data traffic increased by 69% in 2014 and reached 2.5 exabytes per month by the end of 2014 which was previously 1.5 exabytes per month by the end of 2013 [1]. With the anticipated rise in machine-to-machine (M2M) devices, this increasing trend is expected to continue to reach 24.3 exabytes per month by 2019 [1]. Allocating more spectrum and improving the efficiency of its use is a well-known way to scale up capacity of mobile networks and better cope with the growing demand. However spectrum is a limited resource, especially below 6 GHz where most mobile and wireless systems operate and will continue to do so in future. In fact, regulators, industry and research community are all busy working to address this problem from various angles. Traditionally, the spectrum allocated for wireless and mobile services fell into one of two types: *licensed* (or exclusive) and *unlicensed* (or license-exempt). Mobile cellular networks (e.g. 3G, LTE, LTE-A) use licensed spectrum to guarantee the required quality of service (QoS) and have assurance when investing in additional infrastructure. On the other hand, Wi-Fi networks and Short Range Devices (SRDs) make use of unlicensed spectrum with which the QoS related expectations are less. In view of the constraints associated with additional spectrum that could be made available to mobile services, newer spectrum access models such as licensed shared access (LSA) and opportunistic spectrum access (OSA) are highly relevant when we look towards the future. Similarly, spectrum access techniques like geo-location databases and technologies such as carrier aggregation (that was introduced in LTE-Advanced) are also crucial to enable efficient and flexible use of all available spectrum.

In this paper, we present the UK perspective on the outlook for future wireless spectrum availability and access below 6 GHz. Towards this end, we consider four major aspects or drivers that are expected to influence spectrum use and regulation in the near future. These aspects are capacity, coverage, machine-to-machine (M2M) support, and spectrum for wireless backhaul. Capacity scaling is the major and the straightforward reason for the need for more spectrum in the future. However, achieving ubiquitous coverage is a related and an important problem. Due to the low population densities in rural areas, the mobile operators see that it will not be cost efficient to deploy network infrastructure in these areas. In fact, this coverage problem limits the expansion of new technologies and services that would in the future limit revenue. Besides, according to the Cisco forecast [1], M2M connections will grow from 495 million connections in 2014 to 3 billion by 2019; this massive number of devices will wirelessly connect with the rest of the infrastructure and thus increase the demand for spectrum. M2M devices and traffic have different characteristics from the current personal communication devices such as smartphones, and for this reason can benefit from suitable spectrum assignment and well tailored access mechanisms. Increasing densification of mobile infrastructure through massive increase in the deployment of small cells makes their backhaul provisioning a challenge but the traditional Line of Sight (LoS) backhaul links may not be appropriate in this context; Non-LoS (NLoS) may be more appropriate but comes with a different set of spectrum requirements.

Although considerable amount of research has evaluated different spectrum access techniques in different bands (e.g.,

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[2]–[5]), very few works like [6] tried to generally examine which spectrum access technique could be used in which bands. Even so, to the best of our knowledge, none of these works tried to put such analysis in the context of how the future spectrum allocation would be and how the spectrum access model (licensed, LSA, OSA, unlicensed) may affect the choice of a suitable spectrum access technique. In this paper, using UK as a case study and spectrum related plans of Ofcom (the UK telecommunications regulator) as the input, we look into the amount and nature of future spectrum below 6 GHz[1], and find that most of the new spectrum (close to 80%) will be shared whose access will be via LSA/OSA. Moreover, we outline a trend towards hybrid spectrum access techniques, especially combination of geo-location database and sensing, even though some spectrum access techniques are more appropriate for certain bands (e.g., geo-location database for TV bands); additionally, beacon signaling will lead to more efficient spectrum use in future systems when it can be cost effectively realized. Finally we also discuss the spectrum bands that could help realize various 5G design goals being considered.

The remainder of the paper is organized as follows. In section II, we outline the capacity scaling issue and its implication for new spectrum, and elaborate on new licensed and unlicensed spectrum that will be become available in the future to address this issue. Section III describes the coverage problem and different bands/approaches to address it. Section IV summarizes Ofcom plans and various ongoing discussions to handle M2M communications from a spectrum perspective. The spectrum for wireless backhaul is discussed briefly in Section V. Section VI gives a brief overview of newer spectrum access models (LSA and OSA) and then presents our analysis on the amount/nature of future spectrum below 6 GHz from the UK perspective. An overview of spectrum access techniques is provided in section VII, including the Ofcom's geo-location database approach for TV white space (TVWS) spectrum. Section VIII discusses the recent Ofcom spectrum sharing framework and various barriers to sharing spectrum identified in the framework. In section IX, we discuss the issue of selecting the right spectrum access technique in the emerging context. Section X discusses commonly considered 5G aspects and the new spectrum bands below 6 GHz related to those aspects. Finally, section XI concludes the paper.

II. CAPACITY AND INDOORS

Scaling capacity is the need of the hour for wireless broadband industry. The growing demand for wireless and mobile services is fuelling the need for more capacity. The latest Ofcom Communications Market Report [8] indicates that smartphone and tablet ownership in the UK has already reached 66% and 54% of adults, respectively. Furthermore, the growth of machine-to-machine (M2M) communication and Internet of Things (IoT) paradigm will keep this increasing trend in the coming years.

Traffic offloading is one current solution to handle the increasing trend in wireless services demands. Mobile data traffic can be offloaded via Wi-Fi which is considered a cost-efficient approach as it uses the freely accessible 2.4 and 5 GHz bands. Also, traffic offloading can be through femtocells which are quickly deployed base stations that has a potential advantage over the deployment of macrocells that take much longer time due to purchase of radio infrastructure and backhaul. Moreover, starting from year 2010 around 80% of the generated data traffic comes from indoor environment [9]. Both Wi-Fi and femtocell offloading solutions are promising due to the fact that most of the data usage occurs indoors which make these indoor deployed technologies useful to offload the data traffic. A complete study on data traffic offloading via Wi-Fi or femtocells can be found in [10]–[12].

[1]We refer the reader to [7] for a recent Ofcom study on above 6 GHz spectrum.

TABLE I. UK GOVERNMENT 500 MHZ TARGET [13]

Band	Lead Department	Expected Release	Quantum (MHz)
Release Completed			
VHF and L-Band	Emergency Services	2012	13 MHz
870-872 MHz and 915-917 MHz	MoD	H1_2013	4 MHz
2025 - 2070 MHz	MoD	H2_2013	45 MHz (shared)
Total released to date:			**62 MHz**
Upcoming Releases			
2.3 - 2.4 GHz	MoD	2015	40 MHz
3.4 - 3.6 GHz	MoD	2015	190 MHz
4.8 - 4.9 GHz	MoD	2015	55 MHz (shared)
1427 - 1452 MHz	MoD	2015	20 MHz (shared)
Total upcoming releases:			**305 MHz**
Longer term releases			
2.7 - 2.9 GHz	DfT	2016 - 2020	100 MHz
Other	Various	2014 - 2020	Up to 35 MHz
Total longer time releases:			**135 MHz**
Total targeted releases by 2020:			**500 MHz**

A. Spectrum for Mobile Networks

Despite the use of approaches like traffic offloading, it will become necessary to free up more spectrum at some point in the future to address the capacity scaling problem. Towards this end, WRC-15 will discuss adding additional allocations for mobile broadband services and whether to allocate additional spectrum which could be used for Wi-Fi around 5 GHz. Within the UK, Ofcom is in the process of releasing up to 500 MHz public sector spectrum below 5 GHz by 2020 as per the the government target set in 2010 [13].

As shown in Table I, the UK Ministry of Defence (MoD) planned to release 40 MHz of spectrum within 2.3 GHz band (2350 – 2390 MHz). The harmonization process for the 2.3 GHz band over Europe is currently ongoing. In March 2015, Working Group on Frequency Management (WGFM), a part of Electrical Communication Committee (ECC), will submit a final report of technical conditions for using 2.3 GHz band in high power 4G LTE networks while ensuring the protection for currently used systems. According to the 3GPP standard, only unpaired band plan is considered in 2.3 GHz band (2300 – 2400 MHz) which make it suitable only for LTE-TDD. Currently, the UK mobile operators are focusing on LTE-FDD technology and only one operator (UK Broadband) runs a LTE-TDD network currently in bands 42 and 43. Although Vodafone and BT were awarded unpaired (LTE-TDD) spectrum in 2.6 GHz in the 2013 4G auction, they are yet to use that spectrum. The advantage of using 2.3 GHz for LTE and beyond mobile networks is that the propagation characteristics of 2.3 GHz band are very similar to the 2.6 GHz band that is already used for 4G networks in the Asian market. Moreover, as of October 2014, there are 207 LTE-enabled user devices (smartphones, tablets, etc.) supporting the 2.3GHz band [14].

However, using the 2.3 GHz band for high power mobile networks can lead to potential interference with the adjacent 2.4 GHz band used by Wi-Fi, Bluetooth and ZigBee devices. Although there will be 10 MHz separation between the new 2.3 GHz mobile band and 2.4 GHz Wi-Fi band that will provide some protection, the licence-exempt devices are not designed to deal with or take into account the high power users in the adjacent band. In [14], Ofcom concluded that there is no need for any intervention to protect Wi-Fi devices from potential interference arising due to 2.3 GHz band mobile operation. Instead, very simple migration activities such as moving the Wi-Fi routers away from windows, using 5 GHz band instead of 2.4 GHz band especially for Wi-Fi routers, using improved filters in the routers will be developed as part of the natural evolution of the market over the next few years and would solve any light interference between the two adjacent bands.

In addition to 2.3 GHz band, MoD plans to release 150 MHz of spectrum within 3.4 GHz band (3410 – 3480 MHz and 3500 – 3580 MHz). 3.4 GHz band has inferior propagation characteristics than 2.3 GHz band. Nevertheless, mobile services (4G and beyond) are the potential use of this band and it could alleviate the spectrum crunch / capacity problem, especially for small cells. ECC decision (11)06 provides two harmonized band plans in 3.4 GHz. Fig. 1 demonstrates the proposed unpaired and paired band plans for 3.4 - 3.6 GHz band. With the paired band plan, there is a need to separate the band into two frequency blocks with a guard band in between. In addition, we need two 10 MHz block at the start and the end of the band to avoid interference with adjacent bands. Due to the inefficient use of 3.4 GHz band under paired band option (30 MHz unused spectrum) and due to the preferences of industrial and national organizations for unpaired band, ECC decided in its 36th meeting, March 2014, to allow TDD or unpaired option to be the preferred mode of operation in the 3.4 – 3.6 GHz band, whilst allowing FDD as an alternative. Ofcom believes that the unpaired band plan is best suited for realizing the most benefits from this 3.4 GHz spectrum. UK/Ofcom have another problem to solve to free up the 3.4 GHz band. UK Broadband (a mobile/wireless operator in the UK) is currently allocated two separate 20 MHz blocks in this band: 3480-3500 MHz and 3580-3600 MHz. Ofcom needs to relocate the UK broadband blocks to allow larger contiguous assignments which, in turn, give operators the flexibility to deploy larger channel sizes and to reduce the technical constraints due to the lower number of spectrum boundaries between licensees. In fact, the 3.4 GHz band is considered promising for capacity scaling especially indoors. The 3.4 GHz not only has a higher bandwidth than 2.3 GHz band but also the higher propagation loss makes it suitable for small coverage (e.g., femtocells). This small coverage capability helps in the interference management in dense cellular deployment or to avoid the potential interference with the adjacent band where maritime and aeronautical radars operate.

Ofcom plans to make the 2.3 and 3.4 GHz bands accessible for mobile services operator on a licensing basis. To realize this plan, Ofcom decided to migrate the amateurs out of 2350 – 2390 MHz band because of the harmful interference caused by them to the new users [15]. However, the amateurs can continue using adjacent bands (2310 – 2350 MHz and 2390 – 2400 MHz) but with required clarification of the notice period needed by amateur use to cease if amateurs cause interference

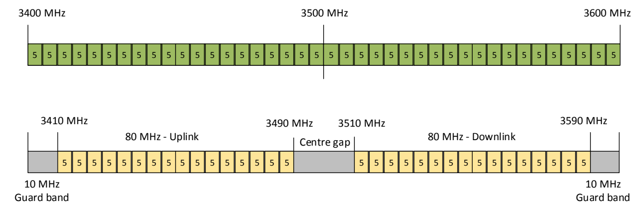


Fig. 1. Unpaired (at top) and paired (at bottom) band plans for 3.4 GHz.

to other users in the newly released band or the adjacent bands [14].

In addition to amateurs, the release of 2.3 and 3.4 GHz bands will reduce the number of PMSE channels to 19 channels (in 2 – 4 GHz range) from the previous 33 channels. Moreover, nine of these channels are currently exclusively assigned to news broadcasters. The remaining 10 channels will be sufficient for 98% of events. However, there are some migration actions needed to support the other events which require more than these 10 available channels such as allocate more spectrum for PMSE uses in other bands (e.g., 7 GHz band) or re-use news channels as appropriate. Due to the fact that the migration to 7 GHz band may take some time to implement, Ofcom is studying the possibility of allowing ongoing PMSE access to the new licensed band (2.3 GHz and 3.4 GHz) in specific areas where the new services have not been rolled out yet.

The use of 3.4 GHz band for 4G (high power) networks will raise concern regarding the radar performance in 2.7 – 3.1 GHz band. Due to the lack of selectivity within these radars (s-band), an inter-modulation interference will affect its operation. A similar concern arised earlier when 2.6 GHz band was allocated to 4G networks. Ofcom suggests limiting the power flux density (pfd) per MHz to $+5dBm/m^2$ across the 3.4 GHz band, the same as with the case of 2.6 GHz band. This limit will alleviate the risk of multiple bands illuminating the radar, especially the case of 2.6 GHz and 3.4 GHz bands being simultaneously within the radar beam-width [14].

Table II summarizes the changes needed to support the operation of mobile networks in 2.3 and 3.4 GHz bands.

B. Wi-Fi Spectrum

Wi-Fi is the dominant carrier of wireless data traffic. A report commissioned by the European Commission showed that over 71% of all wireless data traffic that delivered to smartphones and tablets was delivered through Wi-Fi. In 2013, Ofcom identified that the 2.4 GHz band is much more heavily used than 5 GHz band; on average occupancy of the 2.4 GHz band is approximately ten times that of the 5 GHz band [16]. Although the current use of the 5 GHz band is relatively low, another study [17] commissioned by Ofcom found that the current spectrum allocation for Wi-Fi at 2.4 and 5 GHz is likely to be under pressure by 2022 and the additional spectrum will be required to support the expected demand. Moreover, by 2019 the amount of traffic offloaded from smartphones and tablets will be 54% and 70 %, respectively [1].

A proposal to increase the amount of spectrum allocated to Wi-Fi at 5 GHz band is being discussed in the preparation

TABLE II. PROPOSED CHANGES FOR 2.3 AND 3.4 GHZ BANDS

Band	Affected Industry	Proposed changes
2.3 GHz	2.4 GHz Wi-Fi band	Light interference expected and the natural evolution of the market over the next few years will solve it
	Amateur services	Migrate from 2.3 GHz band and will migrate from adjacent band if they cause interference to users in 2.3 GHz or adjacent bands
3.4 GHz	PMSE	Work only in specific area where new services have not been rolled out yet.
	Radar in 2.7 – 3.1 GHz band	Limit the power flux density (pfd) per MHz to $+5dBm/m^2$ across the band

of WRC-15 under agenda item 1.1. The proposal explores the possibility of making 5350 – 5470 and 5725 – 5925 bands available. Moreover, CEPT is currently working to identify harmonized compatibility and sharing conditions for a shared use of these two bands for wireless access systems [18]. This proposal will create a contiguous 775 MHz block of spectrum for Wi-Fi between 5150 and 5925 MHz. Moreover, the removal of the current gap in the 5GHz Wi-Fi bands would increase the number of wider bandwidth channels (e.g., 80 and 160 MHz) which can be exploited by the latest 802.11ac standard higher data rates.

III. COVERAGE

Wireless services are one of the fundamental services nowadays. Nevertheless, there is a lack of these essential services in several rural areas. The main reason is the economic challenge of network rollouts in these areas with low population densities. Recently, many research studies have been conducted to overcome the problem of lack connectivity in rural areas. The purpose of these studies is to seek an economically viable solution to the rural connectivity problem. Some of these works leverage the openBTS platform to build a GSM cellular network in rural areas (e.g., [19]) whereas others have suggested using VHF and UHF bands in a wireless network (e.g., [20], [21]).

A. *Spectrum for Mobile Services in Rural Areas*

Recently the public policy objectives are to enhance rural broadband availability and mobile coverage [22]. Using the low frequency for cellular network services is a promising solution to enhance the coverage in rural areas with less operating cost, thanks to the superior propagation characteristics of lower frequencies. As a result, Ofcom in the UK has decided to relocate the existing Digital Terrestrial Television (DTT) and Programme Making and Special Events (PMSE) uses and to align the 800 MHz band (790 – 862 MHz) with European harmonised plan for 4G/LTE use. In addition to the 800 MHz band, Ofcom has awarded 2.6 GHz (2500 – 2570 MHz and 2620 – 2690 MHz) band for 4G/LTE networks. These two bands (800 MHz and 2.6 GHz) are expected to enable 4G coverage to at least 95% UK population by 2017. In addition to 800 and 2600 MHz bands, Ofcom has a vision to release the 700 MHz (694 MHz – 790 MHz) band for LTE services as well. In fact, the 700 MHz band is potentially attractive to mobile industry, especially, LTE for multiple reasons. One reason is due to the good propagation characteristics of lower frequencies, using 700 MHz band for mobile networks will increase the cost saving for mobile operators, allowing them to achieve wider coverage with fewer base stations and thereby leading to reduction in per-customer cost and improvement of mobile performance in rural areas, roads and railway lines. This improvement is not limited to just voice traffic, but will also benefit data services too. For example, Ofcom

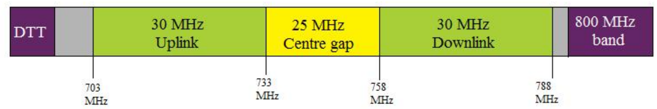


Fig. 2. 700 MHz band configuration under consideration by CEPT.

commissioned study conducted by Analysys Mason [23] found that the deployment of 700 MHz band on all sites will deliver average speed up to 20% faster for some users compared to other bands. Another reason is that many countries all over the world have either decided to use this band for mobile broadband or are in the process of finalizing so. Countries in Latin America and Asia Pacific region have decided to use 700 MHz band for mobile data. Moreover, in 2014, the European Commissions advisory group has recommended that all EU member states make 700 MHz band available for mobile data by no later than 2022 [24]. The advantage of unified usage of mobile spectrum worldwide is economically wise to ensure a wide availability of devices at reasonable cost. However to achieve this international unification, a number of international agreements need to be decided before using 700 MHz band for mobile broadband. First, the International Telecommunications Union (ITU) will need to confirm co-primary allocation for mobile and broadcasting in the 700 MHz in ITU Region 1 (Europe, the Middle East and Africa) and this is expected to be decided at *World Radiocommunication Conferences* (WRC-15) which will take place in November 2015. Also, the European Conference of Postal and Telecommunication Administrations (CEPT) will need to agree on 700 MHz mobile band plan. CEPT has considered 2×30 MHz arrangement to be used in this band with a 25 MHz center gap as shown in Fig. 2. However, the discussion concerning the usage of centre gap (for SDL, PMSE, etc.) is still pending.

IV. MACHINE-TO-MACHINE

License-exempt means that devices do not need to have an individual license to operate in this type of spectrum, however, there are a set of rules that must be complied by these devices [22]. Short Range Devices (SRD) are a type of devices which typically operate in license exempt spectrum using low power and with short range. Some of the machine-to-machine (M2M) applications (e.g., smart metering, healthcare, transport) will be enabled by SRDs. Cisco estimates that M2M traffic will grow at a CAGR of 103% between 2014 and 2019 [1]. Ofcom in a recent study [25] has expected that the number of M2M connections, in UK, could reach up to 369 million by 2022. This rapid increase will create demand for license-exempt and licensed spectrum to support M2M applications. Moreover, GSMA estimates that 2 billion M2M devices will be connected on cellular and about 13 billion M2M devices are expected to be connected using short-range wireless systems by 2020 [26]. Due to this rapid development of Internet of Things (IoT) and

Machine-to-Machine (M2M) communication, it is necessary to design communication systems operating in different wireless spectrum as an alternative to highly congested wireless access systems. IEEE 802.11ah [27] aims to allow wireless access using carrier frequencies below 1 GHz in the ISM (Industrial, Scientific, and Medical) band and that will help Wi-Fi-enabled devices to get guaranteed access for short-burst data transmissions, such as meter data. Therefore, Ofcom mentioned that there will be a potential change in this frequency range to allow licence-exempt use at 870 – 920 MHz for RFID and other SRD use.

In 2013, Ofcom published a consultation setting out a proposal to authorise the use of SRD in 870 – 876 MHz and 915 – 921 MHz bands. ECC, CEPT and Ofcom [28], [29] have developed a deep analysis on the compatibility between SRDs and other devices operating in these bands or those in adjacent bands to work together. In the UK, the adjacent bands are public cellular networks and GSM-R. In ECC report 200, it has been concluded that the SRD devices will not cause harmful interference to other devices operating in the same band or adjacent bands, if and only if the probability of interference is less than 5%. CEPT has concluded that for SRD and GSM-R downlink (operating in 917 – 921 MHz), the probability of interference is less than 2.6% [28]. However, for SRD and E-GSM-R (operating in 873 – 876 MHz and 918 – 921 MHz bands), the probability of interference will exceed 5% unless some constraints are applied to duty cycle and maximum continuous transmission time [28]. For the systems that operate in the same band, in the UK case, the Wind Profiling Radar (WPR) works in the same band of SRD devices (915 – 921 MHz). Ofcom considered that only RFID could have the risk to interfere with WPRs due to their relatively higher power and wider bandwidth compared to other SRDs. Nevertheless, they still have less probability to interfere with WPRs because the latter are deployed in rural areas where the RFIDs will have very low deployment scenarios. Therefore, the idea of having exclusion zones around the WPRs is not required; instead having the rule to state that the license-exempt devices should not cause or contribute to any undue interference to any wireless telegraphy will be enough and allow Ofcom to take enforcement action if needed.

In addition to the new license-exempt allocation for SRD based M2M applications under 1 GHz band, recently, there is consensus in both research and industry communities that some of the M2M communication will also be carried by mobile (e.g., LTE/LTE-A) networks due to the fact that cellular networks are present almost everywhere. Moreover, M2M applications feature different traffic types and associated QoS requirements (classes) which can be better met with mobile networks. The current LTE bands (e.g., 800 MHz and 2.6 GHz) and the future LTE bands (e.g., 2.3 and 3.5 GHz) are expected to be the potential bands carrying M2M traffic. In addition to these bands, the introduction of LTE in unlicensed spectrum (LTE-U), where the coordination between Wi-Fi and LTE are expected in 5 GHz band, will significantly help in growing up and increasing the interest in the market of M2M and SRD devices. However, some industrial work [30] highlighted that the current LTE releases are good enough for high-end M2M applications which require reliable connection and high data rate, but it might not be cost-effective to use LTE for low-end applications. Hence, the new LTE releases should be adapted to support the special characteristics of low-end M2M applications. A recent work [31] has suggested that the design of narrowband machine-to-machine system would be useful in terms of cost, coverage, spectrum and energy efficiency. The reduced bandwidth implies less expensive RF components. Also, the reduced data rate results in simpler baseband side. Furthermore, the concentrated power in a narrowband enhances the coverage capability and provides better downlink and uplink channel characteristics. LTE-M (LTE-Machine-to-machine) is a M2M oriented narrowband variant of LTE, built from existing LTE functionalities. LTE-M [31] exploits the low frequencies GSM band (450 and 480 MHz) by using GSM sized channel (200 kHz) which is efficient compared to realizing the same with standard LTE.

V. WIRELESS BACKHAUL

As the deployment of small cells increase, the demand for backhaul links will increase too. While using fiber backhaul links increase the sharing opportunities, using higher frequencies for wireless backhauling has certain advantages. Non-line of sight (NLoS) wireless links are more appropriate form of backhaul for small cells because such cells will be installed on face of buildings and on street lights and these placements can be 3 – 6 m above the ground. These conditions make it costly to realize a LoS wireless backhaul solution and in most cases it is impossible. From the perspective of provisioning spectrum for wireless backhaul, Ofcom plans to allow shared spectrum access to 3.6 – 4.2 GHz band for NLoS backhaul for small cells [32]. Currently, the primary users of this band are satellite earth stations and terrestrial fixed wireless links. However some studies indicate that higher frequencies above 20 GHz are better for backhaul compared to sub-6GHz bands. Specifically, a study by Ericsson [33] has compared using 5.8 GHz band and 28 GHz band for small cell NLoS backhauling. It shows that the received power at the higher frequency 28 GHz can still be significantly better than 5.8 GHz even though diffraction loss is greater at 28 GHz by about 6dB; this is because of the considerably higher antenna gain possible at 28 GHz for comparable antenna sizes. So it is unclear at this point if and how much spectrum may be needed below 6 GHz for wireless backhauling purposes.

VI. SPECTRUM ACCESS MODELS AND THE NATURE OF FUTURE SPECTRUM

In this section, we focus on analyzing the amount and nature of future spectrum below 6 GHz. It would however be helpful to first give an overview of various spectrum access models. Traditionally, the spectrum use for mobile/wireless communications was authorized in only two ways: (i) licensed and (ii) unlicensed (or licence-exempt). With licensed authorization, a spectrum band (or pair of bands) is allocated to an operator for their exclusive use, typically via an auctioning process (e.g., UK 4G auction held in February 2013 covering 800MHz and 2.6 GHz mobile spectrum). On the other hand, unlicensed spectrum bands allow devices to use those bands without the need for license but they are obliged to abide by certain technical requirements or spectrum etiquette rules (e.g., power limits, restrictions on usage to indoors). The 2.4 GHz band used by Wi-Fi, Bluetooth, ZigBee and other low power devices is the famous example of unlicensed spectrum access model. The exclusive use nature of licensed spectrum offers better control over the interference environment than the open access unlicensed spectrum and thus more likely able to provide quality of service (QoS) guarantees.

Making a spectrum band accessible via either licensed or unlicensed models first requires clearing that band from incumbent use. Below 6 GHz, it is becoming increasingly harder to be able to clear bands as they are held by incumbents unconnected with mobile/wireless communication that have strategic or operational reasons to continue doing so (e.g., military, radars, satellite earth stations). This necessitates sharing that ensures incumbent protection as the only viable approach to make such bands accessible for mobile services. Although there are several sharing based spectrum access models proposed in the recent past (e.g., pluralistic licensing), the two main ones that are gaining traction in practice are Opportunistic Spectrum Access (OSA) and Licensed Shared Access (LSA), which are briefly described next.

A. Opportunistic Spectrum Access (OSA)

The essential idea behind the OSA model is as follows. In a band licensed to *Primary Users (PUs) (also called incumbents)*, *Secondary Users (SUs)* are allowed to opportunistically exploit temporal/spatial spectrum holes (or white spaces) in that band in such a way that the PU operations are protected from SU induced interference. Examples of the OSA model in practice are 5 GHz Wi-Fi spectrum [34] and TVWS spectrum [35]; in the former case, the PUs are radars, satellites etc. whereas digital terrestrial TV (DTT) transmitters/receivers and Programme Making and Special Events (PMSE) microphone devices are the PUs in the latter case. The OSA model can be viewed as the unlicensed model with the addition of PU protection requirement. As such, there can be any number of SUs attempting to use the OSA band at a given time and location, which makes PU protection a non-trivial task. In the next section, we will give an overview of different spectrum access techniques that can be used for PU protection.

B. Licensed Shared Access (LSA)

The LSA model [36] aims to enable secondary access in a band licensed to a PU in a way that resembles the licensed model for the SU. Essentially the idea is for the SUs to sub-license a portion of the PU owned spectrum band in the frequency, space and time dimensions; as such, SUs in the LSA model are referred to as LSA licensees. In the LSA model, an entity called LSA repository continually keeps track of the amount of spectrum available at each time instant and location, and acts as the intermediary responsible for dynamically generating the licenses to LSA licensees. The 3.6 – 4.2 GHz band is an example of a band that could be made available via the LSA model in the future; PUs in this band are satellite earth stations and fixed terrestrial wireless links. The LSA model is attractive for mobile network operators (MNOs) to acquire additional spectrum without risking the ability to provide QoS guarantees because LSA licensees obtain a time-limited *license* on the fly to a slice of incumbent's spectrum band in frequency and space. Limited number of SUs (LSA licensees) in the LSA model eases the task of ensuring PU protection compared to the OSA model.

TABLE III. DISTRIBUTION OF NEW SPECTRUM BELOW 6 GHZ

Frequency Range	Amount (MHz)	Notes	Spectrum Access Model
694 - 790 MHz	286 MHz	MNOs	Licensed
2350 - 2390 MHz			
3410 - 3480 MHz			
3500 - 3580 MHz			
863 - 876 MHz	20 MHz	SRDs (M2M)	Unlicensed
915 - 921 MHz			
470 - 682 MHz	80 MHz	TVWS	OSA
5350 - 5470 MHz	320 MHz	5 GHz Wi-Fi	
5725 - 5925 MHz			
1427 - 1452 MHz	25 MHz	PUs: Military & Satellite	LSA
4.8 - 4.9 GHz	55 MHz		
3.6 - 4.2 GHz	600 MHz		

C. Amount and Nature of Future Spectrum Below 6 GHz

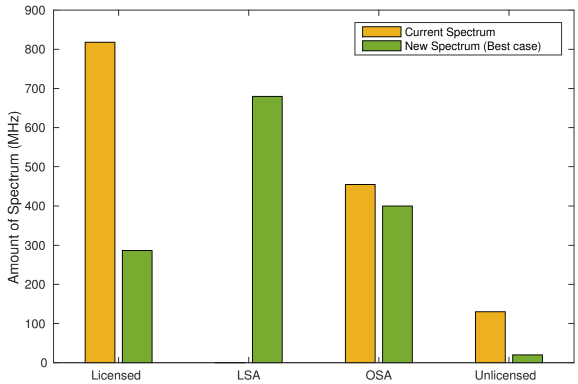
Now we look into the key question of how much new spectrum below 6 GHz is expected to become available in the coming future and the distribution of that spectrum between the different types of access models described above (licensed, unlicensed, OSA, LSA). We compiled this date primarily from Ofcom's various spectrum related publications, including its 2014 spectrum management strategy statement [32]. Resulting data is summarized in Table III and Fig. 3 (a). For comparison, currently allocated spectrum for mobile/wireless services in the UK obtained via Ofcom's UK Spectrum Map[2] is shown in Fig. 3 (a).

We briefly elaborate on how we obtain the figure for TVWS. In [37], the authors stated that on average there is 150 MHz TVWS spectrum available spectrum in the UK. But this figure includes the 700 MHz band which Ofcom has recently decided to allocate to mobile operators on a licensing basis by 2022. So we proportionately reduced the available TVWS spectrum to reflect the reduced TVWS frequency range after discounting 700 MHz band, which gives us 80 MHz.

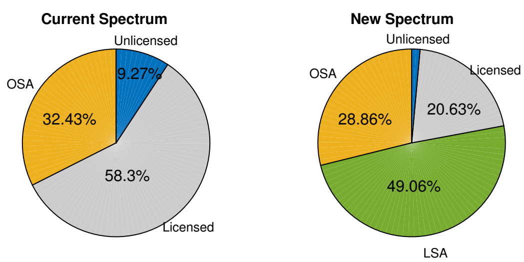
Regarding 3.6 – 4.2 GHz band, currently this band has permanent satellite earth stations and terrestrial fixed links as primary users and UK Broadband (an operator in the UK) as the secondary user. The UK broadband is allocated two blocks of spectrum, 84 MHz each (3605 – 3689 MHz and 3925 – 4009 MHz), shared on a geographic basis with the primary users. In our estimates of new spectrum, we assume that in the best case the whole 600 MHz in this band (3.6 – 4.2 GHz) will be available via the LSA model for mobile and wireless services. But it is worth noting that there are obstacles to be overcome before this can happen. Chief among them is migrating satellite earth stations to a different set of frequencies, which can prove to be expensive.

From Fig. 3 (a), it is clear that most of the new spectrum will be shared (either LSA or OSA). To appreciate the changing nature of spectrum, in Fig. 3 (b), we show the pie charts for current and new spectrum showing the distribution by access model. We see that 58.3% of the current spectrum is licensed and 9.3% is available for unlicensed use (primarily in the 2.4 GHz band). The remaining 32.4% of the currently allocated spectrum is the 5 GHz Wi-Fi spectrum that follows the OSA model as that band has various radars as primary users and radar protection is mandatory through the spectrum sensing based dynamic frequency selection (DFS) mechanism [34]. Looking at the breakdown for new spectrum, almost half of it is LSA type spectrum and close to 80% is shared (LSA or

[2] http://www.ofcom.org.uk/static/spectrum/map.html



(a)



(b)

Fig. 3. Amount and nature of future spectrum below 6 GHz in comparision with currently allocated mobile and wireless spectrum.

OSA). Thus as we go into the future, there is a remarkable shift in the nature of spectrum. Note that in this analysis we have not considered 2 GHz mobile satellite service spectrum and 2.7-2.9 GHz spectrum used by aeronautical radars. Even considering those bands, we expect our general conclusion that shared spectrum will be the norm in the future to still hold.

VII. Spectrum Access Techniques

In this section, we give an overview of different spectrum access techniques that could be used for accessing shared spectrum.

A. Spectrum Sensing

Spectrum sensing is an old and commonly used spectrum access technique to detect the presence of primary user (PU) or equivalently to determine a spectrum white space. The radar detection feature underlying the DFS mechanism in 5 GHz Wi-Fi systems [34] is an example of spectrum sensing use in practice.

1) Local Spectrum Sensing: In this basic form of spectrum sensing, each secondary user (SU) senses the spectrum locally and independently using one of the following methods: *(i) Energy Detection*; *(ii) Waveform Sensing*; *(iii) Feature Detection*; and *(iv) Matched Filtering*. Energy detection is the most common method employed for spectrum sensing because of its low complexity. But it has poor performance since it cannot differentiate between primary user signal and the interference and noise. The Other methods overcome some of these limitations, the detailed discussion on different types of local spectrum sensing can be found in [38].

There are some issues that should be taken into consideration when designing spectrum sensing algorithms such as *Hidden terminal problem, PU Diversity* and *Sensing Efficiency and Sensitivity*. Due to severe multipath fading and shadowing problem, local spectrum sensing techniques suffer from hidden terminal problem in which the primary user could not be detected due to its location. In addition, Different type of primary users could exist in shared spectrum and hence new local sensing techniques should handle PU diversity. Due to the dynamic characteristics of future shared spectrum, both sensing time and threshold should set appropriately in order tackle the trade-off between the complexity and the efficiency and sensitivity of sensing techniques.

2) Cooperative Spectrum Sensing: The shortcomings of local spectrum sensing can be overcome by sharing sensing information between multiple sensors to enhance the ability of SUs to detect and exploit spectrum holes. This mechanism is called cooperative spectrum sensing. The Common control channel (CCC) is used by SUs to report and share their sensing data. Therefore based on the bandwidth of CCC, SUs report different forms and sizes of sensing data. The sensing data can be combined in three different ways: *(i) soft combining*, *(ii) quantized soft combining*, *(iii) hard combining* and the detailed discussion on these methods can be found in [39]

There are some issues that should be taken into consideration when designing cooperative sensing algorithms such as *Spatial diversity* and *Exposed node problem*. Although spatial diversity in cooperative sensing increases its gain especially in the cases like hidden terminal problem but also more spatially correlated SUs participating in cooperative sensing can be detrimental to the detection performance [39]. Moreover, in high mobility scenario, the spatial diversity between the captured measurements can degrade the performance of cooperative sensing techniques. The exposed node problem leads to inefficient utilization of spectrum which occurs when SUs on the boundaries of PUs' exclusive zone share their information with SUs outside the exclusive zone. Therefore, the SUs which are outside the exclusive zone will have inaccurate information about channel occupation. In general, spectrum sensing mechanism introduces overhead especially in case of cooperative sensing which have a significant overhead on common control channel. Therefore, a more cost-efficient access techniques is needed to overcome the spectrum sensing limitation.

B. Geo-Location Database (GL-DB)

With this spectrum access technique, the SUs query a centralized database to get information about the available free channels to use. The centralized database stores PU locations and the channels they use, thus the database has a complete image of the current spectrum usage. Instead of

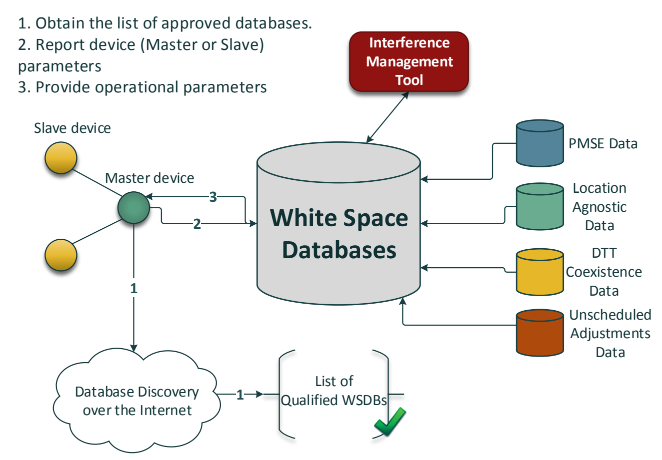


Fig. 4. Ofcom Geo-location TVWS Database Model

sensing the spectrum, SUs estimate their locations (e.g. using GPS, or other localization techniques) and send their location coordinates to the database which replies to SUs with a set of free channels to be used in their locations. The centralized database decides on the free channels based on theoretical propagation models to estimate the interference among PUs and SUs.

There are some issues that should be taken into consideration when designing geo-location database algorithms such as *Hidden terminal problem* and *propagation model complexity-accuracy trade-off*. Although the geo-location database approach looks promising to solve the hidden terminal problem but this only depends on having all PUs registered in the database. That may be optimistic and may not always be practical. For example, in the case of TVWS, it is hard to register the wireless microphone users which would seriously affect using the geo-location database technique in TV band. In addition to hidden terminal problem, achieving the right complexity-accuracy trade-off for the used propagation model is a non-trivial task. Unlike the sensing techniques, the geo-location depends on theoretical propagation model instead of real RF measurement. In this technique, the database periodically updates the spectrum occupation of PUs which increases the complexity of geo-location database especially in the case of mobility. In the following, we will review Ofcom's geo-location database technique and how this model addresses the above mentioned issues.

1) Ofcom GL-DB for TV White Spaces: Ofcom [40]–[43] will allow the secondary users to exploit the holes or white spaces in the TV band via a White Space Database (WSDB); these secondary users called White Space Devices (WSDs). WSDs are classified into two categories: Master and Slave WSDs. Master WSDs will contact the geo-location database directly to obtain the list of available channels and its operation parameters, whereas Slave WSDs operate under the control of Master WSDs. The WSDBs will have information from different data sets provided by Ofcom. (i) DTT Coexistence Data: a set of data containing the allowable transmission power in each 100 x 100 m pixel in the UK taking into consideration the minimum probability of interference with DTT. According to Ofcom the PMSE devices will work on channel 38 to prevent WSDs from interfering with them or with other services in TV adjacent bands, (ii) Location Agnostic data set is added. Location Agnostic data is a set of maximum allowable power for each channel in the TV band regardless the location of WSDs. (iii) PMSE data is the data set of licensed PMSE (different than in channel 38) that work in TV band. (iv) Unscheduled Adjustment data is a set of revised allowable transmission power in certain areas. The complete architecture of Ofcom geo-location database is showed in Fig.4.

The WSD operation will be controlled by White Space Databases (WSDBs). First, the Master WSD sends its parameters to the WSDB (e.g. location) in which the WSDB computes the *operational parameters* and sends them to the Master WSD. These operational parameters could be the available channels, and the allowable transmission power. The WSDBs calculate these parameters based on information that obtained from the different data sets, we defined earlier. Finally, the Master WSD sends the *used parameters* (the chosen parameters from the list) to the WSDBs. In case of Slave WSDs operation, the Master WSD requests *generic operational parameters* to its slaves. These generic operational parameters are restrictive because the database does not take into account the device parameters of Slave WSD. The Master WSD forwards these parameters to its slaves. The Slave WSDs could use these restrictive parameters or they could send to the Master WSD their device parameters to get better operational parameters. At the end, the Master WSD informs the database with the used operational parameters by its slave WSDs.

Ofcom has a very restrictive the out-of-block emission or spectral efficiency which is calculated by [42]:

$$P_{OOB(dBm/(100khz))} <= max(P_{IB(dBm/(8MHz))} - AFLR(dB), -84))$$

Where $P_(IB(dBm/(8MHz)))$ is the WSDs in-block emission within 8 MHz channel. AFLR is the WSDs adjacent frequency leakage ratio. Ofcom classified the WSD devices into four classes where Class 1 WSDs produces the cleanest signal in term of spectral leakage or AFLR.

As discussed before, in Ofcom's geo-location database model the WSDs are required to send several device parameters to geo-location database to be able to obtain the operational parameters. These device parameters are unique device identifier, emission class, technology identifier, device type, device master/slave category, antenna latitude/longitude coordinates and accuracy. Based on these detailed parameters, the geo-location database calculates the allowable operational parameters within specific period of time and geo-location. The geo-location validity is within 50 meters difference between the current position and the position reported to the geo-location database when the operation parameters calculated. Therefore Ofcom's geo-location model is flexible where the operational parameter such as transmission power and allowable time are different from device to another (due to device parameters differences). In addition to these detailed parameters, the white space devices information system (WSDIS) will guarantee to avoid any harmful interference to other devices working on the TV band. WSDIS is an information system which identify the WSDs that causing the interference and allow Ofcom to act accordingly to resolve the interference. Ofcom's geo-location database model solves the hidden terminal problem by allowing the PMSE devices that did not register in the database to operate on channel 38 and hence, the other devices will not interfere with them.

C. Beacon signaling

To avoid the latency associated with accessing the geolocation database, PUs can instead share information regarding their spectrum usage with SUs directly through *beacons*. A transmitter beacon consists of four types [44]: *(i) pre-transmitter beacon*, *(ii) area beacon*, *(iii) unlicensed signalling* and *(iv) receiver beacon*. A detailed discussion on different types of transmitter beacon can be found in [44].

There are some issues that should be taken into consideration when designing beacon signalling algorithms such as *Standardization* and *Cost*. Since beacons can operate in different frequency bands with different policies and regulatory requirements, a standard beacon design is needed to satisfy the different requirements of these bands. Although the beacon approach has the potential to enable more efficient spectrum use and sharing, it requires significant changes in the current infrastructure [40] which in turn increase the cost of implementing this approach on a large scale, making it impractical for legacy systems.

VIII. Ofcom Spectrum Sharing Framework

In [45], Ofcom introduced its spectrum sharing framework which consists of three elements: *(i)* potential sharing barriers; *(ii)* enablers to overcome these barriers, and *(iii)* identifying the needs of both incumbents and new users from their high level characteristics, which include temporal requirements of the services, their coverage area, type of QoS (e.g., guaranteed, or best-effort), technical requirements (e.g., power level), capacity and density of use and the economical benefits.

From our analysis of the nature of future spectrum below 6 GHz in section VI-C, it is clear that we are heading to a future dominated by shared spectrum. However, in order to maximize the sharing benefits, there are certain barriers that need to be tackled. These potential barriers can be classified into four categories [45]: *(i)* Availability of information; *(ii)* Market barriers; *(iii)* Authorisation constraints; and *(iv)* Technological challenges. We briefly discuss each of these barriers in the following.

Concerning the first barrier, the information the actual use of spectrum by licensees and how that use may change over time is commonly not available as it is often deemed commercially sensitive information and cannot be made publicly available. However, the lack of that type of information makes it difficult for other sharers to choose the right band or to identify the spectrum opportunities. Therefore, more information about the actual use would be very useful to overcome the information barriers. Besides, not only real-time information about the current usage of licensees or incumbents but also forward looking information about how the incumbents will use the spectrum. Moreover, information about the spectrum demand for both the incumbents and the potential sharers would help in planning for future growth and expansion. Towards this end, a single source of information on spectrum is needed in which any potential user willing to share unused portion of spectrum can get an up-to-date information on current and future spectrum availability.

In terms of market barriers, the cost of transactions can be very high which may prevent the incumbents from willing to share the spectrum with others when the gain is relatively small compared to the actual cost. Therefore, it is important to establish spectrum pricing scheme which is a fee charged to users of spectrum to encourage them to use the spectrum efficiently from a cost perspective [45]. In fact, setting a pricing scheme will help in reflecting the market demand for the spectrum and would motivate the incumbents to share their unused portion of spectrum. Another concern in term of market barriers, which is due to the dynamic nature of spectrum sharing, is that the incumbent might not be encouraged to share the spectrum because from incumbents' perspective, sharing may limit the flexibility needed to adapt their future business model.

LSA is one of the spectrum access models expected to be used in future for spectrum sharing where the secondary users obtain a licence on demand to access the unused portion of the spectrum. However, the licensing or authorization process itself could limit a desirable goal of spectrum use which is the flexibility. In other words, if the current licensee, due to the dynamic nature of shared spectrum, was willing to vary the terms and conditions of their licence in order to allow others to provide different services, then the current authorization process will not allow the licensee to do so which is limiting the flexible use of the spectrum. In order to overcome the authorization constraints, Ofcom has suggested a *tiered access* approach where different categories of the users have hierarchy of rights in accessing given spectrum. For example, currently the TVWS spectrum has three type of users, where DTT users can be placed in tier-1, PMSE users in tier-2 and TVWS devices in tier-3 which means that DTT users have all the priority over other types. However, managing the access rights for each tier is critical task in order to balance between the impact on incumbents and the constraints on the potential sharers; if access right for lower tier is only for opportuntistic use, then it would not be useful for certain type of industry (e.g., MNOs) where the expansion of their business model is not guaranteed.

From a technological perspective, coexistence is the main challenging task which may prevent the incumbents from sharing their spectrum. This is highly dependent on the choice of spectrum access technique, which is discussed in the next section.

IX. Choosing the Right Spectrum Access Technique

The choice of an appropriate spectrum access technique (between spectrum sensing, geo-location databases, beacon signaling or a combinations of them) is influenced by several factors. Foremost among them is the nature of the primary user or incumbent. This point can be easily made considering the cases of TVWS and 5 GHz Wi-Fi spectrum. While spectrum sensing (plus dynamic frequency selection - DFS) is considered a reasonable solution for Wi-Fi operation in 5 GHz till date, the same cannot be said for TV bands. This is because TV receivers are passive and (local) sensing cannot avoid causing interference to receivers (aka, the hidden terminal problem). Therefore, regulators around the world have opted to use the geo-location database technique for better primary protection. The spectrum access model in use also effects the choice of the spectrum access technique. Spectrum sensing has been considered in the literature for a long time as a natural method with the OSA model (although TVWS spectrum has changed this notion). With the more recent LSA model, the LSA repository is effectively a geo-location database indicating the spectrum availability in space, time and frequency dimensions. In addition, the characteristics of secondary users (e.g., indoor or outdoor, point-to-point or point-to-multipoint, stationary or mobile, high or low power) can play a role in determining the appropriate spectrum access technique.

We are however witnessing a trend towards hybrid database plus sensing as a more effective spectrum access technique. The database approach relies on propagation models which can benefit from actual measurements provided via sensing from secondary users and recover more spectrum for sharing. WISER system [46] illustrates this benefit for more effective indoor use of TVWS spectrum with the aid of sensing. The other way around with sensing aided by database support can also be beneficial as demonstrated in [5] for radar bands. Besides the sensing based radar detection, the use of geolocation database is also being considered in the context of making additional spectrum available for Wi-Fi in 5 GHz (5350 – 5470 MHz and 5725 – 5925 MHz) [47]. Even in cases where the geolocation database may not be essential for primary protection, it can still be useful as an entity for incumbents to seek interference protection, regulatory oversight, monetization of shared spectrum and enabling more efficient/coordinated secondary sharing. Some of these benefits have been mentioned in [48]. In view of the above discussion, we believe that hybrid geolocation database with sensing as a dominant and more generally applicable spectrum access technique in the future in bands with incumbents not involved in providing wireless and mobile services (e.g., military, radars, DTV).

Where possible and can be made cost effective, explicit coordination between primary and secondary users through some form of beacon signaling can be the most efficient spectrum access technique. While this may be impractical with legacy systems, in the future seemingly heterogeneous systems like cellular and Wi-Fi can incorporate this approach for better spectrum sharing in the context of LTE-Unlicensed (LTE-U).

X. 5G Spectrum

The next generation (fifth generation 5G) mobile systems will exploit the higher frequency bands (above 6 GHz) to support high data rates up to multigigabits per seconds. However, spectrum below 6 GHz will be continue to be relevant and important for 5G systems for two main reasons. First, due to favorable propagation characteristics and ease of antenna engineering below 6 GHz. Second, future 5G systems will be backward compatible with current systems most of which operate in sub-6GHz bands. Although the definition of what 5G exactly means is evolving, some broad criteria that are expected to characterize 5G systems include: higher data rates, very low latency (sub 1 milliseconds), much denser, full coverage, low cost and energy consumption. Besides, 5G systems will likely span multiple radio access technologies (RATs); a key implication of this would be that mobile and Wi-Fi networks that are seen distinct currently will increasingly and seamlessly appear as part of a whole.

From a spectrum and this paper's perspective, the natural question is how will sub-6GHz spectrum contribute to the aforementioned key aspects of 5G systems. Table IV summarizes the possible answers to this question. The recent GSMA report [49] published in June 2015 expects that based on the current traffic growth estimation, 600-800 MHz of additional spectrum will be needed for mobile broadband use by 2020. Therefore, WRC-15 will discuss identifying additional frequency bands below 6 GHz for future mobile broadband uses and these bands can be summarized as follow: 410 —430, 470 —790, 1000 —1700, 2025 —2110, 2200 —2290, 2700 —5000, 5350 —5470, and 5850 —6425 MHz [50]. However, these bands already have been allocated to some primary systems, and clearing them for exclusive mobile broadband use will require years to accomplish. Hence, licensed access in these bands is unlikely. Therefore, Licensed Shared Access (LSA) is considered as a promising solution to support more spectrum for mobile broadband use in which 5G systems will exploit the temporal, spatial or frequency holes to access the spectrum without interfering with primary systems. Spectrum sharing in general, is the 5G theme for spectrum below 6 GHz to handle more traffic [48] and improve user QoE [51].

The evolving fifth generation (5G) cellular wireless network is expected to solve the current challenges for cellular networks. One of these challenging problems is the capacity increase. To address this problem, 5G cellular networks will adopt a multi-tier architecture which consist of different technologies and frequency portions such as macro-cells, small cells, device-to-device (D2D), relays, and vehicle communications to serve users with various requirements. This multi-tier architecture will make the 5G systems much denser that gives rise to several challenging issues to be addressed such as the interference management in term of intra-tier and inter-tier interference. To sustain the capacity expansion and to meet the growth in wireless data traffic, 3500 MHz (3400 - 3600 MHz) band is considered as a good candidate to support the capacity requirements, especially for small cells. In addition, the dense environment is expected to lead to more bursty traffic, which suggests the use of Time-Division Duplex (TDD) mode of operation for more efficient use of spectrum resources.

The 5G systems will allow very flexible and dynamic assignment of TDD resources, which is different from the current TD-LTE technology. In the current TD-LTE, the resource assignment is restricted on the uplink and downlink configuration where there is maximum two switching points in the TDD frame. In cellular networks, several TDD cycles are needed to complete one round trip transmission. The basic data transmission requires at least 4 TDD cycles. One cycle for resource request in uplink, one cycle for resource assignment in downlink, at least one cycle for data transmission, and one cycle for the acknowledgement. As a result, the latency required to accomplish this basic transmission procedures is limited to the number of UL/DL switching points. Thus, this limitation in current TDD frame structure will not help in latency reduction, and shorter switching time and guard band are needed to support more flexibility and lower latency. There are several unpaired frequency candidates that could be used to

TABLE IV. 5G SPECTRUM UNDER 6 GHZ

5G key elements	Feature	Candidate bands under 6 GHz
Higher capacity and data rates	New spectrum (largely shared)	See Table III
Denser environment	Multi-tier architecture	3400 - 3600 MHz band for small cells deployment
Latency	Improved TDD technology with shorter guard band, and switching points.	2300 - 2400 MHz and 3400 - 3800 MHz bands
Coverage	Exploiting low frequencies	TVWS and 700 MHz
Energy efficiency and M2M	Low frequencies and narrow-band technology	GSM 450, 480 MHz

exploit TDD technology in current LTE-A systems and future 5G such as 100 MHz in 2300 – 2400 MHz band, 194 MHz in 2496 – 2690 MHz band and 400 MHz in 3400 – 3800 MHz.

In addition to the capacity expansion, 5G cellular networks should handle a full network coverage requirement to enhance the cellular services in rural areas. Although the full coverage target could be achieved by the existing cellular technology, the higher deployment cost always limits the mobile operators from achieving this target. In 5G cellular networks, it is expected that exploiting more lower frequencies such as 700 MHz band and TV white spaces band will help to provide a low cost, full coverage environment.

Beside human centric communication, a substantial part of machine-to-machine (M2M) communications traffic may be carried over 5G cellular networks. Some challenging tasks for 5G cellular networks to support M2M are: *(i)* to provide energy efficient communication for limited power M2M devices and *(ii)* to improve their coverage conditions. Latter is relevant even in dense urban areas because M2M devices are often located in basements and in challenging locations in the industrial applications. Solutions like energy harvesting (solar, wind and RF energy harvesting) could be used to prolong the battery lifetime and improve energy efficiency. But from spectrum management perspective, assigning lower frequency bands (e.g., sub 1 GHz band) for M2M devices will help in providing more energy efficient communication through reduction in transmit power as propagation characteristics are excellent; the same strategy will also improve coverage.

XI. CONCLUSION

In this paper, we have reviewed the UK plans to meet future spectrum needs towards addressing capacity, coverage, machine-to-machine and backhauling requirements, focusing on below 6 GHz spectrum where most of the current wireless and mobile systems operate. Ofcom plans to release some bands that are currently used by Ministry of Defense (MoD), DTV, satellite and radar services to address these needs. More crucially, we have analyzed the nature of future spectrum below 6 GHz and quantitatively confirm that most of the new spectrum (close to 80%) will be shared, accessed via OSA/LSA models. We also outline a trend that suggests hybrid geolocation database with sensing as the dominant spectrum access technique in the future for shared spectrum with non-wireless incumbent, and beacon signaling as an enabler for efficient spectrum sharing among heterogeneous wireless systems. We have also discussed several widely considered criteria for 5G systems and the type of spectrum that can meet those criteria.

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