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Special Interest Group Cognitive Radio in 5G

White Paper

Novel Spectrum Usage Paradigms for 5G

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1 EXECUTIVE SUMMARY

It is an agreed target for future 5th Generation (5G) Wireless Communication systems to provide a capacity increase by a factor 1000x to 10.000x. Obviously, there are further requirements for such 5G systems under discussion, including for example improved user experience, lower latency, support of Machine-to-Machine communication, metering applications, etc. etc. etc. Still, the predicted increase in capacity is probably *the* most crucial element. While there are multiple vectors that need to interact in order to achieve the target capacity increase levels, in the framework of this White Paper, the focus is on Capacity Increase by increased communication spectral bandwidth.

As it will be outlined in Chapter **2 – Introduction**, the traditional approach of repurposing spectrum and allocating it to Cellular Wireless systems is reaching its limits, at least below the 6GHz threshold. For this reason, novel approaches are required which are detailed in the sequel of this White Paper.

Chapter **3 - Spectrum Scarcity - an Alternate View** provides a generic view on the spectrum scarcity issue and discusses key technologies which may help to alleviate the problem, including Dynamic Spectrum Management, Cognitive Radios, Cognitive Networks, Relaying, etc.

Chapter **4 – mmWave Communications in 5G** addresses a first key solution. While spectrum opportunities are running out at below 6 GHz, an abundance of spectrum is available in mmWave bands and the related technology is becoming mature. This chapter addresses in particular the heterogeneous approach in which legacy wireless systems are operated jointly with mmWave systems which allows to combine the advantages of both technologies.

Chapter **5 – Dynamic Spectrum Access and Cognitive Radio: A Current Snapshot** gives a detailed overview on state-of-the-art dynamic spectrum sharing technology and related standards activities. The approach is indeed complementary to the upper mmWave approach, the idea focuses on identifying unused spectrum in time, space and frequency. This technology is expected to substantially improve the usage efficiency of spectrum, in particular below the 6GHz range.

Chapter **6 – Licensed Shared Access** (LSA) enables coordinated sharing of spectrum for a given time period, a given geographic area and a given spectrum band under a license agreement. In contract to sporadic usage of spectrum on a secondary basis, the LSA approach will guarantee Quality-of-Service levels to both Incumbents and Spectrum Licensees. Also, a clear business model is available through a straightforward license transfer from relevant incumbents to licensees operating a Cellular Wireless network in the concerned frequency bands.

Chapter **7 – Radio Environment Map** details a technology which allows to gather the relevant (radio) context information which feed related decision making engines in the Network Infrastructure and/or Mobile Equipment. Indeed, tools for acquiring context information is critical for next generation Wireless Communication systems, since they are expected to be highly versatile and to constantly adapt.

Chapter **8 – D2DWRAN: A 5G Network Proposal based on IEEE 802.22 and TVWS** discusses the efficient exploitation of TV White Space spectrum bands building on the available IEEE 802.22 standard. TV White Spaces are indeed located in highly appealing spectrum bands below 1 GHz with propagation characteristics that are perfectly suited to the need of Wireless Communication systems.

Chapter **9 – Conclusion** presents some final thoughts.

2 INTRODUCTION

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Wireless data traffic is expected to grow substantially by 2020 and beyond as illustrated in Figure 2-1 [1]. Previous traffic growth predications, such as the “baseball-cap” diagram introduced by ITU-R, have turned out to be overly conservative and new forecasts tend to be orders of magnitude above the earlier high-end estimates [2].

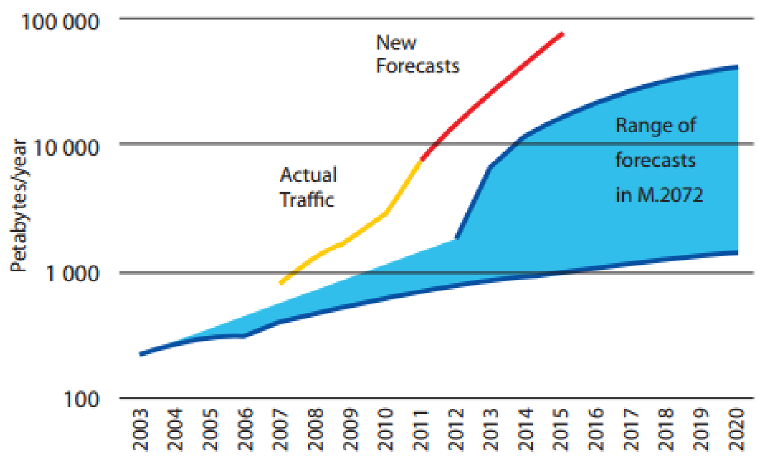

Figure 2-1: Predicted Wireless Data Traffic [1].

While future 5G systems are expected to provide a variety of advantages to End-Users, Mobile Network Operators (MNOs) and the entire Eco-System, a substantial increase in system and link capacity is certainly a key ingredient – it is indeed commonly agreed that a capacity increase per area of a factor 1000 to 10,000-fold will be required for 5G systems by the year 2020 in order to satisfy wireless broadband communication demands [3][4]. Typical strategies for achieving the 5G capacity targets include base station densification approaches, increase of spectral efficiency for example through improved exploitation of the heterogeneous communication framework – and the availability of additional spectral resources. In the framework of this paper, the focus will be on the latter item.

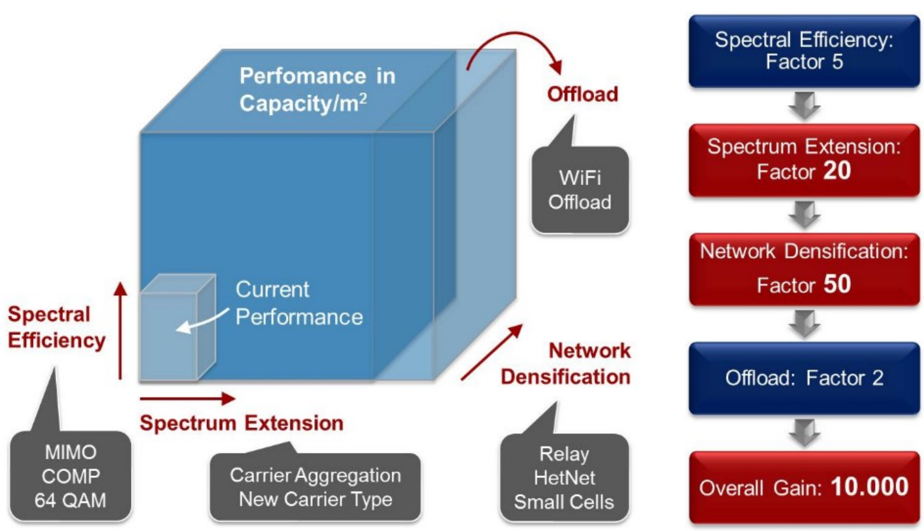

Figure 2-2: Degrees of freedom for areal capacity increase [6].

Indeed, the traditional approach of re-purposing spectrum is reaching its limits. Regulation administrations (such as CEPT in its Project Team CEPT WG FM PT53) therefore consider and develop new spectrum usage approaches including disruptive novel mechanisms such as spectrum sharing, opportunistic usage of spectrum, etc.

In the US, the National Broadband Plan [5] outlines requirements for 500 MHz of new mobile and wireless spectrum below 6GHz by 2020. In Europe, the European Parliament and Council approved the first Radio Spectrum Policy Program (RSPP) [3] with the concrete action that the European Commission together with all Member States will ensure that "*at least 1200 MHz spectrum are identified to address increasing demand for wireless data traffic; and assessing the need for additional harmonized spectrum bands*".

Those additional spectral resources will indeed be required for traditional links between Base Stations and Mobile Devices. Moreover, as outlined in the 5G system vision illustration given by Figure 2-3, new services such as Device-to-Device and Multi-Hop communication, Wireless Backhauling, etc. will consume additional resources.

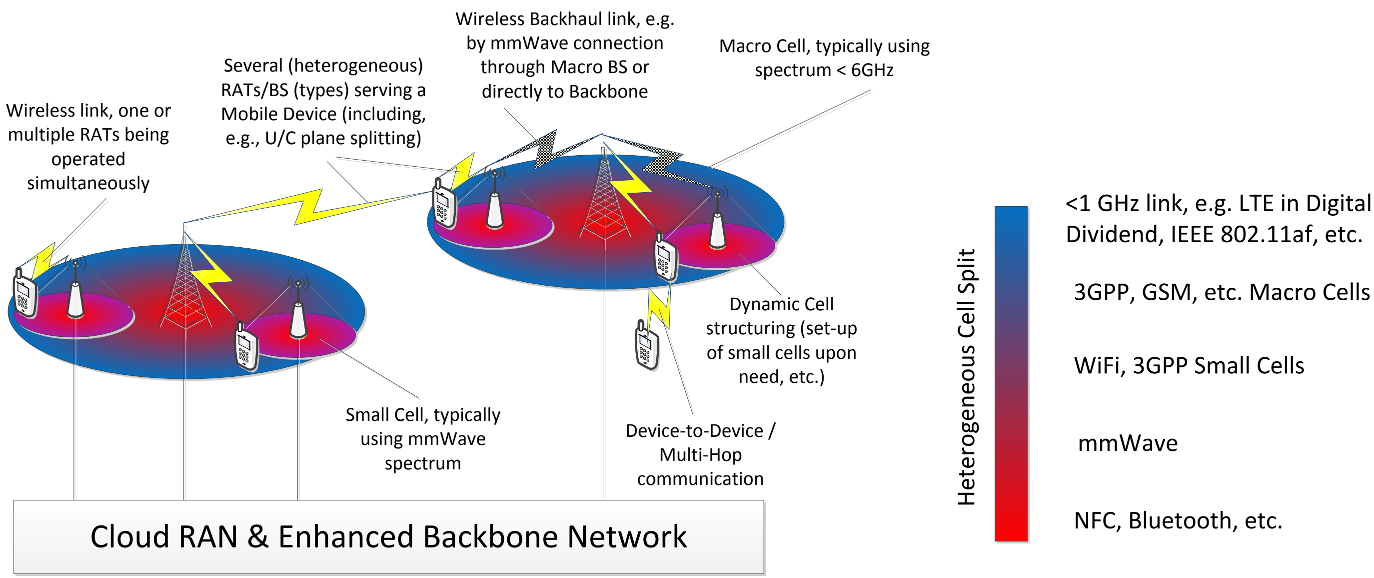

Figure 2-3: A 5th Generation Mobile Wireless Communications System Vision [6].

Furthermore, the identified need for further spectral resources drives current discussions on the introduction of mmWave communication as a novel ingredient to the cellular wireless broadband infrastructure landscape. Utilizing mmWaves, the cell densification can be driven much further than with frequencies below 6 GHz due to reduced coverage range. The inherent relationship between cell sizes and transmit power is illustrated in Figure 2-4. The advantages of Small Cells in terms of overall power efficiency are obvious.

Among the multitude of challenges to be addressed in the design of future 5G systems, this White Paper focuses on the spectrum challenges. In particular, new spectrum usage paradigms will be addressed which are considered to be a key enabler for making more spectrum resources available to 5G systems and services.

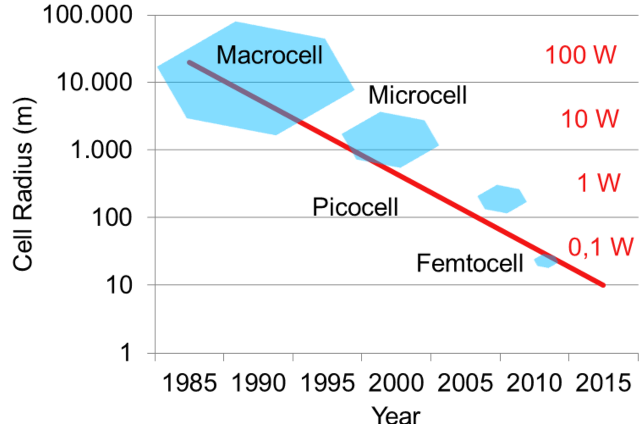

Figure 2-4: Cell Sizes vs Transmit Power in a 5th Generation Mobile Wireless Communications System [6].

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3 SPECTRUM SCARCITY - AN ALTERNATE VIEW

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Abstract *- These days we're often told that radio frequency spectrum is scarce. But is it really or is spectrum scarcity an illusion? This paper discuss about an abundance-based engineering model for the air waves or electromagnetic spectrum, as opposed to the current scarcity-based regulatory model. That is an intelligent move forward from static frequency allocations to dynamic, intelligent, and instantaneous frequency negotiations and assignment. Regulatory model was created when analog filters were hard to build, and well before Shannon and digitization theory exist. Digitalization and related newer implementation techniques make this model obsolete or an unnecessary restriction in spectrum usage. This paper details about the different techniques which make the spectrum abundance model possible, and outline a high level architecture of such a wireless mobile network. The implementation models a distributed cooperative overlay network for spectrum exploration and exploitation. Finally it lists the major use cases or work to be done to make this implementation model or spectrum usage beyond 5G in practice.*

3.1 Current View

3.1.1 What is Spectrum?

Electromagnetic spectrum is not actually a thing. It is simply the range of possible frequencies for electromagnetic radiation. By varying the size and frequency of radio waves, we are capable of sending information without wire. This was first achieved with voice and the telegraph but has now evolved into digital communication capable of transmitting anything that can be represented digitally, from documents to sound to video. The term radio spectrum typically refers to the full frequency range from 3 KHz to 300 GHz (premium frequencies being below 3 GHz) that may be used for wireless communication. The most common problem with wireless communication is weak signals or interference. Interference is anything which alters, modifies, or disrupts a signal or radio wave as it travels along a channel between a source and a receiver. The term typically refers to the addition of unwanted signals to a useful signal. A final important thing to know about spectrum is that not all wireless spectrum is created equal. At the lower frequency end of the radio spectrum, radio waves tend to have better propagation characteristics than at higher frequencies. This means they have better reach because they are capable of travelling through solid objects with less signal loss. While lower frequencies have much better range but are more limited in terms of throughput or broadband capacity. This necessitates different types of services or applications to use different frequency bands of the spectrum for wireless communication.

Radio spectrum may be one of the most tightly regulated resources of all time. From cell phones to police scanners, from TV sets to garage-door openers, virtually every wireless device depends on access to the radio frequency wireless spectrum.

3.1.2 Spectrum Management

When radio waves interfere, they don't impede each other, but they can make the original wave form hard to recognize. That brings us to the most significant reason why radio spectrum is regulated, and that is to prevent interference. Another reason to regulate spectrum is coordination to encourage people doing similar things and using similar technologies to use the same frequencies. In the early days of wireless communication, interference was an easy problem to solve. The range of available spectrum was vast and demand was comparatively small. Interference could be solved by making sure that people using spectrum in the same geographic region were allocated individual bands of spectrum that were well apart from each other in the spectrum band. This strategy was reasonably successful for the last 70 years.

Spectrum management is the process of regulating the use of radio frequencies to promote efficient use and gain a net social benefit. Traditional spectrum licenses were technology and service specific. Most countries consider RF spectrum as an exclusive property of the state. The RF spectrum is a national resource, much like water, land, gas and minerals. Unlike these, however, RF is reusable. The purpose of spectrum management is to mitigate radio spectrum pollution and maximize the benefit of usable radio spectrum. Goals of spectrum management includes rationalize and optimize the use of the RF spectrum, avoid and solve interference, design short and long range frequency allocations, advance the introduction of new wireless technologies, coordinate wireless communications with neighbors and other administrations. The spectrum is divided into different frequency bands, each having a specific application. For instance, the frequency band that covers 300 KHz to 535 KHz is reserved for aeronautical and maritime communications and the spectrum from 88 MHz and 108 MHz for FM radio. This process is called Allocation. The next step is to assign frequencies to specific users or classes of users. Each frequency band has a specific assignment that depends on the nature of the application and the numbers of users. Indeed, some applications require a wider band than others (AM radio uses blocks of 10 KHz where FM radio uses blocks of 200 KHz). In addition, "guard bands" are needed to keep the interference between applications to a minimum.

3.1.3 Spectrum Scarcity

Things might have continued to this day had it not been for the explosion of demand for wireless spectrum from broadband service providers and mobile operators. In the past 15 years, spectrum has gone from an abundant to an apparently scarce resource. But is it truly scarce? It is certainly true that demand currently exceeds supply, but there is debate as to the nature of the scarcity and that debate is rooted in the nature of what spectrum is and how as a result it should be treated.

One of the ways that operators get more out of existing spectrum frequencies is they break geography into cells (hence the name cellular). You can squeeze more out of alleged scarce spectrum by going to smaller and smaller cell sizes. In the current approach as and when more capacity is required out of a wireless network more base stations are added, or more spectrum is brought to use. This approach leads to the scarcity at the available and useful band of the spectrum.

Spectrum scarcity has emerged as a primary problem encountered when trying to launch new wireless services like IoT wireless sensors, M2M communication, Wireless Surveillance, etc. The effects of this scarcity is most noticeable in the spectrum auctions where the operators often need to invest billions of dollars to secure access to specified bands in the available spectrum. In spite of this scarcity problem, recent spectrum utilization measurements have shown that the available spectrum are severely underutilized i.e. left unused. This artificial access limitation based scarcity is often considered to result from the static and rigid nature of the command and control governance regime. Interested parties and stake holders have now started to consider possible improvements in the governance regime by relaxing the constraints on spectrum access by making use of the latest technological capabilities.

3.2 Alternate View

3.2.1 Dynamic Spectrum Management, Cognitive Radios and Cognitive Networks

To date the regulation of spectrum has largely relied on human management and oversight. This places a significant burden on regulators and is necessarily somewhat slow. New technologies offer the potential for the use of spectrum to be managed dynamically. This would not only lower the barrier to access but could be used to ensure fair play among spectrum holders. Allowing computer systems to assign spectrum dynamically and on demand could without manual intervention create both spectrum and organizational efficiencies.

Spectrum is finite, a limited scarce resource, but measurements reveal that several licensed frequency bands are underutilized most of the time. The key advantage of Cognitive Radio (CR), also known as Dynamic Spectrum Access (DSA), is that it can sense an unused channel and switch to it. Cognitive radio is one technology under development that could allow spectrum to be used more efficiently. A CR transceiver scans for unused bands and changes its transmission and reception parameters to different frequencies during heavy data loads without interruption. It also can listen for interference on busy channels and calculate a way to reduce it, so the channels may be used by more people.

Dynamic spectrum management (DSM) or dynamic spectrum access (DSA) is a set of techniques based on theoretical concepts in network information theory and game theory that is being researched and developed to improve the performance of a communication network as a whole. These are techniques for cooperative optimization. The concept of DSM also draws principles from the fields of cross-layer optimization, artificial intelligence, machine learning etc. DSM covers different areas like dynamic channel allocation, frequency assignment, spectrum co-existence, and spectrum access both the licensed and unlicensed frequency bands.

New generation of radio transceivers makes dynamic and opportunistic spectrum access possible. Ability of a device to be aware of its environment and to adapt to enhance its performance and the performance of the network allows a transition from static manual, oversight process to an automated device-oriented process. This allows much more intensive use of the spectrum, and spectrum management policies of the regulator. Radios which are aware of their environment and makes decisions about the radio operating behavior based on that information and predefined objectives. Environmental information may or may not include location and time information. Main functions of DSM are wide band spectrum sensing, spectrum analysis, spectrum decision, spectrum sharing, and spectrum mobility.

A cognitive radio is an intelligent radio that can be programmed and configured dynamically. Its transceiver is designed to use the best wireless channels in its vicinity. Such a radio automatically detects available channels in wireless spectrum, then accordingly changes its transmission or reception parameters to allow more concurrent wireless communications in a given spectrum band at one location for a given time. This process is a form of dynamic spectrum management. A form of SDR or a fully reconfigurable wireless transceiver which automatically adapts its communication parameters to network and user demands. CR can sense its environment and, without the intervention of the user, can adapt to the user's communications needs while conforming to regulatory rules. A CR can intelligently detect whether any portion of the spectrum is in use, and can temporarily use it without interfering with the transmissions of other users. Main functions of CR are flexibility to change wave form, configuration, agility to change the spectral band of operation and power levels, sensing to observe the state of the system and environment, networking to communicate between multiple nodes with relatively big network capacities.

Cognitive Network (CN) as a network with a cognitive process that can perceive current network conditions, plan, decide, act on those conditions, learn from the consequences of its actions, all while following end-to-end goals. The system learns from the past (situations, plans, decisions, actions) and uses this knowledge to improve the decisions in the future. CN is seen as a communication network augmented by a knowledge plane or a cognitive plane that can span vertically over layers making use of cross-layer design, and/or horizontally across technologies and nodes covering a heterogeneous environment.

The knowledge plane needs at least two elements: one a representation of relevant knowledge about the scope (device, homogeneous network, heterogeneous network, etc.); second a cognition loop which uses artificial intelligence techniques inside its states (learning techniques, decision making techniques, etc.). CN is interpreted as a network that can utilize both radio spectrum and wireless station resources opportunistically, based upon the knowledge of such resource availability. Since CR has been developed as a radio transceiver that can utilize spectrum channels opportunistically (dynamic spectrum access), the CN is therefore a network that can opportunistically organize CRs.

3.2.2 Device Relaying and Cooperative Communications

Cooperative communications represent a new class of wireless communication techniques in which network nodes help each other in relaying information to realize spatial diversity advantages. Device terminal relaying makes it possible for devices in a network to function as transmission relays for each other and realize a massive wireless mesh network. Device relaying here refers to a fixed device or cell phone or any other portable wireless device with cellular connectivity (tablet, laptop, robots, etc) a user owns. Device relaying makes it possible for devices in a network to function as transmission relays for each other and realize a massive ad hoc mesh network. Multiple devices communicate with each other using cooperative or non-cooperative communication, and one or multiple devices can play the role of relays for the other devices. Connection setup, interference management, and resource allocation should therefore be addressed using distributed methods. Before the data transmission phase, two devices need to find each other and the adjacent relays (i.e., peer discovery and Device2Device connection setup). The devices can periodically broadcast identity information so that other devices may be aware of their existence and decide whether or not they can start a D2D direct or device relaying communication.

The new abstract wireless links are redefined as arbitrary mutual co-operations among a set of neighboring (proximity) wireless nodes. In comparison, traditional wireless networking relies on point-to-point virtual wired-links with a predetermined pair of wireless nodes and allotted spectrum. In realizing the cognitive wireless networking concept, both the occupied spectrum and the participating nodes of an abstract wireless link are opportunistically determined by their instantaneous availabilities forming an opportunistic wireless link. This principle decides the design of wireless link modules in the wireless link layer. The system performance can improve with larger network scale, since higher network density introduces extra diversity in the opportunistic formation of any abstract wireless link. A wireless mesh network is formed by dynamically changing the path messages take between two given nodes using cooperative diversity, by cognitive radios dynamically changing the frequency band used by messages between two consecutive nodes on the path, and by software-defined radios dynamically changing the protocol used by message between two consecutive nodes.

3.2.3 Spectrum Abundance

Time, space and interference are the three operational dimensions of the spectrum. Spectrum is finite, but for a given time and space with finite set of wireless devices, the finite spectrum of 3 KHz to 300 GHz for use is abundant spectrum than scarce. Because of the steady increase in spectral efficiency in wireless technologies, every year we are able to pack more data into less spectrum using less power. The evolution of radio and antenna design has meant that with increased sensitivity we can now communicate the same information with much less power. It is increasingly possible to design wireless technologies which are sensitive to other radio transmissions and which can operate in noisy environments through techniques like beam forming with multiple antennas, polarization, etc. Which means the authorities manufactured the idea that the electromagnetic spectrum used by wireless devices is scarce. We are now beginning an entirely new era of spectrum abundance. In this new world, services may be driven more by the cycle of new receiver technologies than by access to spectrum licenses, more by engineers and entrepreneurs than by lawyers. Regulators will be much less important. We are moving from scarcity-based regulatory model to abundance-based implementation model for the air waves or electromagnetic spectrum.

Government and regulatory bodies created scarcity through centralization and control. Two main reasons for the past era of scarcity: the state of available radio technologies and government policies. Many regulations intended to promote harmony of the airwaves have instead, by putting artificial limits on technology, created massive inefficiency in spectrum utilization. Decentralizing and de-regulating the spectrum using the latest cognitive radios and dynamic spectrum management techniques is the way forward. Spectrum shortage largely depends not on how many frequencies are available, but on the technologies that can be deployed.

Plenty of spectrum in unused and available for consumers form frequencies greater than 10 GHz, which today can be efficiently and effectively utilized for short range accesses. Ultra wideband or spread spectrum transmissions at lower power levels are possible with today’s radio implementation. Also as wireless infrastructure goes virtual and cloud based, anywhere any device access becomes easy.

Interference is not some inherent property of the spectrum. It's a property or limitation of the devices. A better receiver will pick up a transmission where an earlier one heard only static. Similarly a better transmitter will transmit to avoid interferences to neighboring devices. Adaptive application aware intelligent or smart radios of today can make use of the spectrum in a dynamic and very efficient way. Through spectrum sensing, agile radio identifies the white spaces in the spectrum and then decides whether to occupy those whitespaces opportunistically to transmit data.

The proximity of devices to each other can make a difference too. Low-power devices that are nearby each other can operate in the same spectrum as much higher power technology but below its noise floor. This is similar to the way human cognitive system detects sound, that is on a noisy floor one can hear whispers to the ear. Imagine two people talking to each other at a rock concert. Their conversation doesn't interfere with the very loud concert, yet they are close enough to communicate with each other at low power. Radiation pattern of the radios, both in transmission and reception can be adapted to each user to obtain highest gain in the direction of that user using smart antenna techniques causing less interference and disciplined use of the spectrum.

Cognitive radio system is able to avoid interference to other users while maintaining its own performance. Electromagnetic signal detection techniques need to emulate detection of things by the human cognitive system. How human eye detects two similar entities? Same way newer intelligent devices should be able to detect same frequencies as separate entities by making use of time, space, and other dimensions of the wave forms.

Existing radios and radio regulations remaining, newer intelligent cognitive radios use air waves the way human beings breathe or consume air from the atmosphere. No centralized supervision or co-ordination, but individual devices mutually cooperate and use the spectrum. More number of radios in an area is analogues to more people in an area, and when the number of people reaches certain limit people find breathing difficulty as the radios find difficulty in getting air waves for their operation.

Analogous to an Air conditioner conditioning the air in an area, a Spectrum conditioner also can be thought of which will condition or maintain the use of air waves in the area. This is nothing but a device which does cooperative spectrum sensing with centralized approach to maintain disciplined use of the spectrum in an area, in a fully automated way without any manual intervention. This device should have capabilities to silence the malfunctioning radios, by implementing wireless kill option in newer radios. Such a device can also act as a centralized entity to help in wireless routing and handover in the area.

3.2.4 Implementation model

Current approach for spectrum management includes spectrum allocation/re-allocation by regulators, shift from analog to digital transmission, efficient use of unused bands, spectrum sharing (time sharing, and geo-location based sharing), and dynamic spectrum management or CR with centralized controls. New approach adds or focuses on CR with distributed controls or cooperative communications.

In conventional cellular system, devices are not allowed to directly communicate with each other in the licensed cellular bandwidth and all communications take place through the base stations. Mobile 5G network propose a device tier and D2D communication for fringe area coverage. This includes direct D2D communication as well as device relaying D2D. Extending this and making the network totally device centric or user centric, and a network of intelligent wireless devices where a given device transceiver has the entire spectrum available to operate through community or group co-operation. Radios involved are wideband spectrum agile, location aware radios capable of location discovery and communication with neighboring devices. These smart devices deploy a learning algorithm to find best neighbor. Neighboring nodes in the groups hold social relationship and are committed. Incorporates device relaying with device controlled link establishment where service provider nodes assist in network and session establishment. There is no centralized entity to supervise the radio resource allocation between devices. Every device is capable of radio resource allocation as well as communication session setup and management procedures. Spectrum negotiations are done based on the requested service and availability. Every device cares about only its limited set of neighboring devices and the spectrum usage within that group. Devices select frequency bands based on the availability of other line of sight devices to transceive. Establishes wireless links/service to end points through multiple group co-operations. Once service or session is established, then the intermediate devices act as mere wireless repeaters.

This cooperative communication approach resembles the distributed architecture of the Internet, in which every router can move traffic along an efficient path. Major difference being the radio routers are dynamically added and removed, especially when the wireless devices are mobile. Mobility requirements lead to need for more and more wireless links. A new wireless device which gets into the area adds spectrum sensing difficulty and will necessitate frequency handovers. Similarly when a device which is currently been in the network/session path moves out of the area leads to hand over and need of new wireless links to continue or resume the session. The scenario is more challenging than the current mobile network, where the hand over is guided and coordinated by the central network entities. In the cooperative wireless routing scenario all these decisions also need to be solely performed by the cooperating devices involved within the area. Radios are seen as visitors to the spectrum, a CR which is aware of and adapts the spectrum regulation, local network operators and their services, geographic location, time of the day, user, user objectives and their transactions.

The new network architecture that merges network routing into wireless link and RF design can create a dynamic “fluid wireless network” without predetermined topology and spectrum allocation. In the multi-hop wireless communications, every packet takes opportunistically available paths and spectrum on each hop of the smart wireless system. In the new wireless cooperative mesh network architecture newer smart radios are capable of 5G operation, and treats exiting base stations as just another wireless end point or node. Co-existence of existing non cognitive devices possible and they makes use of the current services as is. The new intelligent devices filter out these frequencies as and when it encounters during its operation. This way new architecture acts as an overlay on top of the existing networks. Every node in the network not bothered about the type of service, and service provider need not have high power base stations. With the use of distributed cloud based service access points or service element cloud, every radio node shall be capable of acting as service provider node. In the Internet of Things (IoT) world, every wireless device is also on the internet and in the cloud. There could be a host of geographically distributed, independent service providers offering services in uncoordinated, ad hoc ways. Basic peer to peer services (voice call, messages, etc.) can be provided without service nodes and just by the end points or radios. Newer devices are that way complex and costlier, but no additional support infrastructure costs and capex required. Cost is also distributed, and affordable semiconductor radios make it a viable option.

In the new radio network implementation, radio links and routing happens much the same way as packet routing happens in an IP network. Intelligent distributed routing decisions are made instantaneously through spectrum sensing at the nodes based on learning techniques and associated databases. Predictable use and learning algorithms are deployed, set of radios and its usage are learned, new radio entry and exit of existing radios are predicted. As user density within an area increases, slower data rates and possibility of no link can happen. Scenario is something similar to traffic on a road high way, and some form of traffic regularization and management protocols are required, which again needs to be distributed and device driven.

3.2.5 Use Cases

1. Wider band spectrum sensing: Spectrum sensing implementation of today is mostly happening and limited to different frequency bands in the spectrum. Wide band spectrum sensing, sensing across the whole spectrum is a requirement for the new network of cooperating devices to operate seamless.
2. Wireless Routing and Handovers: The routing requirements of cooperative mesh networks are different from those of traditional cellular networks and ad hoc networks. Multiplicity of nodes or paths, their mobility requirements and heterogeneous nature makes it extremely complex. Spectrum decision errors can cause bad network performance like service delay or even outage leading to bad quality of service.
3. Highly dense areas: When user density in an area is high, such as in a conference venue with thousands of mobile and Wi-Fi users, cooperative sensing and decision making becomes challenging. New and improved methods need to evolve to handle these scenarios.

4. Highly mobile radios: In high mobility (mobile in moving vehicles, etc.) cognitive radio networks, the fast topology changes increase the complexity of the routing scheme. Cooperative wireless links gets established and removed frequently adding a lot overhead in sensing and routing, leading to link outage and service disruption.
5. No nearby neighbor or no wireless link: In such a case newer radios falls back to the current form of operation and looks for far off base stations to achieve wireless link. When this is also not possible raises an alarm for Emergency Wireless Services (EWS).
6. Spectrum hogging radios: When levels of occupancy increase or when spectrum decision errors happen cognitive radio systems will continually move from one channel to another. This considerably reduces the efficiency and at the worst case could almost render the system inoperable. This can happen because of defective radio or even because of a threat radio been injected in to the system. A wireless kill option for the radios can be thought of to move such radios out of the system.
7. Quality of Service (QoS), and throughput requirements

3.3 Conclusions

Scarcity of wireless spectrum which is been widely discussed is mainly because of the way we view it, regulate it, and use it. From a pure engineering implementation perspective spectrum even though finite is more than sufficient to meet the requirements of wireless devices in a given area at a given point of time. We need to move away from a centrally regulated static deployment of spectrum to a dynamic, distributed, self controlled, automated use of spectrum by deploying the advanced intelligent radios or smart radios and associated implementation techniques like cooperative wireless mesh networks. Better electromagnetic signal detection mechanism, which emulates the way eye detects things needs to be in place. Radio devices then consume air waves in much the same way as human beings consume air from the atmosphere. Fully automated and independent spectrum conditioners can over see the use of spectrum in an area, and regulate the use than a static stringent manual regulation of air waves. The new network architecture that merges network routing into wireless link and RF design can create a dynamic “fluid wireless network” without predetermined topology and spectrum allocation.

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[2] Device-to-Device Communication in 5G Cellular Networks: Challenges, Solutions, and Future Directions by Mohsen Nader Tehrani, Murat Uysal, and Halim Yanikomeroglu

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4 MMWAVE COMMUNICATIONS IN 5G

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Abstract – *Historically, mm-wave (mmW) communications have been used for point-to-point (P-P) terrestrial and satellite links, and more recently for indoor short-distance communications. New network architectures consisting of interwoven networks will be needed to meet the requirements of 5G, particularly an ever increasing demand for high data rates. It is believed that mmW communications will contribute to 5G thanks to large contiguous and available frequency bands. But just where, how and how much? This chapter discusses the state-of-the-art of mmW communications in terms of spectrum availability, standardization advancements and shortcomings. Some application scenarios are detailed. The use of mmW communications introduces challenges at the physical, medium access and link layers, as well as on the network management level. At last, licensing regimes will call for new sharing rules, particularly in the context of an evolving business ecosystem. .*

4.1 Introduction

Improving dramatically the capacity delivered to mobile broadband services is a major concern justifying the jump from 4G technology to 5G. Three generally accepted paths to increase the system capacity are to allocate additional spectrum through re-farming or introducing new bands, to improve the spectral efficiency of the technologies, and cell densification. These paths are not completely independent from each other and improving one path may impinge on the others. For example, network capacity does not improve proportionally with decreasing cell size, as smaller cells may interfere more with each other and negatively affect the spectrum efficiency. This advocates for non-interfering frequencies within dense deployments. To include cells operating at higher frequencies than those currently allocated to 4G networks in an overall network architecture is considered promising, due to the potentially large contiguous bands available at higher frequencies.

The millimeter wave (mmW) band corresponds to the spectrum between 30 GHz and 300 GHz, but is in the literature often used also for lower frequencies down to, e.g., 10 GHz. Historically, mmW communications have been used for point-to-point (P-P) terrestrial and satellite radio links. More recently, solutions for indoors short-distance high-capacity networks have been developed as replacement for High-Definition Multimedia Interface (HDMI) cables or similar. During the last couple of years, outdoor cellular mmW networks have been proposed as one out of several solutions to meet the increasing demand for high data rates in mobile communications. In line with the 5G principle of heterogeneous networks, all modes of mmW communications may be integrated in future 5G networks.

4.2 5G NETWORK ARCHITECTURE INCLUDING MMW COMMUNICATIONS

4.2.1 Heterogeneous nature of 5G networks

One of the novel aspects of 5G will be its network architecture consisting of interwoven networks, probably including both network technologies developed within 3GPP and other networks technologies. The interworking will be emphasized in order to achieve increased network utilization. In this context, cells of different sizes, operating frequencies, topologies and technologies will cooperate according to capacity, coverage and functional needs. An illustration of what a 5G network architecture could be like, with emphasis on mmW, is shown in Figure 4-1. It includes the control (C-) and data (D-) planes, and shows a number of sub-networks and links constituting the heterogeneous network. Scalability is important; control information may be routed through the macrocells in order for the terminals to quickly associate the mmW base stations and facilitate handover for instance. mmW are not expected to be backward-compatible with LTE radio access technologies, but rather be used for backhaul communications to base stations, between base stations, for relay links to improve the coverage within cells, as well as for communications between base stations and user terminals. Backhaul links will most likely operate in licensed spectrum dedicated to Fixed Services (FS). Relay links and radio access links between base stations and user terminals may operate in either licensed bands or in license-exempt bands depending on the configuration of the networks.

For backhaul communications, mmW solutions will have to be competitive with fixed line technologies such as ADSL, VDSL and fibre. One of the advantages of wireless solutions is obviously their easiness of deployment, but prices will also have to positively compare, should fixed links already be available in the vicinity.

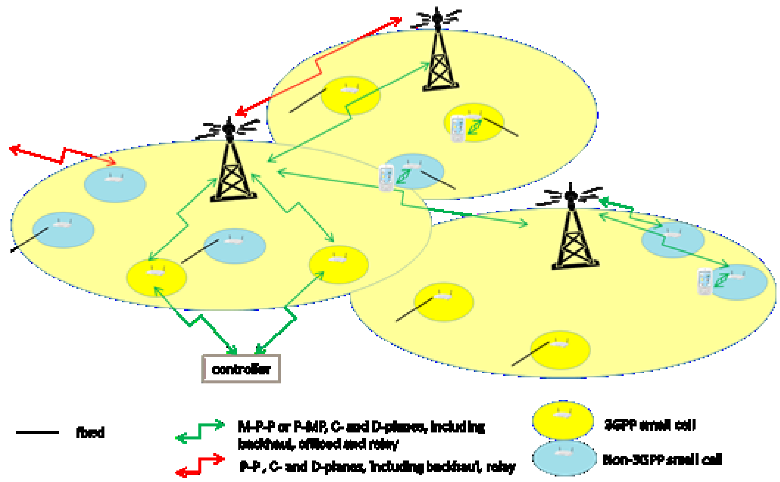

Figure 4-1: A 5G network architecture including mmW communications.

4.3 SPECTRUM AND REGULATORY ASPECTS

4.3.1 Spectrum Opportunities

As can be seen from the European Table of Frequency Allocations (ECA table[1]), a substantial part of the mmW spectrum may be used for FS, and many of these bands may potentially be used by 5G communications, either for backhauling or for network access in small high-density cells. These bands are mainly licensed bands, except for the 57-64 GHz band, which in Europe is license-exempt for indoor use and the 71-76 GHz and associated 81-86 GHz band.

In Norway, parts of the FS frequency spectrum up to 39.5 GHz are currently licensed to operators, while other parts of the spectrum are open to new licensees. All spectrum allocated to fixed services between 40 GHz and 86 GHz is however open to new licensees[2]. In the UK, FS licensing offers a total of 16.4 GHz of bandwidth in the 6 to 55 GHz range, while 18.3 GHz of unlicensed or light-licensed frequency bands are open in the 60 to 80 GHz range.

[1] http://www.erodocdb.dk/docs/doc98/official/pdf/ERCRep025.pdf

[2] http://www.npt.no/teknisk/radiolinje-satelitt-og-pmse/radiolinje/kanalplaner-for-radiolinje

In Figure 4-2, a summary of the most important mmW frequency bands allocated to FS is provided. These have been selected for their large bandwidth, availability (e.g., due to LMDS failed business), lack of sharing constraints and wide international agreement. The latter is very interesting as economy of scale can be realized.

Figure 4-2: Summary of the main potential frequency bands for 5G communications in the mmW range.

Frequency band (GHz)	Available bandwidth (GHz)	Duplexing	Max EIRP (dBm)	Comments
28	1.3	Paired bands with center gap	85	Freed FS spectrum (ITU2). P-P, P-MP, M-P-P for feeding small cells and large cells.
32	1.6	Paired bands with center gap	80	Worldwide freed FS spectrum. P-P, P-MP, M-P-P for feeding small cells and large cells.
40	3	Duplex-neutral blocks	80	Freed FS spectrum (ITU1). P-P, P-MP, M-P-P for feeding small cells and large cells. Block assignment recommended.
60 "V-band"	7	Duplex-neutral blocks	Up to 85 (P – MP) Up to 55 (P – P) Depending on antenna gain (EU).	Worldwide. HDFS in 57-59 and 64-66 GHz. Unlicensed for SRD with EIRP=20 dBm. Gmin=30 dBi (EU only, 0). High attenuation possible, small range or indoor usage preferred.
70&80 "E-band"	10	Duplex-neutral blocks	Up to 85 Depending on antenna gain (EU).	Worldwide FS/HDFS in 71-76 and 81-86 GHz bands, but national allocations vary. Gmin=38 dBi, Pmax=10dBm (EU only, 0). Small range (but higher than at 60 GHz, see next §). P-P, P-MP, M-P-P for feeding small cells and large cells.

Regulatory framework varies from region to region. Besides the EIRP levels, the EU specify (60, 70 and 80 GHz) conditions like maximum output power and correlated minimal antenna gain. In the USA for instance, this is up to the equipment provider to decide, so power and gain tradeoff can be realized.

Since TDD only requires a single channel it will be easier to adapt TDD systems to global spectrum allocations. In duplexing-neutral allocations, TDD systems will benefit from more continuous spectrum. There are a number of reasons to believe that TDD will also be preferred. TDD enables adjustment of the downlink/uplink ratio to match the actual traffic pattern. This is important in the context of multi-hop, ad-hoc configurations where instantaneous traffic needs vary in direction as well, without the ability to predict volume.

4.4 MMWAVE COMMUNICATION STANDARDS

4.4.1 Standards for indoor mmW

The standards currently developed for mmW communications apply to indoor use in the license-exempt 57-66 GHz band. The standards are typically developed for transmission of high-definition content for consumer electronic, e.g., as replacement for HDMI. The different standards are not interoperable, but have coordinated frequency plans with 2.16 GHz wide channels in the 60 GHz license-exempt band. The band can then accommodate up to four channels between 57.24 GHz and 65.88 GHz.

- WirelessHD is the first 60 GHz technology available in commercial products for short range communication. It may theoretically achieve 28 Gb/s data rate using four channels and 4x4 MIMO. Adaptive beam-forming is used for Non-Line-Of-Sight (NLOS) operation. A link is established in ad hoc manner through bi-directional protocol exchange.
- IEEE802.11ad based networks is labelled WiGig, and is the newest of the standards targeting the 60 GHz band. Interoperability testing will be started in 2014. The standard contains both an OFDM air interface (optional) and a single carrier (SC) air interface (mandatory). Equipment will have integrated IEEE802.11n/ac/ad air interfaces, allowing multiband communication and switching between 60 GHz communication and 2.4 GHz or 5 GHz communications. Adaptive beam-forming is included in the standard, allowing two communicating devices to fine-tune their antennas beams in order to optimise the link.
- IEEE802.15.3c is an amendment to the IEEE802.15.3 standard, adding a mmW physical layer to the standard. The use scenarios of the standard are indoor wireless multimedia connectivity and high speed data transfer. Apparently no commercial equipment implementing the IEEE802.3c standard is currently available.
- ECMA387 was published in 2008. Compared to IEEE802.15.3c, this is a simple standard. Apparently no commercial equipment implementing the ECMA387 standard is currently available.

It is expected that the market for 60 GHz indoor systems will grow significantly in the years to come, and that mmW chipsets will be integrated on PCs, tablets and phones. Advances in CMOS RF and digital processing will also most like reduce the cost of mmW chipsets.

4.4.2 Characteristics of the 60 GHz indoor propagation channel

The indoor propagation channel at 60 GHz has been characterized and modelled, based on theoretical assessments, simulations using ray tracing models, as well as on actual measurements in different indoor environments. These activities have led to channel models used in the development of the different standards for 60 GHz indoor communications, both within IEEE802.15.3c and IEEE802.11ad.

The IEEE802.15.3c channel model covers residential, office, library, desktop and kiosk environments 0. It contains a large scale path loss part for both LOS and NLOS communications in different environments, and a small scale channel characterization. The small scale channel characterization is based on an extension of the Saleh-Valenzuela (S-V) model 0, and contains clustering of signal energy both in the temporal and spatial domains. A channel impulse response is shown in Figure 4-3. The number of clusters follows a Poisson distributed process, with a mean ranging typically from 3-4 to 14, depending on the scenario. The model then defines values for the power delay profile and power azimuth profile.

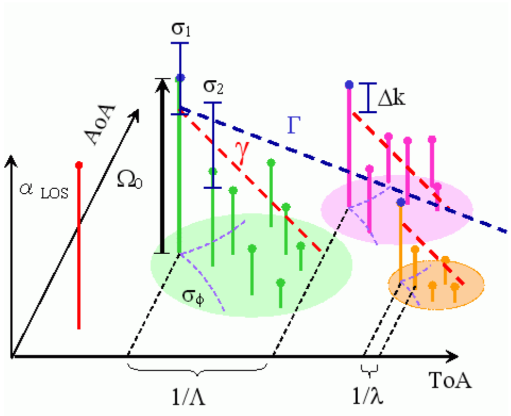

Figure 4-3: Graphical representation of the CIR as a function of Time of Arrival (TOA) and Angle of Arrival (AOA) [4] .

The IEEE802.11ad channel model covers conference room, living room, and cubicle environments 0. It is also based on the S-V model and contains a number of clusters, and various inter cluster and intra cluster parameters are defined.

4.4.3 Characteristics of the outdoor propagation channel

The use of frequencies in the millimeter wave range for outdoor cellular communications is traditionally considered risky due to the propagation characteristics of mmW signals:

- The free space path attenuation increases with the square of the frequencies, reducing the range of a transmission at high frequencies
- Atmospheric losses and rain attenuation increases with frequency, leading to varying received signal strength
- Blocking and shadowing of the signal lead to large attenuations and outage, causing black spots within cell borders without coverage.

The first two bullet points are in fact not that critical. With constant antenna area, the gain of an antenna generally increases with the square of the frequency. Having a directive antenna on one or even both sides of the link balances the increase in free path loss. Directive antennas reduce inter-cell interference significantly compared to 4G networks at lower frequencies, and may allow Spatial Division Duplex (SDD) leading to increased total capacity.

As far as atmospheric losses are concerned, oxygen causes a peak attenuation of 15dB/km at 60 GHz, as shown in Figure 4-4. As a comparison, humidity and oxygen combined cause only 0.1 dB/km attenuation in the 40 GHz range and 0.5 dB/km in the 80 GHz range. In the frame of cell densification, ranges of say 100-200m in radius are envisaged, which considerably limits the importance of path loss below 50 GHz and above 70 GHz.

Blocking and shadowing resulting in outages and black spots without coverage are however a concern.

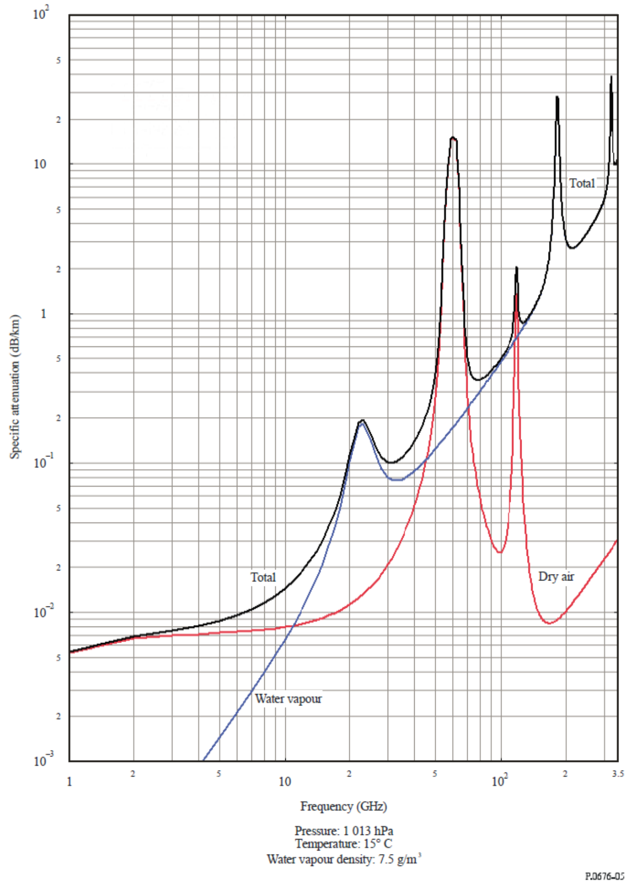

Figure 4-4: Attenuation due to atmospheric gases from [4].

Contrarily to the indoor 60 GHz channel, outdoor mmW propagation is less explored. A few results from activities characterizing outdoor mmW channels have been published, either based on actual channel measurements or using ray tracing software to estimate the channel.

The most extensive characterization and modelling of the mmW outdoor channel so far is based on actual channel measurements in a typical urban canyon environment in New York City 0. The measurements were done at both 28 GHz and 73 GHz. Based on the measurements, path loss models were derived for both NLOS and LOS conditions, using the standard linear model for path loss. In addition, a spatial model including a number of spatial clusters was developed. The number of clusters was between 1 and 4, and as for the indoor channel models modelled as a Poisson distributed process. Measurements in the 38 GHz band have been done in Austin TX at the University of Texas main campus 0. This is a much less cluttered and less dense environment than the one in New York.

Recognizing that good channel models for different environments is a valuable tool when developing new communication systems, there seems to be lack of such models for outdoor mmW communications. There are many environments that most probably exhibit quite different properties than in 0 and 0 that are well suited for mmW cellular communications, such as for instance, parks, stadiums, and more suburban areas.

4.5 RESEARCH OPPORTUNITIES AND CHALLENGES

4.5.1 MIMO

A key property with mmW communications is that directive antennas can be designed with a small form factor. To implement a large antenna array providing maximum adaptivity would however imply a separate RF chain and A/D converter for each antenna element, which leads to a high complexity and high power consumption. Beam-forming algorithms should strike a balance between performance, complexity and power. Hybrid beam-forming may be a good compromise between degree of freedom and performance on one hand side and complexity in the beam-forming on the other hand side 0. Analogue beam-forming generates high antenna gains in a simple and effective way, while digital beam-forming provides higher degree of freedom and offer better performance at the expense of increased complexity, cost and power consumption. By varying the number of RF chains from one to N, where N is the number of antenna elements, an adequate trade-off may be found.

Capacity gain can be obtained from spatial multiplexing. A condition is however that the rank of the channel matrix is larger than one. The channel models described above contain several angular clusters, and each of the clusters has a certain angular spread. There should therefore be a potential for some multiplexing gain in the channel. In 0, results using the channel measurements in New York show that only 50% percent of the channel energy capture by a single spatial dimension, while 80% and 95% of the energy is captured with two and three spatial dimensions. In 0, it is shown that about 10 dB gain is obtained combining four beams coherently compared to using one optimum beam. These results indicate that the propagation channel in fact allows some capacity gains, using for instance some of the MIMO techniques incorporated in 4G communications at lower frequencies, or by developing other techniques adapted to the mmW channels.

TDD assures channel reciprocity for better support of link adaptation. For example, beamforming gain can be based on a number of observations, using TDD's link reciprocity. The devices can report SNIR or terminals interference map in MIMO channels. The base station can perform downlink transmission control considering directional interference at the terminal.

Allowing mobility will create some challenges related to adaptive beam-forming algorithms. The system must also support higher Doppler shifts, as the Doppler effect is proportional to the frequency. The directivity of the antennas will in most cases lead to low Doppler spreads, but if energy from several angular clusters is included in the processing, the Doppler spread may become significant.

4.5.2 Cognitive network control

Effects of obstructions and shadowing are difficult to compensate for. Foliage losses may reach 10 dB or more depending on frequency, foliage depth, humidity and type of vegetation. To provide indoor coverage from an outdoor mmW base station is practically impossible, in particular for brick houses. Relay terminals or repeaters should therefore be included within the network structures, providing coverage for instance behind buildings blocking the LOS path to the base station, or even inside buildings. Allowing more advanced network architectures with mmW frequencies for network access, backhaul and multi-hop links provides a high degree of flexibility to the network. However, it also leads to complex planning, radio resource management and network management.

While directive antennas are favorable to budget links, both the terminals and base stations may need to scan in azimuth and elevation in order to first find each other. The scans may also need to be synchronized, implying a synchronization mechanism common to all terminals in the vicinity. This may considerably complicate the network discovery mechanism. TDD allows for cell synchronization between base stations.

When network discovery is done, broadcasting of control information, managing the network performance and capacity, individual user experience, detecting failures and doing all this in an energy-efficient and automated manner will be needed. Self-organizing functions as above can be executed in a centralized entity like an Operation, Administration and Maintenance (AOM), which limits locations where computational power is needed. Conversely, some functions can be executed at a lower and more local level that would involve coordination between different RATs (marked as controller in Figure 4-1).

As an example, the repartition of radio resources aims to higher network utilization in a given area. These can account for link quality and availability across different RATs before allocating resources. Cooperative approaches seeking a Nash equilibrium is an example of such collaboration across RAT that gives reasonable user experience to a maximum of users within the area. Scheduling mechanisms like Spatial Division Multiple Access (SDMA), where the base station divides the users between numbers of beams, would reduce the complexity in the base station compared to the one beam per user case, and the user terminals would process only one stream within a sub-band.

It is important that these functions be carried out in an automatic manner, as this will reduce installation costs and time, and the networks can be deployed by non-qualified users. Particularly in a light licensing regime, the position and characteristics of the stations can be recorded on a database on a first-come first-served basis, with responsibility for subsequent users to ensure the compatibility with previously notified stations. A neutral party could record simple criteria for each authorized link and make the data available publicly to assist in the identification of operational parameters and to conduct interference analyses, similarly to the criteria needed for a cognitive geo-location database. The main advantage of a cognitive database is to concentrate the computational power to dynamically manage several devices, while the end devices complexity can remain modest. A base station can also manage its relay to another base station.

4.6 CONCLUSION

To incorporate systems operating in the mmW frequencies in future 5G systems is a compelling idea due the large amount of bandwidth available. However, including a mmW interfaces introduces a number of challenges, from the pure physical level such as antenna and RF-design, via PHY, MAC and link protocol design, up to radio resource management and network management. New channel models, beam-forming techniques, cognitive control have to be designed and integrated with the rest of the 5G networks at lower frequencies.

Unlicensed spectrum brings along attractive business models but also need for sharing rules in the long run. In the USA for instance low-gain antennas and higher power can be used while power limitation is enforced in Europe, in an emphatic approach. License exempt bands, both below 3 GHz (current WLAN) and at mmW such as 60 GHz could be incorporated in a global 5G approach. It is likely that mmW access will have other operators than the traditional 4G/5G operators, particularly in the case of indoor communications. Issues related to roaming between operators would then be accentuated.

[1] ETSI EN302217-3 v2.2.1, "Fixed Radio Systems; Characteristics and requirements for point-to-point equipment and antennas; Part 3: Equipment operating in frequency bands where both frequency coordinated or uncoordinated deployment might be applied; Harmonized EN covering the essential requirements of article 3.2 of the R&TTE Directive", April 2014.

[2] ITU-R, Recommendation ITU-R P.676-10: Attenuation by atmospheric gases, 09/2013.

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5 DYNAMIC SPECTRUM ACCESS AND COGNITIVE RADIO: A CURRENT SNAPSHOT

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Abstract – *Cognitive Radio (CR) has received tremendous interest during the past decade from almost all research disciplines in wireless communications. Meanwhile, companies across the world in the value chain are showing more and more interest in CR. This is due to the expected significant scarcity of spectrum caused by data-consuming modern smartphones or similar mobile devices. However, partly conflicting interests and severe technical challenges remain for a successful commercialization of CR ideas, in particular for Long-Term Evolution (LTE) cellular systems. The aims of this chapter are as follows: 1) we try to limit the various physical parameters (e.g. the carrier frequency range, the cell size) being relevant for cognitive cellular systems either in qualitative or in quantitative terms, 2) a conceptual approach for a performance bound being of practical relevance will be pointed out, 3) different players in the value chain of cellular systems and potential conflict of interests will be discussed, 4) the technical state-of-the-art CR and the remaining major challenges will be highlighted, 5) a current snapshot about the quickly evolving area of regulation and standardization will be provided. Finally, some products, services and prototypes for CR will be presented.*

5.1 Introduction

There are several trends in the wireless industry demonstrating the need of significantly more bandwidth in the next years, e.g.,

- the *major philosophy* behind the “Internet of Things” idea: “Everything can be connected”,
- the *empirical observation* that data traffic doubles almost per year [1],
- the *rapid increase* in the number of mobile devices [2].

Therefore, it is of no surprise that CR plays a leading role in research about future wireless communication systems in order to successfully master these challenges by technical innovations and by more flexible frequency regulations.

This survey will therefore provide, on the one hand, a current snapshot about the status of CR from different perspectives, and, on the other hand, some thoughts on commercialization of CR with focus on cellular systems. This paper is organized as follows. In Section II, some thoughts on key CR-relevant issues are explained. In Section III, the development status of CR key techniques will be presented. The regulation and standardization activities for CR are summarized in Section IV, and a brief view for the current products, services and relevant prototypes of CR is given in Section V. Finally, Section VI concludes the paper.

5.2 General Thoughts

Frequency range of CR systems: The lower end of relevant carrier frequencies for CR is determined by the fundamental need of a bandwidth of at least several MHz for data-hungry mobile devices. Studies have shown that the UHF TV band starting at 470 MHz and ending up at 698 MHz (US) or 790 MHz (Europe) with favorable propagation characteristics is significantly underutilized. For this reason the interest in CR is most focused today on the locally unused TV channels in this band, which is normally called TV whitespace (TVWS). Locally unused TV channels with a typical bandwidth of 6-8 MHz can be exploited, in particular in an aggregated way, to provide the required bandwidth for mobile communications. In order to better understand the upper end of relevant carrier frequencies, let us first note that the major need of CR is caused by possible interferences among the multitudes of wireless systems. Moreover, with increasing carrier frequency, the radio power attenuation by material (e.g. walls) is typically increasing while the antenna size is decreasing, both of which decrease the coverage. As a result, carrier frequencies above 10 GHz will likely not contribute to the commercialization of CR principles in the next decade, since such high frequencies are severely attenuated by walls leading to “in room mobile communications” only. However, even below 10 GHz the material attenuation significantly limits the coverage resulting in the major use of CR for carrier frequencies likely below 5 GHz, in particular below the ISM band (5.2-5.8GHz).

Cell size of CR systems: Since the maximum transmit power in wireless communication generally varies only within a small range, say from 100 mW up to 1 W, the maximum cell size is basically bounded by the same physical phenomena as mentioned in the preceding paragraph. Therefore, the cell size of a TVWS communication system may extend up to several kilometers (even up to 100 kilometer, see Section IV) while for carrier frequencies close to 5 GHz, only a few hundred meters are feasible with today’s state-of-the-art receiver technology. Nevertheless, the cell size of a CR system should be smaller compared to regular wireless systems due to its inherent overlay character. Having in mind that base stations of cellular systems are today mainly classified into macro cells, micro cells, and small cells, it can be concluded that CR principles are seemingly most promising for future cellular small cells.

Localization of CR devices: Todays regulation of TVWS requires a Geo-location DataBase (GDB) for avoiding interference to the incumbent users, here the TV receivers, since the more flexible Spectrum Sensing (SS) is still considered as too immature for primary user detection. However, future GPS-based outdoor localization systems can achieve the accuracy within the centimeter range, while for future indoor localization system the accuracy in the meter range seems to be feasible without providing a proprietary and therefore costly localization infrastructure. SS combined with such accurate positioning and tracking systems can achieve the targeted robustness for primary user detection. Therefore, Dynamic GDBs can exploit more efficiently the locally unused spectrum.

Practical performance bound for CR systems: The following approach can be considered as a practically relevant performance bound for the efficiency of CR systems: each primary or secondary user device, even a pure receiver (like a TV receiver), informs its local environment by an underlay low data rate in-band transmission about its relevant technical specifications, e.g. the receiver sensitivity level, the used frequency range, the modulation scheme etc.. Such a low data-rate underlay system, similar to Ultra-WideBand (UWB) technology, could be hidden in the thermal noise level and basically cause litter interference to any other potential secondary transmitter. Note that the recommended in-band transmission enables channel estimation at the secondary device, so that the interference for this particular primary device could be kept at an extremely low level by proper signal pre-coding at the secondary transmitter. In the case of TVWS, this means that any TV receiver has to be enriched with a transmitter which increases the device cost. However, once spectrum truly becomes scarce, this additional cost will be easily tolerated. Even if such an approach sounds too ambitious for realization in cellular systems, at least it could serve as the aforementioned practical relevant performance bound for any CR system nowadays. In other words, this general approach allows quantifying the performance gap of an arbitrary CR system compared to its close-to-optimum.

Relevant players in the CR value chain: Significant contributions of various players in the value chain of cellular systems are needed in order to successfully deploy CR systems, in particular:

- *Chip manufacturers* provide the key ingredients for any mobile or stationary device. With today’s chip technology, any BaseBand (BB) CR algorithm could be basically realized. Moreover, since the Software Defined Radio (SDR) concept is already mature and also often utilized in today’s base stations, in particular in small cells, CR baseband algorithms could be easily implemented even without modifying available LTE chipsets. The situation for the cognitive Radio Front-End (RFE) is different: while for Time Division Duplex (TDD) schemes the manufacturing of suitable cognitive RFE chip sets remain an engineering effort only, a cognitive RFE for Frequency Division Duplex (FDD) systems is not realizable today. This holds true not only because two well separated unused frequency bands should be reliably detected, but much more challenging, the limited isolation between the transmit and receive paths results in a damaging self-distortion. Without a major breakthrough in

RF technology, the only feasible close-to-FDD solution seems to be a half-duplex FDD scheme, where simultaneous transmission and reception is avoided by construction.

- *Software suppliers* integrate algorithms and protocols towards a well-tested, verified and standard compliant communication system. Therefore, except of algorithm research, the extensions towards a CR system is a pure engineering problem.
- *Device manufacturers* integrate a chip platform with the associated software and further hardware into a compact device, so that the manufacturing of CR devices also remains an engineering activity only without CR specific challenges.
- *Network operators* are always in the need of spectrum to well serve the demands of the numerous end users. Therefore, they should generally be in favor of “spectrum generating” CR principles. However, CR is considered controversial in the operator community for several reasons: First, CR enables new entrants to compete with existing operators. Second, CR could negatively impact the end user satisfaction in the case of erroneous primary user detection. Third, the general acceptance of CR principles by operators may also reduce the willingness of regulatory bodies to open up new licensed bands, which are the key differentiators to competitors for any operator worldwide. For example, consider the following scenario: if the majority of operators would support a TDD-based CR in the TVWS, then there is no further need for the regulatory bodies to open up highly valuable frequencies below 790/698 MHz for future cellular systems in a licensed manner. Nevertheless, it seems that in TDD-centric countries operators are not only more open to CR, but also heavily driving the technical progress of CR with the aim of its straightforward deployment in TVWS. In conclusion, the network operator is the only player in the value chain with a potential conflict of interest when introducing CR principles into cellular systems.

5.3 STATE OF THE ART OF CR KEY TECHNIQUES

In this section, we summarize the state of the art of CR key techniques enabling wireless systems to opportunistically operate in the underutilized spectral bands, including emerging RFE techniques, baseband spectral shaping, spectrum awareness, cognitive engine, and location awareness.

5.3.1 Challenges in RFE

Due to the severe signal attenuation in wireless channels and implementation limitations in RF circuits, the frequency bands allocated to uplink and downlink should be well separated, for example, a 20MHz guard band is utilized in the legacy GSM system with FDD. Beside the previously mentioned isolation challenge, this separation requirement doubles the technical efforts to find a pair of spectrum than just an unpaired one. However, TDD system also has its intrinsic disadvantages such as the cell coverage limitation due to the guard interval between the uplink to downlink handover in the frame structure and the high transient speed of RF circuits between the transmission and reception states, but all of them can be seen as negligible compared to the full-duplex FDD challenges.

Moreover, the required high flexibility regarding spectral resources of CR systems demands the use of an SDR platform intelligently operating in the complex scenario of multi-band/multi-channel/multi-standards, which in turn causes stringent challenges on the RFE hardware. For example, the sampling rate and dynamic range requirements of *Analog-to-Digital Convertor* (ADC) and *Digital-to-Analog Convertor* (DAC) are widely extended, opposed to fixed implementation parameters for the legacy systems with dedicated frequency bands. Therefore, the conventional analog RF architecture might be generally substituted by a *Digital Front-End* (DFE) initially proposed in [3]. In addition to an easier RF configurability, DFE can also enable digital pre-distortion at the transmitter, spectrum sensing in CR capable node, and the multi-channel simultaneous transmission or reception within a single wideband RFE.

5.3.2 Baseband and Spectral Shaping

Although accessing white spaces after reliably determining the absence of the primary users' signal is allowed, *Out-Of-Band* (OOB) power radiation of the secondary users' signals must be strictly suppressed to avoid harmful adjacent-channel interferences. As specified by FCC, for instance, only the cognitive devices transmitting signals with an *Adjacent-Channel power-Leakage Ratio* (ACLR) no larger than -72.8dB may operate over TVWS.

With the scalability of transmission bandwidths through manipulating the on/off status of each subcarrier, multicarrier transmission schemes provide much flexibility to use available spectral holes for signal transmission, especially in the noncontiguous spectrum case. Due to its robustness to multi-path fading and a low-complexity implementation using fast Fourier transform *Orthogonal Frequency-Division Multiplexing* (OFDM), as one prevailing multicarrier technique, has been extensively applied to wireless broadband transmission systems.

However, the rectangular-pulsed OFDM signals exhibit a sidelobe of high magnitude leading to considerable adjacent-channel interference. Therefore, effective sidelobe suppression methods must be applied to OFDM signals in CR systems [4]. Note that because of the low implementation complexity, the insertion of guard band is commonly utilized in practical transmitters, such as in LTE systems. This measure comes at the price of sacrificing spectral efficiency, while the sidelobe suppression is still marginal. Thus, time windowing [5] and spectral pre-coding [6], which can provide very small power spectral sidelobes, have been studied in the research literature. It is also pointed out that additional *Low-Pass Filtering* (LPF), which is transparent to the mobile terminals and standard-compliant, facilitates a successful commercialization of CR principles [7].

Another multicarrier technique, i.e. *Filter-Bank based Multi-Carrier* (FBMC), also referred to as OFDM/OQAM because of its using *Offset Quadrature Amplitude Modulation* (OQAM), have been extensively restudied recently. Early in the mid-1960s, the seminal work on FBMC was published by Chang [8]. Then, Saltzberg [9] claimed that a transmission speed close to the Nyquist rate and perfect signal reconstruction without inter-symbol and inter-carrier interference can be achieved by properly designing the underlying prototype filter. Thanks to the excellent time-frequency localization of such prototype filters, the spectral compactness can be well achieved both in contiguous and noncontiguous spectra.

On the other hand, one major drawback of FBMC is its high *Peak-to-Average Power Ratio* (PAPR) caused by a large number of subcarriers with random phase and amplitude. This highly fluctuating signal will suffer from severe nonlinear distortions when passing through high power amplifier in RFEs. Although high PAPR is a common drawback in all multicarrier schemes, FBMC is more sensitive since its well-shaped OOB radiation is very small compared with such spectral regrowth introduced by nonlinear distortions. Another main challenge is its specific signal waveform, which overlaps among several adjacent FBMC symbols because of a longer length of impulse response of the prototype filter. Due to such intrinsic inter-symbol interference, the channel estimation and synchronization are more challenging than the conventional OFDM systems whose inter-symbol interferences can be avoided by the well-designed cyclic prefix. Last but not least, the frame structure should be redesigned if being applied to standard-compliant LTE systems, which may also hinder the commercialization of CR. Compared to the conventional OFDM, FBMC requires several times of computational complexity in terms of the required number of complex multiplication. In order to satisfy the ACLR requirements specified by the regulation bodies such as FCC and Ofcom, at least one spectral shaping scheme should be applied to OFDM, whereas FBMC itself already achieves an excellent OOB suppression. Therefore, the complexities of the spectral shaping scheme and conventional OFDM itself should be both considered, in fairness to compare computation complexities. As given in [7], it can be concluded that most of the spectral shaping schemes for OFDM comes at the price of considerable complexity, while the FBMC scheme causes only moderate overall costs.

5.3.3 Spectrum Awareness

In the context of CR, the spectrum awareness should be prominently considered since spectral holes are randomly distributed in frequency and spatial domains. It is a prerequisite to acquire the knowledge of spectral holes prior to opportunistic access by the secondary users. The two spectrum awareness approaches, SS and GDB, have been intensively studied in the literature.

Spectrum sensing

Energy Detection (ED) [10] determines the status of primary users through comparing the predefined threshold with the output of the energy detector. From the perspective of implementation complexity, this method is most preferable since the receiver doesn't require any *a priori* knowledge of the primary users' signals. The drawbacks are: first, the difficulty of choosing appropriate threshold that depends on the noise floor; and, second, the worse performance under low *Signal-to-Noise Ratio* (SNR). Another method, referred to as *Matched Filter Detection* (MFD), could generally achieve the optimal performance in a simplified set up. However, the perfect knowledge of the primary users' signals, such as the carrier frequency, bandwidth and modulation, are required, resulting in a complex implementation especially in a multi-standard scenario. Other methods relying on advanced signal processing, such as *Feature Detection* (FD) and *Waveform-based Feature Detection* (WFD), have been also widely reported in the literature. Based on these methods, [11], [12] studied the improvement of the robustness of sensing with practical receivers in terms of eliminating spurs and mitigating noise uncertainty problem using the proposed *DImension Cancellation* (DIC) method. And a novel approach of using *Embedded Cyclostationary Signatures* (ECS) has been proposed in [13], which has the potential to significantly enrich the information obtained via sensing.

Geo-location database

GDB is based on refining and reasoning of the information from so-called *Radio Environment Maps* (REMs), spectrum policies and parameters of user networks/devices, etc. The existing GDB approaches [14] mainly aims at authorizing TVWS devices to operate with specified parameter (e.g. channel number and transmit power) while protecting incumbent users. As previously mentioned, GDB has been a more preferable approach in WS communications since SS is seen as still not mature enough to reliably detect primary users' signal at a very low SNR level.

5.3.4 Cognitive Engine

The cognitive engine, whose main function is to make adaptive decisions regarding the radio transmission parameters based on the environmental conditions and capabilities of the transmitter, also plays a key role in CR-enabled networks. Due to its required intelligent behavior, methods from the field of artificial intelligence have been applied to cognitive engines. As an example in [15], the heuristic *genetic algorithm* has been introduced into cognitive engines for seamless reconfiguration of SDR platform. Besides, the following approaches also have been discussed for assisting cognitive engines to enable *Dynamic Spectrum Access* (DSA).

Mathematical Optimization

The tasks of DSA are maximizing the network capacity, keeping the interference level acceptable, and maintaining fairness among the secondary users. It is mathematically convenient to formulate these issues as a constrained optimization problem. In [16], for instance, the resource allocation in multicell multicarrier CR-enabled networks has been modeled as an optimization problem and solved by the Lagrangian decomposition.

Game Theory

Due to the complexity of solving multi-objective optimization equations when multiple decision makers are involved, game theory turns out to be a suitable tool for these challenges. One of the earliest examples of applying game theory to cognitive engines in DSA is given in [17], where the channel selection procedure was formulated as a potential game.

Machine Learning

Additionally, *reinforcement learning*, a kind of machine learning, has also been considered. The environment is modeled as a Markov process. It is sometimes difficult to determine the required state transition probabilities. Therefore, *Q-Learning* developed by Watkins [18] was considered. Q-Learning is an attractive tool due to its inherent simplicity. However, its convergence rate is too slow to be used in practice. This issue can be addressed by *Docition* [19] where experienced learners share their knowledge with inexperienced learners to significantly improve the convergence rate.

5.3.5 Location Awareness

Thanks to awareness capabilities of CR, the location awareness can not only adjust positioning accuracy adaptively in both indoor and outdoor environments, but also assist to improve the spectrum utilization and enable location-based applications in CR-enabled networks. The *Cognitive Positioning System* (CPS) [20] is a good example to show how spectrum awareness can assist location awareness to achieve adaptive positioning accuracy. Vice versa, the derived location information can also facilitate spectrum awareness to achieve reliable and efficient dynamic spectrum management through GDB or local beacon techniques [21]. Similarly, as illustrated in [22], the environment awareness provides wireless propagation channel information, such as non-line-of-sight, to improve localization accuracy. Then, location information can be feedback to environment awareness modules, which select the optimum empirical model to estimate both large-scale and small-scale statistics of the channel since most of them are terrain-dependent parameters (e.g. rural, urban, and indoor).

5.4 CR REGULATIONS AND STANDARDIZATIONS

The major driving force of regulation bodies for enabling CR access of TVWS is the FCC in the US. In 2007 and 2008, FCC performed two actions for evaluating the prototypes of TVWS devices submitted by several companies and research institutes, such as Microsoft, Motorola, Philips, Adaptrum and the Institute for Infocomm Research (I2R). The evaluations finally concluded that these prototypes had met the burden of “proof of concept” in their ability to detect and avoid legacy transmissions. On November 4 of 2008, the FCC voted 5-0 to approve the unlicensed use of white space. Some detailed rules are released ten days later and the final rules are released in a Memorandum Opinion and Order [23] on September 23, 2010. The final rules removed the sensing requirement which greatly facilitates the use of GDB for inquiring unused TV channels and allowed transmitting power, because the current SS techniques are not mature enough for giving adequate protection to incumbent primary users. However, the FCC stated that “they believe that spectrum sensing will continue to improve and some form of sensing may very well be included in *TV Band Devices* (TVBDs) on a voluntary basis for purposes such as determining the quality of each channel and enhancing spectrum sharing among TVBDs”. FCC is also trying to free up the upper parts of the conventional TV band and auction them to other licensed users. In 2008, FCC has made the 700MHz band auction (Auction #73) covering 108MHz from channel 52 through 69. The freeing-up and auction of the 600MHz band [26] for broadband wireless has been planned by FCC. Its impact to DSA in TV bands and emerging new mechanisms in dynamically accessing the auctioned 600MHz and 700MHz bands is still an open topic.

In the UK, the Digital Dividend Review was started by the *Office of Communications* (Ofcom) since 2005. The latest document [24] suggests a sensitivity level for sensing-only devices of -120 dBm for digital TV and -126 dBm for wireless microphones, which is more stringent than the sensing requirements from FCC. However, the Ofcom also seems to be more focused on the GDB approach [25] due to the immaturity of low-cost sensing hardware.

The *European Communications Committee* (ECC) is the business committee of the *European Conference of Postal and Telecommunications Administrations* (CEPT). In May 2009, a project called SE43 [30] on white space and CR issues was launched and completed in January 2011, and the report ECC 159 was published [31]. This report mainly addresses the protections of broadcast service, *Programme Making and Special Event* device, *Radio AStronomy* in the 608-614 MHz band, *Aeronautical Radio Navigation* in the 645-790 MHz band and mobile/fixed services in bands adjacent to the band 470-790 MHz as well as the definition of the requirements for the GDB approach, assessment of the spectrum potentially available for white space devices and some further activities. The protection approaches of SS, GDB and beacons are all taken into account in this report. CEPT has subsequently developed the ECC Report 185 and 186 as complementary studies to ECC Report 159. In particular, the geo-location approach is considered in more details in ECC Report 186. These reports provide comprehensive references for the further development of CR for TVWS. The Report 159 analyzed several typical *Digital Terrestrial Television* (DTT) receiver configurations and shows that the sensing sensitivity requirement would range from -91 dBm down to even -165 dBm which is not achievable by current technology. Therefore, the GDB is the favorable approach.

The major standardization efforts on CR and DSA are briefly outlined as follows.

5.4.1 IEEE DySPAN-SC

The IEEE *Dynamic Spectrum Access Networks Standards Committee* (DySPAN-SC) [27], formerly named as IEEE SCC41, focuses on the following issues:

- dynamic spectrum access radio systems and networks with the focus on improved use of spectrum,
- new techniques and methods of dynamic spectrum access including the management of radio transmission interference, and
- coordination of wireless technologies including network management and information sharing amongst networks deploying different wireless technologies.

The IEEE DySPAN-SC consists of working groups P1900.1~7 addressing many aspects of DSA and CR and an ad-hoc group on DSA in *Vehicular Environments*.

5.4.2 ETSI RRS

The ETSI *Technical Committee* on *Reconfigurable Radio Systems* [28] is standardizing system solutions related to SDR and CR. It has four working groups which address the issues of system aspects, radio equipment architecture, cognitive management and control and public safety.

5.4.3 ITU-R

One of the important works of ITU-R is to give global recommendations of available “services” within the radio spectrum, which are presented in the so-called *Radio Regulations* and revised every two to three years on the regular *World Radio Conference*. The work on CR systems done in Study Group 1 0 focuses on spectrum management and that in Study Group 5 focused on terrestrial services.

5.4.4 IETF PAWS

The IETF has established a working group on *Protocol to Access White Space* database [32], which mainly focuses on standardizing the mechanisms of a TVWS database.

5.4.5 IEEE 802.22

The IEEE 802.22 WRAN (Wireless Regional Area Network) [33] is the first worldwide wireless standard based on CR aiming at sharing geographically unused TVWS for providing broadband access with coverage up to 100 km. The standard is essentially based on TDD OFDM waveforms with bandwidth options of 6, 7 and 8 MHz for conforming different TV channel bandwidths in different countries. A proper *channel aggregation* scheme can be applied for enhancing the throughput by combining multiple unused TV channels. The newest version was completed and published in March 2012 (802.22-2012) [34], which not only defines the specifications for communication, but also gives informative contents on SS and the recommended beacon signal defined in 802.22.1 [35].

5.4.6 IEEE 802.11af

The IEEE 802.11af task group [36] aims to define modifications of the PHY and MAC layers of 802.11 to standardize a new Wi-Fi technology utilizing TVWS with coverage of a few kilometers. The standard is essentially based on OFDM waveforms and a CSMA/CA based MAC. The newest standard draft of IEEE 802.11af was released in September 2012 (Draft 2.0) [36].

5.4.7 IEEE 802.19

The IEEE 802.19 Wireless Coexistence Working Group (WG) [38] reviews *Coexistence Assurance* documents produced by working groups developing new wireless standards for unlicensed devices, such as the IEEE 802 standard family. It also develops standards for coexistence between wireless standards of unlicensed devices.

5.4.8 ECMA-392

The ECMA-392 [39], developed by ECMA TC48-TG1, specified a physical layer and a medium access layer for wireless devices to operate in the TV frequency bands. The application of such devices includes high speed video streaming and internet access on personal/portable electronics, home electronics equipment, and computers and peripherals, which is similar to that of IEEE 802.11af.

Similar to IEEE 802.22, ECMA-392 uses OFDM waveform which supports 6, 7 and 8 MHz bandwidth configurations and synchronized quiet period for in-band SS. The MAC layer supports both Prioritized Contention Access (PCA) and Channel Reservation Access (CRA). The newest edition of this standard was released in June 2012.

5.5 CR PRODUCTS, SERVICES AND PROTOTYPES

This section will give a broader view of the nowadays application and markets of the CR technology by outlining some existing products and services.

5.5.1 TVWS Broadband Accesscess

Super Wi-Fi, sometimes also called *WhiteFi*, is a term coined by the FCC in the US to describe wireless networking using TVWS especially for broadband wireless internet access, which is actually not endorsed by the Wi-Fi Alliance.

The IEEE 802.22 and 802.11af are well known standards suiting this concept. Although NICT in Japan recently announced the world's first 802.11af and 802.22 prototypes [40], there is still no corresponding product on the market yet available.

Some Super Wi-Fi networks have been trialed or deployed by companies and universities such as Microsoft, Google, Adaptrum and Rice University, etc., which are mainly using GDBs for obtaining the vital knowledge about the locally available white spaces.

GDB services from Spectrum Bridge, Telcordia, Google [41] and Shure in the US and Fairspectrum in Finland are being tested or are partly already available to the market. Although GDB is considered as the primary approach to CR rather than SS, *Shared Spectrum Company* (SSC) developed a spectrum sensing toolbox[42], which is claimed to be consistent with FCC guidelines for TVWS spectrum.

5.5.2 CR in ISM Band

The CleanAir [43] technology developed by Cisco uses silicon-level intelligence to create a spectrum-aware, self-healing and self-optimizing wireless network which can mitigate interference and provide performance protection for 802.11n networks.

The *COgnitive Radio Learning Platform* (CORAL) [44] is a CR platform developed by *Communication Research CentreCanada* for research and commercial applications. The radio is based on the IEEE 802.11 standard (WiFi) and operates in the license-exempt (ISM) 2.4 and 5.8 GHz. It can undertake radio interference sensing and autonomously adapt to the sensed interference.

5.5.3 CR Enhanced Beyond 4G Cellular Communication

Although standardization of CR in 4G LTE-A is at the very beginning phase, some pioneer research and prototyping work has already been conducted.

The kogLTE and CoMoRa projects [45] in Germany are aiming at innovating enhanced “Beyond 4G systems” with advanced spectrum awareness, spectrum management and cognitive engine, which are based on state-of-the-art software defined baseband relying on standard-compliant LTE software and RF technologies.

In the EU FP7 ABSOLUTE project [46], CR is extensively applied to a wireless network for the scenarios of disaster relief and unexpected events, being mainly built upon LTE-A technology. A novel low-altitude aerial platform for providing CR-enhanced LTE-A link for first responder will be developed within this ambitious project.

5.6 CONCLUSION

Although CR is in principle independent of carrier frequencies, its first deployment in cellular systems is reasonable to be in the 470 MHz to 5 GHz frequency range and in small cell devices operating in TDD mode. A more and more attractive market is caused by the urgent need for backhauling numerous small cells. CR TVWS is seemingly a good technological fit to this need due to the excellent propagation properties and sufficient bandwidth, if aggregated. Moreover, there is no direct need for SS since GDB is sufficient due to the missing mobility requirement of stationary backhaul links. Such CR systems might become part of LTE Rel. 13 products being commercially available in, say, 2017.

However, operators and regulatory bodies will play two dominant roles for the successful commercialization of CR principles in cellular systems. For instance, the FCC is currently extensively investigating the concept of so-called “incentive auctions”, which would result in a demand-driven re-ordering of the attractive TV frequencies by proper sharing between the network operators and the TV broadcasters – this may serve both at its best, without any need of CR principles.

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6 LICENSED SHARED ACCESS

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Abstract – *Licensed Shared Access (LSA) is an emerging concept for spectrum sharing under an exclusive license regime. This chapter reviews the concept of LSA. In particular it covers recent standardisation activities, possible cases for LSA use, and an evolution framework towards a more dynamic LSA operation over short time scales. The chapter also discusses LSA integration with LTE and WiFi systems and possible business cases for spectrum sharing between Incumbents and LSA Licensees.*

6.1 Introduction

Spectrum scarcity is one of the key issues that need to be faced in 5G networks. In the past, new cellular spectrum has typically been made available through reframing of spectrum. The affected incumbents were moved to other parts of the spectrum or lost the corresponding bands. An instance of such an event is the refarming of TV Broadcast Spectrum which produced a Digital Dividend. For 5G systems, a part of the solution is expected to lie in millimetre-wave communication, in particular for small cells and low mobility usage. Wide Area cell types, however, will need further spectrum resources below 6 GHz and that is where the National Regulation Authorities (NRAs) are currently running out of options. Spectrum sharing is contemplated as the primary candidate in addressing this issue.

6.2 Licensed Shared Access

In attempt to promote spectrum sharing in 5G networks, the European Telecommunications Standards Institute Reconfigurable Radio Systems (ETSI RRS) Technical Standardisation Committee has produced a detailed outline of a new approach named Licensed Shared Access (LSA) [1] [2]. LSA is a spectrum sharing approach designed to serve short-term to mid-term industry needs through a quasi-static allocation of shared spectrum to cellular operators. In general this framework allows a LSA licensee (i.e. a cellular operator) to access the spectrum that has already been allocated to an incumbent. During the entire licensed period the incumbent forfeits the spectrum access right to the LSA licensee. Therefore the quasi-static licensing agreement guarantees the Quality-of-Service (QoS) in a LSA licensee network. This is a major difference in comparison to the traditional cognitive radio approaches that allow access to TV white space on an unlicensed basis without any QoS guarantee.

In the context of the LSA framework proposed by ETSI, a spectrum allocation period will be in the order of multiple years. This allows operators to provide a predetermined level of QoS. However the long time base for sharing will confine the amount of candidate spectrum that can be utilised by the LSA framework. Further spectrum opportunities can be exploited as the time interval is reduced, possibly down to weeks, days or even seconds and below. Although many challenges need to be overcome, eventually LSA is expected to evolve towards a sharing framework with much smaller time intervals than what is being considered currently. In other words, LSA will ultimately fit the Dynamic Spectrum Access model as defined by IEEE DySPAN Standards Committee [3]. During this convergence phase which will undoubtedly go on for a number of years, the existing rather static LSA approach will need to be enriched by knowledge management mechanisms making also short-term spectrum opportunities available to QoS guaranteed, licensed sharing.

A prominent example for the justification of LSA is where a Mobile Network Operator (MNO) may choose to enter into a contract with an Incumbent, to augment the MNO's load capacity. The MNO may have more than sufficient capacity for the majority of the day which is easily handled by their current spectrum licenses and network infrastructure. However during peak times, the MNO may not have sufficient capacity in particular regions or locations of which to ensure a service level agreement. The solution to this is to increase the available spectrum to the MNO for only the geographical locations and peak times where low quality conditions or higher than normal densities of users of the MNO's network are prevalent.

As such, the MNO may only need a license for a portion of the spectrum, during peak times and only for particular areas, rather than a country wide license for that spectrum. This 'peak spectrum' license could be a very lucrative business arrangement for both the MNO and the Incumbent which is happy to enter into the licensing agreement. The advantage is the MNO does not need an entire country spanning license, reducing the total cost of ownership and in addition the Incumbent leasing the spectrum to the MNO can generate additional revenue of their spectrum license. This is even more advantageous to the Incumbent if the particular spectrum is not used at all in the geographical location under demand by the MNO. This arrangement is not possible under current spectrum licensing and sharing frameworks, but is a very powerful enabling feature of LSA.

6.3 USE CASES

To compete for market share, manufacturers and operators in 5G network must emphasize user Quality of Experience (QoE) by way of competing for extra spectrum and offering flexible access. LSA produces more possibilities for different markets, for example, transportation, commercial centres, mobile network operators and sport venues. In a word, many people or organisations can benefit from the LSA system because LSA facilitates spectrum as a portable product.

6.3.1 MNOs

In this use case, spectrum demands are over a wide area and Mobile MNOs can access the LSA band. A live field trial of LSA has been implemented in Finland, using TD-LTE base stations, network management system and a real core network [19]. To solve the problem of overloading during peak time periods, MNOs would like to use the LSA band to offload traffic from their own spectrum. To achieve this they require a spectrum license only for a short-time in a given geographical area.

6.3.2 WiFi

In this use case, spectrum demands are over small areas. The LSA band is not only to be used by MNOs but also other organizations willing to pay for the spectrum rental. The content generated by WLANs is still growing rapidly, WiFi devices can be provided an LSA license to use the LSA band.

6.3.3 Internet of Things

This use case considers the fusion of wireless services. Internet of Things (IoT) is a trend of the smart planet and smart city. Apart from handheld equipment such as laptops, smart phones and tablets, other wireless equipment, e.g, wearable devices, are expected to generate a large amount of traffic. Their spectrum usage may be low if they use a fixed spectrum band because some devices may have a long interval between transmitting wireless data. Internet of Vehicles (IoV) is an important part of the IoT. Vehicle wireless communication technologies are expected to play a vital role, involving Radio Frequency Identification (RFID) and mobile Internet. LSA spectrum can be allocated to such devices to satisfy their transmission demands.

6.3.4 Advertising

Although advertising is a major contributor of generating Internet content, it is not sensitive to real-time communication. Advertising services can use the spectrum in off-peak periods at a low spectrum leasing price. It means that they can take advantage of time periods when the LSA band usage is low.

6.4 LSA Architecture

Licensed Shared Access based spectrum sharing is being considered by ETSI to enable the opening up of additional spectrum of interest to MNOs to augment their existing radio access network portfolios. The current proposed implementation for LSA is being defined in Europe for the 2.3-2.4 GHz Band (other bands may be considered in other regions). This band is currently used by cordless cameras, SAP/SAB portable video links, telemetry, radiolocation and defense systems applications across Europe.

An LSA approach is also being considered within the United States for the same purposes. [14] However the particular frequency of interest is within the 3.55-3.65 GHz band, which is currently occupied for Federal aerial radionavigation and radiolocation services within the US.

LSA will enable MNOs to obtain additional spectrum on a secondary basis. However, in contrast to other sharing approaches (e.g., TVWS, WiFi, etc.), there is exclusive and guaranteed access for cellular operators for an agreed geographic area, time frame and frequency range. Due to this fact, QoS can be guaranteed for LSA shared bands. Also, due to expected long sharing intervals (typically several years), MNOs will be able to develop a clear business model with predictable revenue estimations and thus infrastructure investment can be planned and evaluated economically.

The current ETSI architecture for LSA is highlighted in Figure 6-1. The LSA system consists of a repository (LSA Repository) and a controller (LSA Controller). The repository (or repositories) has a direct link with the controller (or controllers for varied deployments) and the Incumbents of interest. Within the repository information regarding the Incumbents' spectral usage from a geographical, temporal and frequency point of view will be stored for interrogation by the controller. It is also assumed that the LSA system, in particular the controller and repository will be owned and maintained by a third party to ensure compliance of agreements between both the MNOs and Incumbents within the framework.

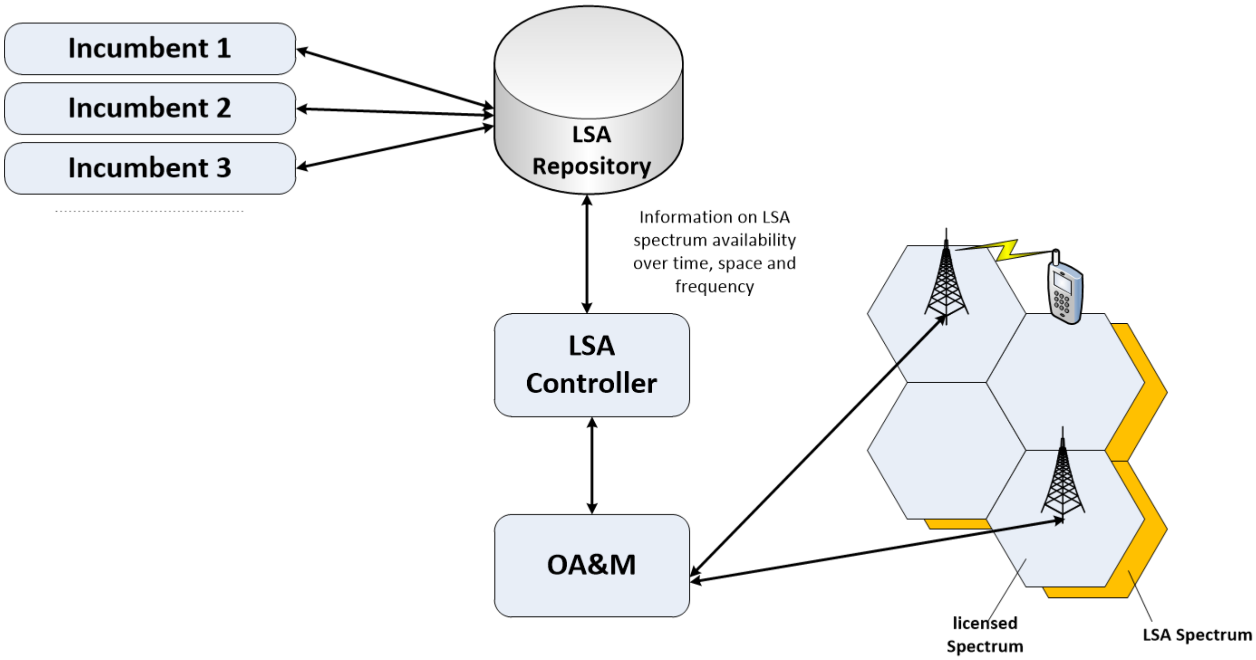

Figure 6-1: LSA Architecture currently being defined by ETSI.

The repository will notify the controller of changes to the sharing agreement or the creation of agreements. The controller will use the information from the repository and communicate with the appropriate MNO network to ensure proper transmission and compliance of the agreement by the MNO. In order for the MNO to operate on the secondary spectrum it must first be given a grant by the controller to do so, ensuring that the MNO does not impact upon the Incumbent's access to the spectrum owned by the Incumbent.

The intended method of operation of the LSA architecture is for the system to operate as an intermediary for the purpose of enforcing and maintaining sharing agreements between Incumbents and LSA Licensees with a future-proof implementation to facilitate a possible shift from relatively static sharing agreements to more dynamic agreements in the future to maximise the reuse of the available spectrum.

6.4.1 LSA Architecture Interfaces

The LSA system has 3 primary interfaces for efficient secondary spectrum reuse while satisfying the requirements of the 3 (or more) parties required to operate such a system.

These interfaces are:

- Incumbent to LSA Repository
    - This interface is necessary for the Incumbent to provide updated LSA radio resource allocations in the geographical, space, power and time domains.
    - Incumbent provides information on the availability of spectrum, including: geographical area, frequencies, time and power levels. Power level information is necessary to assist with the definition of the protection areas that must be complied with by any LSA Licensee. These protection regions are to ensure interference protection for the incumbent.
    - Security, reliability and quality of service information will also need to be provided by the Incumbent and agreed upon by the LSA Licensee. It is likely that these parameters will need to be standardised.
    - The Incumbent to LSA Repository interface should be standardised to ensure harmonisation of potential cross or multiple country spectrum markets. This interface is to ensure that the LSA Controller

    can retrieve the necessary license agreement information by interrogating the LSA Repository when requests for LSA spectrum are received from the LSA Licensee.
    - The LSA Controller should also be able to perform updating of the LSA Repository for Radio Environment Maps (REMs), as the REM data could be supplied from the LSA Licensee side of the system as well.

- LSA controller to MNO/LSA Licensee
    - Standardisation of this interface is critical for both market harmonisation activities as well as ease of interoperability and deployment amongst various types of LSA Licensee.

In addition to the primary system interfaces, there are several additional interfaces that must be considered:

- Interface between different LSA Repositories
    - Required for cross-border agreements as well as enabling distributed LSA Repositories should a decentrallised approach prove to be preferred.
    - Security concerns must be taken into account for preservation of Incumbent and LSA Licensee information as well as ensuring the integrity of the information exchanged between repositories.

- Interface between different LSA Controllers (assuming a distributed control scheme)
    - This interface is required for coordination purposes if distributed LSA Controller schemes are preferable for deployment.
    - Multiple LSA Controllers are important from a reliability perspective as to not have a single point of failure within the system.

- Interface between regulator and LSA Repositories/Controller.
    - Integrity and compliance of the LSA Repository information must be ensured so that the license agreements meet the required specification and are compliant with regulatory requirements for spectrum access as well as the semantics of individual commercial license agreements.

It is proposed that the LSA Controller is responsible for:

- Managing and maintaining sharing agreements
- Updating the LSA Repository and REMs data retrieved from LSA Licensee systems (if UEs are configured to perform such tasks in an OEMs network)
- Updating license agreements
- General enforcement of agreements
- Ensuring that correct periods of uptime and QoS are met
- Declining or acting upon retake requests from the Incumbent

6.4.2 LSA Standardisation Activities

The CEPT Working Group Frequency Management (CEPT WG FM) is currently working to ensure the LSA framework is ready to be introduced to the market from a regulation perspective. In fact two project teams are producing deliverables within the following scope:

> **CEPT WG FM PT52** [6]: "… The Project Team shall: develop a draft ECC Decision, aimed at harmonising implementation measures for MFCN (including broadband wireless access systems) in the frequency band 2300-2400 MHz…". PT52 has finalized ECC Decision (14)02 on "*Harmonised technical and regulatory conditions for the use of the band 2300-2400 MHz for Mobile/Fixed Communications Networks (MFCN)*" [21] and ECC Recommendation (14)04 on "*Cross-border coordination for mobile/fixed communications networks (MFCN) and between MFCN and other systems in the frequency band 2300-2400 MHz*" [22]. Currently, PT52 develops a "*ECC Recommendation to provide guidance to administrations in implementing a sharing framework between MFCN and PMSE within 2300-2400 MHz*" [23] and prepares a response [24] to the EC Mandate on 2300-2400 MHz [25].
>
> **CEPT WG FM PT53** [7]: "… The Project Team shall handle the following tasks: … Develop an ECC Report on general conditions, including possible sharing arrangements and band-specific (if not dealt with by a specific project team) conditions for the implementation of the LSA that could be used as guidelines for CEPT administrations. …". As a result, "ECC Report 205: Licensed Shared Access (LSA)" [26] was published in 2014.

Additionally, there is some substantial political support from the European Commission (EC). The EC has indeed issued a standardization mandate (EC Mandate M/512) with a specific request to develop LSA standards [8]. This complements the overall picture, leading to an efficient interaction between ETSI Standardization, CEPT regulation activities and alignment with political objectives across Europe. While Europe is definitely on the forefront on licensed Spectrum Sharing technology, it should be mentioned that this approach is of course applicable to any other region and broad acceptance is expected to be seen over time.

6.5 Integration of LSA with LTE and WiFi

A core consideration when employing an LSA enabled RAN, is that the UEs accessing the RAN in question must be compliant with the additional spectrum that has been enabled by the LSA agreement. Thus the most sought after spectrum would be that which currently is utilised by existing UE models.

A good example is for international versions of UEs, where particular countries may only have MNOs with the spectrum that relates to only a couple of the bands supported by the UE but not all. Thus a third party or existing MNO could engage in an LSA agreement with the particular owners of additional spectrum that the UE in question supports, but currently is not licensed for RANs. The MNO could rebrand the international version UE as an ‘LSA enabled UE’. The only hardware requirement by the MNOs is to upgrade their existing networks to access the LSA band.

6.5.1 LSA and LTE/WiFi

The primary uses for integrating LSA with current LTE and WiFi networks are to maximise the spectrum that is regionally specific to LTE (TDD and FDD) and WiFi deployments. This approach is not as necessary when addressing WiFi as WiFi operates within the 2.4 and 5 GHz ISM bands which have a greater harmonisation across the 3 ITU regions than LTE deployments.

Certain regions only implement or have licensed the use of LTE in a small subset of all the bands that the LTE specification is written for. LTE bands 1 through 31 are specified for FDD communications and bands 33 through 44 are for TDD communications.

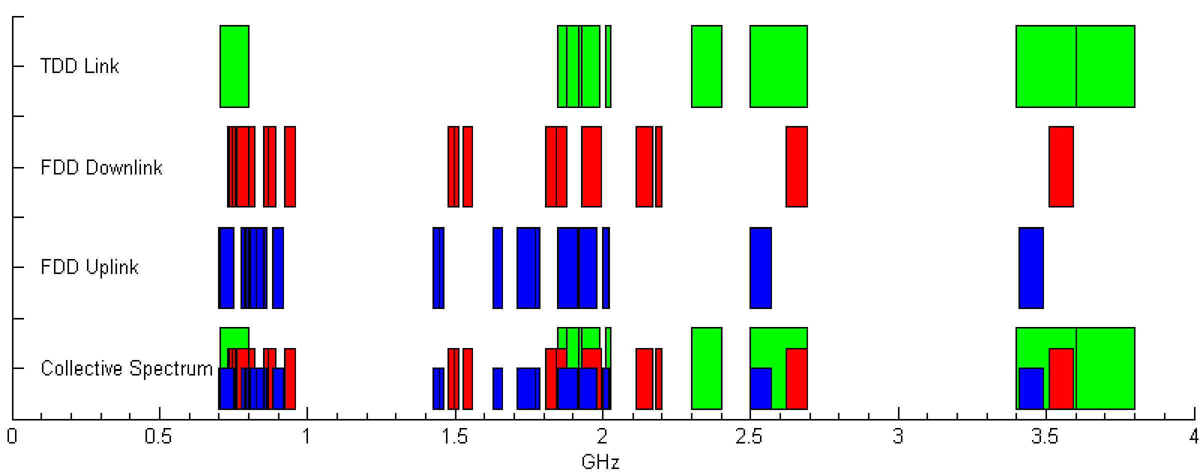

Figure 6-2: LTE Channels 1 through 44 (Reserved channels omitted). Highlighting the collective spectrum spanned according to the LTE standard.

From Figure 6-2 it can be seen that the particular frequencies of interest are between:

- 700 – 960 MHz
- 1425 – 2690 MHz (significantly broken up)
- 3400 – 3800 MHz

These 3 frequency blocks, comprise of bands already defined under the LTE specification, thus it is more likely that hardware already exists to support these bands. It should be the focus of LSA systems to target these bands to minimize the amount of new infrastructure that needs to be deployed.

6.5.2 Current State of LSA – United States

It should be noted that the EU is currently looking at deploying LSA within the 2.3 GHz band, indicated by ECC report 205 [6]. Additionally, the US is looking at implementing LSA type agreements within their 3.5 GHz band under the President's Council of Advisors on Science and Technology (PCAST) spectrum report from July 2012 [15], which was forwarded to and adopted by the FCC in April 2014 [14]. The US band of interest is between 3550 and 3650 MHz.

The 3550 to 3650 MHz band in the US is currently occupied by Radiolocation (Primary and Secondary services) and Aeronautical Radionavigation services under rules G110 and US245 [16] which are currently Government exclusive allocations and only secondary non-government radiolocation services are additionally permitted. Due to the limited use of these frequencies under current conditions, the 3550 - 3650 band would require a minimal regulatory and commercial effort to implement the LSA framework. Table 6-1 highlights the spectrum allocations by the FCC for the 3500 to 3650 MHz band. (Primary services are in ALL CAPS, whereas secondary services are all lowercase)

Frequency	Service	Application
3500 MHz - 3600 MHz	• RADIOLOCATION • AERONATUICAL RADIONAVIGATION (federal, ground-based) • Radiolocation (non-federal)	• Telemetry (civil) • G110, US245
3600 MHz - 3650 MHz	• RADIOLOCATION • AERONATUICAL RADIONAVIGATION (federal, ground-based) • FIXED-SATELLITE (non-federal, space to Earth)	• Amateur • Defence systems • Radiolocation (military) • G110, US245

Table 6-1 - Spectrum Allocations for the 3550 to 3650 MHz band in the United States of America

- G110 - Federal ground-based stations in the aeronautical radionavigation service may be authorized between 3500-3650 MHz when accommodation in the 2700-2900 MHz band is not technically and/or economically feasible.

- US245 - In the bands:
  - 3600-3650 MHz (space-to-Earth),
  - 4500-4800 MHz (space-to-Earth), and
  - 5850-5925 MHz (Earth-to-space),

  The use of the non-Federal fixed-satellite service is limited to international inter-continental systems and is subject to case-by-case electromagnetic compatibility analysis. The FCC's policy for these bands is codified at 47 CFR 2.108. [16]

6.5.3 Current State of LSA – European Union

In Europe using Germany's spectrum allocation as the basis for this analysis, the 2.3 to 2.4 GHz bands are currently allocated as follows [17]:

- Within the 2300 to 2320 MHz band, the primary service allocated is for Mobile services with civil telemetry identified as the primary use of the band.
- Within the 2320 to 2400 MHz band, the primary service allocated is for Mobile services with Amateur and Radiolocation services as secondary users. The sub bands 2320 - 2350 and 2385 to 2400MHz is typically used for SAP/SAB portable video links, the 2333 to 2350, 2347 to 2385 and 2385 to 2400 MHz sub bands are typically used for cordless cameras. It can be seen that there is a significant spectral reuse for multiple secondary services within this band.

Frequency	Service	Application
2300 MHz - 2320 MHz	• MOBILE	• Telemetry (civil)
2320 MHz - 2400 MHz	• MOBILE • Amateur • Radiolocation	• Amateur • Defence systems • Radiolocation (military)
2320 MHz - 2350 MHz		• SAP/SAB portable video links
2333 MHz - 2350 MHz		• Cordless cameras
2347 MHz - 2385 MHz		• Cordless cameras
2384 MHz - 2400 MHz		• SAP/SAB portable video links
2385 MHz - 2400 MHz		• Cordless cameras

Table 6-2 - Spectrum Allocations for the 2300 to 2400 MHz band in Germany

It can be seen from Figure 6-2 and Tables 6-1 and 6-2, from the ECC recommendations and adoptions by the FCC that the 2.3 and 3.5 GHz bands coincide quite well with channels that comprise the LTE standard, which will ensure initial commercial interest and uptake of the LSA framework to augment existing spectrum portfolios.

6.5.4 LSA used in LTE

LTE has some features that can help the integration with LSA implementation. The LTE resource allocation unit is a resource block which contains 12 subcarriers and each subcarrier's bandwidth is 15 kHz. If the available spectrum is not a continuous band and the number of users in the operating network increases but the bandwidth requirement from the users is not high, current LTE resource allocation can use this available spectrum without making any changes. If the users' bandwidth requirements also increase, e.g. many users are requesting services such as video downloading that consume large bandwidth, LTE-A provides a feature of carrier aggregation that can assemble separate frequency resources together for single stream transmission. A constraint for using carrier aggregation is that the aggregated frequency range has to satisfy the existing RF capability. It is perceivable that LSA can leverage this carrier aggregation functionality that is already built in to the LTE standard to provide additional LSA spectrum to the MNO without significant modification to existing base station deployments.

6.5.5 LSA used in WiFi by MNOs

There are WiFi services that are operated by MNOs to provide users with a complementary service to the MNOs existing cellular infrastructure, enabling higher coverage densities and load alleviation off the cellular core network. Users access these WiFi networks provided by MNOs using their SIM IDs and the MNO can appropriately deliver the service of which the users' rate plan entitles them.. If MNOs have access to available spectrum via an LSA sharing agreement and the spectrum is covered by a WiFi frequency band, the LSA spectrum can be geographically assigned for the installed WiFi capacity rather than the cellular network to avoid interference. This case seems most probable within the 2.3 – 2.4 GHz LSA band due to there being minimal changes to the RF electronics of WiFi systems to operate within this frequency as it is adjacent to the 2.4 GHz ISM band that WiFi typically operates. The 3.55 – 3.65 GHz LSA band would require additional engineering effort to be utilised for WiFi deployments.

6.5.6 Coexistence of LTE and WiFi using LSA

Current mobile devices are widely equipped with both LTE and WiFi components. The manufacturers of these components are normally different and the components are highly integrated, e.g. baseband chips and RF front ends. Thus it will be difficult to implement the coexistence of LTE and WiFi in the lower layers. Taking the downlink transmission as an example, one possible scheme is to change the software in the application layer, to schedule and decompose packets in the application layer of the transmitter then recover and recompose packets in the application layer of the receiver. This requires a constraint that the transmitter provides LTE and WiFi at the same time, which means that the LTE provided by MNOs and WiFi owned by others can not be used in this scheme. However, LTE and WiFi both provided by MNOs are suitable for this scheme. The MNO will schedule, decompose and allocate the packet. The users only need to update the software application, no changes need to be done to the physical components in user equipment.

For LSA, the vacant frequency from the incumbent may be available by chance. The current potential frequency band is 2.3-2.4 GHz, which could be used for LTE and WiFi transmission. Coexistence of LTE and WiFi gives the MNO more choices in LSA. MNOs will, however, incur an extra cost in the computation for scheduling, resource allocation, optimization and decision making for LTE and WiFi data streams. Also, a coexistence scheme needs to be designed to meet backward compatibility. The scheme should be able to switch to single transmission, LTE or WiFi according to user application version, QoS or channel quality.

6.5.7 LSA Implementation with LTE

Chips capable of non-continuous frequency carrier aggregation (CA) are readily available [18], thus the current state of the art could realise an LSA implementation with minimal additional infrastructural cost. CA enabled technologies are critical for the operation of LSA, as initially LSA aims to open up additional bands for LTE (2.3 GHz TD-LTE band 40 in the EU). There is no guarantee that across various MNOs the spectrum opened up to an LSA system would be contiguous with the spectrum already owned by a particular MNO. Thus it becomes important that the UE attempting to use the LSA spectrum is capable of non-contiguous CA.

Most MAC, and PHY signalling required on the UE/BS side of the implementation is sufficient under the current LTE specification, for a system supporting Release 11 or higher. Power control signalling would need to be adapted to account for different maximum power levels according to the individual LSA license agreements, as maximum power level settings are currently not conveyed within the LTE specification. BSs and UEs with appropriate RF electronics capable of communicating over the spectrum where the LSA channels exist would also be required to utilise the LSA spectrum. The more challenging implementation issues will come from the interfacing requirements of the LSA Controller and the MNOs network.

In order for the MNO to get the most out of their contracted sharing agreement, it would make sense for the LSA Controller to be closely connected to the MNOs LTE infrastructure (eNBs). If this link were to be performed via IP, the link would be considerably latent thus missing potential opportunities (at sufficiently short timescales) as well as being unable to rapidly respond to retake requests. While very short latencies is not a core consideration for initial deployment of LSA, it may become a larger issue within future LSA deployments. Thus considering such requirements early on in the lifecycle of LSA is a recommended practice.

From the perspective of latency, the LSA Controller should interface with the MNOs core network through some kind of entity that has a direct connection to either the serving gateway or the mobile management entity (MME) over the S1 interface. Maximising the coupling of the LSA Controller requests to the MNOs infrastructure, will enable more rapid responses to change (if changing at all) in licensing agreements and potential whitespace opportunities when moving toward a more dynamic LSA agreement.

Alternatively for more static type agreements, with whitespace intervals greater than hours, it would be sufficient to interface the LSA Controller with the serving gateway or even packet gateway to convey the necessary LSA control messages to the core network. This way may be initially preferable by MNOs as direct connections to the MNOs hardware from the LSA Controller do not need to be created.

There would need to be an interpretation layer within the LTE core network to route the appropriate LSA Controller information to where it is required within the network. This layer would be responsible for forwarding messages to turn on or off the LSA spectrum for given BSs in the network. Spectrum information for which bands are available, and broadcast power limits would also need to be conveyed to the appropriate BS. It must also be considered, the rate at which an MNO must react to a retake request according to their licensing agreement, and how that will impact upon the MNOs access strategy as well as traffic offloading if the LSA band is heavily utilised at the point of retake.

6.6 Evolution Towards Dynamic LSA

An LSA system comprises one or more incumbents, one or more licensees and the means to enable a coordination between incumbents and LSA licensees, such that the latter may deploy their networks without harmful interference. As the evolution to 5G, LSA may grow from common to smart, as shown in Figure 6-3. Incumbents can lease the spectrum in three domains, time, region and band. As the time interval gets smaller, spectrum usage efficiency will increase while also increasing the complexity of the LSA Controller. LSA is not only technology driven but also needs to consider commerce or business. Incumbents will benefit from those three domains by leasing spectrum to operators. A Sharing Agreement should be made based on a contract.

The LSA framework enables licensed and shared access to spectrum that would otherwise be unavailable for mobile use. This section outlines a possible LSA evolution path towards dynamic LSA and defines examples of technical parameters, interfaces, functionalities, compatibility, etc., that may be used as a basis for developing the necessary standards. An LSA Evolution Framework is introduced followed by the technical details of the stages to enable a smooth evolution towards dynamic LSA.

6.6.1 LSA Evolution Framework

The proposed LSA evolution framework enables a smooth evolution towards dynamic LSA in 3 dimensions: frequency diversity, time interval and radio access technologies (RATs). The main goals of the LSA evolution framework are:

- Supporting smooth evolution: easy to implement and less impact to operators
- More efficient and flexible radio resource management
- From less dynamic to more dynamic
- Reasonable incentives for incumbents

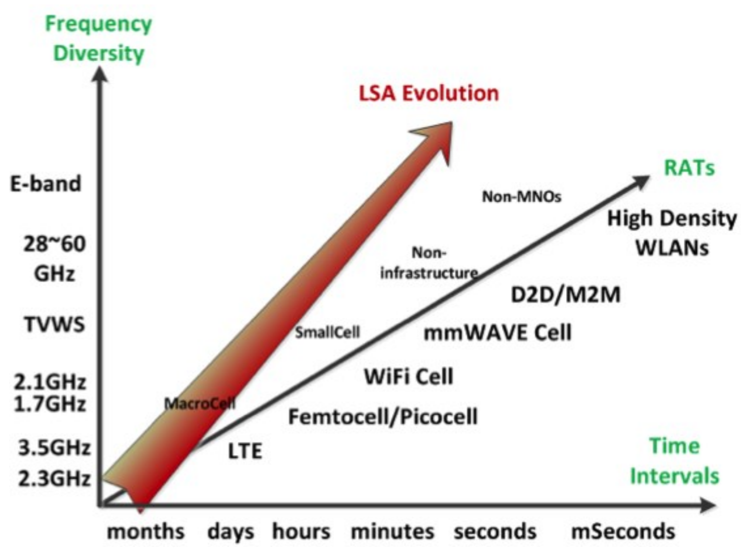

Figure 6-3: Three-Dimensional LSA Evolution Cube.

Frequency diversity defines possible LSA frequency candidates and channelization to support the spectrum sharing between incumbents and LSA licensees. The LSA spectrum may start with 2.3 GHz in EU and 3.5 GHz in US that are supported by the current LTE standard and then will consider other spectrum bands such as the TVWS bands and 28~60 GHz mmWave bands.

The time interval dimension defines the time scale at which the LSA system will share the LSA spectrum between incumbents and LSA licensees. A long-time interval will have less impact to the MNOs, thus it means better Quality of

Service and less infrastructure investment while a short-time interval means no guarantee of QoS, and interference from and to the Incumbents. In order to find the available shot-term time slots, sensing and other interference management technologies may need to be developed for current operator infrastructures. Dynamic operation in the sub-second time interval is currently limited by protocol performance. The next generation LTE needs to develop new RF solutions and new protocols to support short-term time intervals.

The RATs dimension defines technologies that will be applied to implement LSA systems which may include LTE macro and microcells, WiFi and mmWave pico/femto cells, D2D and M2M and future generation WiFi deployments. The long-term time interval combined with LTE macro cells may be the easiest case to implement since from the MNOs point of view, the LSA spectrum akin to a bandwidth expansion which means there is very little impact to the infrastructure of the legacy mobile networks especially over the 2.3GHz and 3.5GHz bands. Three aspects of RATs can be considered: Cell Size (macro cells vs small cells); Technologies (eg. LTE vs WiFi) and infrastructure vs non-infrastructure.

Taking the above LSA evolution framework into account, we divide the LSA evolution path into four stages as shown in Figure 6-4, considering LSA sharing and compatibility, implementation and functionalities of the LSA system.

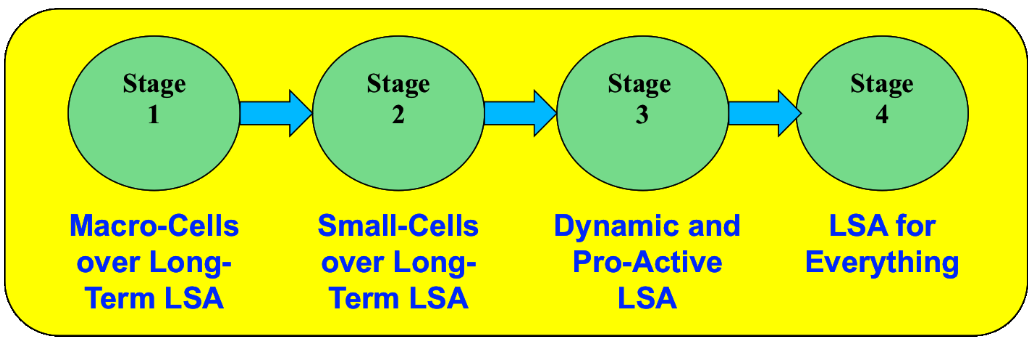

Figure 6-4: Four-Stages of LSA Evolution.

In Stage 1, the main goal is to enable the availability of extra frequency bands for mobile broadband services in a long-term manner and with harmonized technical conditions while taking into account the various incumbent uses. It is simple and easy to implement without any extra new components and interfaces needed from the MNOs. Stages 2 through 4 will be explored in the following sections.

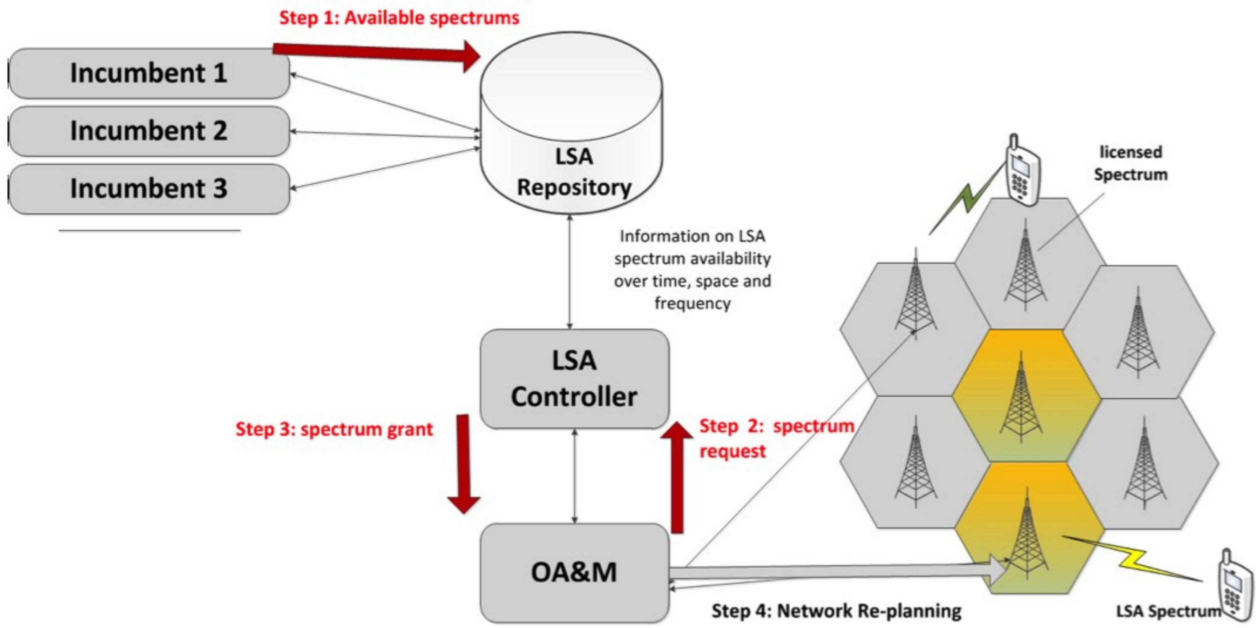

Figure 6-5: Architecture of Macro Cells over Long-Term LSA.

With reference to Figure 6-5, the characteristics of the initial LSA architecture are:

- Predefined spectrum, for example, 2.3 GHz in EU, 3.5 GHz and 1.7/2.1 GHz bands in US
- Pre-scheduled and fixed spectrum availability in time and space domains
- Long-term agreement based spectrum usage: hours, days
- Incumbents determine the availability of the spectrum to LSAs
- Easy to implement, minimal upgrade is necessary for MTs and RANs: LSA controller informs about the availability of the new spectrum to OA&M
- Typical applications: periods of high traffic, e.g. special events in certain localized areas without the need for a long-term license
- Impact on MNOs: spectrum expansion, minimum impact on the infrastructure

6.6.2 Use Case: Mobile Network Operator Bandwidth Expansion

During an event (lasting for hours, days or months), an MNO operating LTE in a licensed band in the region of the event applies for an individual authorization to use the LSA spectrum. For example, the MNO can apply to use a portion of the 2.3-2.4 GHz band in the region for LTE macro Base Stations. As a result, the LSA spectrum is used to offload high traffic in that area. MNOs do not need the long-term license. Usage is based on an on-demand LSA license.

An application for accessing the LSA spectrum may include (but is not limited to) the geographical region and the time period in which the MNO plans to access the allowed portion of the LSA band. The National Regulatory Authority, which has the sole responsibility of granting such individual authorization, plays a key role in determining with relevant stakeholders (i.e. Incumbent and MNO) the conditions of the LSA sharing framework including sharing options and modalities. The conditions to use the spectrum may be made available in an information repository that may be accessed by the mobile network operator's Operation, Administration and Maintenance system (OA&M) through the LSA Controller. There are no new interfaces and components from the MNO’s network point of view.

6.6.3 Interfaces, Components and Functionalities

An LSA system includes Incumbents, LSA Repository and LSA Controller. Incumbents need to report the spectrum availability to LSA Repository as shown Step 1 in Figure 6-5. OA&M will send spectrum requests to the LSA Controller when the MNO needs a short-term license in a geographic area. The LSA Controller will then interrogate the LSA repository to find the right LSA spectrum and send back the spectrum grant, including pricing information to OA&M.

Once granted the LSA spectrum, OA&M will use the LTE radio resource management signaling to reconfigure the related LTE Base Stations to LSA bands.

6.6.4 Spectrum Sharing

Spectrum sharing under the LSA framework is binary by nature, as it permits spectrum use by either the Incumbent or the LSA Licensee. The LSA Licensee enjoys exclusive spectrum rights of use where and when the spectrum is not used by the Incumbent. Incumbent and LSA Licensee may share the same spectrum in the same location on a time basis, thus there is no interference issue. If Incumbent and LSA Licensee use the same spectrum at the same time in different locations, interference avoidance must be considered. If an LSA Licensee uses in the same location and time a portion of the band not being utilized by the Incumbent, inter-service compatibility studies need to be performed for protecting the Incumbent from harmful interference (out-of-band and blocking) caused by MNO under LSA.

The availability and conditions of the LSA spectrum need to be defined in the sharing agreement considering at least the following parameters: geographical information: in which area LSA spectrum is available and spectrum information: transmission power; how Incumbents will reclaim the LSA spectrum and operating frequency.

Spectrum sharing can be seen as a future potential solution for providing efficient capacity expansions in ultra-dense network environments. It is envisaged that there may be companies, like legacy wireless network operators that own spectrum, however, these companies may not possess small cell infrastructure to maximize their spectral reuse. They may enter in agreements with localized, collaborating small cell operators in order to offload traffic, by using the spectrum already owned by the wireless operator. In this respect, the customer continues to use the same 3GPP-based RAT, with a guaranteed quality of service, rather than being forced to use an open Wi-Fi connection due to lack of service in their area.

Through the distinction of operators to collaborating small cell operators and legacy wireless network operators it will be possible to create more flexible environments where competition for 'best' frequencies and cells (e.g., according to certain technical, propagation characteristics and pricing) will be present. As a result, new business models and new stakeholders are added to the broader picture of the wireless networks market.

Moreover, some small cells could potentially utilize lightly-licensed bands (e.g., by focusing on bands 2.3/3.5 GHz). Specifically through light-licensed bands it will be possible to achieve good QoS in a cost-efficient manner. Framed in this context, a problem statement can be provided as follows:

Given:

- Traffic levels in a specific area;
- Mobility levels of users in the area;
- Presence of collaborating small cell operators and legacy wireless network operators,

Find:

- The spectrum allocation that needs to be done;
- The assignment of traffic to collaborating small cell operators;

- The selection of small cells that could use light-licensed spectrum so as to achieve good QoS in cost efficient manner in ultra-dense environments.

6.6.5 Quality of Service

Quality of Service (QoS) of both Incumbents and LSA Licensees is based on the sharing agreement which defines how the sharing will happen between Incumbents and LSA Licensees. The LSA Controller computes the LSA spectrum availability in the spatial, frequency and time domains based on rules (sharing agreement) built upon the LSA rights of use and information about the Incumbent's use provided by the LSA Repository. Since this stage is virtually a spectrum expansion for MNOs, QoS is guaranteed at a high level considering the long-term time intervals and that the Incumbents will give an LSA Licensee enough time to evacuate and switch to a licensed band.

In Stage 2 of the evolution model of Figure 6-4, an MNO decides to deploy its allowed portion of the LSA frequency band using low power small cells. The term "Small Cell" should be understood as including all variants of deployments resulting in a coverage area smaller than the typical area covered by a macro cell deployment. This includes, but is not limited to, micro cells, pico cells and femto cells. An MNO may choose such a deployment topology to ensure it can satisfy the Incumbent's protection requirements over a larger coverage area.

In Stage 3, a highly efficient and flexible use of the LSA spectrum is the goal. LSA Licensees will determine the availability of the LSA spectrum by themselves under the LSA umbrella. Individual rights of use through sharing agreements may be granted as opposed to general authorisations. LSA Licensees need to:

- Avoid harmful interference to incumbents
- Ensure quality of service to the customers
- Ensure efficient use of LSA spectrum
- Fulfill other objectives if necessary

The main aim of Stage 4 is to let LSA become the ultimate spectrum manager through which any wireless network will request for spectrum availability in the frequency band of interest. Depending on the type of the applications, networks and technologies, the LSA Controller may grant the spectrum request an appropriate type of LSA band for sharing with the Incumbent or even for sharing with other LSA Licensees in competition. An MNO becomes the carrier through which other networks can send their requests. An MNO itself is also an LSA licensee.

6.7 Business Model

6.7.1 Spectrum sharing market considerations

In markets, when spectrum trading happens, incumbents obviously need a reward to share their spectrum with licensees. This reward probably will be monetary or in terms of resources that incumbents need to achieve their own wireless communication goals. Compared with the money-exchange method, resource-exchange involves additional communication protocols which need a longer time to set up in standards. This method is neither more flexible and nor attractive to incumbents. Considering security issues, incumbent may be reluctant to transmit their data in licensees' networks. To guarantee that the incumbents' property rights are protected, they prefer to lease their unused spectrum and withdraw the licensee at any time. Therefore, money-exchange is a more practical solution in the LSA system.

There are some issues that should be considered when discussing business mechanisms:

- Rationality
    - Everyone is rational and hopes to gain as much a benefit as possible. In the competitive activity, the strategy set is important for the LSA Controller to make an all-satisfactory decision. Everyone in the system will get a non-negative utility, i.e., buyers will pay no more than their estimated values and sellers will set the price no less than their cost.

- Competition
    - In markets, competition is common. In order to attract more LSA Licensees, Incumbents would compete with each other to provide a low price or high quality of service. For LSA Licensees, they would compete for maximizing their profit. Consequently, in the non-cooperative environment, how to balance double-side benefits becomes a significant problem.

- Fairness and Truthfulness
    - In the marketing process, because of rationality, cheating and conspiracy may often happen. Some solutions should be proposed to guarantee a fair competition environment. For instance, in the auction behaviour, the VCG mechanism [20] is proposed to force each bidder to provide his true valuation for an item.

- Demand and Supply
    - Demand and supply are two direct influential factors of price determination in a market. The unit price will vary up and down until it settles at a point where the demand quantity equals the supply quantity. This point is called price equilibrium.

- Utility and Efficiency
    - How to maximize the utility of the LSA system? Competition exists between Incumbents and LSA Licensees. Each LSA Licensee and Incumbent is likely to reach an agreement that can maximize their own interests.

6.7.2 Incumbent Considerations

Incumbents are willing to offer their available spectrum to LSA Licensees for the purpose of earning extra revenue. Their market behaviour could be defined by the following parameters:

- Utility = revenue - cost
- Cost = administration maintenance
- Revenue = charge fee of spectrum use + license fee

Three cases for the marketing structure may be considered. In the first case, the market structure is simple, an Incumbent may have a single LSA Licensee in a certain time and in a region. There is no competition in spectrum trading between LSA Licensees. When there are multiple LSA Licensees vying for a limited LSA band, it means that the Incumbent has more possibilities to earn more profit by leasing the LSA band to the highest bidder. This is a case of a monopoly by the Incumbent. In the third case we have multiple Incumbents. This means that an Incumbent cannot be in a dominant position any more. Incumbents now have to consider their opponents' strategies.

6.7.3 LSA Licensee Considerations

Because LSA Licensees have their spectrum demands, they need to rent the spectrum by taking into account the service quality and the cost in terms of payment. Their market behaviour could be defined by the following parameters:

- Cost = payment to the incumbent
- Revenue = the quality of service or capacity of channel
- Utility = revenue - cost

Three cases for the marketing structure may be considered. Similar to case 1 above, an LSA Licensee may rent only the LSA band from a single Incumbent. It has to weigh its cost of buying the LSA band and profit it earns from its customers. In the second case when there are many Incumbents but a single LSA Licensee, the LSA Licensee will dominate the market. In the third case of multiple Incumbents and multiple LSA Licensees, a more stable market can be established for trading spectrum between Incumbents and LSA Licensees.

6.7.4 System Considerations

The LSA is the state-of-art of complementary regulatory framework. It is flexible and provides allocation of spectrum based on space and time. Concerning dynamic spectrum allocation, the decision making has a great influence on spectrum use efficiency. As LSA will be used for commercial purposes, spectrum allocation is supposed to be driven by monetary considerations.

Below we provide a brief introduction of auction models for LSA spectrum leasing. First, some factors should be quantified to measure this system.

- Efficiency = (estimated value of LSA Licensees – factual price)/(factual price - estimated price of Incumbents)

Incumbents and LSA Licensees have their respective estimated price/value for the LSA spectrum band. They will adjust the trading prices by the market environment and rationality, from their respective points of view, which means that estimated prices/values of Incumbents and LSA Licensees are subject to some distributions. The efficiency metric provides a measure of their joint expectation for the spectrum trading. Other metrics can be considered as follows.

- Utility = total revenue (Incumbents + LSA Licensees)
- Capacity = total spectrum leasing in a cycle period

These metrics may not reach their peaks simultaneously and to balance them we need to consider most influential factors. When the cycle period is short, this will be a challenge for the LSA Controller. An architecture for decision making is shown in Figure 6-6.

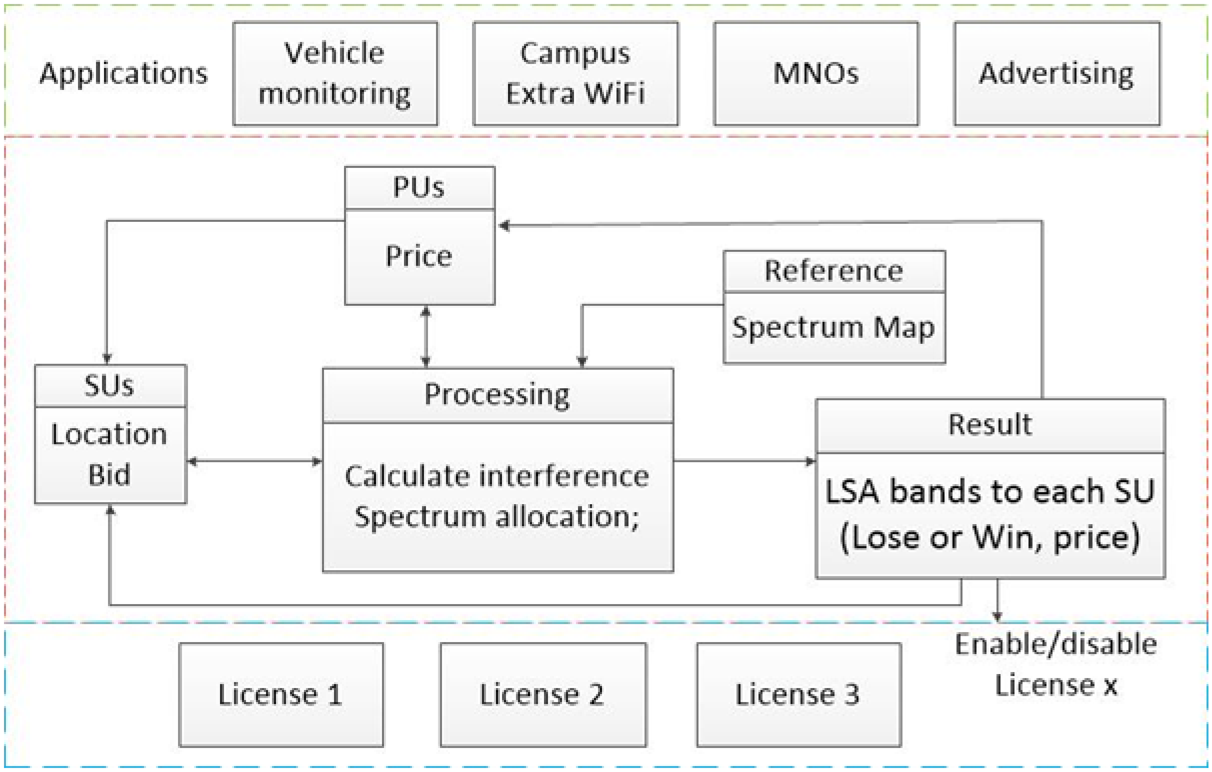

Figure 6-6: Decision making architecture.

6.8 CONCLUSION

The LSA architecture proposed by ETSI enables more efficient usage of the electromagnetic spectrum to meet consumer, commercial, industrial and federal spectrum demands and provide a potential pathway toward spectrum harmonization. LSA provides an engineered solution to retain the protections offered by conventional spectrum allocation methods, reducing spectral resource waste, increasing existing infrastructure reuse and better meeting the requirements of both incumbents and secondary users to generate value for all involved parties. In this chapter we presented several use cases for LSA, explored issues relevant to the integration of LSA with LTE and WiFi, proposed an evolution framework towards dynamic LSA and discussed auction-based business models for spectrum sharing in LSA. The concept of LSA and its evolution towards more dynamic spectrum sharing presents rich opportunities for further research to contribute to the evolution of mobile networks towards 5G.

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7 RADIO ENVIRONMENT MAP

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Abstract – *A Radio Environment Map (REM) is a framework that enhances contextual awareness of spectrum in the spatial domain through geolocation aware spectrum measurements. Having access to geolocation aware measurements allows the RF propagation pattern of a transmitted RF signal to be detected reliably. In the context of LSA, a REM can be used to determine the RF propagation pattern of incumbents and/or LSA licensees. This vital information helps to manage and mitigate the interference between incumbents and LSA licensees. In this chapter we illustrate the functional architecture of a REM. We also discuss how REMs are expected evolve when the LSA sharing time base is shrunk from a time scale on the order of years/months down to a scale on the order of seconds.*

7.1 INTRODUCTION

Future 5G networks are expected to evolve into a complex network of interconnected heterogeneous cells exploiting LSA spectrum. In managing such a network, enhancing the awareness of operational radio environments is of paramount importance. A Radio Environment Map (REM) is an advanced framework for collecting, storing and processing data that characterises the radio environment. Such data can be gathered from geolocation tagged spectrum measurements taken by Measurement Capable Devices (MCDs), which could be mobile devices/handsets.

In general, REMs may store geographical characteristics, available Radio Access Technologies (RAT), spectral regulations, profile of device capability/activity and historical data. Availability of such information is expected to improve radio resource management. In the context of LSA, REMs can be envisioned as a large-scale navigator that helps network management. It can provide cognition on long-term behaviour of other transmitters (possibly incumbents in this context) as well as propagation characteristics in the operational environment. Literature shows that having access to geolocation tagged measurements provide a clear edge in managing vertical interference between incumbents and LSA licensees [1-3].

7.2 FUNCTIONAL ARCHITECTURE OF REM

A functional block diagram showing interaction between different network components in REM framework is shown in Figure 7-1. It should be noted that REMs are considered to be an asset for an operator, therefore not expected to be shared with other operators.

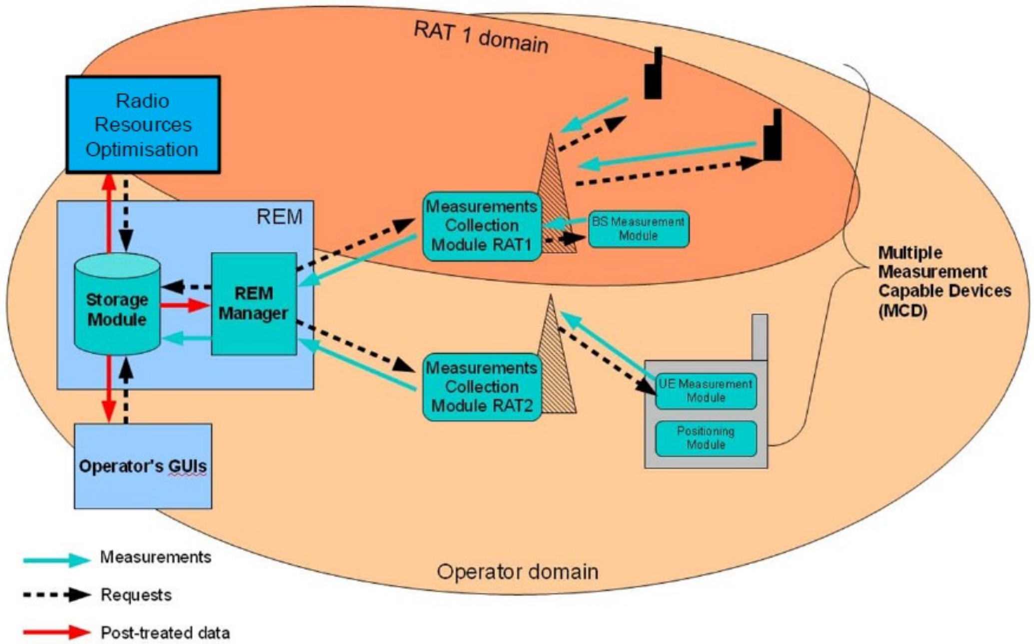

Figure 7-1: Generic REM description in intra-operator domain [1]

One primary difference between existing measurement module of LTE and the proposed REM architecture is that the latter attaches the geolocation when taking spectrum measurements. As shown in Figure 7-1, Measurement Collection Modules (one for each RAT domain) request geo-located measurements from Measurements Capable Devices (MCDs), such as Mobile Devices. The gathered data is processed and stored at the REM entity which is comprised of two sub entities Storage Module and REM Manager. The processed data is then used for Radio Resources Optimisation.

Some attributes of the REM framework are:

- Spectrum measurements taken by MCDs are for the benefit of the operator network. Those specific MCDs who take measurements may or may not have a direct benefit.
- MCD may take field strength measurements on frequency bands they are not operating at any given time.
- Spectrum measurements are tagged with geolocation information which adds an extra dimension of contextual awareness.

More information on how REM framework fits in standard LTE interfaces, protocols and data/information models can be found in [4-6].

7.3 REMs IN THE CONTEXT OF LSA

In the context of LSA, REMs can be envisioned as a central database that contains the active incumbent location (and/or geographical area), frequency band and time duration. This information helps the LSA controller to determine the spectrum availability. Therefore, REMs will be a core requirement in deploying LSA.

Additionally, REMs are expected to be a fundamental technology that enables the evolution of LSA towards a more dynamic access scheme where the sharing time scale is shorter. Over the course REM construction technique is expected to go through multiple stages.

7.3.1 REM STAGE 1

- Incumbent network is static
- Active incumbents provide complete information on their activity – predetermined operational geographical area, frequency and active time
- Operational geographical area is predetermined based on some historical channel characteristics
- Geographical separation between the incumbent and LSA licensee will be in the order of 10 km or more to provide necessary statutory interference protection to the incumbents
- REM update rate is in the order of months/years

The primary benefit of REM Stage 1 is the ability to estimate the incumbent active area using a-priori knowledge, while keeping the directly relevant overhead at a negligible level. This stage of a REM is illustrated in Figure 7-2.

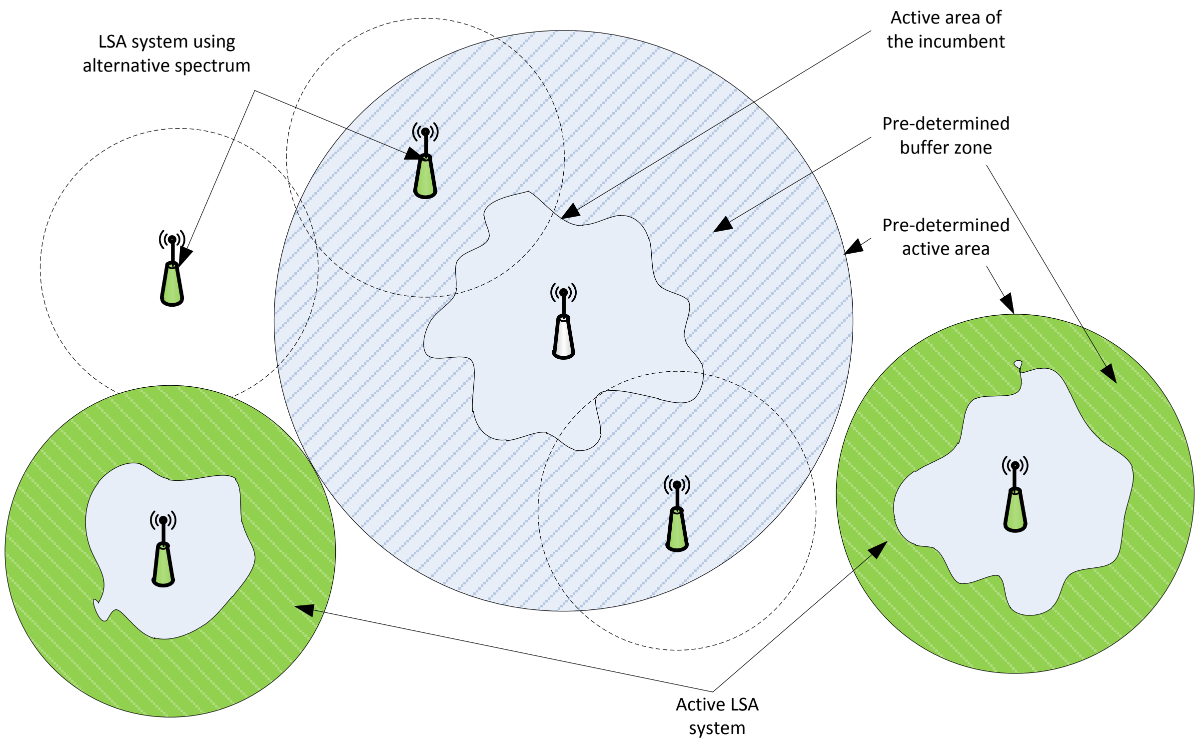

Figure 7-2: Illustration of REM Stage 1 – with large predetermined buffer zones of stationary incumbents (omnidirectional antennas are assumed in this illustration).

At REM Stage 1, incumbents report the intended locations of active incumbent transmitters to the LSA operator. The coordination mechanism between the incumbents and LSA licensees is similar to the centralised incumbent database approach proposed in IEEE 802.22 [7]. A major task of the REM manager is to translate the incumbent locations to active areas through a predetermined channel model. Terrain data is essential for active area prediction. In this stage, terrain data could be made available through field tests carried out before the deployment stage. Long-term variations of atmospheric absorption due to climate conditions can be captured using statistical models. Incumbents should provide predetermined incumbent antenna height and radiation pattern while LSA licensees also provide their own. This information is put together at the LSA controller to determine the incumbent active area based on predetermined channel models.

However, such predetermined models based on a priori channel parameters may not represent the actual channel gain. To provide for such mismatch, the LSA controller leaves a substantially large buffer zone. Additionally, REMs are updated monthly if not yearly, as required. Therefore at REM Stage 1, the overhead penalty incurred will be minimal although a significant fraction of LSA opportunities are left unutilised. Further discussion on predetermined model based REM can be found in [8] and [7].

7.3.2 REM STAGE 2

- Incumbent network is static
- Active incumbents provide information on their activity – potential operational geographical area, frequency, active time
- Operational geographical area is determined based on measurements
    - MCDs in the LSA licensee network perform geolocation aware measurements on the incumbent signal strength
    - MCDs also take geolocation aware measurements on the LSA licensee signal strength
    - LSA licensee is held responsible for determining active area of the incumbent
- Geographical separation between the incumbent and LSA licensee will be in the order of 1-10 km
- REM update rate is in the order of minutes/hours
- The main benefit of REM Stage 2 over its predecessor stage is that, it achieves a narrow buffer zone through collecting empirical RF measurements. LSA controller is able to discover more underutilised LSA spectrum in spatial domain by using REM Stage 2. This stage of REM is illustrated in Figure 7-3.

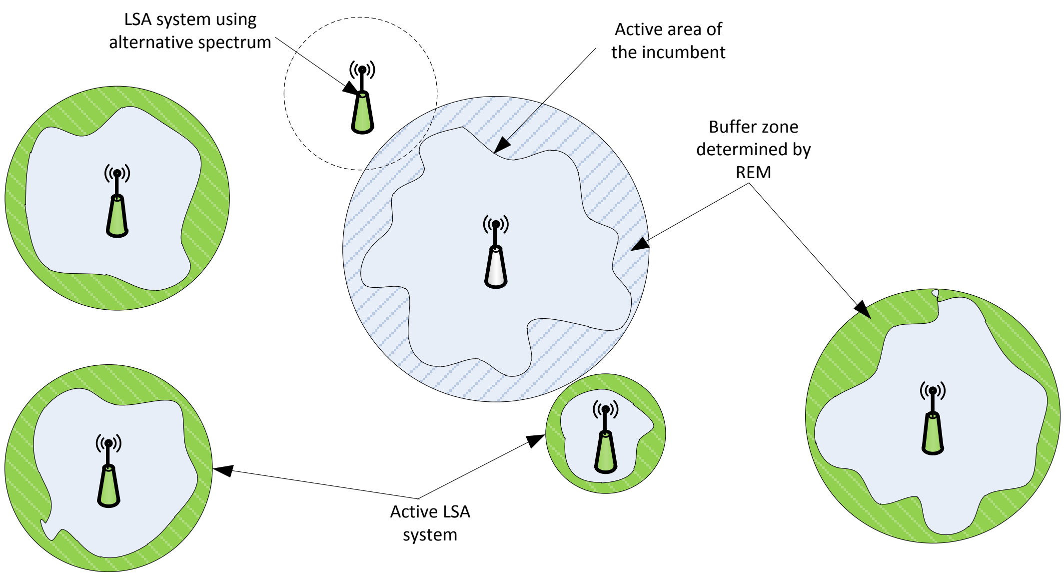

Figure 7-3: Illustration of REM Stage 2 – with narrow buffer zones of stationary incumbents, determined based on measurement from MCDs (omnidirectional antennas are assumed in this illustration).

The primary difference in REM Stage 2 in comparison to the predecessor stage is that MCDs take measurements of the incumbent signal. The incumbent signal strength and report produced by the MCS are forwarded to the attached LSA licensee base station. This measurement data is put together at a central measurement collection point of the LSA licensee network. A-priori channel characteristics used in REM Stage 1 can be replaced, or can be used along with empirical measurement data from MCDs when determining the incumbent active area. Having access to actual channel measurements the LSA licensee is able to have a better estimate of the incumbent active area, capturing the effects of incumbent antenna radiation pattern, actual terrain data, current atmospheric absorption and climate conditions. Hence, the allocated buffer zone can be reduced to closely match the detected active area.

Incumbents provide only a coarse estimate of their active area in which LSA licensee collects incumbent signal strength and construct a REM. Having to collect measurement data from MCDs naturally results in an overhead penalty. REM construction frequency is expected to be in order of minutes or hours. In this time scale, the overhead incurred will be minimal in comparison to the benefits of more LSA spectrum opportunities detected in the spatial domain. At this stage, REM construction is expected to reduce to an interpolation problem. In [9] authors investigate this problem at a system level.

Additionally, the REM is detecting an active area of the incumbent network in seconds/minutes time scale, not the locations of active incumbent transmitters. Therefore the problem of detecting and tracking mobile incumbents is not dealt with in REM Stage 2.

7.3.3 REM STAGE 3

- Incumbent network is slowly moving
- Active incumbents provide information on their activity – potential operational geographical area, frequency
- Operational geographical area is determined based on measurements
    - MCDs in the LSA licensee network perform geolocation aware measurements on the incumbent signal strength
    - MCDs measure the channels between them
    - MCDs also take geolocation aware measurements on the LSA licensee signal strength
    - LSA licensee is held responsible for determining active area of the incumbent
- Geographical separation between the incumbent and LSA licensee will be in the order of 1-10 km
- REM update rate is in the order of seconds

In this stage the REM is capable of locating and tracking the behaviour of slowly moving incumbents. In the previous stage incumbent was detected as an area, not the individual locations. Therefore the analysis on the incumbents' movement is limited. However REM Stage 3 eliminates such limitations by detecting the incumbent locations instead.

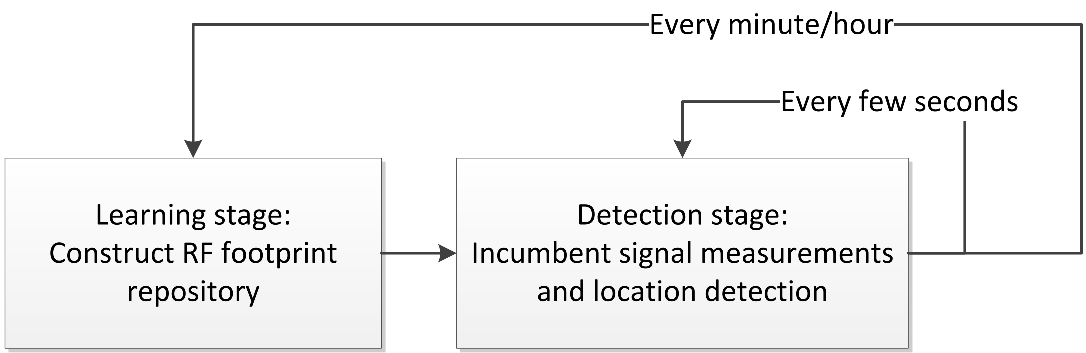

Figure 7-4: Flow diagram illustrating REM Stage 3 construction in the presence of multiple slowly moving incumbents.

At REM Stage 3, incumbents provide a coarse estimation of a geographical area containing active incumbent nodes. The LSA licensee is required to collect estimations for point to point power gains (a function of path loss and shadow fading) between various points across this area. Such measurements are in addition to those collected in REM Stage 2. The empirical channel measurements from one point in space to multiple other points produce a RF footprint of a transmitter at that point. Through measurements LSA licensee network forms a repository of RF footprints at different points in discrete space. Following this learning phase, LSA licensee matches the received signal of the incumbent against the RF footprint repository to determine its location and transmit power. This information is then translated to the corresponding active area using the RF footprint information. This two stage REM construction process shown in Figure 7-4, a detailed illustration can be found in [2] and [10].

It is expected that learning phase will incur an overhead and energy consumption penalty. However, the learning process expected to happen in a timescale of minutes/hours. Therefore the overhead is expected to be minimal. Having access to RF footprint patterns at discrete points in space, incumbent location and transmit power allows the LSA licensee to effectively monitor the incumbents' movements and reliably estimate the impact of the incumbent active area.

7.4 CONCLUSION

REM is a tool that helps manage interference between incumbents and LSA licensees through geolocation aware spectrum measurements. This chapter illustrated the functional architecture of the REM framework. We expect that REMs will evolve into three different stages as LSA sharing time scale is reduced to the order of seconds. In the first stage, REM construction is based on predetermined channel models which incur no ongoing overhead penalty, although accuracy is limited. In stage two, REMs are constructed from ongoing geolocation aware measurements. Interference protection is more reliable in minutes/hours sharing time scale. In the final stage, REMs utilise learning and detection stages to determine the active area of slowly moving incumbents. In this stage, sharing time scale will be on the order of seconds.

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8 D2DWRAN: A 5G NETWORK PROPOSAL BASED ON IEEE 802.22 AND TVWS

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Abstract – *IEEE 802.22 is the first world-wide standard for wireless regional area networks (WRANs) using cognitive radio technologies operating on TV white spaces (TVWS). The major drawback of WRAN is the limited network capacity. Since IEEE 802.22 employs a cellular topology, one potential solution to increase the network capacity is Device-to-Device (D2D) communication. Therefore, we propose D2DWRAN which enables direct intra-cell communication, reuse of channels, and use of multiple operating channels. In this article, we introduce D2DWRAN including the main ideas, use cases, the re-defined Orthogonal Frequency-Division Multiple Access (OFDMA) system and the requirements to achieve D2DWRAN. Compared to WRAN, the network capacity of D2DWRAN can be increased significantly, and D2DWRAN could be integrated in the next generation (5G) networks.*

8.1 Introduction

The standardization of IEEE 802.22 is a milestone for cognitive radio networking (CRN) technology. As the first world-wide wireless standard based on cognitive radio technology, IEEE 802.22 provides network access for users in a cell by reusing vacant TV white spaces (TVWS) [1]. However, the capacity of IEEE 802.22 networks is significantly limited by cellular topology and provision of single operating channel. The usage of TVWS could be more flexible. In principle this can be overcome by enabling device-to-device (D2D) communication and employing multiple operating channels.

In this chapter, we propose IEEE 802.22-based device-to-device WRANs (D2DWRANs) to increase the network capacity by flexible usage of TVWS via supporting direct intra-cell D2D communication, channel reuse and multiple operating channels. The main goal of this chapter is to give an overview of D2DWRAN system and flexible usage of TVWS amongst secondary users, and the detailed studies can be found in our previous works [2]–[4].

In the rest of the chapter, we introduce the specifications and limitations of WRANs in Section II. Then the main ideas of D2DWRANs (the advantages of D2DWRANs, the re-defined Orthogonal Frequency-Division Multiple Access (OFDMA) system and the requirements of devices) are described with use cases in Section III.

8.2 An Overview of WRAN

The configurations of the physical (PHY) and medium access control (MAC) layers, and the cognitive capability of WRANs are based on the architecture shown in Figure 8-1 [5]. A station management entity (SME) is designed to manage the PHY, MAC and higher layers, in which the MAC layer management entity (MLME) and PHY layer management entity (PLME) can be found. Spectrum management (SM) is the responsibility of the MAC layer. There are three main functions in the PHY layer i.e., data communication, spectrum sensing function (SSF) and geo-location. The cognitive radio capability is supported by the SSF and geo-location. Details of the PHY and MAC configurations, the cognitive radio capability and limitations of WRANs are explained in the following sections.

8.2.1 PHY/MAC Configurations

The OFDMA system is designed in WRANs to have a large coverage (typically 30 km and up to 100 km). In this OFDMA system, upstream and downstream communication are supported in each frame via time-domain duplex (TDD) or frequency-division duplex (FDD) [1].

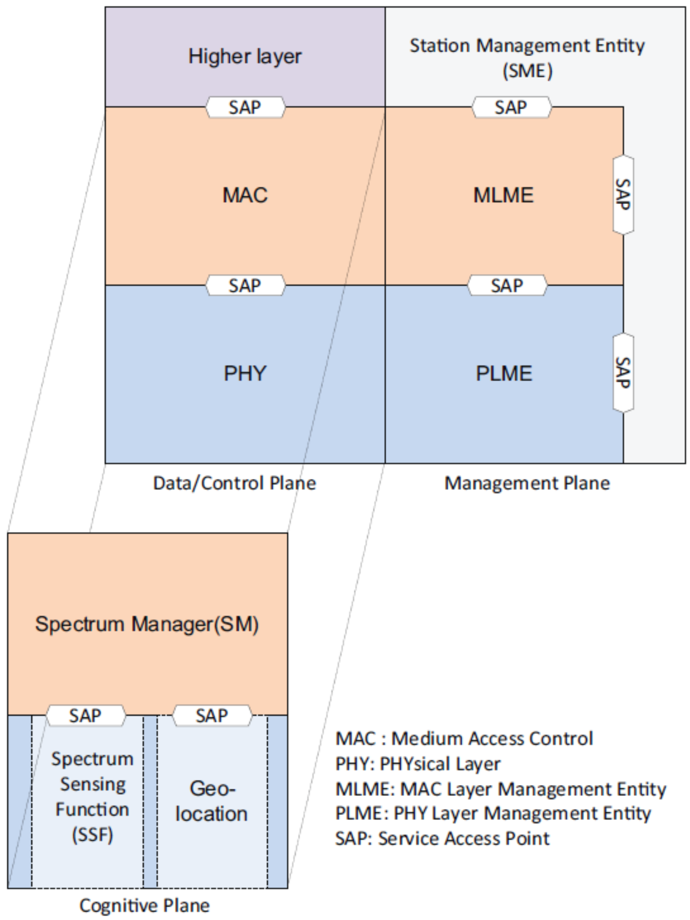


Figure 8-1: The architecture of IEEE 802.22 [5].

IEEE 802.22 networks use TVWS with bandwidth of 6, 7 or 8 MHz according to the regulations of different countries and regions. Totally 1680 subcarriers are grouped in 60 subchannels in a TVW S. A polite OFDMA symbol for channel estimation and synchronization is required every seven symbols - both in the time and the frequency domains of frames. Four different cyclic prefixes are defined as 1/4, 1/8, 1/16 and 1/32 with a symbol duration corresponding to different channel delays. Currently, four types of modulation and coding schemes (MCSs) are supported, which are binary phase-shift keying (BPSK), quaternary phase shift keying (QPSK), 16-quadrature amplitude modulation (16-QAM) and 64-QAM. Four coding rates (1/2, 2/3, 3/4 and 5/6) are associated with the MSCs. Different MCSs are selected dynamically according to the channel and interference information.

For the MAC layer, a point-to-multipoint (P2M) mode is adopted in IEEE 802.22. This cellular topology consists of a single base station (BS) and many customer premises equipment (CPEs). The BS manages the network and resource allocation, and all CPEs communicate with the BS in a cell. In the downstream direction, the BS broadcasts both control and data information to all its CPEs. In the upstream direction, CPEs request for channel and upload data to the BS. IEEE 802.22 adopts a superframe/frame structure for efficient data communication and channel management. A superframe consists of a superframe control header (SCH) and 16 frames. When a CPE intends to join an IEEE 802.22 cell, the SCH in the cell is scanned, which contains all necessary information. Once a CPE joins this cell, the geo-location of this CPE is reported to the BS. The self-coexistence of WRAN cells is achieved by the coexistence beacon protocol (CBP). A separate subframe for CBP is attached at the end of some frames. The CBP subframe may contain the sensing results of CPEs and channel usage of the neighboring cells.

Due to the cellular topology, the antennas of the BSs should be sectored or omni-directional to communicate with all CPEs in a cell both in the upstream and downstream directions. Since CPEs in a cell only need to communicate with the BS and IEEE 802.22 is designed for fixed networks, the directional antennas are used in CPEs. Although Multi-input-multi-output (MIMO) is not supported originally because of the physical size of the antennas operating in TVWS [1], it is being considered in IEEE 802.22b [6].

8.2.2 Cognitive Radio Capability

Since IEEE 802.22 networks use vacant TVWS based on cognitive radio technology, protection of PUs is managed by SM as shown in Figure 8-1. SM is in charge of the cognitive functionality, in which the incumbent database and spectrum sensing functions are used.

The incumbent database contains channel availability information of all TVWS in certain areas. It is maintained by spectrum management regulators. All devices are required to be equipped with locating systems, e.g., global positioning system (GPS). CPEs need to report their locations to the BS and then the BS queries the incumbent database for channel availability information in the local area.

Spectrum sensing is also enabled in WRANs to detect channel information in a realtime manner because of the possible latency of the incumbent database. Quiet periods (QPs) are scheduled in each cell, during which all devices stop communication and sense both in-band (being used) and out-band channels (not being used currently). The sensing results are reported to the BS and the BS aggregates all channel availability information and makes spectrum allocation decisions.

Additionally, a TV channel can be used as an operating channel in a cell only if both the low and high frequency adjacent channels are available. The purpose is to eliminate adjacent channel interference to PUs. Channel bonding is also supported in WRANs to increase the network capacity, in which up to three adjacent channels can be used as one channel but with more subchannels.

8.2.3 LIMITATIONS

IEEE 802.22 networks are developed to provide broadband services for CPEs in rural areas. However, a data rate of only 1.5 Mbps in the downstream and 384 kbps in the upstream for edge CPEs can be guaranteed (at least 12 active CPEs). The low network capacity is one of the main challenges in WRANs and this is because of the inflexible spectrum usage.

- All packets in a cell (including intra-cell packets) need to go through the BS. Direct CPE to CPE communication is not supported. Thus, the network capacity is limited by the processing ability of the BS. Besides, extra delay is added to intra-cell packets compared to direct CPE to CPE communication.
- In the OFDMA system designed for WRANs, each slot can be allocated to only one CPE. Multiple links cannot use the same subchannels simultaneously.
- Even though channel bonding is supported, non-adjacent channels cannot be used simultaneously resulting in a very busy 6 MHz channel when there are many other vacant channels.
- QPs are frequently scheduled for spectrum sensing, which also limits the network capacity. For example, some channels need to be sensed at least once in every 2 s.
- MIMO is not supported and more advanced MCSs than 64-QAM are not considered [1].

To increase the network capacity, the IEEE 802.22 working group has started a new task group IEEE 802.22b (Amendment Project for Enhanced Broadband Services and Monitoring Applications) in March, 2012 [5]. New technologies might be introduced in IEEE 802.22b to provide higher data rates, e.g., MIMO, direct CPE to CPE communication. However, it is still under discussions and no draft is finalized. D2DWRANs can be considered as a solution for IEEE 802.22b networks.

8.3 Flexible TVWS Usage

The concepts of D2D and peer-to-peer (P2P) need to be clarified before further discussions. D2D communication (also called D2D technology) indicates direct communication of two devices on the PHY layer, but P2P technology designates end-to-end communication between two devices at the application layer regardless of how they are connected. In this chapter, we mainly discuss D2D (CPE to CPE) communication. The cellular topology enables a simple centralized network management by the BSs in WRANs, but severely limits the network capacity. Direct CPE to CPE communication, as an enhancement for D2D communication in cellular networks, is able to increase the network capacity and channel utilization [7]. Therefore, D2D technology could be a solution for the limited network capacity in WRANs. We adopt the D2D communication and design device-to-device WRANs (D2DWRANs) to increase the network capacity.

8.3.1 Flexible Approaches

Three main ideas on flexible spectrum usage are proposed in D2DWRANs to increase network capacity: CPE-CPE communication, channel reuse and multiple operating channels.

1) CPE-CPE Communication*:* As we mentioned before, TDD is employed in the IEEE 802.22 standard for duplex communication. The downstream is mainly for BS-CPE communication, in which the BS broadcasts resource allocation decisions (both for upstream and downstream), channel state information and data to CPEs. CPEs communicate with the BS only. The downstream in D2DWRANs is the same as WRANs because a cell is still centrally managed by the BS. Hence, CPE-CPE directional communication is enabled in the upstream. Note that so far only intra-cell CPE-CPE communication is considered since inter-cell CPE-CPE communication is more complicated.

Direct CPE-CPE communication in a cell can avoid unnecessary routing via the BS with several benefits such as decreased end-to-end delay and decreased traffic load on the BS. In WRANs, the BS in a cell is not just the central management unit and gateway as in a regular cellular network, but it also manages spectrum allocation. The BS needs to access the incumbent database for channel information, it senses both the in-band (currently in use) and out-band (currently not used) channels frequently, processes the sensing results, and allocates resources in every frame (5 ms). Therefore, off-loading some of the tasks of BS may improve the network performance significantly.

When using TVWS, D2DWRANs are required to protect all PUs efficiently. Therefore, spectrum management in D2DWRANs is centrally controlled by BSs. If a CPE attempts to start a communication with another CPE in the same cell, it sends the request to the BS and then waits for the allocation decision by the BS. This way, the destination CPE can receive packets from another CPE properly.

2) Channel Reuse: Before discussing the channel reuse, we first define the interference area or transmission area of a transceiver pair (CPE-BS, BS-CPE, or CPE-CPE). It is the area in which another receiver would be interfered with on the same channel (or OFDMA slots). In other words, it is the field of signal coverage of the transmitter. The size of an interference area is mainly determined by the transmission power, receive power, pathloss and channel fading characteristics. Interference areas have two properties:

- The simultaneous communication of two transceiver pairs on the same channel (or OFDMA slot) do not interfere with each other if neither of the receivers are in the interference area of the other transceiver pairs.

- If adjacent-channel interference is not considered, the simultaneous communications of two transceiver pairs with different channels (or OFDMA slots) do not interfere with each other.

We give some simple examples to explain interference areas and properties in Figure 8-2. As shown in the figures, two identical transceiver pairs (A-A' and B-B') exist, in which A and B are the transmitters and A' and B' are the receivers. All devices are equipped with omni-directional antennas and use the same channel. In case of Figure 8-2(a), there is no overlap between the two interference areas, therefore, no interference is caused whereas in case of Figure 8-2(b), even though A-A' and B-B' overlap, no interference is caused because receivers cannot detect the signal from the other transmitter. In cases of Figure 8-2(c) and 8-2(d), there are collisions because the receivers are in the coverage of both interference areas. If two transceivers work on different channels, then there is no collision in all the cases of Figure 8-2.

By considering the *first* property of the interference area, a channel (or OFDMA slot) can be reused by multiple CPE-CPE communication in a cell if power control is employed [8], [9]. Power control strategy assigns minimal transmission power to the transmitter with reasonable channel state at the receiver side. Hence, the size of the interference area of a CPE-CPE link can be reduced and a *channel* (or OFDMA slot) can be used simultaneously by multiple CPE-CPE communication links thus resulting in channel reuse. Hence, the spectrum utilization can be increased.

3) Multiple Operating Channels: Channel bonding is supported in WRANs for adjacent vacant TV channels, in which up to three channels are combined as one channel with wider bands [1]. Therefore, each cell can use only one TV channel if the vacant channels are scattered in the bands. For example, if two TV channels are available, but they are not adjacent, then they cannot be used simultaneously. This leads to wastage of resources. Therefore, we consider to use multiple non-adjacent channels to enhance channel utilization in D2DWRANs. Channel aggregation can be used to achieve multiple operating channels in both downstream and upstream.

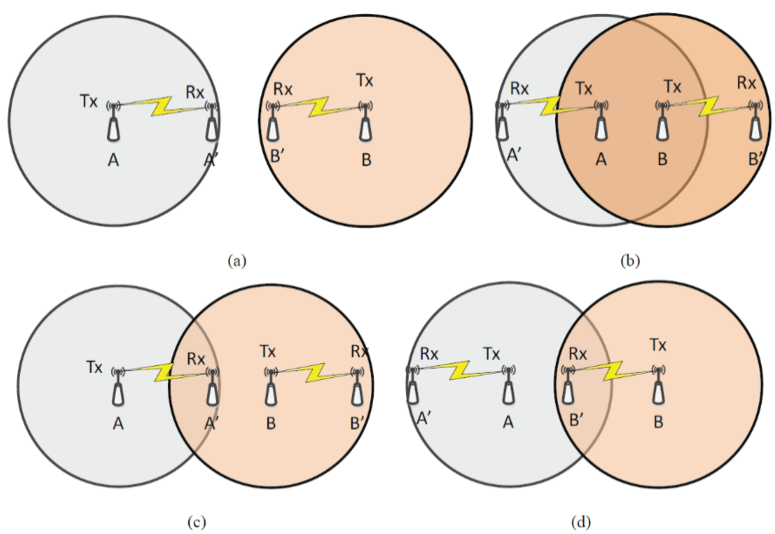
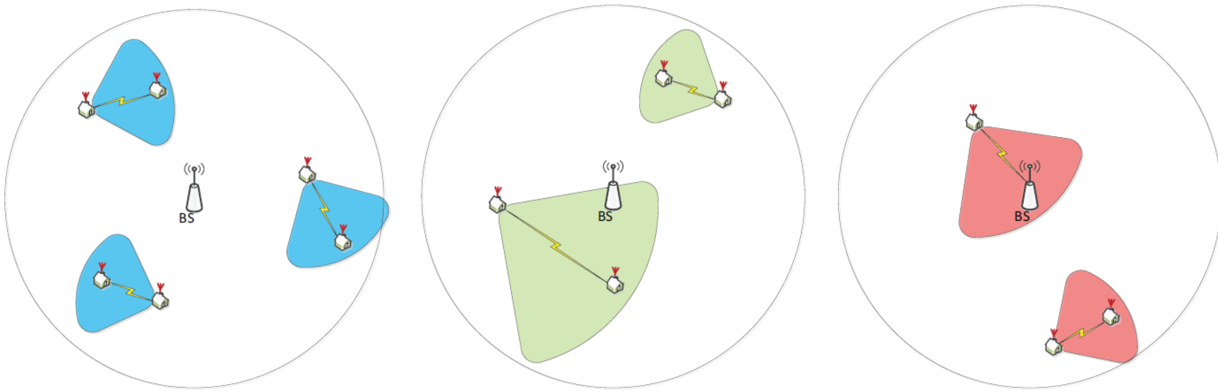
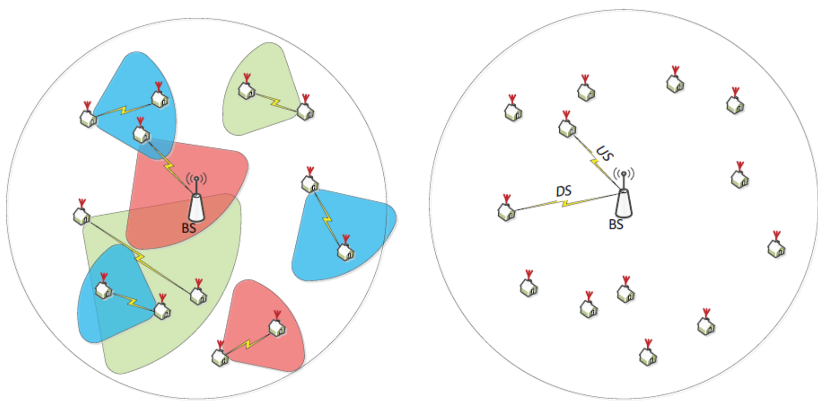


Figure 8-2: Examples of interference areas.



(a) Channel 1. (b) Channel 2. (c) Channel 3.

Figure 8-3: An example of a D2DWRAN cell in the upstream. Three TV channels are used with direct CPE-CPE communication and channel reuse.



(a) The upstream of a D2DWRAN cell. (b) Downstream and upstream of a WRAN cell.

Figure 8-4: A comparison of D2DWRAN and WRAN in the scenarios of Figure 8-3.

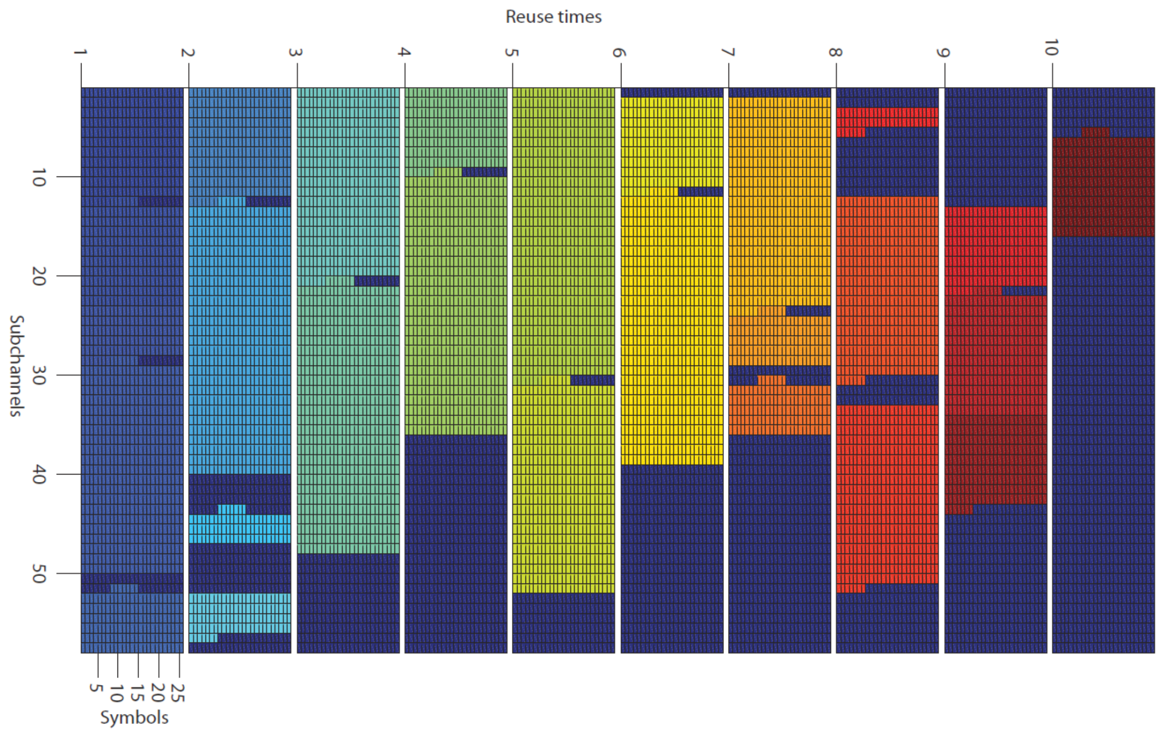


Figure 8-5: The simulation results of OFDMA slot allocation in a D2DWRAN cell with 100 CPEs in an upstream subframe (US-subframe). In this US-subframe, there are 58 subchannels and 26 symbols (a typical setup in WRANs). Different colors indicate the slots that are allocated to different CPEs.

4) Examples: We give an example of a D2DWRAN cell with three available channels in Figure 8-3. We can see that each CPE works on only one channel and multiple CPE-CPE communication can be allocated on one channel simultaneously. Then, the channel allocation in the whole cell is shown in Figure 8-4(a) where seven links can transmit at the same time in the upstream. On the contrary, there is only one communication in the upstream of a WRAN cell. With this simple example, we can see that the network capacity can be increased significantly in D2DWRANs.

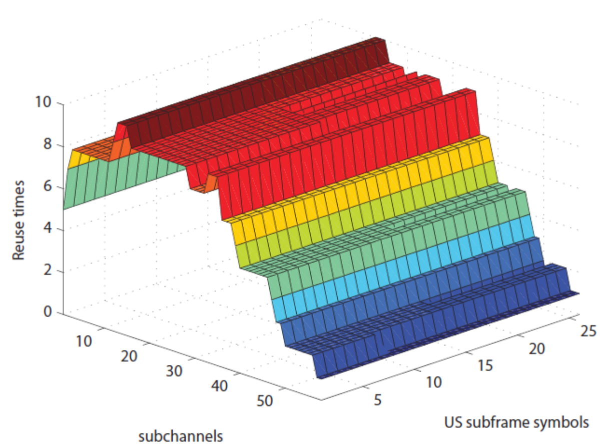


Figure 8-6: The slot reuse times of slots in the example of Figure 8-5.

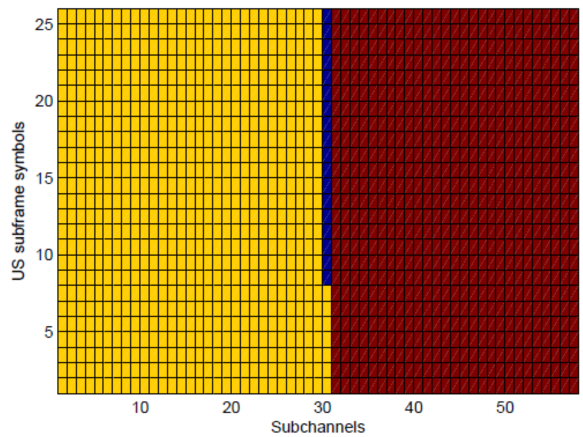


Figure 8-7: The simulated results of OFDMA slot allocation in WRAN with the same setup as Figure 8-5.

Note that to show the essence of D2DWRANs, the examples discussed in Figure 8-3 and Figure 8-4 are not considered in the scope OFDMA system. However, the ideas are the same. We also give some simulation results of OFDMA slot allocation in a D2DWRAN in Figure 8-5[3]. The reuse times of the slots are also shown in Figure 8-6. Some slots can be used by 10 links at the same time whereas in WRANs, one slot can be used only once as shown in Figure 8-7.

8.3.2 LIMITATIONS

Aiming at broadband service for CPEs, D2DWRANs can be implemented for many use cases. We list some applications and scenarios to show the necessity of enhancing network capacity.

1) Applications: From the above discussion, we know that D2DWRANs have higher network capacity than WRANs due to channel reuse by CPE-CPE communication in the upstream. Many peer-to-peer (P2P) applications are able to be found in D2DWRANs, because of the large coverage of a single cell.

- Video streaming: Video content is the major Internet traffic and it is predicted by Cisco that 80 to 90 percent of the Internet traffic will be videos by 2017 [10]. P2P video streaming is an efficient way to offload the traffic from backbone networks in a large cell. The basic idea of P2P video streaming is that all users share their video resources with others directly. There are already some successful examples of P2P video services, e.g., PPSTREAM and PPLIVE [11], [12]. It was reported that there were more than 32,210,000 daily users just on PPSTREAM every day and more than 60,000,000 users in total on P2P video streaming in China before September 3, 2012 [13]. The occasions of national/local events may also cause many repeated video traffic on the Internet. For example, more than 30,000,000 users watched the live streaming of the spring festival concert in China via PPSTREAM in 2012 [14]. It is believed that more than 100,000,000 people watched the live show over Internet excluding replays afterwards. We believe P2P video streaming could be used in WRAN because of the large single cell coverage. When there is lots of intra-cell traffic, D2DWRANs can achieve much better performance than WRANs by allowing CPE-CPE communication.
- File sharing: According to the Cisco report, file sharing also takes a large portion of the Internet traffic including the traditional P2P file sharing applications and new applications [10]. For example, the quick growth of cloud storage and computing services show the perspective of file sharing [15]. There are many applications based on cloud storage, e.g., Dropbox, iCloud, Google Cloud Storage and SkyDrive. These applications normally involve a person or a group of people with frequent file sharing amongst different devices, which can be easily covered by a D2DWRAN cell.

[3] Details of the OFDMA system in D2DWRANs will be introduced later in this chapter. The results presented here showcase the significant increase in the network capacity.

- Other applications can also be found too, e.g., video conferences and video chat between the CPEs in the same cell.

The burst of Internet traffic is one of the main challenges of the network services today. D2DWRANs could be a solution in the rural areas to provide broadband services to users.

2) Scenarios: There are many discussions on how to improve network performance in IEEE 802.22b task group [5]. D2DWRANs provide solutions for IEEE 802.22b. We take two similar scenarios[4] that have been discussed in the IEEE 802.22b task group in [5] to explain the structure and applications of D2DWRAN. The scenarios of archipelago networks and emergency networks are presented in Figure 8-8[5] and Figure 8-9[6] respectively.

In the archipelago area, the cost of cables that reach all islands is very high. Traditional cellular networks are also not cheap because of the limited coverage area of each cell. However, D2DWRANs can manage to access all islands and ships together and provide Internet services as shown in Figure 8-8. D2DWRANs cost much less than cables and traditional cellular networks, because of the large coverage of each cell. In this scenario, some BSs are connected to the backbone network in the mainland either through cables or other wireless technologies. The incumbent database is also connected to the Internet so that BSs can inquire channel information. A CPE could cover a hotel, a school, a ship or even a whole island, and provide broadband services. CPEs can also communicate with each other directly under the supervision of BSs. With direct CPE-CPE communication, not just the network capacity can be increased, but the coverage of cells can also be stretched when CPEs relay for others.

Another scenario for D2DWRANs is emergency networks. Natural disasters can cause the connection outage of a very large area for a very long period because of the failure of infrastructure. However, a large amount of local traffic can be generated within hours, days, weeks or even months after a disaster. For example, the rescuers need to communicate frequently with their officers, including the sending of image and video data; families want to check if everyone is safe. In the medical camps, doctors and nurses need medical data of patients to be analyzed and processed in a central hospital and probably also get remote supports and guidance for certain operations. Also, journalists need to report the news. A D2DWRAN based emergency network can provide temporary broadband services for these requirements as shown in Figure 8-9. The large coverage of a single BS is the main advantage for this scenario. Portable CPEs access BSs provide connection to instructors, rescuers, doctors, citizens, the policemen, firefighters and all related users. CPEs can also relay on other CPEs to reach out beyond the network coverage too.

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[4] We assume that all CPEs have similar capacity in contrast with IEEE 802.22b [5].

[5]The background picture is from http://www.indiedb.com/games/0-ad/images/cycladic-archipelago-ii, which is a map from the video game 0 A.D. We have chosen this archipelago map because it reveals the typical archipelago terrain.

[6] The background of this scenario is a village near the coast of Sumatra that lays in ruin after the Tsunami that struck South East Asia. It is photographed by Philip A. McDaniel. All related information can be found on webpage http://www.navy.mil/view single.asp?id=19968.

Figure 8-8: The scenario of an archipelago D2DWRAN network.

8.3.3 The OFDMA System of D2DWRAN

In recent 3GPP release (Release 12), similar OFMDA-based D2D communication is considered for the Long Term Evolution (LTE) devices [16]. However, it is not suitable for D2DWRAN, because single- carrier in the upstream is adopted in LTE devices and it is different from the multiple-carrier OFDMA in IEEE 802.22 upstream. Thus, we cannot adopt the LTE OFDMA-based D2D communication in WRAN. In this section, we develop a D2D OFDMA based on IEEE 802.22 for D2DWRAN.

The OFDMA system of IEEE 802.22 standard cannot be used as is in D2DWRAN because of channel reuse and CPE-CPE communication leading to some necessary changes. We keep these changes to a minimum. The superframe structure is the same and also the DS-subframe in case of single operating channel. The DS-subframe is used to broadcast from the BS to CPEs, and contains spectrum sharing information in the DS-MAP and US-MAP. The US-subframe is for CPE-BS and CPE-CPE communication. Using transmission power control, an OFDMA slot can be reused by different links simultaneously as long as no interference is caused. While using multiple operating channels both the DS- and US-subframes need to be modified. Note that the self-coexistence window in the OFDMA system is used for neighboring cells to communicate with each other to share vacant TV channels [1]. Since it is the same in D2DWRAN as in WRAN, we mainly describe the modifications to DS- and US-subframes.

1) DS-subframe: In the DS-subframe, multiple operating channels are divided into main operating channel (MOC) and data channels (DCs). A MOC contains the spectrum sharing information (US-MAP and DS-MAP), US and DS channel descriptors (UCD and DCD), and the frame control header (FCH) to manage the data transmission. In this way, all control information of this frame is received by the CPEs via MOC. Data units are also transmitted in the MOC similar to IEEE 802.22 standard. However, the DCs only carry the data units (BS-CPE broadcast). The DS capacity can be increased almost linearly with number of operating channels.

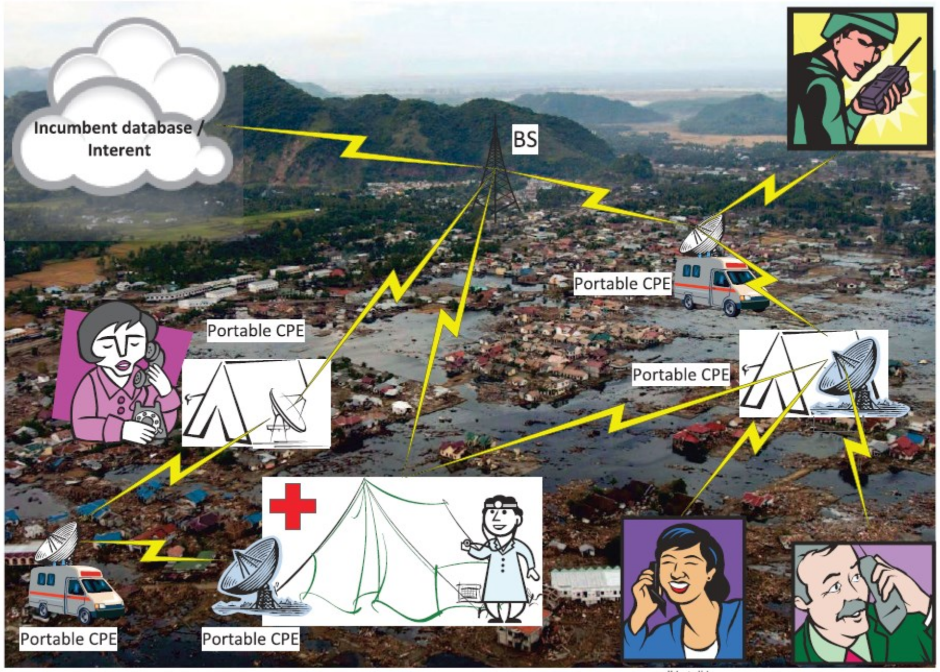

Figure 8-9: The scenario of a D2DWRAN based emergency network.

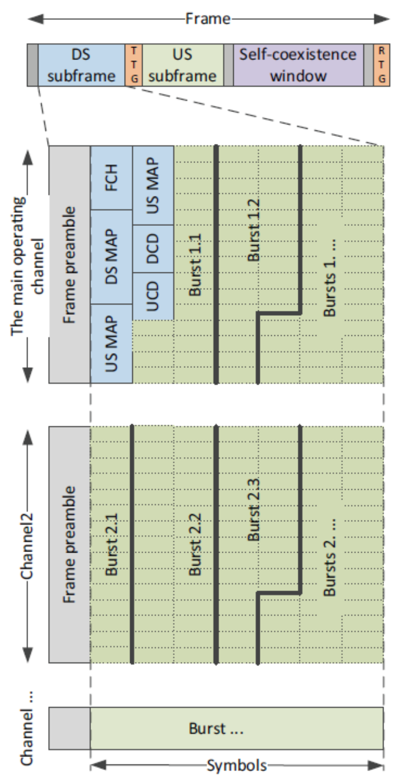

Figure 8-10: The OFDMA structure of the DS-subframe with multiple operating channels in D2DWRAN.

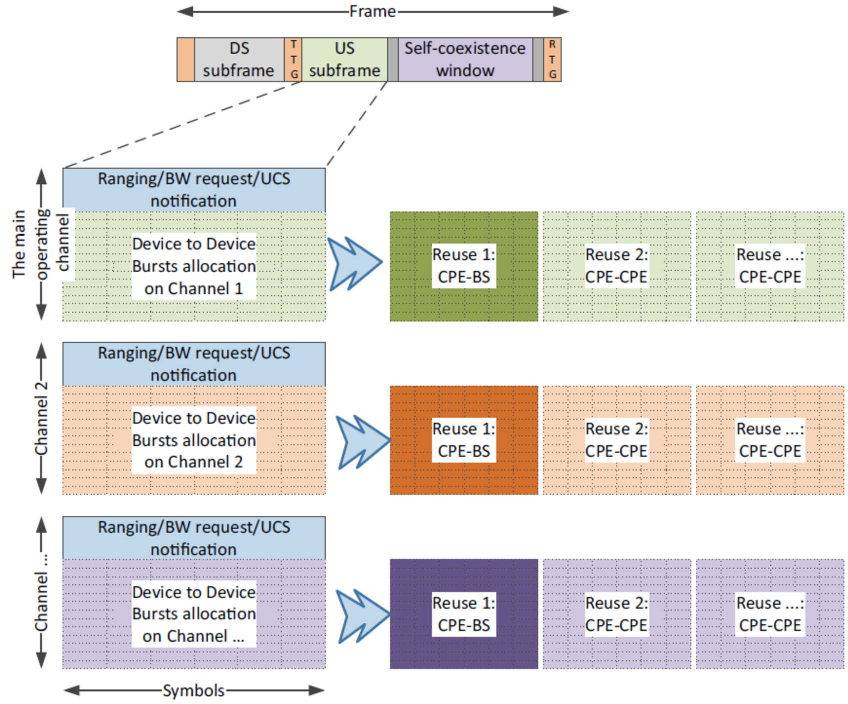

Figure 8-11: The OFDMA structure in the US-subframe with multiple operating channels in D2DWRAN.

8.3.4 Advantages and Requirements

According to the above discussions, D2DWRANs have many advantages with the flexible TVWS usage:

1) Easy spectrum and network management in a cell by the BS.

2) With CPE-CPE communication, packet delay of intra-cell communication can be decreased, total network capacity can be increased significantly, while traffic is off loaded from the BS.

3) One channel can be reused simultaneously by multiple links (either CPE-to-CPE or CPE-to-BS) in the upstream direction with power control. This is because, if two D2D requests are geographically far from each other, they can use the same channel at the same time without causing any harmful interference. This increases the network capacity significantly by reusing the channel.

4) Multiple available channels can be used in a cell with channel aggregation. Therefore, the available channels that are not adjacent can be used simultaneously, which enhances the network capacity too.

D2DWRANs can achieve much higher network capacity than WRANs, but there are some extra requirements for the devices. We list the main considerations for the implementation of D2DWRANs:

- The CPEs should have the ability to communicate with other CPEs in any direction on any possible vacant channel. First of all, communication in any direction means the CPEs have to be equipped with either omni-directional antenna with high transmission power or directional antennas with the azimuth adjustment done automatically in realtime. Such antennas have already been developed for Wi-Fi networks [17]. Even though the size is different, we expect that this type of antennas for TV channels will be in market in the near future. Secondly, the ability of switching channels in realtime, which is required in all cognitive radio networks, should be considered in D2DWRANs too.

- Transmission power control is required to achieve the reuse of channels without interference. Theoretical analysis based on different fading and path loss models can provide quick guidance for transmission power allocation, but the accuracy is a major concern. Some related discussions can be found in [18]–[20]. Experimental testing such as ranging can provide accurate power information, but it is time-consuming. Therefore, a combination of theoretical models and experimental methods should be considered in the power control strategies. Note that we will not discuss further on power control in this article since many related studies can be found in the literature [18]–[20].

8.4 CONCLUSION

We presented the introduction of D2DWRANs in this chapter with the flexible usage of TVWS compared to WRAN. Three main ideas for TVWS usage were presented: direct CPE- CPE communication, channel reuse and multiple operating channels. Then, use cases with applications and scenarios of D2DWRANs were discussed to show the advantages of D2DWRAN. Even though there is a significant improvement in network capacity, there are additional requirements for CPEs in D2DWRAN. There are still many practical issues in D2DWRAN, e.g., self-coexistence between neighboring cells, resource allocation in the OFDMA system, intra-cell multi-hop communication and so on.

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9 CONCLUSION

This paper gives an overview on key technologies which will enable future 5G systems to exploit additional spectral resources and thus provide a substantial increase in system capacity to the eco-system. While theoretical studies have been under elaboration for 20 years and more, the concepts are currently becoming mature and they are transformed to the needs of practical systems and the requirements of customers. The challenge indeed lies in the identification of the key building blocks to be defined in standards bodies and the development of valid business models. Many of the technological ideas in the field of opportunistic spectrum usage and cognitive radio have indeed failed because of an unclear commercial basis. The industry has taken the lessons - the definition of the 5G has begun and it will serve as a suitable framework to bring those technologies to a success.

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