# On the Deployment of Large-Scale High-Capacity Wireless Systems with Secondary Spectrum Access

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Doctoral Thesis in
Information and Communication Technology
Stockholm, Sweden 2014

Akademisk avhandling som med tillstånd av Kungl Tekniska högskolan framlägges till offentlig granskning för avläggande av Teknologie Doktorsexamen i Informations- och Kommunikationsteknik måndagen den 26 maj 2014 klockan 14.00 i sal D, Forum, Kungliga Tekniska Högskolan, Isafjordsgatan 26, Kista.

# Abstract

The avalanche in mobile data consumption represents a big challenge for mobile networks operators and national regulators. This thesis focuses on finding additional spectrum to meet this demand in a cost-efficient way by considering shared spectrum access. Our studies aim at identifying key factors in achieving large-scale business success, quantifying the spectrum availability and identifying suitable regulatory/sharing polices for large-scale secondary access in the aeronautical and radar bands.

This thesis proposes a research methodology, that considers business, technical and regulatory aspects involved in assessing commercial viability of large-scale deployment of wireless networks, employing vertical spectrum sharing in the aeronautical and radar bands. We pinpoint the following criteria which are critical in ensuring business success: spectrum availability, radio technology availability, low-cost end-user devices, system scalability and quality of service. Our investigation centers on the technical aspects of these criteria, and thus deals mainly with the assessment of spectrum availability. The availability of spectrum opportunities is found to be ample for adjacent channel usage despite the strict requirements of the radar receiver. However, it is also very location-dependent and mostly non-contiguous.

Finally, with regard to the regulatory aspects, our results show that applying regulatory policies, especially to the deployment of secondary users, can boost availability in cities or urban areas where the capacity demand is high. In addition, Licensed Shared Access (LSA) is identified as a suitable regulatory framework to meet tough protection criteria of the radar receivers and to apply the selected regulatory policies to improve exploitation of sharing opportunities. Based on our results and analysis, we conclude that there is a significant amount of spectrum opportunities for large-scale secondary access in the aeronautical and radar bands from the technical point of view. However, the commercial viability of secondary spectrum access is still undetermined given the remaining uncertainties regarding its total cost and the exact time needed for relevant technology to become available. Moreover, there is no single answer to the commercial viability since it will most likely depend on the country or region in question, which affects the spectrum availability, which in turn is a key criterion for business success. Future work should therefore strive to clarify these uncertainties and to identify new responsibilities for all the entities involved in the LSA framework. Moreover, a quantitative evaluation would be needed to obtain more explicit conclusions on the business viability.

# Acknowledgements

These years of graduate studies have been such a journey while I have grown as a professional and, more importantly, as a person. I would like to thank many people who have, directly or indirectly, contributed to making this journey an unforgettable experience.

My most sincere gratitude goes to my main advisor, Professor Jens Zander, for giving me the opportunity to take this challenging journey, and for his guidance and encouragement throughout these years. I am greatly indebted to Dr. Ki Won Sung, my co-advisor, who has always been a source of new challenging ideas and very valuable feedback, improving significantly my research work. I have been fortunate to have two supervisors who cared about my work and my personal development.

I am very thankful to Dr. Mikael Prytz for reviewing and providing valuable feedback on my PhD thesis, and to Professor William Webb for accepting the role of opponent on my dissertation.

For creating a friendly working environment, I am thankful to my colleagues and friends at the communication systems department: Sibel Tombaz, Serveh Shalmashi, Ali Özyagci, Du Ho Kang, Andres Laya, Ashraf Widaa, Vlad-Ioan Bratu, Yanpeng Yang, Amirhossein Ghanbari, Haris Celik, Luis Martinez, Miurel Tercero, Pamela Gonzales, Saltanat Khamit, Dr. Sang-wook Han, Dr. Tafzeel ur Rehman Ahsin, Dr. Jan Markendahl, Prof. Claes Beckman, Prof. Ben Slimane, Prof. Guowang Miao, Dr. Luca Stabellini, Göran Andersson, Anders Västberg and many more. I am particular grateful to Lei Shi and Javier Ferrer, with whom I have collaborated during some phases of my studies. A sincere thanks goes to Irina Radulescu, Sarah Winter and Gunilla Gabrielsson for their help in all administrative matters.

I would like to give special thanks to my parents, Eva and Victor, who have been an endless source of unconditional love and amazing inspiration in my life. Finally, but by no means least, the biggest thank you goes to my beloved husband Sandro: You have been the most important person for the completion of this thesis. Your love, patience and tireless encouragement have given me great motivation to accomplish this goal.

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# Part I

# Chapter 1

# Introduction

## 1.1 Background

The explosive growth in mobile data consumption caused by the proliferation of high-end handsets and the large increase expected in the average traffic per device brings new capacity requirements to current wireless networks [1]. Mobile broadband has become part of our everyday life as well as a huge challenge for traditional Mobile Network Operators (MNOs) who need to expand the capacity of their current networks, and at the same time to keep their business profitable. One of the key methods to increase the capacity of mobile networks in a cost-efficient way is to find additional radio spectrum. However, this is not an easy task since most of the suitable radio spectrum for mobile communications is already allocated to other non-communication services on a long-term basis. Even though current licensing regimes are not efficient in terms of spectrum utilization [2], these regimes are preferred by MNOs since they provide guaranteed access to spectrum over long periods of time for the long-term investments made by MNOs. Therefore, to seek a potential solution for making additional radio spectrum available for mobile communications, there is a need for innovation not only in the technical but also in the regulatory and business domains, demonstrating both improvement in spectrum utilization and the feasibility of long-term investments.

Spectrum sharing has been presented as a practical solution as by this means additional radio spectrum that is currently underutilized will open quickly for mobile communications [3]. This thesis focuses on the aeronautical and radar spectrum, which shows low utilization [4, 5]. By applying the so-called secondary spectrum access, i.e. vertical spectrum sharing or vertical coexistence, we concentrate on having additional spectrum for massive deployment of high-capacity wireless systems in areas or environments where the capacity demand is extremely high. These areas are typically urban hotspots, particularly those covering indoor locations where approximately 70% of the current data consumption is generated [6].

### 1.1.1   The Mobile Broadband Challenge

Mobile broadband has reached mass adoption, driven mainly by high-end web-based applications, the evolution of existing services and the introduction of new services, and the availability of affordable and powerful devices. In 2011, the global mobile data traffic reached a growth rate of 133%, more than doubling for the fourth consecutive year. The overall mobile data traffic is expected to increase 15-fold between 2013 and 2019, as shown in Fig. 1.1 [7]. This phenomenon brings huge opportunities for the society, but it also poses great challenges to different entities. These challenges can be different depending on the role of the entity in society. In this thesis, we focus on two entities, namely MNOs and national regulators.
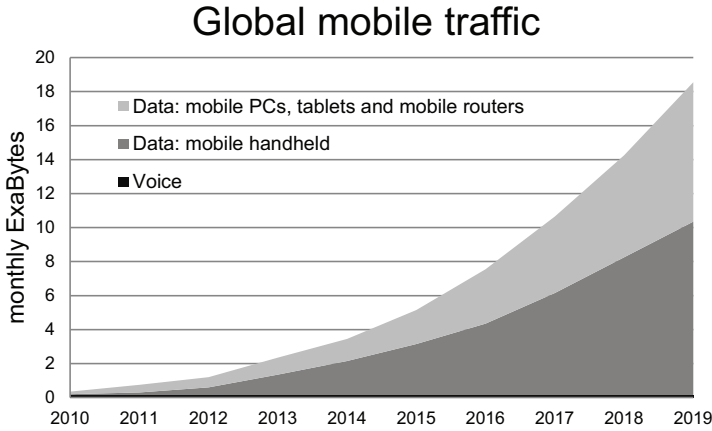


Figure 1.1: Mobile traffic: voice and data, 2010-2017.

**From the operator's perspective**

During the last years, traditional MNOs have been challenged by the increasing demand for mobile broadband services and the decrease of revenues. This phenomenon is often called *revenue gap*, which first occurred when mobile broadband services became popular due to the introduction of a new pricing strategy, namely flat rate subscriptions, which boosted usage without increasing revenues to the same extent[1] [8]. Given that the highly competitive market keeps diminishing their profit margins, MNOs are pressured to differentiate their products and services in order to reduce the revenue gap. Accordingly they need to improve two key dimensions of their business: greater network flexibility and new capabilities for identifying

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[1]The old pricing strategy used by MNOs was based on the customer's usage of voice service, which means that revenues grew in proportion to service usage (i.e. minutes per call)
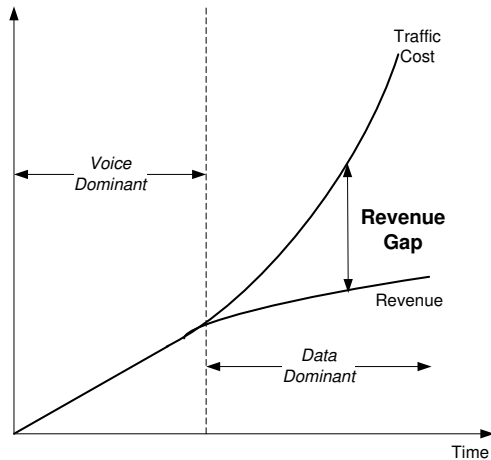
Figure 1.2: Revenue Gap

and tailoring new and existing services to meet the needs of their customers [9]. To achieve these, MNOs need to improve the capacity of their networks to meet the customer's insatiable demand. Meanwhile, it has become crucial to find a good trade-off between performance and cost of their networks.

A significant amount of research on wireless communications has focused on different aspects that impact the trade-off between performance and cost of wireless networks, such as spectral efficiency[2], deployment of the networks and its cost, and spectrum allocation. Traditionally, the main strategies used to provide additional network capacity have been to improve spectral efficiency and to increase the network density. The mobile network capacity can be increased significantly by improving spectral efficiency, which may, however, entail high complexity and costs. The deployment of denser networks represents a major investment for the MNOs [10]. From the operator's perspective, finding additional spectrum will certainly bring economic benefits because the network capacity is proportional to the spectrum bandwidth. Thus, an efficient combination of the solutions in terms of technology, infrastructure and spectrum is needed to meet the explosion of traffic demand [11]. In this thesis, we aim at finding additional spectrum to improve capacity in a cost-efficient way in key urban and hotspot areas. Such a study is of particular interest to MNOs.

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[2]Bits per Hertz for a given wireless channel.

**From the regulator's perspective**

International standardization bodies, such as the International Telecommunications Union (ITU), have the task of allocating spectrum bands to different wireless technologies with the objective of guaranteeing transnational coordination and interoperability. National regulators are in charge of allocating spectrum bands to different technologies and stakeholders. The assigned spectrum can then be accessed by those who are entitled to it. National regulators must ensure that radio spectrum is allocated and used to benefit society at large.

As previously mentioned, in order to meet the data tsunami in wireless networks, it is crucial to find additional spectrum for mobile broadband services. Even though there seems to be a shortage of spectrum, extensive measurement campaigns have shown that much of the prized spectrum lies idle at any given time and location [5, 12]. This discrepancy is due to the static spectrum allocation approach taken by the current licensing regime, which offers a licensed user exclusive access to spectrum in both spatial and time domains. This means that if the licensee is not transmitting, the assigned spectrum lies idle.

Not only does exclusive access lead to inefficient spectrum utilization, but it is also inappropriate to meet the current traffic demand [13]. Therefore, national regulators face a challenge of seeking alternative spectrum allocation regimes that can overcome the shortcomings of the current regime. A main shortcoming is its lack of flexibility in a time of rapid change [14]; that is to say, current regime is typically designed to meet spectrum requirements during peak traffic hours and in worst case scenarios (e.g. simple transmitters, poor filtering, etc.). However, with current technology, such scenarios rarely happen, and the traffic reaches its peak only for short periods of time, resulting in a great deal of spectrum lying idle most of the time. Moreover, changes in the regulatory framework are extremely time consuming in the current regime [15].

Despite the shortcomings of the current regime, it is preferred by MNOs since it makes their long-term investments feasible. National regulators need to devise policies which are more efficient in terms of spectrum utilization and which provide a strong incentive for investments, leading to a real benefit to society. This thesis considers that radio spectrum should be flexibly shared by multiple spectrum users or entities, which is a key requirement for future regulatory frameworks to bring significant benefits to society.

## 1.2   Spectrum Sharing

Spectrum sharing refers to the simultaneous usage of a specific radio frequency band in a specific geographical area by a number of independent entities, leveraged through mechanisms other than traditional multiple- and random-access techniques [16]. Spectrum can be shared in different domains: frequency, space, time, vector, code and business [14]. This thesis focuses on the first three domains.

Spectrum sharing is most valuable in frequency bands where spectrum refarm-

ing/clearing[3] cannot be done within a reasonable time frame (i.e. less than 5 years). Different types of spectrum sharing can be found in the literature [16]:

- *Horizontal Sharing.* All participating systems have equal rights to a spectrum band with/without spectrum ownership. This type of sharing can happen with licensed or unlicensed spectrum.

- *Vertical Sharing.* This type of spectrum sharing is also called secondary spectrum access. Participating systems have different rights to a spectrum band. There is a primary system, most typically the license holder of that specific band, which is given the highest priority in accessing the resource. There is also a secondary system which is accorded a lower priority in accessing the spectrum and which should comply with the primary system's protection requirements. Such requirements might include interference avoidance rules, the maximum allowable interference, and other constraints.

Spectrum sharing can be further classified depending on whether the systems involved cooperate or coexist, which has a significant impact on the system design [17].

- *Cooperation.* Devices under the same or different administrative control must communicate and cooperate with each other to avoid mutual interference. For this purpose, a common protocol must be defined and supported by all the cooperating systems in a particular spectrum band. In doing so, it makes sharing easier because it creates opportunities for the participating systems to maximize their joint benefits and to reduce the risks and costs of resource usage.

- *Coexistence.* Devices attempt to avoid harmful interference without explicit signaling or a common protocol. At most, devices sense each other's presence as interference. Cognitive radio is a powerful tool for sharing based on coexistence; the ability to reconfigure a device based on the sensed interference levels from neighbors is valuable when avoiding mutual interference.

This thesis focuses on vertical spectrum sharing, or secondary spectrum access, where systems coexist or have no explicit cooperation mechanism. We can further classify secondary spectrum access into three different models based on the access technology involved [18, 19]:

- Overlay Model: In this sharing model, the secondary system is aware of the signal characteristics of the primary system, and thus secondary users are allowed to transmit in a licensed spectrum band even when the primary is accessing the band. In this model, secondary users try to maintain, and

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[3]Refarming is a set of measures (administrative, economic and technical) aimed at recovering a frequency band from its current users so that it can be re-assigned, either for new uses or for the introduction of more spectrally efficient technologies [14].

preferably improve the performance of the primary system rather than limiting their own interference to a certain threshold. This is an essential characteristic of the overlay model, which is expected to motivate the primary to cooperate. There are different approaches to implementing this model, such as dirty paper coding and network coding.

- Underlay Model: This model allows the secondary users to transmit in licensed spectrum whether the primary users are accessing the band or not. However, interference from the secondary system should be kept below a certain threshold. The typical approach is that the secondary users begin their transmissions at such low transmit power that they are regarded as noise by the licensed users of the band. Spread spectrum techniques are exploited by the secondary users to utilize the bandwidth which is wider than that in the overlay model.

- Interweave Model: The secondary users are allowed to access a portion of spectrum that is not used by the primary, meaning that the secondary users have access to and utilize spectrum holes or white spaces in the temporal, spatial and/or frequency domains. As a result, interference to the primary system is minimized.

This thesis employs the interweave model to consider sharing opportunities for secondary spectrum access in the time, space and frequency domains. Moreover, sharing opportunities are discovered by means of spectrum sensing and/or geo-location databases, whose basic definitions are as follows [20]:

- Spectrum Sensing: A device can scan across a range of frequencies and identify unused frequency portions before transmitting. However, detecting unused frequencies can be a challenging task due to the presence of very weak signals or passive receivers (e.g. TV receivers). These issues are commonly known as the "hidden terminal problem". A way to resolve this problem is to make the scanning receiver much more sensitive. It is however difficult to achieve the level of reliability on the detection of vacant frequencies.

- Geo-location Databases: A device determines its own location, using methods such as GPS or a pre-programmed location. Then, it sends this information to the database via backhaul connection or wireless communication. The database contains enough knowledge of the device, licensed user and spectrum usage to determine the unused frequencies in a given location. This information is sent back to the device, which then starts to transmit. Geo-location approaches are the only ones that appear workable at present, at least in those situations where the licensed users must have a high level of protection from harmful interference.

### 1.2.1 Challenges for Secondary Spectrum Access

This subsection briefly overviews different challenges facing secondary spectrum access, and in particular coexistent systems, in a large-scale deployment of high-capacity wireless networks in secondary spectrum. These challenges are related to the technical, regulatory and business domains [18, 21].

**Technical challenges**

- Assessing the impact of secondary transmissions on the primary system with the objective of establishing how to measure the total interference to the primary users, what metrics to use to prevent harmful interference and how to impose these constraints on the secondary users.

- Designing efficient and reliable mechanisms to detect the presence of the primary users. It is also of particular interest to disseminate the results of these mechanisms to all the devices involved within an adequate time frame.

- Designing an effective coexistence mechanism that allows scalability of secondary systems, and that guarantees a reliable control of interference for the primary system as well as quality of service for the secondary users.

**Regulatory challenges**

- Establishing an incentive mechanism that motivates the licensed holders to share their spectrum and cooperate with potential newcomers.

- Enforcement of dynamic policies: finding a balance between making the system more dynamic, which implies that more violations are possible, and enforcement of the policies, which is easier with static systems.

- Designing regulatory policies that not only protect the primary system, but also guarantee the performance of the secondary system.

**Business challenges**

- Uncertainty in the economical return, which makes industry reluctant to invest on the development and deployment of secondary spectrum access. This uncertainty is caused by a variety of factors such as regulatory conditions, technology availability, deployment costs and system performance, which are still undefined.

- Uncertainty in the appearance of new actors and in the development of new business models, which could challenge the current model.

### 1.2.2   Secondary Spectrum Access to the Aeronautical and Radar Bands

Previous technical and regulatory studies have mainly focused on a specific portion of spectrum, i.e., VHF/UHF band primarily allocated to digital terrestrial television (DTT) and the so-called TV white spaces (TVWS) [22–25], leaving other frequency bands largely unexplored with regard to their potential for secondary usage. ITU spectrum allocation table indicates that the majority of frequency bands below 6 GHz are currently allocated to various systems such as aeronautical navigation, radar, satellite, and fixed links. This thesis focuses on spectrum allocated to aeronautical navigation and radar systems. In Europe, radio spectrum allocated to the aeronautical and radar bands makes up a significant portion (approx. 1 GHz) of the allocated spectrum below 6 GHz and exhibits low utilization [4,5]. Their propagation characteristics make these bands ideal candidates for providing additional capacity for indoor and outdoor communications in urban hotspot areas.

Secondary spectrum access to the aeronautical and radar bands faces technical challenges that are different from those faced by the TVWS. Therefore, different regulatory policies are needed to enable large-scale secondary access. A critical technical challenge is the control of the aggregate interference over a large area; this is particularly difficult due to the high sensitivity levels of the receivers and the extremely low permissible outage probability at the primary system which performs safety-of-life operations. In the regulatory and business domains, key challenges include the selection of a regulatory regime that guarantees protection of the primary system, which is important given its safety-related functionality, and the identification of a business case that promotes long-term investments.

## 1.3   Problem Formulation

### 1.3.1   "High-Level" Problem Formulation

Secondary spectrum access to licensed spectrum that is underutilized has been proposed as an effective solution to the problem of meeting the growing demand for wireless broadband capacity. Even though substantial work has been done on assessing the technical feasibility of secondary spectrum access, little research has focused on its real-world benefits or *commercial viability*. Thus, the overall focus of this thesis is on:

- *examining the commercial viability of large-scale secondary access to the aeronautical and radar bands*

In this thesis, *commercial viability* basically means that both technical and regulatory conditions are favorable enough to make sharing opportunities attractive from a business perspective. The term *sharing opportunity* is employed in this thesis to refer to the available spectrum portion or *channel* where secondary spectrum access is feasible, and which satisfies the primary protection criteria and the minimum

transmission probability for the secondary system. Notice that not only does this thesis focus on protecting the primary system, which is the principal goal of most of the previous work, but it also aims at meeting the requirements of secondary systems. The latter is crucial in attracting investments in secondary systems.

### 1.3.2 Scope of the Thesis

To limit the scope of our investigation, we select two multi-user networks as secondary systems. The selected secondary access scenarios are the following:

- Indoor broadband in aeronautical and radar spectrum.

- Outdoor hotspot communication in radar spectrum.

In our studies, secondary spectrum access in frequency, location and time domains is enabled by the use of the interweave technique, and sharing opportunities are discovered by means of spectrum sensing and/or geo-location databases. In order to analyze the commercial viability of the selected secondary access scenarios, this thesis aims at answering the following research questions:

- RQ1: What are the conditions for achieving large-scale business success in the deployment of ultra-dense networks (UDNs) in the aeronautical and radar bands?

Factors that would facilitate business success are identified and then used as evaluation criteria for analyzing the business potential of a given case. This thesis focuses on the business case of large-scale deployment of high-capacity wireless networks in the aeronautical and radar bands, offloading mobile traffic demand in indoor and hotspot environments where the capacity demand is extremely high. One condition necessary for establishing the commercial viability of the business case under consideration is its technical feasibility, which prompts the following research question:

- RQ2: What is the amount of spectrum that can be used for large-scale secondary access to the aeronautical and radar bands from the technical perspective?

The technical feasibility and availability of sharing opportunities for large-scale secondary systems depend highly on the characteristics of the secondary access scenario, defined by the primary system, the secondary system, the propagation environment and the sharing mechanism. These characteristics are tied to the regulatory conditions and policies that are applied. Given the importance of guaranteeing enough available sharing opportunities for the secondary system to ensure business success, it is thus crucial to identify:

- RQ3: Which regulatory/sharing polices should be used for large scale deployment of UDNs in the aeronautical and radar bands?

The last research question also establishes a link between the technical and regulatory requirements. Notice that suitable regulatory policies are those that can provide protection for the primary system as well as enough sharing opportunities available for secondary spectrum access to make it commercially attractive.

## 1.4  Previous Work

In this section, we overview previous work relevant to the "high-level" problem and the three research questions that drive the entire thesis project. In order to address the different research questions, we have divided the thesis into three main parts: interference modeling at the primary systems, technical availability assessment of large-scale secondary access, and commercial viability of secondary access in the radar bands.

### 1.4.1  Modeling Interference at the Primary System

In the last decade, extensive work has been done to address the technical, regulatory and business challenges of secondary spectrum access. Previous technical work was mostly focused on protecting the primary receivers from harmful interference. Considering this as the main constraint, the theoretical capacity limits [26, 27] and the coexistence conditions for different secondary system scenarios have been established, and spectrum sensing techniques devised [28]. However, these studies have mainly focused on the co-channel interference (CCI), leaving the impact of adjacent channel interference (ACI) almost unaddressed. ACI becomes also critical when the primary receiver's filter characteristics are not ideal, which is typically the case in real scenarios. In this thesis, we focus particularly on assessing the impact of ACI under realistic scenarios, which was not previously addressed. The ACI limitations have been incorporated in recent academic and regulatory work to determine the maximum transmission power of the secondary users [29, 30].

### 1.4.2  Technical Availability Assessment of Large-Scale Secondary Access to the Aeronautical Band

Another bulk of mainstream technical research has been concerned with the availability and scalability assessment of wireless systems with secondary spectrum access. Considerable efforts have been dedicated to the problem of detecting primary signals and "spectral holes" via spectrum sensing. Diverse aggregate interference models have also been proposed [31, 32]. Moreover, the amount of white spaces or spectrum holes in the TV broadcasting band in the US and Europe has been determined with the objective of evaluating potential public benefits [23, 24]. Some

recently concluded EU projects, such as FP7 QUASAR[4], FARAMIR[5], QoSMOS[6] and CogEU[7], have shifted the focus from simply detecting white spaces or spectrum holes to actually analyzing the exploitation of sharing opportunities with secondary spectrum access using spectrum sensing and geo-location databases. In particular, the FP7 QUASAR project (a significant part of this thesis was performed in this project) aimed at quantifying the availability of real-life sharing opportunities. However, most of these previous studies only addressed diverse challenges of secondary spectrum access considering the TV band as the primary system [23,33], and leaving other frequency bands such as the aeronautical and radar bands largely unexplored.

Although low spectrum utilization has been detected in the radar and aeronautical bands, little work has been done to quantify the spectrum opportunities in these bands [34–36]. Unlike in the TV band, the locations of radar receivers are known but the high sensitivity of the receivers makes it challenging to control the aggregate interference of the secondary system over a large geographical area. In this thesis, we have investigated the impact of aggregate interference on the requirements for secondary spectrum access. These requirements have a direct effect on the spectrum availability for large-scale deployment of secondary systems.

### 1.4.3 Commercial Viability of Secondary Access to the Radar Bands

In the regulatory domain, significant efforts have been made to devise new frameworks to meet the technical requirements of vertical spectrum sharing, such as carrier aggregation [37], fairness between the primary and secondary users considering availability of spectrum at a given location/time [38], and the presence of databases [39]. In the business field, investigations are conducted to identify the impact of spectrum sharing on the market and business relationships. The role of new actors, such as geo-location databases, real-state owners or spectrum brokers [40,41], has recently been analyzed. In addition, previous studies have looked into various techno-economic aspects of spectrum sharing for different types of operators, such as the potential cost savings by employing cognitive radio technologies [42,43]. However, the majority of these studies address the different domains separately, without providing any link between them. A major contribution of this thesis is that it provides a comprehensive methodology for assessing the commercial viability so as to minimize uncertainty in business scenarios which may delay the commercial deployment of secondary systems.

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[4]QUASAR: Quantitative Assessment of Secondary Spectrum Access, http://www.quasarspectrum.eu/

[5]FARAMIR: Flexible and spectrum-Aware Radio Access through Measurements and modelling in cognitive Radio systems, http://www.ict-faramir.eu/

[6]QoSMOS: Quality of Service and MObility driven cognitive radio Systems, http://www.ict-qosmos.eu/

[7]CogEU: COgnitive radio systems for efficient sharing of TV white spaces in EUropean context, http://www.ict-cogeu.eu/

## 1.5   Thesis Contributions and Outline

This thesis mainly focuses on the technical and regulatory domains. Thus, most of our contributions are concerned with RQ2 and RQ3. The contributions to the three main areas of this thesis are outlined in Section 1.5.1. It is also important to underline that apart from addressing the research questions, another significant contribution of this thesis lies in the development of a methodology, which considers technical, regulatory and business aspects and the relationship between them, for analyzing the commercial viability of large-scale secondary access to the aeronautical and radar bands.

### 1.5.1   Overview of Contributions

**Interference Modeling at the Primary Systems**

In this part of the thesis, we consider the digital TV (DTV) systems as the primary system to study the impact of ACI on the primary receivers under realistic scenarios. Even though this thesis focuses mainly on the aeronautical and radar bands, the DTV receivers are studied owing to their availability and their bad performance in the presence of ACI. The results of our investigations have been published in three conference papers. Paper 1 determines if there are sharing opportunities for a low-power indoor single secondary user accessing the TV band where the DTV receivers are susceptible to *adjacent channel interference*. This paper shows the importance of considering adjacent channel interference, which was not done in the literature. Paper 2 presents the models and assumptions, which were validated using measurement campaigns. In Paper 3, we extend our previous study, which involved a single secondary user by investigating the characteristics and interference rejection capabilities of the primary receiver in the presence of multiple secondary users. The paper proposes a model for computing the maximum aggregate adjacent channel interference that the DTV receiver can tolerate without experiencing any distortion or quality degradation. The proposed model and assumptions are validated by measurement campaigns. The list of papers are as follows:

- **Paper 1**, [44]: E. Obregon and J. Zander, "Short Range White Space Utilization in Broadcast Systems for Indoor Environments", In *IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)*, 6-9 April 2010.

- **Paper 2** [45]. E. Obregon, L. Shi, J. Ferrer and J. Zander, "Experimental Verification of Indoor TV White Space Opportunity Prediction Model", In *Proceedings of the Fifth International Conference on Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM)*, June 2010.

- **Paper 3**, [46]: E. Obregon, L. Shi, J. Ferrer and J. Zander, "A Model for Aggregate Adjacent Channel Interference in TV White Space", In *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, 15-18 May 2011.

The author of this thesis proposed the original problem formulation and acted as the lead author of these papers. The measurement campaigns were designed and conducted jointly with Lei Shi and Javier Ferrer. The proposed model in Paper 3 was elaborated by all the authors of the paper. Professor Jens Zander provided guidance and valuable insights for all these papers. The author of this thesis was the main contributor to the writing and editing process of the papers.

### Technical Availability Assessment of Large-Scale Secondary Access to the Aeronautical Band

This part of thesis deals with the quantification of the technical spectrum availability for large-scale deployment of high-capacity secondary systems in the aeronautical spectrum, whose technical characteristics are similar to those of the radar spectrum. Two conference papers and one journal article were published as a result of the thesis work.

Paper 4 investigates the requirements for secondary access in order to avoid harmful interference to the primary system. We propose a practical sharing scheme based on geo-location databases and spectrum sensing tailored to the particular characteristics of the primary system. Paper 5 develops mathematical models to compute the aggregate interference in the spatial domain when there is uncertainty over the detection mechanism. This paper also evaluates the technical feasibility of secondary access to the aeronautical band. Finally, in Paper 6, we develop an assessment methodology for a country-wide evaluation of the availability of spectrum opportunities in the aeronautical band. Through the use of this methodology that incorporates the mathematical models into the sharing schemes proposed in the previous papers, this paper provides quantitative results regarding the spectrum availability in the aeronautical band. The contributions made by these investigations are shown in:

- **Paper 4**, [36]: K. W. Sung, E.Obregon, and J. Zander, "On the requirements of Secondary Access to the 960-1215 MHz Aeronautical Band, In *IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)*, 3-6 May 2011.

- **Paper 5**, [47]: E.Obregon, K. W. Sung, and J. Zander, "On the Feasibility of Indoor Broadband Secondary Access to the 960-1215 MHz Aeronautical Spectrum," *in Transactions on Emerging Telecommunication Technologies*, August 2013.

- **Paper 6**, [48]: E.Obregon, K. W. Sung, and J. Zander, "Availability Assessment of Secondary Usage in Aeronautical Spectrum," *in IEEE Wireless Communications and Networking Conference (WCNC)*, April 2013.

Dr. Ki Won Sung was the main contributor to Paper 4. The author of this thesis contributed to the paper by refining the problem formulation and simulating the different scenarios. In Paper 5 and Paper 6, the original problem formulation,

models and assumptions were the result of research discussions between the author of this thesis and Dr. Ki Won Sung. The author of this thesis derived the mathematical models and computed the numerical results as presented in Paper 5 and Paper 6. These papers were jointly edited by the author of this thesis and Dr. Ki Won Sung. Research discussions with Professor Jens Zander improved the quality of all these papers.

### Commercial Viability of Secondary Access to the Radar Bands

This part of the thesis looks into the regulatory and business aspects of large-scale deployment of high-capacity secondary systems in the radar bands. Two conference papers were published and one journal article was submitted as a result of our investigations.

Paper 7 specifies sharing conditions between an UDN and the radar bands; it also identifies regulatory policies that not only protect the primary system, but also set minimum requirements for the secondary. Paper 8 explores the regulatory and business implications of policies previously devised. This analysis is further developed in Paper 9 where we propose a methodology that establishes a clear relationship between the technical and regulatory conditions in order to analyze business viability. These contributions have been previously published in the following papers:

- **Paper 7**, [49]: E.Obregon, K. W. Sung, and J. Zander, "On the Sharing Opportunities for Ultra-Dense Networks in the Radar Bands", to appear in *IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)*, April 2014.

- **Paper 8**, [50]: E.Obregon, K. W. Sung, and J. Zander, "Secondary Access to the Radar Spectrum Bands: Regulatory and Business Implications," *24TH European Regional Conference of the International Telecommunications Society*, October 2013.

- **Paper 9** [51]: E.Obregon, K. W. Sung, and J. Zander, "Is Spectrum Sharing in the Radar Bands Commercially Attractive? - A Regulatory and Business Overview," *submitted to Telecommunication Policy*, 2014.

The author of this thesis proposed the original problem formulations and acted as the lead author of these papers. Professor Jens Zander and Dr. Ki Won Sung provided directions and valuable insights for all these papers.

### 1.5.2 Thesis Outline

This subsection provides the outline of this composite thesis, which is divided into two main parts. The first part consists of four chapters: in addition to Chapter 1, Chapter 2 describes the overall approach as well as the methodologies employed

in this thesis; Chapter 3 provides a brief overview of the key results and contributions; and Chapter 4 summarizes and discusses the main conclusions, ending with suggestions for future work. The second part contains *verbatim* copies of the papers introduced in Section 1.5.1, including seven published conference papers, one published journal article and one submitted journal article.

# Chapter 2

# Research Approach

This chapter provides an overview of the overall research approach and the main methodological contributions of this thesis. The methodologies have been devised to address the "high-level" problem formulation and the research questions described in Sec 1.3.

## 2.1   Overall Research Approach

This thesis analyzes the selected secondary access scenarios using holistic and sequential approaches that consider all three domains: technical, regulatory and business. Notice that the sequence of the research process does not follow the order of the research questions described in Sec 1.3, starting from the technical feasibility of large-scale deployment of secondary systems with secondary spectrum access. This is because the feasibility study is a necessary condition for determining regulatory policies and assessing business viability. It is important to note that the contributions of this thesis mainly lie in the technical domain. Fig. 2.1 illustrates the different components of our approach and the interaction between them. Specifically, the overall research approach starts by:

- *Analyzing the impact of secondary user transmission on the primary receiver.* We aim at establishing limits for tolerable interference at the primary victim by considering not only co-channel, but also adjacent channel interference.

- *Proposing and evaluating a practical sharing scheme.* To enable secondary access, we devise sharing schemes that are customized according to the characteristics of the primary system.

- *Determining the requirements for secondary access.* We specify a range of operational conditions and constraints affecting the secondary system multiuser secondary access scenarios, including the minimum distance between the primary receiver and the secondary transmitter, the maximum secondary transmission power, and individual interference thresholds.
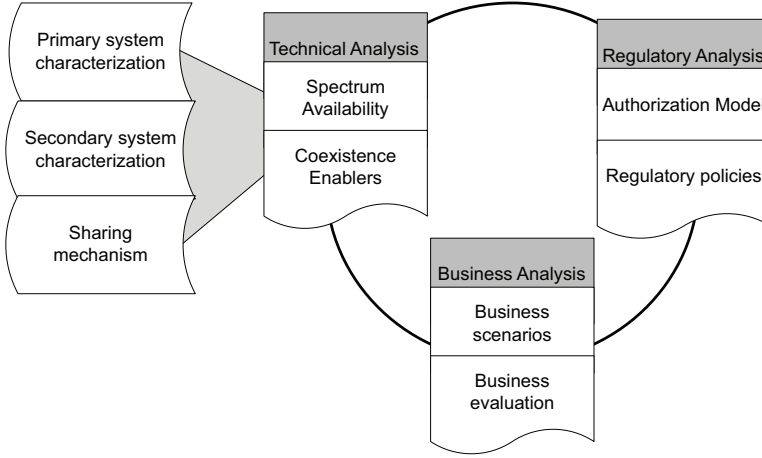
Figure 2.1: Overall Research Approach

- *Estimating the amount of sharing opportunities available for secondary systems.* The final output is given in terms of the number of available channels for secondary access in a given geographical area.

Based on the results of the technical assessment, we examine the regulatory domain aiming at:

- *Identifying regulatory policies* which can better exploit the spectrum sharing opportunities not only from the primary system's perspective, but also from the secondary system's perspective.

After identifying the technical and regulatory conditions, we proceed with

- *a qualitatively assessment* of the business potential of the secondary access scenarios in consideration.

Notice that our work emphasizes the interdependency between the technical and regulatory domains, which needs to be clearly defined in order to analyze the business domain.

In the following sections, we describe the methodologies developed in this thesis to achieve the key milestones in the research process.

## 2.2   Methodology for analyzing the impact of secondary user transmission on the primary receiver

In order to model the interference from secondary transmissions to the primary receiver, we adopt mixed methodologies combining simulation-, experimental- and
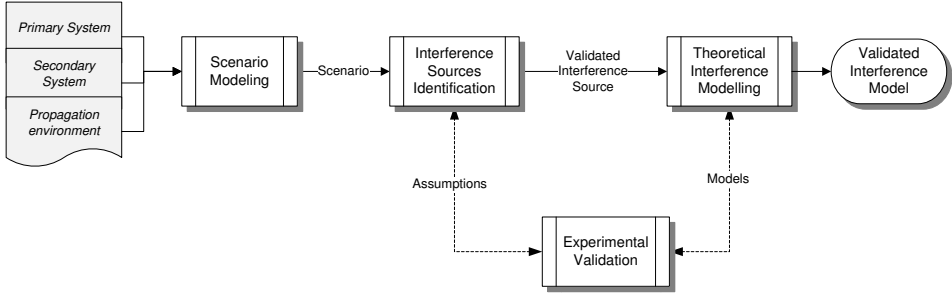
Figure 2.2: Methodology for analyzing the impact of secondary user transmission on the primary receiver

theory-based methods in order to identify the key interference components and to propose theoretical interference models to efficiently and reliably avoid harmful interference to the primary receiver. These models are then verified by multiple measurement campaigns, as shown in Fig. 2.2.

### 2.2.1 Scenario Modeling

Scenario modeling is an essential process in the analysis of secondary access scenarios. In this thesis, we focus mainly on key components of the process and their relevant characteristics. The selected components are: the primary system, the secondary system and the propagation environment. Notice that other components can also be incorporated into the analysis; but for the purpose of this particular investigation, we are interested in the three components mentioned above.

In the experiments, we consider the DTV broadcasting service as the primary system, and as regards the secondary user, we consider a short range device used in WLAN-type applications, which can cause potentially harmful interference to the DTV receiver. For the propagation environment, an indoor environment is selected given its complex interference characteristics due to the close proximity between the secondary user and the primary victim. In addition, three different types of DTV receptions are considered: rooftop, set-top and cable DTV reception, as shown in Fig. 2.3. Even though we have not specified a sharing mechanism, the underlying assumption is that the secondary user is connected to a geo-location database where basic information about the primary system is provided.

### 2.2.2 Identifying Interference Sources

The interference is assumed to reach the primary receiver over three different paths: $L_1$, $L_2$ and $L_3$ represent the propagation loss[1] to the DTV receiver antenna, the

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[1]Propagation loss represents the combined effect of distance-based path loss and shadowing.
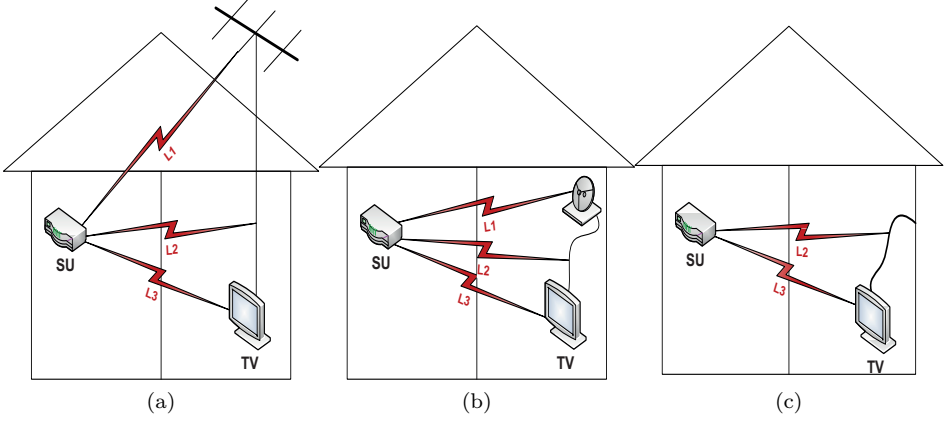
Figure 2.3: DTV reception types: a)Rooftop Antenna, b)Set-top Antenna and c)Cable Antenna.

cable and the DTV receiver equipment, respectively. Fig. 2.3 illustrates the different interference paths for the three types of DTV reception. Then, the total interference at the primary victim or the DTV receiver in channel $N+k$ ($I_{N+k}$) is calculated by:

$$I_{N+k} = P_{SU}G_{SU} \left( \frac{G_{TV}(\theta)}{L_1} + \frac{G_2}{L_2} + \frac{G_3}{L_3} \right) \tag{2.1}$$

where $P_{SU}$ and $G_{SU}$ represent the transmit power and the antenna gain for the secondary user, respectively. $G_{TV}(\theta)$ is the gain of the DTV receiving antenna, which depends on the incidence angle, $\theta$. Cable attenuation and DTV receiver isolation are represented as $G_2$ and $G_3$, respectively. We also assume that the secondary users have fixed channel bandwidth as that of a DTV signal. We define $\gamma_k$ as the required threshold of desired-to-undesired (D/U) power level ratio at the DTV receiver in channel $N + k$ for successful DTV reception:

$$\frac{S_N}{I_{N+k}} \geq \gamma_k \tag{2.2}$$

where $S_N$ is the received DTV signal power in channel $N$. If $\gamma_k$ and $S_N$ are known with regard to a particular DTV receiver, then we can calculate the maximum interference power that can be tolerated in a given channel.

**Experimental Verification**

We test and verify our assumptions about the impact of low power indoor secondary transmission on the quality of DTV reception in real indoor environments: laboratory environment and home environment. For the home scenario, we conducted our measurements in two apartments of approximately 70m$^2$ located in the

city of Gävle. The aim of our measurement campaigns is to verify our previous assumptions by answering the following questions:

- Is $\gamma_k$ a good reference for estimating the spectrum opportunities for secondary users in TVWS?

- Is direct radiation to the DTV receiver significant enough to influence the separation distance?

The results confirmed that $\gamma_k$ was a good reference. However, direct radiation in the TV receiver was not found to be significant enough, nor was interference to the cable feeder. Thus, the total interference at the DTV receiver in channel $N+k$ ($I_{N+k}$) can be reformulated as:

$$I_{N+k} = P_{SU}G_{SU}\left(\frac{G_{TV}(\theta)}{L_1}\right) \tag{2.3}$$

We employed (2.3) in the simulations and mathematical formulations in the remainder of this thesis .

### 2.2.3 Modeling the aggregate interference

To model the aggregate interference, we employ a scenario that is slightly different from the one previously described in Section 2.2.1. The only difference between the two scenarios is that the present on has multiple secondary users who simultaneously access multiple adjacent channels ($N + k, N + j$). This scenario is called multi-ACI scenario and it is illustrated in Fig. 2.4. In this case, we assume that there is an aggregate effect considering all the interference received at different adjacent channels. We therefore propose an analytical expression to approximate the tolerable aggregate adjacent channel interference (AACI) at the DTV receiver:

$$\sum_{k \neq 0}^{m} I_{N+k}\gamma_k \leq S_N \tag{2.4}$$

Our model shows that not only should the interference received in each adjacent channel stay below the corresponding threshold for that particular channel, but that also the weighted sum of the total ACI should be kept below a certain threshold.

**Experimental Verification**

The methodology to determine the existence of AACI is as follows:

i. We consider that multiple adjacent channels are simultaneously used by multiple secondary users.

ii. Vacant TV channels or adjacent channels are randomly selected for secondary user transmissions.
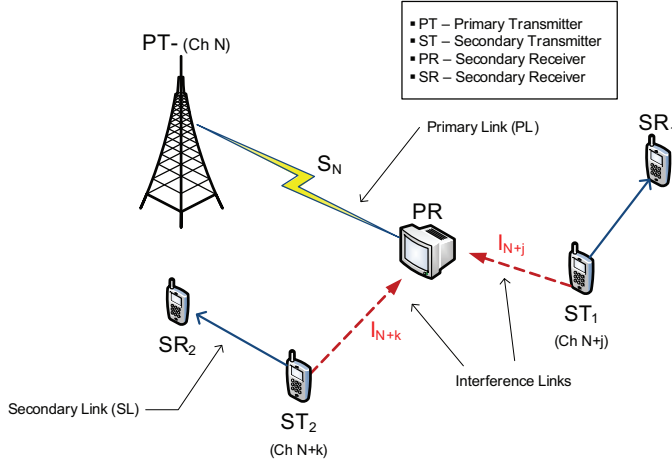
Figure 2.4: Multi Adjacent Channel Interference scenario

iii. We use $\gamma_k$ values to set the maximum permissible interference that a secondary user can generate at the DTV receiver $(I_{N+k})$ in the selected adjacent channels. $\gamma_k$ values are measured considering that a single secondary user is accessing one adjacent channel.

iv. In case that any distortion is observed in the DTV signal, we decrease the secondary user interference until the quality of DTV reception is acceptable.

v. Finally, we record the received interference power from the secondary user at the DTV receiver so as to ensure that no harmful interference is caused to the DTV receivers $(\hat{I}_{N+k})$.

Our assumptions and model are verified by the measurement results: there is a linear decrement of the maximum tolerable interference in a given adjacent channel when the number of adjacent channels used by secondary users is increased. The results can be used to set new constraints for realistic performance evaluation of secondary systems operating in the TVWS.

## 2.3   Methodology for Technical Availability Assessment

We develop an assessment methodology for quantifying the availability for large-scale secondary usage in a large geographical area where aggregation of interference in the spatial and frequency domains is considered. The different processes involved in this methodology are shown in Fig. 2.6 and will be explained in the remainder of this section.
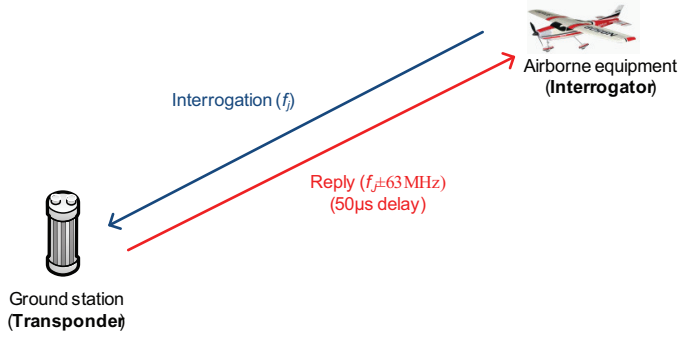
Figure 2.5: Basic operating principle of DME

### 2.3.1 Scenario Modeling and Interference Calculation

For this investigation, the selected components for describing the secondary access scenario are: the primary system, the secondary system, the propagation environment and the sharing mechanism. Our assessment is focused on the aeronautical band - specifically the DME system - as the primary system. Fig. 2.5 shows the basic operation of DME consists of two steps: first, the airborne equipment sends an interrogation signal down to the Earth; second, the ground station responds on a frequency of +63 or -63 MHz from the interrogation frequency after a delay of 50 micro seconds ($\mu$s). The secondary system concerns a large-scale deployment of indoor access points and mobiles that provide high-capacity broadband services. The secondary system applies sharing mechanisms that combine geo-location databases and spectrum sensing in order to control the aggregate interference at the primary receiver.

The aggregate interference is calculated based on the characteristics of the secondary access scenario, employing theoretical models of interference aggregation in the spatial and frequency domains. For the interference aggregation in the frequency domain, we employ the model given in 2.4. With regard to the the spatial domain, detailed explanation of the interference models can be found in [36, 47].

### 2.3.2 Availability Quantification

In our assessment, a DME channel is considered *available* if the secondary user, under a given sharing scheme, is able to successfully access the channel without violating the following primary protection criteria.

$$\Pr\left[\sum_{k \in N_v} I_{k,a}^v W_k \geq A_{thr}\right] \leq \beta_{PU} \tag{2.5}$$

where $N_v$ is the set of channels whose interference aggregate at the primary receiver $v$. The weighting factor, $W_k$, depends on the filter's characteristics and $\beta_{PU}$ is the
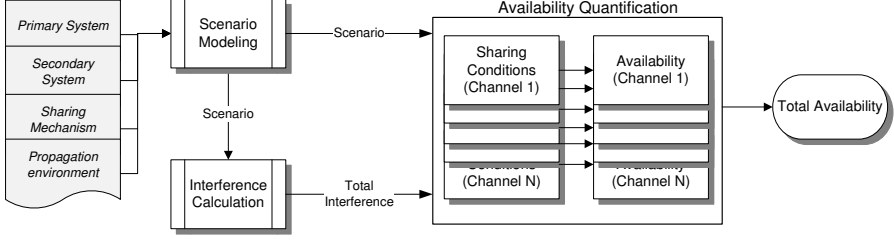
Figure 2.6: Methodology for Technical Availability Assessment

maximum permissible probability of harmful interference at the primary receiver. Considering the safety-of-life functions of the DME, $\beta_{PU}$ needs to be extremely small. Accordingly, we adopt a value used for air traffic control radar in 2.7-2.9 GHz, $\beta_{PU} = 0.001\%$ [52].

In order to simplify the computation, we assume that all channels in $N_v$ generate the same amount of interference $M$ at the primary victim $v$. Therefore,

$$W_k I_{k,a}^v = M, \ \forall k \in N_v \tag{2.6}$$

Then, (2.5) can be re-written as:

$$\Pr[n(N_v)M > A_{thr}] \leq \beta_{PU} \tag{2.7}$$

where $n(N_v)$ is the number of elements in $N_v$. Then, the aggregate interference in channel $k$ at the primary victim $v$, $I_{k,a}^v$, is regulated as follows:

$$\Pr\left[I_{k,a}^v > \frac{A_{thr}}{n(N_v)W_k}\right] \leq \beta_{PU} \tag{2.8}$$

By applying (2.8), the numerical analysis can be performed on a single-channel basis, leading to considerably reduce computation complexity. We compute $I_{k,a}^v$ and determine the minimum requirements to satisfy (2.8). The primary receiver, the ground station and the airborne interrogator are all considered in our calculation. The constraints set to protect the primary victim $v$ in channel $k$ are given in terms of the individual interference threshold, $IT_k^v$, or the minimum separation distance between the DME receiver and the secondary users, $ER_k^v$. Finally, a DME channel is considered as *available* in pixel $i$ if

$$D_{k,i} = \left\{ \begin{array}{ll} 1, & \text{when } \mathbb{E}[\tilde{\xi}_{k,j}^v] \leq IT_k \\ 0, & \text{otherwise} \end{array} \right. \tag{2.9}$$

where

$$IT_k = \min(IT_k^1, ..., IT_k^v) \tag{2.10}$$
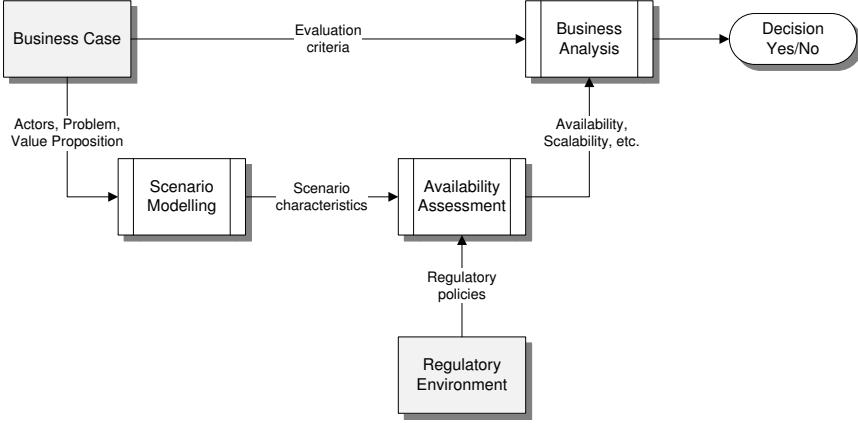
Figure 2.7: Methodology for Assessing Sharing Opportunities

Notice that $IT_k^v$ depends on the transmission power and the density of secondary users. To calculate the number of available channels in a pixel $i$, we simply sum all the channels where the secondary user fulfills the requirements for protecting the primary victim.

$$D(i) = \sum_{k \in K} D_{k,i} \tag{2.11}$$

Similar to the work done in [53], we consider the *average* number of channels available by *area* of a region:

$$m_a = \frac{1}{A_t} \sum_{i \in I} A_r^i D(i), \tag{2.12}$$

where $A_t = \sum_{i \in I} A_r^i$ is the total area of the region. In the same manner, we calculate the *average* number of channels available by *population* in the region:

$$m_p = \frac{1}{p_0} \sum_{i \in I} P_i D(i). \tag{2.13}$$

where $p_0 = \sum_{i \in I} P_i$ is the total population of the region.

## 2.4 Methodology for Assessing Commercial Viability of Secondary Access to the Radar Bands

Towards assessing the real-life sharing opportunities in the radar bands, we propose the methodology illustrated in Fig. 2.7. This methodology includes technical, regulatory and business aspects which are needed to make an assessment whether
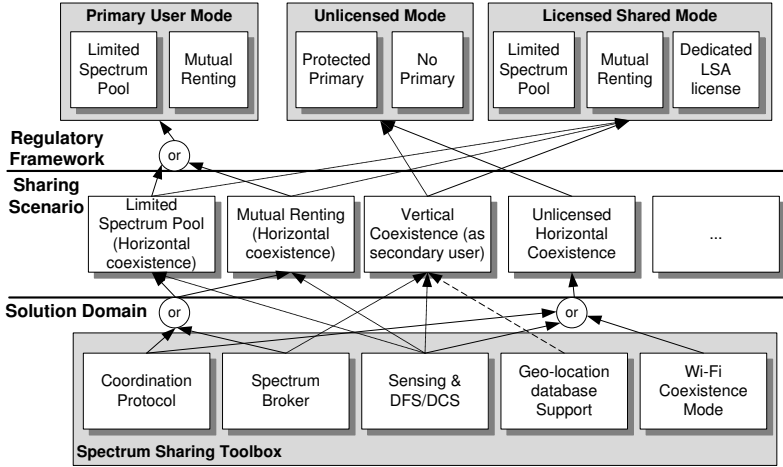
Figure 2.8: Spectrum Sharing Toolbox

spectrum sharing in the radar bands can take-off or not from the commercial point-of-view.

We start by devising a business case, for which we identify the main actors, problems, value proposition and competitors. This allows us to have a clear view of the conditions that will facilitate business success. These conditions are used as the evaluation criteria for the business analysis. Based on the output data of the business case, we perform scenario modeling process which defines the key characteristics for the technical availability assessment. This assessment is conducted following the methodology depicted in Fig. 2.6 [54]. Notice that such an assessment depends heavily on the selected regulatory policies, such as sharing mechanisms and spectrum etiquettes. For this evaluation, we employ the tools or technical enablers that make the regulatory policies and secondary access scenarios technically feasible.

Based on the results of the technical assessment, we then identify a regulatory framework which guarantees the implementation of policies that are beneficial from a business perspective. To determine the suitability of the regulatory framework in a systematic way, we employ a spectrum sharing toolbox proposed within the FP7 METIS project [54], which allows a direct mapping between technical enablers, secondary access scenarios or spectrum sharing scenarios and the regulatory framework, as shown in Fig. 2.8. Given that the toolbox is not a direct contribution of this thesis, it will be explained in Section 3.3.3, together with the outcomes obtained by using the toolbox.

Having defined the evaluation criteria and the (technical and regulatory) characteristics of the available spectrum, we proceed to a *qualitative* assessment of the business potential of the secondary access scenarios in consideration. Notice that this methodology can be used for different business cases.

# Chapter 3

# Key Results

This chapter provides a brief overview of the key results in the three main parts of this thesis: interference modeling at the primary system, technical availability assessment of large-scale secondary access, and commercial viability of secondary access in the radar bands. The results were obtained by employing the methodologies described in Chapter 2.

## 3.1 Interference Modeling at the Primary System

### 3.1.1 Assessing the impact of secondary user transmissions on the primary receiver

A realistic assessment of spectrum opportunities for indoor environments must take into account not only CCI caused by the secondary user's operation, but also ACI at the DTV receiver. The close proximity between the secondary user and the primary victim in an indoor environment makes ACI a serious problem. Basic information about the primary system is provided to the secondary user through a geo-location database. The secondary user is randomly deployed in indoor environments, e.g. home or office. Three different DTV reception scenarios examined in this investigation (rooftop, set-top and cable reception) are depicted in Fig. 2.3.

With regard to the spectrum sharing scenarios under consideration, we found plenty of channels available for indoor low-power secondary users, or the so called White Space devices (WSD). Such secondary users are able to access the majority of the vacant channels without causing any harm to the DTV reception. However, the number of channels available for secondary transmissions can vary significantly depending on the type of DTV reception, as shown in Fig. 3.1 and Fig. 3.2. ACI is critical for indoor set-top DTV reception due to the small separation distance between the DTV receiver and the secondary user. Therefore, a separation distance of more than 2 meters is needed to find channels available for secondary users. In the case of rooftop or cable DTV reception, secondary users can always find at
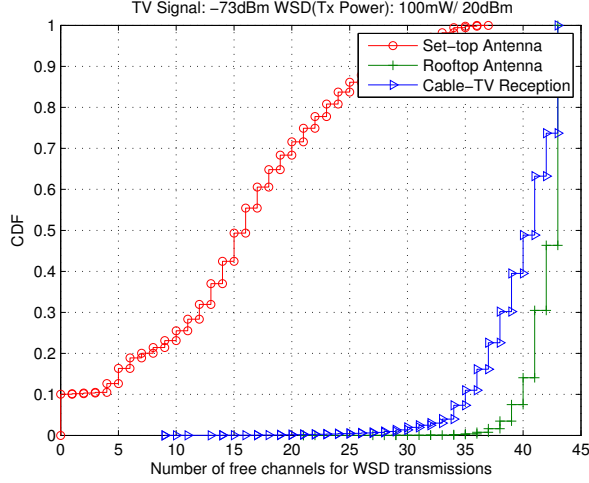
Figure 3.1: CDF of the number of free channels for WSD transmission, Weak TV signal.

least one available channel despite short separation distances. This means that the impact of ACI is not significant in these scenarios even if the number of DTV channels occupied is increased.

We evaluated our assumptions about the relevant interference sources and the proposed interference model, using measurement campaigns. The results verified the importance of ACI when quantifying real-life opportunities for short-range secondary systems. It was also confirmed that direct radiation from secondary users into cables and the set-top box DTV receiver is negligible. With regard to cable-TV and rooftop antenna reception, ACI was not severe and indoor low-power secondary users could operate in the majority of the vacant DTV channels without having any noticeable effect on the quality of DTV reception. However, ACI can significantly reduce the number of channels available for secondary transmissions for indoor set-top antenna reception. In addition, we observed a good agreement between simulation and measurement results in the channels available for secondary access, as shown in Fig. 3.3. Even though the simulation results are slightly pessimistic, compared to the measurement ones, the assumptions and the overall performance predicted by the theoretical models were proved to be reasonable and could be used as a lower-bound reference. More details of the models and results can be found in [44, 55].
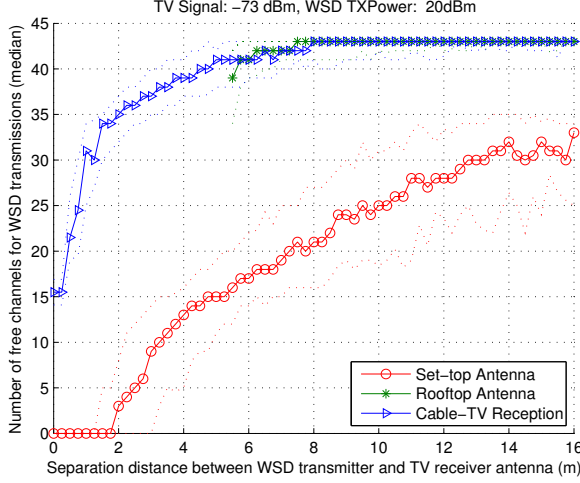
Figure 3.2: Median number of free channels for WSD transmissions depending on the separation distance between the WSD and the TV receiver antenna. WSD transmit power: 100 mW/ 20dBm. 90 and 10- percentiles are shown for each scenario.

### 3.1.2 Modeling the aggregate interference in the frequency domain

In this part of work, we focused on the characterization of aggregate adjacent channel interference (AACI) in the multi-ACI scenario (i.e. multiple secondary users simultaneously accessing multiple adjacent channels $(N+k, N+j)$), as shown in Fig. 2.4. Using the methodology described in Section 2.2, we were able to propose and verify a theoretical model that can effectively establish limits on the maximum tolerable AACI at the DTV receivers. A detailed explanation of the interference model is as follows:

**Definition:** The *equivalent CCI* $(\hat{I})$ is the co-channel interference that would result in having the same effect as does the aggregate interference from the multiple interferers $I_{N+k}$, that is, the quality of DTV reception is sufficiently good if :

$$\frac{S_N}{\hat{I}} \geq \gamma_0 \tag{3.1}$$

**Proposition:** We propose that $\hat{I}$ is estimated by:

$$\hat{I} = \sum_{k \neq 0}^{m} I_{N+k} \frac{\gamma_k}{\gamma_0} \tag{3.2}$$
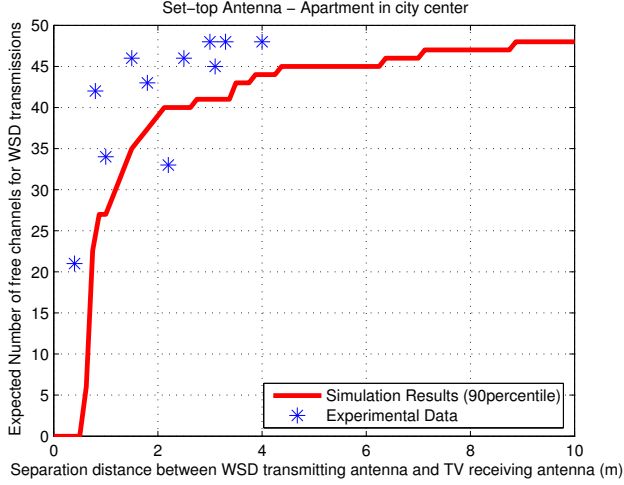
Figure 3.3: Expected Number of available channels for WSD transmissions (high directivity set-top antenna)

where $\gamma_k$ values are considered as a weighting factor in the aggregate interference generated by $m$ different adjacent channels. Values of $\gamma_k$ are taken as a linear approximation of the DTV filter's characteristics.

Based on (3.2) and (3.1), an analytical expression was proposed to approximate the tolerable AACI at the DTV receiver:

$$\sum_{\substack{k \neq 0}}^{m} I_{N+k}\gamma_k \leq S_N \tag{3.3}$$

Our model states that not only should the interference received in each adjacent channel stay below the corresponding threshold for that particular channel, but that the weighted sum of ACI should be kept below a certain threshold. The results of measurement campaigns confirmed that ACI should not be treated separately since there is a cumulative effect on the interference in the frequency domain. A good agreement between the theoretical model and the measurement results can be clearly seen in Fig. 3.4. Additional description of the models and results can be found in [45, 46, 55].

### 3.1.3   Modeling the aggregate interference in the spatial domain

In this section, we modeled the aggregate interference in the spatial domain where there is uncertainty involved in fading estimation. Different levels of uncertainty in fading estimation are represented by a correlation coefficient $\rho$. We adopted the mathematical frameworks proposed in [31, 36, 56] with slight modifications to take
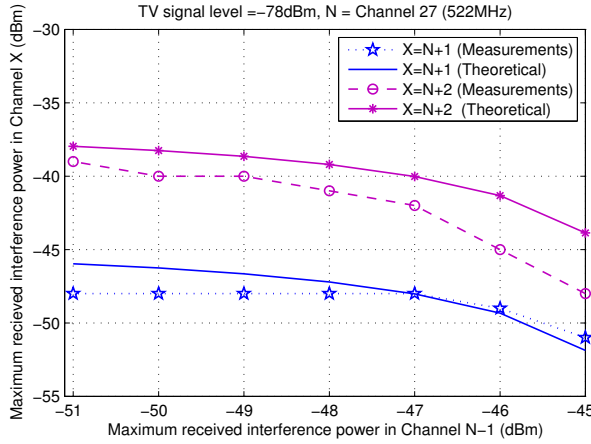
Figure 3.4: Relation between the maximum received interference power level in two different TV channels.

into account the proposed spectrum sharing mechanism which combines spectrum sensing and geo-location databases.

Let us consider that an arbitrary secondary user $i$ is distributed in a circular area of radius $R$ by a homogeneous Poisson point process. The path loss between the primary receiver and the secondary user $i$ is modeled as $g(r_i) = Cr_i^{-\alpha}$, where $C$ is a constant and $\alpha$ stands for the path loss exponent. The user $i$ will then cause interference $\xi_i$ to the primary receiver if it is to transmit, which can be expressed as:

$$\xi_i = P_t^{eff} g(r_i) Y_i \tag{3.4}$$

where $P_t^{eff}$ refers to the effective transmission power of the secondary user including antenna gains and bandwidth mismatch. $Y_i$ is a random variable modeling the fading effect. It is generally considered that the fading consists of shadow fading, which follows a normal distribution in dB scale, and multi-path fading, by which the instantaneous power varies in accordance with an exponential distribution. We assumed that the composite fading $Y_i$ follows a log-normal distribution. It is known that this assumption works well when the standard deviation of shadowing is higher than 6dB, i.e. when shadowing is a dominant factor in the composite fading [57]. The user $i$ will decide to transmit if $\tilde{\xi}_i \leq I_{thr}$. Let $I_{thr}$ denote the interference threshold imposed on the individual secondary users. The value of $I_{thr}$ is given to the secondary users by a central spectrum manager. This ensures that the secondary users make their own decisions without interacting with each other. Note that $\tilde{\xi}_i$ is affected by the fading in the sensing channel. That is,

$$\tilde{\xi}_i = P_t^{eff} g(r_i) X_i \tag{3.5}$$

where $X_i$ is modeled as a random variable which is log-normally distributed, and whose parameters are the same as those of $Y_i$. The joint distribution of $X_i$ and $Y_i$ is given by the following bivariate log-normal distribution:

$$f_{X_i,Y_i}(x,y) = \frac{1}{2\pi x y \sigma^2 \sqrt{1-\rho^2}}$$
$$\times e^{-\frac{(\ln x)^2 - 2\rho(\ln x)(\ln y) + (\ln y)^2}{2\sigma^2(1-\rho^2)}} \tag{3.6}$$

where $\rho$ is the correlation coefficient of $X_i$ and $Y_i$:

$$\rho = \frac{Cov(\ln X_i, \ln Y_i)}{\sqrt{Var(\ln X_i)Var(\ln Y_i)}}. \tag{3.7}$$

We considered that the components of the composite fading, $X_i$ and $Y_i$, will be partially correlated ($0 < \rho < 1$). The exact value of $\rho$ depends on the propagation environments. Note that full correlation ($\rho = 1$) represents an ideal scenario where the secondary user has an accurate knowledge of interference. Zero correlation ($\rho = 0$), on the contrary, stands for a pessimistic assumption - that is, the fading is completely unknown to the secondary user. For the sake of simplicity and mathematical tractability, we adopted the assumption that secondary users in the whole area under study are affected by a homogeneous fading distribution. The aggregate interference $I_a$ can be expressed as:

$$I_a = P_t^{eff} C \underbrace{\sum_{i \in N_t} r_i^{-\alpha} Y_i}_{I_{N_t}}. \tag{3.8}$$

Hereafter, we omitted the index of the secondary user $i$, which is chosen in an arbitrary manner. By applying Campbell's theorem, the characteristic function of $I_{N_t}$ is as follows:

$$\psi_{I_{N_t}}(jw) = \exp\left(-2\pi\lambda \int_X \int_Y \int_{r_o}^R [1 - \exp(jwyr^{-\alpha})]\right.$$
$$\left.\times \mathbf{1}_{[0,\hat{I}_{thr}]}(r^{-\alpha}x) f_{X,Y}(x,y) r \mathrm{d}r \mathrm{d}y \mathrm{d}x\right). \tag{3.9}$$

where $j = \sqrt{-1}$ and $\hat{I_{thr}} = I_{thr}/(P_t^{eff}C)$. The activity of the secondary users is represented by $\mathbf{1}_{[0,\hat{I}_{thr}]}(r^{-\alpha}x)$, which is a Bernoulli random variable. The indicator function is defined as:

$$\mathbf{1}_{[a,b]}(z) = \begin{cases} 1, & \text{if } a \leq z \leq b \\ 0, & \text{otherwise} \end{cases} \tag{3.10}$$

Figure 3.5: A comparison between the analytic CDF of $I_a$ and the result of Monte Carlo simulation; primary receiver is the DME ground transponder ($I_{thr} = -150$dBm and $\lambda_{SU} = 20/\text{km}^2$)

where the value "1" of the Bernoulli variable denotes that the secondary user is able to transmit. We used (3.9) to derive the exact expressions for the $n^{th}$ cumulant of the aggregate interference in a limited circular region $[r_o, R]$. We considered a case where there is a partial correlation between the two fading effects that affect the sensing and interfering channels, $X$ and $Y$.

$$
\begin{aligned}
k_{I_{N_t}}(n) = \frac{2\pi\lambda}{(n\alpha - 2)} \Bigg[ & (r_o^{2-n\alpha} - R^{2-n\alpha}) \int_0^\infty y^n f_Y(y)\Phi(L_i)\mathrm{d}y \\
& - R^{2-n\alpha} \int_0^\infty y^n f_Y(y)[\Phi(L_s) - \Phi(L_i)]\mathrm{d}y \\
& + \hat{I_{thr}}^{\frac{n\alpha-2}{\alpha}} \int_0^\infty y^n f_Y(y) \times \int_{r_o^\alpha \hat{I_{thr}}}^{R^\alpha \hat{I_{thr}}} \frac{x^{\frac{2-n\alpha}{\alpha}}}{\sqrt{2\pi}x\sigma\sqrt{1-\rho^2}} e^{-\frac{(\ln x - \rho\ln y)^2}{2\sigma^2(1-\rho^2)}} \,\mathrm{d}x\mathrm{d}y \Bigg]
\end{aligned}
$$

(3.11)

where,

$$
L_i = \frac{\ln(r_o^\alpha \hat{I_{thr}}) - \rho\ln y}{\sigma\sqrt{1-\rho^2}},
$$

$$
L_s = \frac{\ln(R^\alpha \hat{I_{thr}}) - \rho\ln y}{\sigma\sqrt{1-\rho^2}}.
$$

In the special case of full correlation ($\rho = 1$) or zero correlation ($\rho = 0$), the closed-form expressions of cumulants can be found in [31] and [56], respectively. Using the cumulant of $I_{N_t}$, as shown in (3.11), we can obtain the $n^{th}$ cumulant of the aggregate interference $I_a$ as follows:

$$k_{I_a}(n) = (P_t^{eff} C)^n k_{I_{N_t}}(n). \tag{3.12}$$

The probability density function (pdf) of $I_a$ can be approximated by a known distribution through a moment-matching method. In [31, 56], both shifted log-normal and truncated-stable distributions are employed to address the skewness of the aggregate interference. In our model, the strong interferers are effectively removed as the stringent threshold only allows secondary transmissions if $\tilde{\xi}_i \leq I_{thr}$. Therefore, a simple log-normal distribution is sufficient to describe $I_a$. The pdf of $I_a$ can be approximated with the first and second order cumulants of $I_a$ being obtained by (3.12).

$$f_{I_a}(y) = \frac{1}{y\sqrt{2\pi\sigma_{I_a}^2}} \exp\left[\frac{-\ln y - \mu_{I_a}}{2\sigma_{I_a}^2}\right], \tag{3.13}$$

where

$$k_{I_a}(1) = \exp[\mu_{I_a} + \sigma_{I_a}^2/2], \tag{3.14}$$

$$k_{I_a}(2) = \exp(\sigma_{I_a}^2 - 1)\exp(2\mu_{I_a} + \sigma_{I_a}^2). \tag{3.15}$$

With regard to the ground transponder, the cumulative distribution function (CDF) of $I_a$ calculated by (3.13) for different values of $\rho$ is shown in Fig. 3.5. A good agreement between the analytical CDF of $I_a$ and the simulation results can be verified if $\rho > 0$. When the fading is unknown to the secondary user ($\rho = 0$), the analytical CDF matches the tails of the simulation-based CDF of $I_a$. Since we consider $\beta_{PU} = 0.001\%$, it is still possible to employ the log-normal approximation of the probability distribution of $I_a$ to analyze the impact of fading uncertainty on the feasibility of secondary access.

## 3.2 Technical Availability Assessment of Large-Scale Secondary Access to the Aeronautical Band

### 3.2.1 Feasibility Assessment of Large-Scale Secondary Access to the Aeronautical Band

We analyzed the feasibility of large-scale indoor broadband secondary access to the 960-1215 MHz spectrum where there uncertainties in the fading and the location of the primary receiver. This analysis was done in terms of the number of secondary users who are able to operate with an acceptable transmission probability and the exclusion region size imposed on the secondary users. We employed the scenario
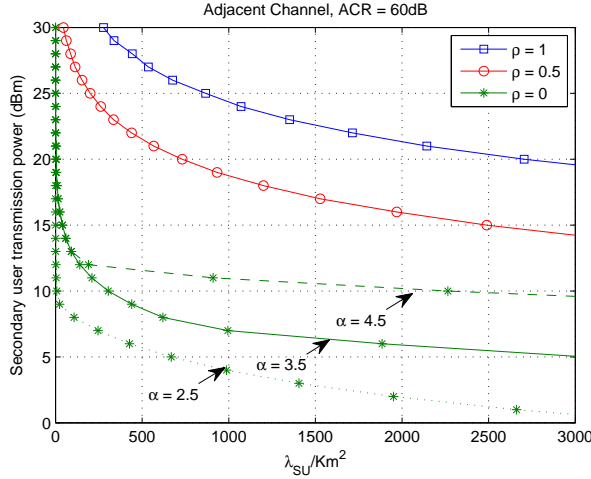
Figure 3.6: Impact of different correlation coefficients ($\rho$) on the maximum secondary user transmission power for a given $\lambda_{SU}$ when $Pr(\tilde{\xi}_i(r_i) \leq I_{thr}) \geq 90\%$ at $r_i = 5$km; the primary receiver is the DME ground transponder

described in Section 2.3.1. A full explanation of the scenario is provided in [36, 47, 55].

Our numerical results are presented in Fig. 3.6 and Fig. 3.7, from which we concluded that massive indoor low-power secondary access to an adjacent channel - with adjacent channel rejection (ACR) or attenuation higher than 60dB - is feasible with a high transmission probability and a small exclusion region size, even when the secondary users do not have an accurate knowledge of the propagation loss or the location of the airborne interrogator.

### 3.2.2   Availability Assessment of Large-Scale Secondary Usage in the Aeronautical Band

We investigated the availability of massive indoor broadband secondary access in the 960-1215 MHz band, primarily allocated to the DME system. We applied the practical sharing mechanisms proposed in [47], where the secondary users share the DME spectrum by means of spectrum sensing and geo-location databases. We employed the methodology described in Section 2.3 to calculate the amount of available spectrum in a large geographical area where there are uncertainties concerning fading estimation and the location of the primary receiver. As different uncertainty levels could affect the opportunity detection schemes applied, we considered pessimistic scenarios where uncorrelated fading ($\rho = 0$) is experienced in the interfering and sensing channels, and where the update delay ($t_u$) between the geo-location database and the secondary users is 150 seconds or 2.5 minutes. Additional details
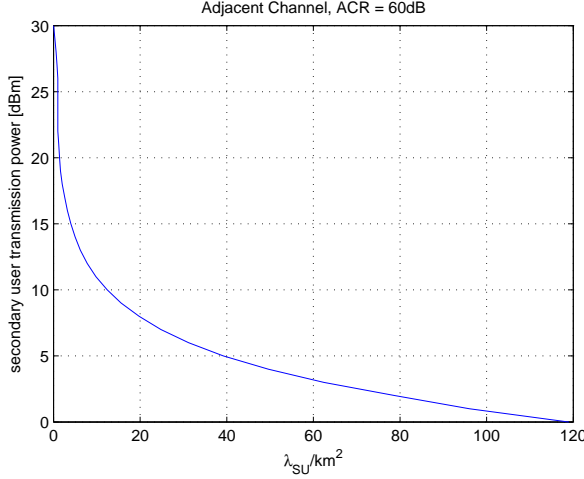
Figure 3.7: Maximum secondary user transmission power for a given $\lambda_{SU}$ when no exclusion region is needed ($r_o = 0$km), the primary receiver is the DME airborne interrogator. Secondary user transmission power vs. density of secondary user($\lambda_{SU}$).

can be retrieved from [48].

Our numerical experiments showed that availability is location-dependent. In dense cities where additional spectrum is actually needed, the availability is considerably lower that that in rural areas. This is mainly due to the effect of the aggregate interference and a higher density of DME transponders close to the urban areas. Moreover, Table 3.1 shows that the impact of fading uncertainties is stronger on the situation of dense secondary networks and high density of primary receivers, which is typical in urban areas. This means that accurate sensing becomes more important in urban areas where the probability of harmful interference is higher. By contrast, the impact of the update delay ($t_u$) is more relevant to sparse secondary networks.

Nonetheless, at least 57 MHz is available everywhere in Germany and Sweden, as shown in Fig. 3.8. The uncertainties in the estimation of propagation loss that accompany the practical sharing schemes being applied do not have a critical impact on the average availability, which only decreases up to 6% with high levels of uncertainty. Our results also show that good carrier aggregation capabilities are crucial for the secondary users in order to fully utilize the available spectrum which is mostly non-contiguous.
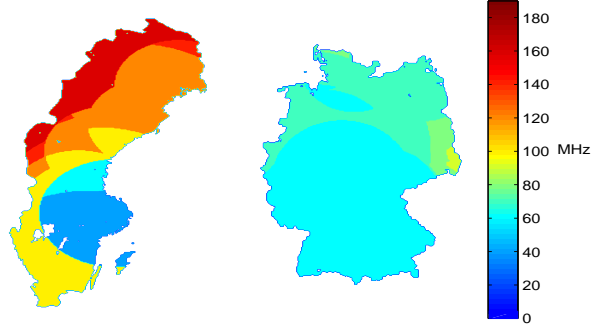
Figure 3.8:  Availability in Sweden (left) and Germany (right).  ($SU_{Ptx} = $
0dBm/MHz, $f_a = 1$, $\rho = 1$ and $t_u = $ 0min)

Table 3.1: Average availability in Sweden and Germany

| Country | Sharing schemes | Average availability by area (MHz) | Average availability by population (MHz) |
|---|---|---|---|
| Sweden | $\rho$=1, $t_u$=0min | 117.6970 (61.30%) | 85.6323 (44.60%) |
| | $\rho$=1, $t_u$=2.5min | 110.1365 (57.36%) | 81.2953 (42.34%) |
| | $\rho$=0, $t_u$=0min | 114.5914 (59.68%) | 83.0755 (43.26%) |
| Germany | $\rho$=1, $t_u$=0min | 69.0680 (35.97%) | 68.5318 (35.69%) |
| | $\rho$=1, $t_u$=2.5min | 68.7083 (35.78%) | 68.1942 (35.51%) |
| | $\rho$=0, $t_u$=0min | 58.1505 (30.28%) | 57.8966 (30.15%) |

## 3.3   Commercial Viability of Secondary Access in the Radar Bands

### 3.3.1   Business Case and Evaluation Criteria

In this section, we defined a business case of interest and the evaluation criteria for
the business analysis. The business case is expressed as follows:

- Main Actors: An *incumbent MNO* who has a strong incentive to offer sig-
  nificantly higher indoor capacity to satisfy *their customer's* demands. We
  consider the incumbent MNO in this study given the argument in [42] that a
  new entrant does not have a competitive advantage over the incumbent MNO
  in the deployment of wireless network with secondary spectrum access.

- Problem: The MNO needs a solution that offers the best cost-performance

trade-off since it has already been *challenged by the revenue gap*, i.e., difference between soaring mobile data demands and dwindling revenues.

- Value Proposition: Short-range communication in the radar bands *offloading mobile traffic demand in indoor and hotspot* environments where the demand is extremely high.

In order to analyze the business potential of the case, we need to identify the factors that could influence business success, or in other words *what should the radar bands offer*.

- **Enough Spectrum Availability** to alleviate the increasing data demand in current MNO networks in hotspots and indoor locations.

- **Availability of radio technology** is crucial in estimating when the solution can be deployed and the cost it will generate.

- **Low-cost end-user devices** are crucial in reaching mass adoption. As current alternatives have these characteristics, it is thus critical for the proposed solution to also have low-cost end-user devices or to be able to use existing devices with minor modifications, which could have a significant impact on the cost.

- **System Scalability** is also important in motivating investments. Moreover, given that this solution is proposed to alleviate the high capacity demand, the system scalability is a therefore must.

- **Guaranteed quality of service** should be provided in order to attract investments given that other best-effort alternatives are available for free. Thus, there is a need to establish a regulatory framework that could guarantee quality of service for short range communication in the radar bands.

### 3.3.2  Impact of regulatory policies on the sharing opportunities in the radar bands

We analyzed regulatory policies that could improve the sharing opportunities for ultra-dense networks (UDNs) in the radar bands allocated below and above 10 GHz. We considered Air Traffic Control (ATC) radars (2.7-2.9 GHz) and Surveillance Radars (15.7-17.2 GHz) as examples of primary systems operating in the S- and Ku-Bands, respectively. By UDN we refer to a massive scale deployment of indoor/outdoor APs and mobiles providing high capacity broadband services in future scenarios of 2020 and beyond [58]. The UDN shares the spectrum with a rotating radar by means of geo-location databases and spectrum sensing which also enable the secondary users to have prior knowledge of the radar's rotation pattern, location, operating frequency, and transmission power. As a result, the secondary
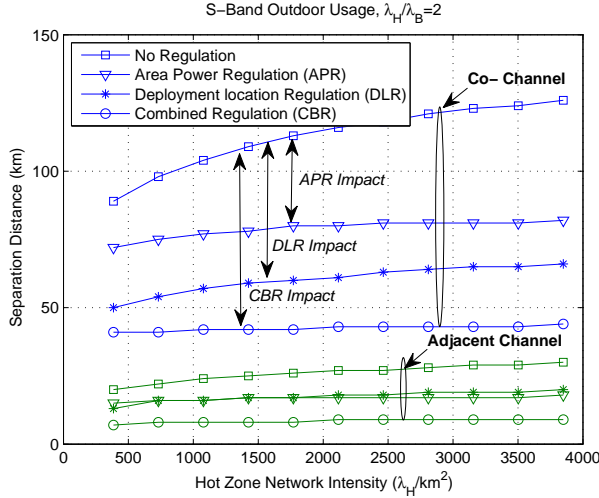
Figure 3.9: S-Band Outdoor Usage, $\lambda_H/\lambda_B = 2$

users can reliably exploit the sharing opportunities in the time/space domain. In our evaluation, these opportunities are inversely proportional to the required time-averaged separation distance $\bar{r_H}$ between the primary victim and the secondary transmitter in the hot zone where a minimum secondary transmission probability of $TX_{min}$ is guaranteed.

The sharing opportunities in the time/space domain depend highly on the aggregate interference, which is determined by the characteristics of the secondary system. Thus, regulatory policies are needed to better exploit the trade-off between the density of active secondary users and the required separation distance. We considered three alternatives:

- Area Power Regulation (APR): Secondary-system transmissions are based not only on the protection of the radar system or of the primary, but also on the number of simultaneous transmissions within a contention area of each secondary user.

- Deployment Location Regulation (DLR): Secondary-system transmissions are only allowed within a specific geographical area (e.g. a city or a town).

- Combined Regulation (CBR): This option is a combination of APR and DLR - that is, secondary-system transmissions are only allowed within a specific geographical area (e.g. a city or a town), and if the number of simultaneous transmissions within a contention area is also regulated.

Numerical results showed that indoor and outdoor co-channel sharing opportunities for UDNs in the S-Band are limited in cities which are near the radar. This is
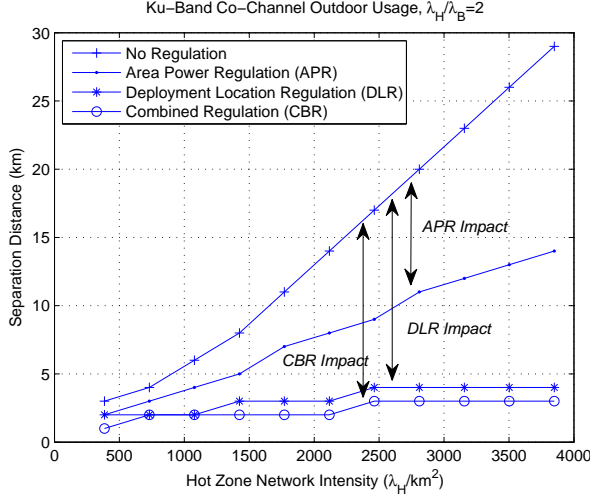
Figure 3.10: Ku-Band Co-Channel Outdoor Usage, $\lambda_H/\lambda_B = 2$

because large separation distances (around 40 km) are required even when CBR is applied. On the other hand, indoor and outdoor adjacent-channel sharing opportunities for UDNs seem to be promising, and the application of CBR could lead to very small separation distances (less than 10 km), even for networks with very high density. In the Ku-Band, the impact of interference aggregation is much less critical so that it is possible to exploit indoor sharing opportunities in urban areas near the radar even if no regulation is applied (13 km separation distance for the highest network density). In the case of outdoor scenarios, adjacent-channel sharing opportunities can be fully exploited without regulation and blind co-channel deployment of UDNs is possible if any of the proposed regulatory policies is applied.

Overall, the results are more beneficial with regard to the S-Band when the proposed regulatory policies are applied, due to the higher impact of interference aggregation. In the Ku-Band, however, the benefits gained from applying any of the policies are less significant since (almost) blind deployment of UDNs is feasible without requiring any restrictions. The heterogeneity in the spatial distribution of secondary user impacts the selection of a regulatory policy: the application of DLR has the strongest impact on reducing of the required separation distance, especially when the difference in network density between urban and rural areas is negligible (homogeneous environment).

### 3.3.3   A suitable regulatory framework

The methodology to identify the most suitable regulatory framework to enable spectrum sharing in the radar bands is a sequential approach, which was employed

in a systematic way with the help of the spectrum sharing toolbox proposed in the EU FP7 METIS [54]. First, we defined vertical coexistence as the spectrum sharing scenario under study, where the radar systems are the incumbent and a short-range UDN providing broadband services is the newcomer.

Next, based on the particular characteristics of this scenario and the proposed sharing mechanism, we identified the tools, or technical enablers, which make this scenario and sharing mechanism feasible. These enablers are a combination of geo-location database support and detect-and-avoid mechanisms. Notice that the combination of these two enablers is not necessary, but is advantageous in improving sharing conditions. This means that it is possible to employ geo-location databases alone. However, the spectrum sensing, if used alone, cannot provide the required accuracy because it could be affected by detection errors. Any detection error in the vicinity of the primary user could be critical to the radar operation.

Finally, with the enablers and scenario ready, the regulatory framework was determined. In order to select a suitable framework, we evaluated different regulatory policies that could improve the exploitation of sharing opportunities. The results showed that applying regulation to the deployment would improve spectrum availability in urban environments. More specifically, the transmission power level and operating frequency (which are traditionally regulated), and the location of the UDN all need to be strictly regulated to fulfill the primary protection criteria, and more importantly to make sharing conditions less rigid. Considering these requirements, we suggested that Licensed Shared Access (LSA[1]) would be the suitable regulatory framework for real-life implementation of the identified regulatory policies in order to enable the deployment of UDNs in the radar bands.

### 3.3.4 Business analysis

In this section, we discuss what the radar bands offer with respect to the evaluation criteria. Moreover, we identify potential competitors and analyze how short-range communication in the radar bands is positioned in relation to other alternatives.

- **Enough Spectrum Availability** in the radar bands can vary significantly from country to country. For instance, in Macedonia, there is one single civilian ATC radar in the whole country. In the UK, however, we find around 77 ATC radars of different civilian and military types. Based on our previous work [48] where we found that at least 30% of the DME band was available for secondary usage, we estimated that similar results would be obtained in other radar bands below 10 GHz frequency. Moreover, by applying the

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[1]Notice that LSA concept is still under development. Hence, our discussion is based on the definition given by CEPT: *"A regulatory approach aiming to facilitate the introduction of radio communication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the LSA framework, the additional users are allowed to use the spectrum (or part of the spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorized users, including incumbents, to provide a certain QoS"* [59].

regulatory policies devised in [49], availability could be further improved in the urban areas. According to the European Allocation Table, below 10 GHz frequency there is around 1.2 GHz allocated to radar applications. Assuming that 30% would be available, short-range communication could get access to up to 400 MHz in the radar bands. However, availability would be very much fragmented in the frequency domain. This means that a device would be able to access at most 100 MHz in a given location, even if it has advanced carrier aggregation capabilities. It is important to notice that spectrum availability in the radar bands has low spatial granularity, which means that the available amount of spectrum is spatially uniform over large areas. Therefore, spectrum availability will most likely be constant in cities in the space/time domain, which is a key difference from that in the TV bands.

- **Availability of radio technology** depends on the selected radar band. In this study, we mainly considered the bands below 10 GHz (i.e. L-Band and S-Band) which are located close to frequency bands where radio technology is already available for mobile communications. Moreover, filter characteristics, sensing capabilities and carrier aggregation functionalities, which are extremely relevant to enable secondary access to the radar bands due to the noncontiguous availability, are already quite advanced in their development. Thus, the adaptation of available technology to being able to operate in the radar bands below 10 GHz can be done within a reasonable period of time and at reasonable costs. In contrast, it would require much more time to make radio technology available for the radar bands above 10 GHz since there is currently no radio technology for mobile communications in these bands.

- **Low-cost end-user devices** operating in the radar bands require additional spectrum sensing capability, which could increase their production cost but not significantly.

- **System Scalability** in the radar bands has been previously demonstrated in [47–49]. A system with a very high network density can share the radar bands with reasonable requirements (i.e. small exclusion region size), especially for adjacent channel access. Moreover, it does not require complex cross-layer interference between the outdoor and indoor networks in order to ensure quality of service.

- **Quality of service** can be guaranteed in the radar bands as the selected regulatory framework, LSA, only allows access to a limited number of licensees so that the sharing rules can be effectively enforced and hence ensuring quality of service for all licensees.

Below, we identify the alternatives that are currently available in the market:

- Indoor offloading in the license-exempt ISM bands (2.4 GHz or 5 GHz band) by employing Wi-Fi technology.

- Indoor offloading in the frequency band exclusively licensed to the MNO by employing LTE technology.

Table 3.2: Comparison between three solutions for indoor offloading

|  | **Unlicensed** | **Licensed** | **LSA** |
|---|---|---|---|
| Spectrum availability | Anywhere (538 MHz) | Anywhere (100 MHz) | Location-based (approx. 100 MHz) |
| Technology | Available | Available | Near-Term Available |
| System Scalability | Poor | Good | Good |
| Quality of Service | Best-effort | Guaranteed | Guaranteed |
| Spectrum access cost | Free | Marginal | Undefined |
| Spectrum access | Open | Exclusive | Few Licensees |

As one can identify in Table 3.2, there are both advantages and disadvantages for the MNO if indoor secondary access with the LSA model is chosen. One of the main disadvantages is the location-based availability of the radar bands. However, applying regulation to the deployment of secondary users makes it possible for us to have area-based or city-based availability, which in turn makes this solution relatively competitive in comparison with the other alternatives in the areas with high capacity demands. This solution offers guaranteed quality of service and a level of system complexity that is perfectly manageable for a traditional MNO that is used to complex systems. In addition, the fact of that only a few licensees can access the available spectrum makes this option more valuable in competition with the other players.

Finally, we recognized that spectrum access cost is still an undefined parameter which has direct impact on the business potential of this solution. It is critical to establish an appropriate spectrum access cost or license fee in order to motivate the MNOs to make long-term investments on this solution. We suggested that it should be set according to the potential benefits that the solution could bring to the licensees. The benefits depend highly on the characteristics of the secondary access availability, such as the amount and the granularity of the available spectrum in the space/time domains, which in turn may vary greatly according to the region or country where the evaluation is made.

# Chapter 4

# Conclusions and Future Work

## 4.1 Conclusions

The explosive growth in mobile data consumption represents a big challenge for mobile network operators and national regulators. While MNOs are seeking to improve the capacity of their networks in a cost-efficient way to fight the revenue gap, national regulators are looking for more flexible regulatory frameworks that will lead to a better utilization of the available spectrum for mobile communications. Radio resources, e.g. technology, infrastructure and *spectrum*, need to be efficiently used to meet the growing mobile traffic demand. This thesis attempts to find additional spectrum to meet this demand by considering secondary spectrum access. We proposed a research methodology for assessing commercial viability of large-scale deployment of wireless networks employing vertical spectrum sharing or secondary spectrum access in the aeronautical and radar bands. This methodology takes into account the technical, regulatory and business aspects of secondary spectrum access.

By employing this methodology, we identified the conditions or *criteria necessary for achieving business success* in the deployment of high-capacity wireless systems with secondary spectrum access to the aeronautical and radar bands, which are the following: spectrum availability, radio technology availability, low-cost end-user devices, system scalability and guaranteed quality of service.

Our investigation looked into the technical aspects of these criteria, for which we focused on modeling the interference at the primary system as an initial step towards a technical assessment of spectrum availability. Regarding the interference modeling at the primary receiver, we investigated mainly the impact of interference from one or multiple secondary users on the DTV receiver. We verified, through measurement campaigns and simulations, that not only CCI but also ACI need to be taken into account when determining the maximum tolerable interference at the primary victim. Moreover, the impact of ACI becomes even more critical when different frequencies are simultaneously accessed by secondary users, mainly

because the interference aggregates not only in the spatial but also in the frequency domain.

We then conducted a *technical assessment of spectrum availability* in the aeronautical and radar bands. Our results showed that there are ample adjacent channel sharing opportunities for ultra-dense networks offloading mobile traffic in indoor and hotspot environment. Moreover, imperfect knowledge of the propagation loss and of the primary victim's location does not have a significant impact on the country-wide availability in the aeronautical band and high availability was observed even in urban areas. Overall, the availability was shown to be location-dependent and mostly non-contiguous; thus it is crucial for secondary users to have good carrier aggregation capabilities in order to fully utilize the available spectrum.

We also examined the *regulatory domain* where it was found that applying regulatory policies, especially to the deployment of secondary users, can boost availability in the cities or urban areas where the capacity demand is high. It was also shown that if no regulation is applied or if only basic sharing rules are followed (similar to the ISM bands), the availability can actually deteriorate and the enforcement of rules would be challenging. With regard to the regulatory policies under evaluation, our results showed that applying regulation to the deployment of secondary users can bring significant benefits in terms of the available sharing opportunities or the minimum required separation distance from the primary receiver. Finally, we identified Licensed Shared Access (LSA) as a suitable regulatory framework to meet the tough criteria for protecting the radar receivers and to apply the selected regulatory policies to boost the exploitation of sharing opportunities.

Finally, this thesis provided a comprehensive qualitative assessment of the *commercial viability of secondary access in the radar bands*, focusing on indoor and hotspot communications in the radar bands offloading mobile traffic demand. Based on our results and analysis, we concluded that there is a significant number of sharing opportunities for large-scale secondary access to the aeronautical and radar bands from the technical point of view. However, the commercial viability is still not clearly determined given the remaining uncertainties in the total cost and the exact time needed for the relevant technology to become available. Moreover, there is not a single answer to commercial viability since it will most likely depend on the country or region involved, which affects the spectrum availability, which in turn is a critical criterion for business success.

## 4.2   Future Work

The investigations of this thesis centered on the protection of the primary victim and the performance of a single multi-user secondary system. What remains under explored are the technical and regulatory conditions for enabling horizontal sharing among multiple multi-user secondary systems. So far, we have established that one way to facilitate efficient spectrum sharing is by exploiting the presence of geo-location databases. Future work should carefully study how these multiple

secondary systems deployed by potentially different actors with different requirements could effectively share the available spectrum in the aeronautical and radar bands from technical, regulatory and business perspectives.

As a result of our analysis, we identified LSA as a suitable regulatory framework for the aeronautical and radar bands. Given that the definition of LSA is still under development, there is a need to clarify the relevant uncertainties and to identify new responsibilities for all the entities involved in this framework.

Finally, we provided an assessment methodology for country-wide evaluation of spectrum availability for secondary access as well as a methodology for assessing commercial viability which combines technical, regulatory and business aspects. However, business analysis is still in its initial stage. There are still many uncertainties (e.g, technology cost, spectrum access cost) to be addressed before we can proceed to a quantitative evaluation of the business viability, which will lead to more explicit conclusions.

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# Part II

# Paper Reprints

# Chapter 5

# Short Range White Space Utilization in Broadcast Systems for Indoor Environments (Paper 1)

E. Obregon, L. Shi, J. Ferrer and J. Zander. Short Range White Space Utilization in Broadcast Systems for Indoor Environments. In *IEEE Symposium on New Frontiers in Dynamic Spectrum (DySPAN)* 6-9 April 2010.

# Short Range White Space Utilization in Broadcast Systems for Indoor Environments

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*ABSTRACT* – **As Digital Television Broadcasting spreads over the world, existing (and more) TV channels can be distributed in less spectrum in the spectrum traditionally allocated to TV broadcasting. This freed spectrum is also referred to as the "Digital Dividend" and its use has been debated around the world. In addition, there is also a debate about the potential use of the "white space" <u>within</u> the TV-bands. This is due to the sparse frequency planning with large interference margins, which is typical in wide area broadcasting.**

**Various technical approaches using Opportunistic Spectrum Access (OSA) have been proposed for unlicensed "white space" access to the TV bands. Most of previous studies have focused on spectrum sensing, i.e. detecting "free channels", where secondary users, utilizing White Space Devices (WSD) could avoid causing harmful interference to the TV receivers. However, interference caused by WSD is not only limited to co-channel interference. In particular, in short-range scenarios, the adjacent channel interference is an equally severe problem. Assessing the feasibility of WSDs in short-range indoor scenarios, taking more interference mechanisms into account is the objective of this paper.  An Indoor home scenario with Cable, Rooftop antenna and Set-top antenna reception of DVB-T, has been analyzed. The spectrum reuse opportunities for WSDs have been determined, using the number of channels where it is possible to transmit without causing harmful interference to DVB-T receivers as performance measure. Simulation results show that the number of available channels for indoor unlicensed white space transmission appears to be significant in most of the studied scenarios.**

*Key Words: White space, Digital Television Broadcasting, White Space Devices, Opportunistic Spectrum Access*

## I.  INTRODUCTION

The analogue broadcasting system for TV transmission is being replaced by Digital Television Broadcasting (DVB-T) by which the existing TV channels can be reallocated to spectrum portions with less bandwidth. Spectrum freed up due to the switchover from analog to digital terrestrial TV is known as the Digital Dividend. This could allow new wireless services and applications to operate in the free portions of spectrum, bringing enormous social and economical benefits [1]. However, this is not the only opportunity for more effective use of the TV bands. Claims have been made that it is also possible to find temporally unused parts of the TV spectrum, also known as "spectrum holes" or "white space". The latter can be defined as those portions of the spectrum licensed to a primary user, which at a particular time and specific geographic location, are not being utilized and could potentially be temporarily used by secondary users [2].

Actual spectrum usage measurements obtained by FCC's spectrum Policy Task Force suggests that much of the prized spectrum lies idle at any given time and location [3].  To respond to changing demands and technologies, traditional spectrum regulation framework have moved to a flexible market-oriented spectrum regulation  that allows multiple uses of the available spectrum; so new spectrum opportunities can be exploited to meet the needs of users.

The debate about allowing the operation of unlicensed access to (temporarily and locally) vacant channels between DTV transmissions, so called "white space", is currently ongoing. The approach proposed for the access of such White Space Devices (WSD) operating on a secondary basis in this spectrum is Opportunistic Spectrum Access (OSA).  In this approach, the unlicensed devices periodically sense the spectrum in order to detect the presence of DTV signal and adapt their transmissions to avoid mutual interference. The main concern is about the potential harmful interference to the DTV receivers, which are not aware of the WSDs.

Previous studies have used various scenarios and have provided quite diverse results about the feasibility of WSD operation in TV-bands.  In [4], FCC proposed several different approaches for avoiding co-channel interference in occupied TV channels. However, the interference eventually generated to DTV signal reception is not well investigated. The feasibility of secondary users operating in underutilized TV bands is analyzed for outdoor scenarios in [5]. The study done in [6] shows the possibility to exploit OSA for short range radio communication systems within indoor locations in urban areas; this study was conducted to determine space opportunities.

In previous work (e.g. [5],[6]) the feasibility of the operation of WSDs has been assessed based on co-channel interference levels. The interference from a WSD on the same channel as the DTV-receiver is, however, not the only cause of TV-service disruption. In [7], the availability of TV White Space has been quantified for different geographic locations and transmit power of cognitive radio devices. Constraints only on the first adjacent channel were taken into account to determine variations in the TV White Spaces. However, the adjacent channel interference (ACI) should be analyzed for the whole frequency band under study, not only for the first adjacent channel.
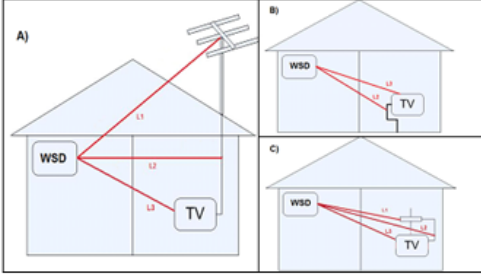
Figure 1 Indoor Scenarios: Rooftop Antenna (A), Cable reception (B) and Set-top Antenna (C). Radiation into the receiver antenna (L1), the cable (L2) and the receiver (L3).
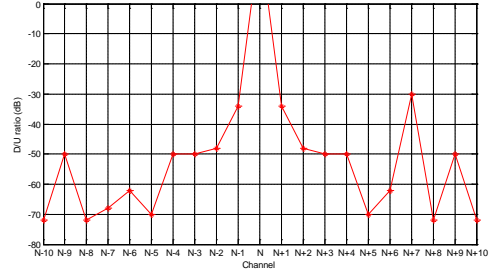


Figure 2 CCI/ACI limits for DVB-T receiver using channel N with typical operating performance [9], Desired to Undesired Received Power (D/U) ratio in dB vs. Adjacent Channel



Figure 3 Apartment plan, TV receiver (square), Active WSD (full circle), Potential WSD locations (empty circle)

A realistic assessment of spectrum opportunities for indoor environments must take into account not only the Co-Channel Interference (CCI) caused by the WSD operation, but also the Adjacent Channel Interference (ACI) and the potential direct radiation into the TV receiver. The tolerance of DTV receivers to Adjacent Channel Interference (ACI) has been quantified in several studies, e.g.[8][9][10], demonstrating that WSD transmission on Adjacent Channel can actually cause harmful interference if the WSD output power exceeds the maximum undesired power received tolerable by the DTV receiver, especially for indoor environments where the distance between the WSD and DTV receiver is short and intermodulation or spurious signals effect could occur. This paper has the objective to use these results to determine the conditions (i.e power level, distance, etc) under which the co-existence of short-range WLAN-type WSD devices and DTV receivers is feasible for indoor environments. The key question is how large part of the TV spectrum is available for these services under realistic interference assumptions. Therefore, we target to find the number of channels available for WSD transmissions in various settings.

## II. METHOLODOGY & SCENARIOS

In this paper, we consider three domestic TV-reception scenarios, where a (distant) broadcast transmitter is received using a DTV receiver (or set-top box). We consider rooftop antenna, set-top (indoor) antenna and a cable-TV reception (see Figure 1). In the same building a short range WSD is used in a WLAN-type application that potentially can cause harmful interference to the TV-receiver. The TV receiver is placed in a fixed location, whereas the WSD is placed at various (random) locations in the model building. The interference is assumed to reach the DTV receiver over there different paths as illustrated in Figure 1:

    a)   Through the antenna (path L1)
    b)   Through the feeder cable /cable TV system (path L2)
    c)   Direct radiation into the TV-receiver (path L3)
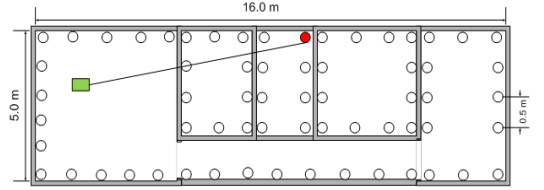
The combined interference power for the three paths is evaluated and compared with the desired signal level. Our ongoing measurements show that the receiver and the feeder cable are sufficiently shielded, thus the interference in path L3 and path L2 can be neglected. In this paper, a very pessimistic assumption is done for the radiation through the feeder cable (path L2) which will be calculated assuming a low quality cable with leakage attenuation ($G_2$).

A channel is considered as "free" or available for WSD transmissions when the Co-channel and Adjacent Channel Interference (CCI/ACI) ratios do not fall below the required desired CCI/ACI limits of the TV receiver. In the study, typical CCI/ACI limits from measurements in [9] have been used (see Figure 2).

The White Space spectrum opportunities are quantified as the number of available channels for WSD transmission ($N_{ch}$). Since, due to the random placement of the WSDs in relation to the TV receiver, this is a random number, we also consider the probability of having zero available channels for WSD transmission ($P_0$). The sensitivity of the performance measures with respect to the WSD transmit power $P_{WSD}$, the separation distance between the TV receiving antenna and the WSD transmitting antenna d and the number of channels used for TV transmission to the TV-receiver in question $N_{TVch}$

**Table 1 Simulation parameters for typical indoor scenario**

| Parameter | Values |
|---|---|
| TV Channel Bandwidth | 8 MHz |
| WSD Max. Transmit Power ($P_{WSD}$) | 100mW / 20dBm |
| WSD Antenna Gain ($G_{WSD}$) | 6 dBi [12] |
| TV Rooftop Antenna Gain ($G_{TV}$) | 7dB |
| TV Set-top Antenna Gain ($G_{TV}$) | 0 dB |
| TV Rooftop Attenuation ($G_1$) | -10 dB |
| TV Set-top Attenuation ($G_1$) | 0 dB |
| TV Cable Attenuation ($G_2$) | -25 dB |
| Building penetration losses | -7dB |
| Wall Attenuation ($W(k)$) | 3.4 dB |
| Slow fading standard deviation ($\sigma$) | 8dB |
| Noise Level ($N$) | -118 dBm |
| Occupied TV Channels | 23, 42, 50, 53, 55, 56 |

## III. INTERFERENCE MODELLING

A DVB-T network in the UHF band[1] is considered as the primary system. The desired received power $P_D$ at the TV receiving antenna will be calculated as follows:

$$P_D = \left(\frac{E^2 c^2}{4\pi Z_0 f^2}\right) . G_{TV} \qquad (1)$$

Where E is the field strength at the TV receiving antenna, $c$ is the light speed; $Z_o$ is the free space impedance, $f$ is the operating frequency and $G_{TV}$ is the antenna gain of the TV antenna. For set-top antenna, we assume an isotropic TV receiving antenna. In the rooftop case, a directional antenna with a gain of 7dB and front to back ratio of 17dB is considered as the TV receiver antenna.

The DVB-T system is designed to provide minimum desired signal level ($E$) of 50dBuV/m in a radius of 25km from the DVB-T antenna transmitter, this field strength is approximately equivalent to a received power of -73dBm for a 75Ω system [9]. The WSD uses the same channel bandwidth as the DVB-T signals, and ideal filtering is assumed for the output signal. WSDs are considered to be fixed in location (their position may however be random).

A single TV receiver is placed a one floor building with 3 apartments, each apartment with a total area of 80m², containing 5 rooms with areas between 8m² and 25m², rooms are separated by concrete walls. The licensed device or DVB-T receiver will be located randomly according to a uniform distribution. Trying to make the scenario under study more realistic, a different deployment scheme for WSDs is used (see Figure 3). The WSDs will be deployed along the walls with a separation distance of 50cm between them. White Space Devices will be randomly activated.
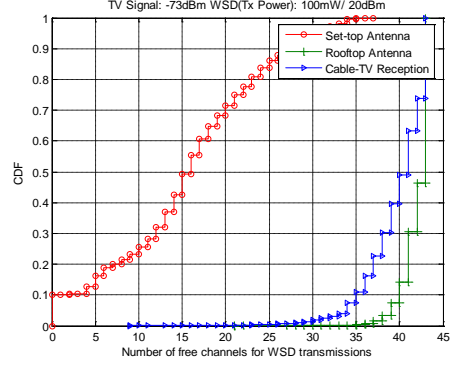
Figure 4 CDF of the number of free channels for WSD transmission, Weak TV signal

### A. Indoor Propagation Model

The path loss, $L$, in the link between the WSD transmitter and DVB-T antenna receiver will be calculated based on [10] where it is proposed an extension of the Keenan Motley (KM) model.:

$$L(dB) = L_f + L_i + L_g + kF(k) + pW(k) + S \qquad (2)$$

Where $L_f$ is the free space path loss, $L_i$ is a linear attenuation factor dependent on the separation distance between the licensed receiver and the WSD transmitter, $L_g$ is the difference between the theoretical and effective gain of the two antennas, 3dB in this case, $F(k)$ is a floor attenuation factor, $W(k)$ is a wall, $k$ is the number of floors and $p$ is the number of walls crossed by the direct path between the WSD transmitter and the DVB-T receiving antenna. Shadowing effect from furniture, people, etc. are modeled by a lognormal shadow fading process $(S)$ with zero mean, standard deviation σ and correlation distance of 5 meters. We consider path L3 as negligible, thus the total undesired received power ($P_u$) will be the sum of the interference powers at the receiver input from each interference path (L1 and L2):

$$P_U = \sum_i P_{U,i} = \sum_i \frac{P_{WSD}.G_{WSD}.G_i}{L} \qquad (3)$$

Where $P_{WSD}$ is the transmit power of the WSD, $G_{WSD}$ is the antenna gain of the WSD in the direction of the TV receiving antenna, $G_1$ is the attenuation in path L1 and $G_2$ is the TV cable attenuation (path L2). A pessimistic assumption is that the WSD antenna is pointing towards the TV receiving antenna.

In the Indoor (Set-top Antenna) case, the received power is lower than the received power in rooftop case, due to the building penetration losses and the low gain of the set-top TV antenna.

Figure 5 Median number of free channels for WSD transmissions vs. WSD transmit power



Figure 6 Median number of free channels for WSD transmissions depending on the separation distance between the WSD and the TV receiver antenna, WSD transmit power: 100 mW/ 20dBm. 90 and 10- percentiles are shown for each scenario.

For the rooftop and set-top scenarios, the radiation into the receiver antenna constitutes the main component in the interf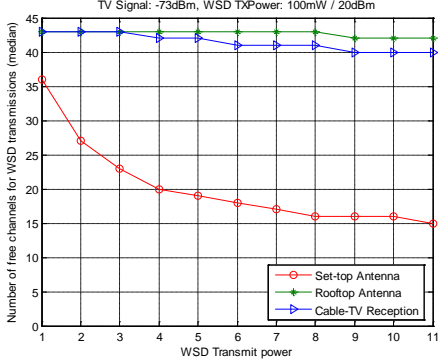erence model. Radiation into the cable will be calculated assuming a low quality cable with leakage attenuation ($G_2$) equal to 25dB. Finally, the Desired to Undesired (D/U) power ratio will be calculated as the ratio between $P_D$ the desired received power (Equation 1) and $P_u$ the undesired received power (Equation 3) at the TV receiving antenna.

$$\frac{D}{U} = \frac{P_D}{P_U} \qquad (4)$$

### IV. NUMERICAL RESULTS

For the simulations, the environment described in section II will be considered a typical home scenario. Table 1 summarizes the most important simulation parameters. It was observed that the intensity of the TV signal does not considerably affect the results. Result simulations will be given for a weak desired

signal and for a medium size city. Stockholm has been taken as example where six TV channels are occupied. Larger cities in Europe, for example London, could have in average eight occupied channels in a specific geographic location [12] [13].

In Figure 4, we note that the location of the TV receiving antenna plays an important role in the number of free channels for unlicensed transmission. The worst scenario is set-top antenna, where the available bandwidth for WSDs is much smaller compared with the other scenarios, rooftop and cable-TV reception. The best scenario is rooftop antenna because of the location and the characteristics of the TV receiving antenna, even if there is only one floor between the WSD transmitting antenna and TV receiving antenna. Cable-TV reception is also a good scenario for unlicensed transmission, due to the attenuation level of the coaxial cable used to deliver the TV signal.
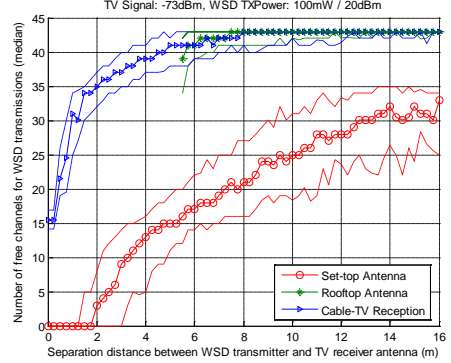
In Figure 5, the effects of the WSD transmit power on the number of available channels for unlicensed transmissions are shown for all scenarios. For Rooftop antenna and Cable-TV reception scenarios, the number of free channels for unlicensed transmission is very high for any values of WSD transmit power. We also observe that the effect of the WSD transmit power is considerable for Set-top antenna scenario. The median available bandwidth for unlicensed transmission considerably decreases when the power increases. This means that the interference caused by the WSD has a more critical effect on the adjacent channels since there is line of sight between the DVB-T receiving antenna and the WSD antenna in many cases, which does not occur in rooftop scenario.

Figure 6 demonstrates that separation distance between DVB-T receiving antenna and WSD transmitting antenna distance has an important effect on the number of free channels for unlicensed transmission for all scenarios. This effect is more noticeable for the first ten meters. The 90 and 10-percentiles for each scenario are also plotted in Figure 6, they show the possible variations with respect to the median number of free channels for WSD transmissions. Larger variations are observed for set-top antenna scenario where the separation distance has a strong effect.

Figure 7 shows how the number of free channels for unlicensed transmission can be affected when multiple TV channels are simultaneously active in a region. In the rooftop antenna and cable-TV reception scenario, the number of channels that are vulnerable to WSD interference is typically 3, the actual TV-channel plus the adjacent channel on either side. This is seen as the number of available decreases linearly with an average of 3 channels per each active TV channel. For the set-top antenna case the number of affected channels by the WSD transmission is much larger as can be seen in the rapid decrease in available channels.
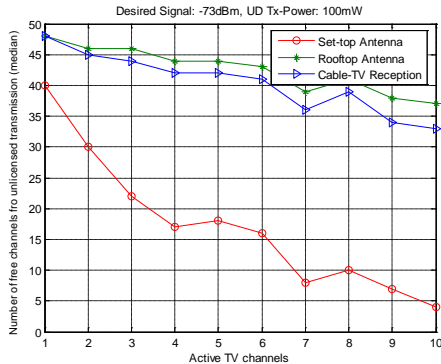
Figure 7 Median number of free channels for WSD transmissions depending on the number of active TV channels



Figure 8 Probability of having zero free channels for different maximum separation distances and for different number of active TV channels

In Figure 8, the probability of having zero available channels in the set-top antenna scenario for different maximum separation distance is shown. WSDs were placed in an area with a radius equal to the maximum separation distance with respect to the TV receiver location. The situation of having zero free channels is only observed in set-top antenna, for other scenarios there is always at least one free channel for unlicensed transmission, even if there are more than one WSD and the maximum permissible power is used. It is possible to observe that when WSDs are located in a radius or maximum separation distances shorter than six meters; the effect of the number of active TV channels can be drastic.

For instance, the probability of having zero free channels when the maximum separation distance is two meters can increase from 24% for one active TV channel until 87% for ten active TV channels. However, considering that the maximum separation distance is sixteen meters; the probability of having zero free channels does not have a drastic increment when the number of active TV channels increases.

## V. CONCLUSIONS AND FUTURE WORK

Based on the assumptions and indoor scenarios considered for this study, indoor unlicensed devices have been able to transmit successfully in the majority of the unused channels in the TV band. We conclude that indoor unlicensed transmission seems to be feasible in the white space without causing harmful interference.

TV Reception with rooftop antennas or cable TV is favorable scenarios for unlicensed transmission because there is always at least one free channel for unlicensed transmission. For these scenarios, there are no placement restrictions for White Space Devices (WSDs) and harmful interference is tolerable for environments with multiple indoor WSDs.
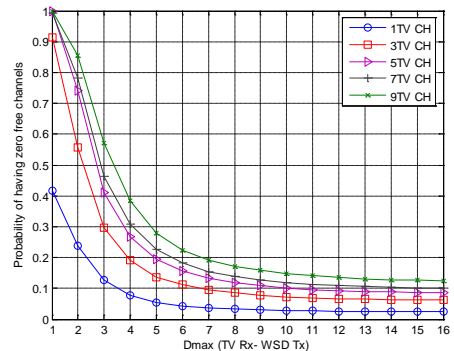
This study has taken as example the city of Stockholm. However for larger cities with more active TV channels, unlicensed transmission seems to be still feasible. TV Reception with set-top antenna is a bad scenario for unlicensed transmission, but still manageable in most cases. The probability of causing harmful interference in the unused TV channels is very high; especially for short separation distance, which means that there is placement restriction for WSDs in order to make feasible their operation.

Future work can extend the analysis of the interference in a multi-floor environment. Other issues to investigate in future works would be the analysis of the spectrum opportunities considering another deployment scheme (i.e. uniform distribution, normal distribution, etc.) and power control in White Space Devices (WSDs).

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# Chapter 6

# Experimental Verification of Indoor TV White Space Opportunity Prediction Model (Paper 2)

E. Obregon, L. Shi, J. Ferrer and J. Zander, Experimental Verification of Indoor TV White Space Opportunity Prediction Model, In *Proceedings of the Fifth International Conference on Cognitive Radio Oriented Wireless Networks & Communications (CROWNCOM)* June 2010.

# Experimental Verification of Indoor TV White Space Opportunity Prediction Model

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*Abstract*—**Recent work has demonstrated that the underutilized spectrum in the Digital Television Bands, commonly referred to as TV White Space (TVWS), is a prime candidate for opportunistic spectrum access (OSA). However, a systematic assessment of the availability of this spectrum for secondary transmission was, until very recently, lacking [5] [6]. In [6] a TVWS opportunity prediction model to estimate indoor secondary usage probability was proposed. In this paper we aim at verifying this model by means of measurement campaigns in both laboratory and real indoor environments. The match between the predictions from the simulation models in [6] and measurement results suggest that the model provides a realistic evaluation of the opportunities in TVWS for low power indoor secondary usage.**

*Key Words: White Space, Digital Television Broadcasting, Opportunistic Spectrum Access.*

## I. Introduction

The constantly increasing need for new wireless services and applications has put the problem of spectrum scarcity in the spotlight. A potential opportunity is the spectrum freed up due to the switchover from analog to digital terrestrial TV, known as the Digital Dividend. However, also it has been suggested that temporally or spatially unused spectrum portions in TV bands, so called spectrum holes or white spaces could be used for other services. The suggestion is that frequencies assigned to the primary users (i.e. TV broadcasters), that are not being utilized in a particular time and specific geographic location, could be temporarily used by secondary users [1] [2].

The debate about allowing the operation of unlicensed access to temporarily vacant channels between occupied DTV channels is still ongoing [1]. Television broadcasters state that operations in the spectrum holes or white space will result in harmful interference to the DTV receivers due to their particular filter characteristics. Industrial and academic studies on the TV White Space claim that unlicensed devices operating (so called White Space Devices, WSDs) in the white space will not affect the quality in the reception of the DTV signal if Co-channel interference is avoided. In such an opportunistic spectrum access (OSA) approach, White Space Devices will periodically sense the spectrum in order to detect the presence of DTV signals and adapt their transmissions to avoid mutual interference.

Previous work on the feasibility of White Space Device (WSDs) operation in different scenarios has given quite diverse results [3] [4].Of critical importance to avoid harmful interference from WSDs are the spectrum sensing techniques, the separation distance between WSD and DTV receiver, the power levels and modulation techniques used by WSDs. Further, some theoretical studies have been done to quantify the real spectrum opportunities in the TV white space [5] [6].

Previous experiments in [7] and [8] have analyzed the interference generated by a DTV or NTSC signal into DTV reception. The interference generated by outdoor WRAN BS into DTV reception was studied in [9], that experiment was limited to the case of a single interferer with high transmit power. Measurements to quantify the interference effects of 3G and WiMAX signals on typical DVB-T receivers were conducted in [10]. The outdoor scenario with two different types of TV receiving antenna, outdoor and indoor antenna, was considered. Generally, these experiments aimed at specifying recommended thresholds or protection level required to guarantee the quality of DVB-T reception. However, the scenario where low power indoor WSDs are transmitting in the close proximity of the TV receiver has to our knowledge not been analyzed in any of the previous experiments.

As the WSDs become very close to the TV receivers in short-range indoor scenarios, it was demonstrated in [6] that not only the co-channel interference is a problem. Due to the limited Adjacent Channel Interference (ACI) rejection capabilities of simple TV-receivers, also the interference on near-by channels has to be considered. When determining spectrum reuse opportunities for WSDs. The interference models used in [6] are partially well-known but also some new assumptions are made, that need experimental verification. The purpose of this work is to verify the assumptions and interference model proposed in [6] by assessing the impact on TVs reception quality when low power WSD interference is operating in different channels in a real indoor environment.

The rest of the paper is organized as follows: section II gives a short introduction of our interference model proposed in [6];in section III, we briefly explain our objectives and approach; section IV explains our measurement setup; section V presents our results from both simulation and measurement as well as our interpretation of the results. Finally, we conclude this work in section VI.

## II. Interference Modelling

Three different indoor scenarios are considered in this paper (See Figure 1). In all scenarios, the primary user is the Digital TV receiving broadcasting signal from either
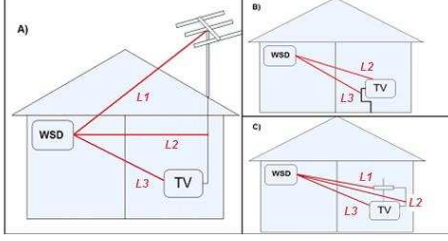
Fig. 1. Indoor Scenarios: Rooftop Antenna (A), Cable Antenna (B) and Set-top Antenna (C) Radiation into the receiver antenna ($L_1$), the cable ($L_2$) and the receiver ($L_3$)

TABLE I
MEASUREMENT PARAMETERS

| | |
|---|---|
| WSD Signal Bandwidth ($W$): | 8 MHz |
| WSD Wireless Interface: | OFDM |
| WSD Modulation Scheme: | QPSK |
| WSD Maximum output power: | 10dBm |
| WSD Duplex Scheme: | TDD |
| WSD Maximum Antenna Gain: | 16 dBi |
| TV set-top antenna 1: panel (Low Directivity) | 4dBi (Main Lobe Gain) 0dB (Back Lobe Gain) |
| TV set-top antenna 2: Yagi (High Directivity) | 8dBi (Main Lobe Gain) −10dB (Back Lobe Gain) |
| TV Rooftop antenna gain: | 6 dBi |
| TV signal: | −55dBm (Strong Signal) −75dBm (Weak Signal) |

antenna or cable. The secondary user or White Space Device (WSD) is a Wi-Fi like low power local broadband access point operating in both spectral and spatial proximity of TV transmission, with the same bandwidth as a Digital TV channel, i.e. 8MHz (Table I).

The proposed interference model in [6] assumes the interference reaches the DTV receiver over three different paths: through the antenna (path $L_1$), through the coaxial TV cable (path $L_2$), direct radiation into the TV-receiver (path $L_3$).The combined interference power for the three paths was evaluated. (See Figure 1).

The desired received power ($P_D$) at the TV receiving antenna for channel $N$ will be calculated as follows:

$$P_D = \frac{E^2 c^2}{4 Z_0 f^2} G_{TV}(\theta_D) \qquad (1)$$

where $E$ is the field strength at the TV receiving antenna, $c$ is the light speed; $Z_0$ is the free space impedance, $f$ is the operating frequency and $G_{TV}$ is the gain of the TV antenna. We assume the incoming TV signal is received in the main lobe of the TV antenna ($\theta_D = 0^o$). The total undesired received power ($P_U$) will be the sum of the interference powers from the WSD transmission (could be operating in a different channel $N+k, k = -3, -2, ..0, ..20$) at the receiver input from each interference path ($L_1$, $L_2$ and $L_3$):

$$P_U = \sum_{i=1}^{3} P_{U_i} = P_{WSD} G_{WSD} \left( \frac{G_1}{Lb_1} + \frac{G_2}{Lb_2} + \frac{G_3}{Lb_3} \right) \quad (2)$$

where $P_{WSD}$ is the transmit power of the WSD, $G_{WSD}$ is the antenna gain of the WSD in the direction of the TV receiving antenna; $G_1$ is the gain of the TV receiving antenna which depends on the incidence angle of the received signal from the WSD which is equivalent to $G_{TV}(\theta_U)$ (path $L_1$); $G_2$ is the TV cable attenuation (path $L_2$) and $G_3$ is the TV receiver attenuation (path $L_3$). The path loss, $Lb$, in each interference path is calculated based on an extension of the Keenan Motley (KM) model [12]. A pessimistic assumption was that the WSD antenna was always pointing towards the TV receiving antenna. The radiation into the receiver antenna constitutes the main component in the interference

model. The direct radiation (EMC effects) into the receiver or interference in path $L_3$ is assumed to be negligible due to its presumed isolation characteristics. Thus, the total undesired received power ($P_U$) can be expressed as follows:

$$P_U = P_{WSD} G_{WSD} \left( \frac{G_{TV}(\theta_U)}{Lb_1} + \frac{G_2}{Lb_2} \right) \qquad (3)$$

Finally, the Desired to Undesired ($D/U$) power ratio on channel $N + K$ was calculated as the ratio between $P_D$, the desired received power (Equation 1) and $P_U$, the undesired received power (Equation 3) at the TV receiving antenna.

$$\frac{D}{U} = \frac{P_D}{PU} \qquad (4)$$

A channel is considered as free or available for WSD transmissions when the $D/U$ ratio does not fall below the required $D/U$ limit of the TV receiver.

### III. EXPERIMENTAL METHODOLOGY

We aim to verify the assumptions and parameter settings in the interference model proposed in [6] by measurement comparing with the simulation results. Based on this knowledge we could further analyze the real opportunity for secondary transmission in TVWS. We will address the following questions:

- Is it enough to account the $D/U$ ratio (Desired to Undesired received power ratio) of neighboring 10 channels? Is the $D/U$ ratio valid as a good reference for estimation of white space opportunities?

- Is the direct radiation in the TV receiver significant? If yes, when is that radiation important? How far should be placed the WSD to make it irrelevant?

- Are the results obtained in [6] comparable to results obtained from experiments carried out in real environments? Our experiments are composed of three main measurements:

1. Calibration– the first measurement will determine the adjacent channel rejection or $D/U$ ratio of our DTV receiver under both strong TV signal level and weak TV signal level conditions And the results will be used as references for the following measurements and simulations;

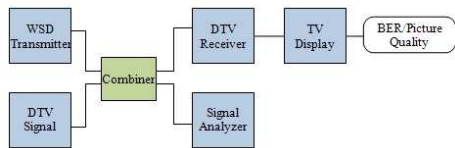2. Verification of the direct radiation impact– the second
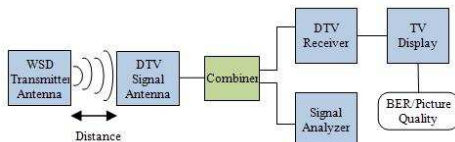
Fig. 2.   Setup for Measurement 1



Fig. 3.   Setup for Measurement 2

measurement aims at detecting the possible effect of the direct radiation into the DTV receiver generated by the WSD, and thus confirm or falsify the assumption in [6] that the interference from $L_3$ is negligible;

3. Validation of the prediction model– the last measurement is conducted in real environment (two different apartments). The measurement results are collected and compared with the simulation results based on the predication model proposed in [6].

## IV. EXPERIMENTAL SETUP

The first measurement has calibration purposes, since we aimed at determining the $D/U$ ratio for acceptable TV reception in the different channel of the TV receivers. Given a fixed DTV signal in channel $N$, we increase the WSD interfering power in channel $N + K$ until the visible deterioration occurs on the TV display. Then the power ratio between the interference and TV signal is the $D/U$ limit on $N + K$ channel. We repeat the experiment with different TV signal levels. The setup used for the first measurement is shown in Figure 2.

The second measurement is carried out in a laboratory environment with high isolation to any external signals. The DTV signal input is connected to the DTV receiver via high quality cables. In this way we isolated the effect of direct radiation into receiver. The WSD interfering antenna is transmitting at maximum output power (20-23dBm EIRP) with varying distance from the TV receiver. Thus, measurement results provide a lower bound approximation.

The third measurement is performed in the two different apartments using setup shown in Figure 3. The WSD antenna is placed randomly in the apartments. In order to create the worst case, the WSD antenna is always directed to the TV receiving antenna (see Table I) and transmitting at the maximum output power. At each location, the WSD operating channel varies along the whole UHF band. If the TV display glitches, then that channel is marked as unavailable for WSD transmission.
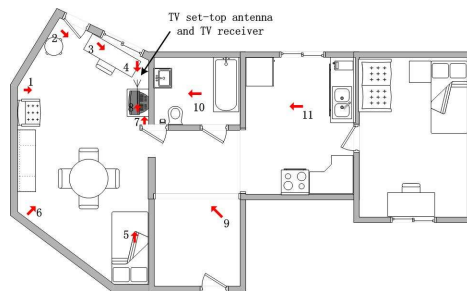


Fig. 4.   Floor plan for Apartment 2 (city center) with red arrows indicating location and direction of the WSD transmitter
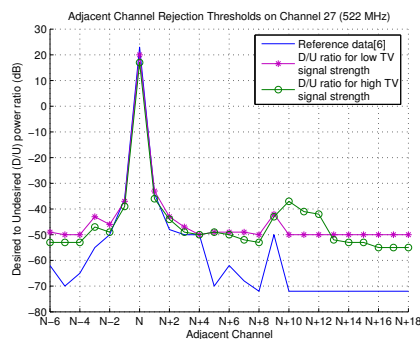


Fig. 5.   Adjacent Channel Rejection Thresholds on Channel 27 (522 MHz) ratio

Apartment 1 is located in a suburban area with weak TV signal strength and Apartment 2 in the city center with strong TV signal strength. Both apartments have an average area of $70m^2$. The floor plan of Apartment 2 is illustrated in Figure 4. We use R&SFSQ 26 as a signal Analyzer and R&SMV 200A to generate WSD interference signal, parameters are shown in Table I.

## V. EXPERIMENT RESULTS

### A. Calibration

From the measurements, we can verify the performance variations for different TV signal strengths. An observation that had also been confirmed in previous studies is the anomalies in adjacent channel $N+9$, which is less noticeable when a receiver with bad performance is tested. In addition, intermodulation effects [9] are observed in channels $N+11$, $N+12$ and $N+13$ for a strong TV signal level. From Figure 5, we can also observe that the receiver used in our measurement campaign can be categorized as a receiver with bad performance, since the $D/U$ thresholds are above the reference level for a regular receiver [7].
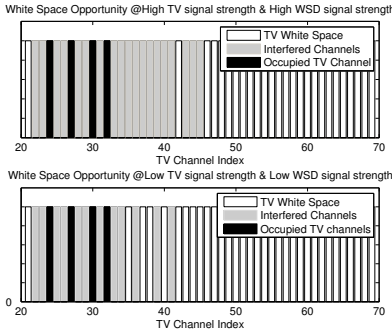
Fig. 6. Illustration of White Space Opportunities in the city of Gävle for different TV signal levels



Fig. 7. Expected Number of available channels for WSD transmissions (low directivity set-top antenna)



Fig. 8. Expected Number of available channels for WSD transmissions (high directivity set-top antenna)

Given the $D/U$ characteristic of TV receivers, we could estimate the TV White Space Opportunities. Figure 6 illustrates the possible opportunities for a typical indoor scenario in an apartment in the City of Gävle, where WSD is operating in the proximity of TV with set-top antenna. There are four channels occupied by the TV broadcasting, so in theory all the other 45 channels could potentially be used for WSD transmission. However, due to the Adjacent Channel Interference, only 70% of the potential free channels can actually be used when we have low interfering power and low TV signal strength. This percentage is further reduced to 55% if strong signals cause intermodulation effect to the TV receiver.

### B. Verification of the direct radiation impact on TV receiver

This experiment was carried out in a lab environment where the isolation is high and external signals are eliminated. The transmitting WSD antenna was moved around in the very close proximity of the DTV receiver, with separation distance in the range of zero to two meters. However, we were not able to notice any distortion on the TV display at any separation distance, even when the TV input signal was attenuated to a very low level and WSD transmitting at maximum EIRP. The assumption of neglecting direct radiation from the WSD into the receiver (path $L_3$) could thus be verified. In addition, noticeable interference through the cable feeder (path $L_2$) was not observed in any case.

### C. Validation of simulation results

We counted the number of available channels for WSD transmission with different type of TV signal receiving setups. (Rooftop, Cable, Set-top) in both apartments. The results indicates severe co-channel interference for all configurations, thus co-channel transmission should be avoided. But we also noticed there are no harmful adjacent channel interference for cable and rooftop antenna scenarios, due to the high isolation of the cable and high pathloss between WSD antenna and TV rooftop antenna. For the case of set-top antenna, WSD
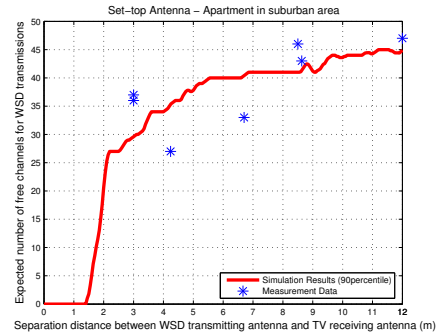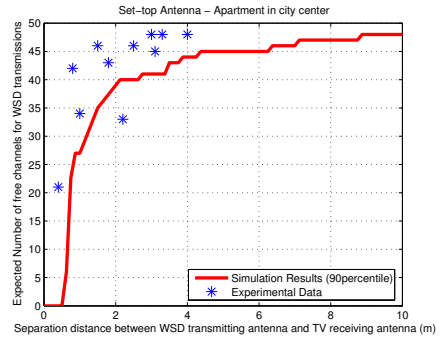
transmissions could cause harmful interference to TV signal not only when the WSD is transmitting in the first adjacent channels ($N + 1$ and $N - 1$), but also when the transmitting channel of WSD is far away in frequency from the channel used by the TV broadcasting (channel $N$).

From Figure 7, we notice that for Set-top antenna, adjacent channel interference causes distortions to TV signal, especially for short separation distances. In comparison, with a high directivity TV set-top antenna and higher TV signal strength (Figure 8), the number of available channels for WSD increases even at shorter separation distance. Previous studies [6] have analyzed the effect of the WSD transmit power on the the number of available channels, their results demostrated that decreasing the WSD transmit power can actually increase the number of available channels for set-top antenna, however adjacent channel interference is still an important issue even for very low WSD transmit power.

As for the allocation of the available channels, we define
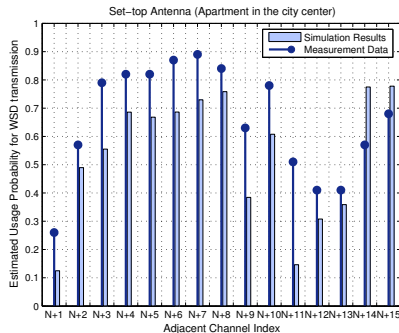
Fig. 9. Estimated Usage Probability for WSD transmission in each adjacent channel

the Expected Usage Probability of each adjacent channel as the probability that the WSD transmission on one adjacent channel will not cause severe interference to the TV reception in set-top antenna scenarios. We estimate this probability with the ratio between the number of experiments with successful reception and the total number of experiments, where the WSD transmitter is uniformly placed along the wall of the apartment. From Figure 9, it can be seen that the WSD transmissions on $N+1, N+2$ and $N+9$ will be most likely to affect the TV reception in both simulation and measurement. In addition, the possible intermodulation between WSD signal and strong TV signals in other broadcasting channels would also lower the Usage Probability in channel $N+11, N+12$ and $N+13$. (Channels with index larger than $N+15$ is not shown, since usage probability remains above 90%). In all the figures above, the measurement results match the numbers we obtained from simulation, which was adjusted according to the real environment and the characteristic of the particular receiver. The simulation results are more pessimistic due to the worst-case assumptions in our prediction model, but they can be used as lower-bound reference.

## VI. Conclusions

In this paper we have evaluated a prediction model for assessing the TV white space availability through a series of measurements in both laboratory and real environments. In general, we have demonstrated that the assumptions and parameter settings of the model proposed in [6] are reasonable and the overall performance predicated by the model matches to our measurement results.

In particular we have confirmed that the direct radiation from WSDs into cables and the TV receiver set-top box can be neglected. For cable-TV or roof top antenna reception, adjacent channel interference was not severe and it is possible to use WLAN-like low power indoor WSD in almost any

vacant TV channel without any noticeable effects on the TV reception quality. However, when an indoor, set-top antenna is used for TV reception, our measurements have verified that the number of available channels for WSD is significantly reduced, due to adjacent channel interference. Strong ACI causes intermodulation products between the signals from the WSD and other TV broadcasting channels. To achieve acceptable results for WSD, lower power than typical Wi-Fi devices or careful placement has to be employed.

Further work includes studies of a more realistic scenario with multiple WSDs simultaneously operating in different frequency channels in TVWS. Also the cumulative effect of multiple WSD interference to the TV receiver performance is of interest to provide a more comprehensive assessment of the opportunities in TVWS.

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## Chapter 7

# A Model for Aggregate Adjacent Channel Interference in TV White Space (Paper 3)

# A Model for Aggregate Adjacent Channel Interference in TV White Space

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*Abstract*—**The presence of white spaces and spectrum holes in the TV bands represents potential opportunities for alleviating the apparent spectrum scarcity. Opportunistic spectrum access (OSA) has been proposed for the secondary user's operation and the main concern is the harmful interference that secondary systems could cause to the primary receivers. Existing studies have focused on establishing the limits for co-channel and adjacent channel interference when only one adjacent channel is used by a single secondary user. This paper presents a characterization of the aggregate adjacent channel interference (AACI) when different adjacent channels are simultaneously accessed by multiple secondary users or white space devices (WSDs). An analytical expression is proposed to approximate the limits of the tolerable AACI. Our model states that not only the interference received in each adjacent channel should stay below the corresponding threshold for that particular channel, but also the weighted sum of the total adjacent channel interference power should be kept below a certain threshold. Measurement campaigns show the cumulative effect of the adjacent channel interference (ACI) when multiple WSDs access multiple adjacent channels at the same time. The proposed analytical expression for AACI closely matches the measurement results.**

*Index Terms*—**White Space, Opportunistic Spectrum Access, Adjacent Channel Interference, Measurements**

## I. INTRODUCTION

The growing demand for higher data rates for existing services and the need for new wireless services has led to an apparent shortage of the available spectrum. However, studies have shown that the spectrum is mostly underutilized due to the regulatory and licensing process that limits the possibility to access the available spectrum [1] [2]. An example of underutilized spectrum band is the TV broadcasting band, where we can find white spaces or portions of spectrum not used in a specific region [3]. Due to its favorable propagation properties and the presence of white spaces or spectrum holes, TV frequency band can be considered as a good candidate for opportunistic secondary usage [4].

A WSD uses OSA to dynamically access the TVWS. This means that a WSD should detect the presence of the Digital TV (DTV) signal and adapt its transmission parameters to avoid harmful interference to the DTV receivers. Since the main concern regarding the access to the TVWS is the potential harmful interference that those secondary users could cause to the DTV reception, it is important to the determine maximum tolerable interference at the DTV receivers. Due to the limited ACI rejection capabilities of commercial DTV receivers, not only Co-Channel interference (CCI) but also

Adjacent Channel Interference (ACI) should be taken into account when analyzing the potential harmful interference generated by the WSDs [5] [6] [7].

Previous studies have established the required threshold of desired-to-undesired power (D/U) ratio for CCI and ACI when there is only one WSD accessing a single channel [8] [9] [10] [11]. However, the threshold for the maximum tolerable received interference at the DTV receiver when different channels in the TVWS are simultaneously accessed by multiple WSDs has not been addressed yet. Fig. 1 illustrates a multi-ACI scenario where the DTV signal is transmitted in channel $N$ and the DTV receivers experience interference in different adjacent channels ($N+k, N+j$) simultaneously used by different WSDs.

This work aims at determining the limitations on the ACI in a multi-ACI scenario. Therefore, we focus on the following uncertainties:

- How can multiple WSDs accessing different adjacent channels affect the maximum permissible interference that an adjacent channel can tolerate without causing harmful interference in the DTV receivers?
- How to establish limits or constraints for the interference generated by multiple WSDs accessing multiple adjacent channels? Is there an aggregate interference effect?

In this paper, we verify by measurements the aggregate adjacent channel interference (AACI) when multiple WSDs access different vacant TV channels. Our measurement campaigns show that it is not sufficient that interference received in each adjacent channel fulfills the required threshold desired-to-undesired power (D/U) ratio to avoid harmful interference to the DTV reception. Instead, the weighted sum of the power of all adjacent interferers or equivalent co-channel interference should be kept below a certain threshold. An analytical expression is proposed to approximate the limit or threshold for the maximum tolerable AACI to avoid any distortion in the DTV reception.

The rest of the paper is organized as follows: a summary of the related works is presented in section II. Section III shows the proposed model for aggregate adjacent channel interference; in section IV, we briefly explain our proposed approach and main components of our measurement setup; section V presents the effect of the AACI as well as the comparison between the proposed model and our measurement results. Finally, we present our conclusions in section VI.
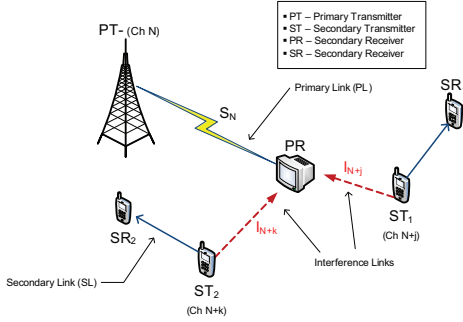
Fig. 1.   Multi Adjacent Channel Interference scenario



Fig. 2.   Adjacent Channel Rejection Thresholds on Channel 27 (522 MHz) ratio or threshold D/U ratios ($\gamma_k$) for a particular DTV receiver

## II. RELATED WORK

Previous measurement campaigns have quantified the effect of a single DTV signal, 3G or WiMAX interferer signal on typical commercial DTV receivers. They focused on characterizing the ACI rejection capabilities of the DTV receiver in terms of the required D/U ratios to avoid harmful interference to the DTV reception [8] [9] [10].

The quantification of the available white space for cognitive radio in TV bands has been done in [4] [12]. These studies show that when adjacent channels are also protected, the number of white space channels considerably drops. The importance of the ACI when evaluating the real number of opportunities for short-range secondary system has also been shown in [6] [7]. Both studies suggest that even if the devices operating in a vacant TV channel are low-power, energy leakage to adjacent channels could cause harmful interference to the DTV receiver. Consequently, constraints regarding the power and spectrum allocation are given for the WSDs. All previous mentioned studies considered a single interferer or single WSD accessing one vacant TV channel. However, in a realistic scenario, many secondary systems could access different adjacent channels at the same time.

In [13], the authors suggest that multiple low-power secondary users behave as a single high-power user. This applies when they all are using the same frequency. Nonetheless, in the multi-ACI scenario we proposed, WSDs have different transmit powers and operate in different frequencies. Thus, WSD's transmit powers cannot be simply summed up and treated as one high-power interference.

An analysis of the effect of cumulative interference generated by multiple secondary users is presented in [14]. In this work, the authors generalized their results and proposed a generic formula to calculate the keep-out region for a typical deployment and for a variety of technologies. In [15], a strategy to control the aggregated interference at the primary receivers and maintain it under a given threshold is proposed. Only CCI is considered in [14] [15] and limitations regarding the ACI to the primary receivers are not clearly detailed.
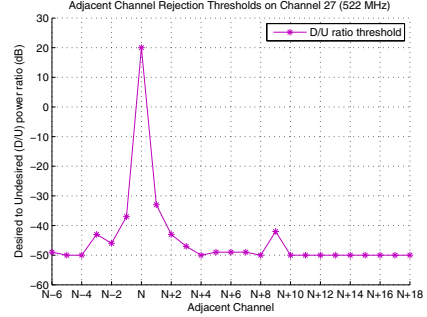
Therefore, we consider relevant to have a deeper understanding of the required thresholds or protection ratios for the ACI in real scenarios with multiple WSDs simultaneously using different adjacent channels.

## III. MODEL FOR AGGREGATE ADJACENT CHANNEL INTERFERENCE

### A. Single adjacent channel interference

In previous studies of ACI, when only one adjacent channel is being used by a secondary user, the threshold D/U ratio is determined to characterize the TV receiver's performance in presence of CCI or ACI. The primary signal is received in channel $N$ and a WSD accesses one adjacent channel $N + k$ at a particular time. In our work, we assume that WSDs have fixed channel bandwidth which is the same as DTV signal channel bandwidth. We define $\gamma_k$ as the required threshold D/U ratio in channel $N + k$ for successful DTV signal reception.

$$\frac{S_N}{I_{N+k}} \geq \gamma_k \tag{1}$$

where $S_N$ is the received TV signal power in channel $N$ and $I_{N+k}$ is the received interference power in channel $N + k$. When $\gamma_k$ and $S_N$ are known for a particular TV receiver, then we can find the maximum interference power that can be tolerated in a certain adjacent channel.

For CCI, the required threshold D/U ratio ($\gamma_0$) for sufficient quality in the DTV reception is given by (2), where $I_N$ is the received co-channel interference power.

$$\frac{S_N}{I_N} \geq \gamma_0 \tag{2}$$

Our measurement results for $\gamma_k$ are shown in Fig. 2. These values are valid for a particular commercial receiver. However, the behavior with respect to CCI and ACI shown in Fig. 2 is representative of many other DTV receivers. In fact, the authors in [11] tested different DTV receivers and got

results similar to ours. Therefore, the results shown in Fig. 2 can be taken as a good reference for analyzing the AACI.

### B. Multiple adjacent channel interference

For the case of multiple adjacent channels used by secondary users, we assume that there is an aggregate effect due to the interference received in different adjacent channels. This assumption was verified in the measurement results: we observed a linear decrement of the maximum tolerable interference in an adjacent channel when we increased the number of adjacent channels used by WSDs.

*Definition:* The *equivalent CCI* $(\hat{I})$ is the co-channel interference that would result in the same effect as the aggregate interference experienced in multiple adjacent channels $I_{N+k}$, i.e. the DTV reception quality is sufficient if :

$$\frac{S_N}{\hat{I}} \geq \gamma_0 \qquad (3)$$

*Proposition:* We propose that $\hat{I}$ is estimated as:

$$\hat{I} \approx \sum_{k \neq N} I_{N+k} \frac{\gamma_k}{\gamma_0} \qquad (4)$$

where $\gamma_k$ values are considered as a weighting factor for the sum of the interference $(I_{N+k})$ experienced in all adjacent channels. When there is no secondary user causing interference in adjacent channel $N + k$, then $I_{N+k} = 0$. $\gamma_k$ can be considered as a linear approximation of the TV filter's characteristics, since it characterizes DTV receiver's co-channel and adjacent channel rejection capabilities. When WSDs have different channel bandwidth, we need to obtain new values for $\gamma_k$. However, our methodology would still be applicable to determine maximum AACI that a DTV receiver can tolerate.

By replacing (4) in (3), we can give an approximation of the upper bound power levels for interference coming from multiple WSDs accessing multiple adjacent channels.

$$\sum_{k \neq N} I_{N+k} \gamma_k \leq S_N \qquad (5)$$

The proposed relation between the weighted sum of the power of the interferers transmitting in different adjacent channels at the same time and the power of the desired TV signal is shown in (5). The weighted sum of the total received interference should be kept below the received desired power level $(S_N)$ in order to avoid harmful interference to DTV receivers.

### IV. EXPERIMENTAL METHODOLOGY

The measurement campaign was carried out in a laboratory environment with high isolation characteristics. A WSD interference signal is generated using R&S SMU200A[1] and the TV signal is received using an outdoor antenna.

[1]R&S SMU200A Vector Signal Generator. Data sheet available in http://www2.rohde-schwarz.com/file_8104/SMU_dat-sw-en.pdf.
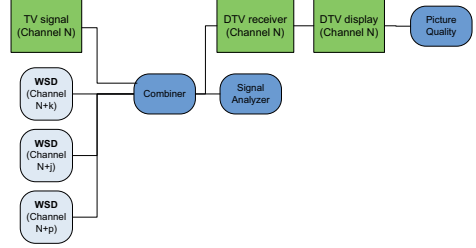


Fig. 3.   Measurement Setup

Table I shows important parameters used in the measurement campaign. Also, the measurement setup is shown in Fig. 3. It is important to mention that WSD interference is directly connected to the DTV receiver through loss-less cables, thus the received interference power at the DTV receiver in channel $N + k$ $(I_{N+k})$ can be expressed as follows:

$$I_{N+k} = P_{W_k} - L - K \text{ dBm} \qquad (6)$$

where $P_{W_k}$ is WSD's transmit power in channel $N + k$, $L$ is the propagation path loss and $K$ are the losses due to the cables and combiners. Since we are working in a laboratory environment, $L$ is not considered and $K$ is constant.

The methodology to determine the existence of AACI is as follows:

  i. We consider that multiple adjacent channels are simultaneously used by multiple WSDs.
 ii. Vacant TV channels or adjacent channels are randomly selected for WSD transmissions.
iii. We use $\gamma_k$ values to set the maximum permissible interference that a WSD can generate at the DTV receiver $(I_{N+k})$ in the selected adjacent channels. $\gamma_k$ values were measured considering single WSD accessing one adjacent channel. Measurement results for the $\gamma_k$ are shown in Fig. 2.
 iv. In case that any distortion is observed in the DTV signal, we decrease the WSD interference until the quality of DTV reception was acceptable.
  v. Finally, we recorded the received interference power from the WSD at the DTV receiver that guarantees not harmful interference to the DTV receivers $(\hat{I}_{N+k})$.

In the case where there is AACI effect, $\hat{I}_{N+k}$ should be lower than $I_{N+k}$. Moreover, the relation between the different WSD's maximum allowable interference at the DTV receiver should be correctly described by (5).

In our measurement campaign, our main objective was to verify or falsify the proposed model for AACI when different adjacent channels are acccessed by multiple WSDs at a given time. Based on the results, we aim at providing new constraints for realistic performance evaluation of secondary systems operating in the TVWS.
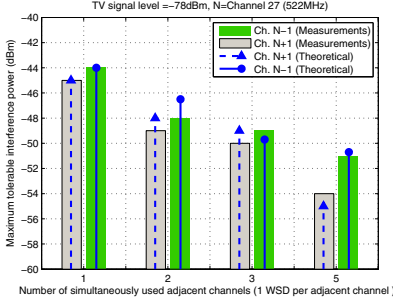
Fig. 4.   Maximum Interference Power Level that a certain adjacent channel can tolerate vs. the number of adjacent channels simultaneously used by WSDs



Fig. 5.   Relation between the maximum received interference power level in channel X and the maximum received interference in Channel N-1



Fig. 6.   Comparison between the safe region without AACI and safe region with AACI

## V.  Results

In this section, we present our measurement results which show how tolerable interference level in a particular adjacent channel reduces when multiple WSDs access different adjacent channels at the same time. Also, we compare the proposed model for AACI and our measurement results. Finally, the impact of the aggregate effect of the interference received in multiple adjacent channels is verified. Measurement results were obtained following the methodology described in section IV. Theoretical results were obtained by using the proposed AACI power constraint for multiple WSDs accessing multiple adjacent channels.

Fig. 4 illustrates how the maximum permissible received interference power in each adjacent channel linearly decreases when we increase the number of adjacent channels simultaneously used by WSDs. Therefore, the WSDs should reduce their transmit power or increase their distance from the DTV receiver in order to keep sufficient quality for the DTV reception.

Since $\gamma k$ varies for each adjacent channel, the DTV receiver can tolerate different amount of interference depending on which adjacent channel is selected for WSD transmission. Thus, the maximum permissible WSD's transmit power will depend on the channel selection. A suitable channel allocation method for WSD operation may help to decrease the effect of AACI on the performance of the primary receivers and increase the opportunities for secondary users.    In Fig. 5, we show the relation between the maximum permissible received

interference power level in two different adjacent channels when both are simultaneously used for WSD transmissions. Also, a comparison between measurements and theoretical results is depicted in Fig. 5.

We could observe that when the received interference power in one of the channel increases, then the received interference power in the second channel should be reduced to avoid harmful interference to DTV receivers. Measurement results support the premise that ACI generated in different adjacent channel cannot be treated separately, so what actually matters to avoid harmful interference is that the equivalent sum of the received interference in different adjacent channels is kept below a certain threshold. The proposed model in section III well describes the inter-relation between the maximum received interference powers in different adjacent channels observed in the measurement results.

Finally, the aggregate effect of ACI or AACI can be clearly seen in Fig. 6. We define a *safe region* as an area where the interferers or WSDs can take any value for their maximum interference that they can generate at the the DTV receivers without causing harmful interference.

Fig. 6 shows two different safe regions when two different

### TABLE I
### MEASUREMENT PARAMETERS

| | |
|---|---|
| WSD Signal Bandwidth ($W$): | 8 MHz |
| WSD Wireless Interface: | OFDM |
| WSD Modulation Scheme: | QPSK |
| WSD Maximum output power: | 10dBm |
| WSD Duplex Scheme: | TDD |
| TV Rooftop antenna gain: | 6 dBi |
| Combiner Loss: | 6 dB |

adjacent channels are used by WSDs at the same time. Safe region 1 applies when there is no AACI or no aggregate effect in interference received in the adjacent channels, so WSDs could generate any level of interference within the safe region 1. However, we found that there is an inter-relation between the ACI received in two different adjacent channels. In this case, the maximum allowable interference power that each WSD can generate is considerably reduced and limited within safe region 2.

## VI. CONCLUSIONS

In this paper we present a characterization of the AACI when different adjacent channels are simultaneously accessed by multiple WSDs.

From our measurement campaigns, we observed how the maximum permissible received interference power in each adjacent channel linearly decreases when we increase the number of adjacent channels used by WSDs. Our measurements also indicate that there is an aggregate effect for the ACI received in different adjacent channels accessed by multiple simultaneous WSDs. Thus the weighted sum of the total received interference power in the adjacent channels or the equivalent co-channel interference should be kept below a certain threshold. This means that even if individual received interference power generated by each WSD in a particular channel stays below its threshold D/U ratio, the WSD transmissions in multiple adjacent channels could still cause harmful interference to the DTV reception.

We proposed a model for the maximum AACI that a DTV receiver can tolerate without experiencing any degradation in the quality of the DTV reception. This model shows a good agreement with the measurement results.

Future work can incorporate video quality metrics to improve the accuracy of measurement results. In addition, it can also include a more comprehensive assessment of the opportunities for secondary systems in the TVWS when AACI is taken into account. The performance evaluation of secondary systems under the AACI constraint needs as well to be addressed.

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# Chapter 8

# On the requirements of Secondary Access to the 960-1215 MHz Aeronautical Band (Paper 4)

# On the Requirements of Secondary Access to 960-1215 MHz Aeronautical Spectrum

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*Abstract*—In this paper, we investigate the spectrum sharing requirements of secondary access to 960-1215 MHz band which is primarily allocated to aeronautical usage. Primary system of interest is distance measuring equipments (DME) aiding navigation of airplanes. We consider a scenario where indoor femtocells share the spectrum as secondary users. For the protection of the primary system, each secondary user decides whether to transmit or not depending on an interference threshold established by a central network. We provide a simple mathematical framework for analyzing the aggregate interference generated by multiple secondary users spreading in a large area. Requirement for the secondary access is established in terms of the size of exclusion region depending on the density of secondary users. Numerical results suggest the use of adjacent DME channel is required for a dense deployment of the secondary users. We discuss the challenges and implementation issues of practical secondary access, and suggest the directions of further research.

*Index Terms*—Secondary spectrum access, aeronautical navigation, distance measuring equipment, aggregate interference

## I. INTRODUCTION

The explosive growth of wireless and mobile services has made radio spectrum a scarce resource. However, the results of measurement campaigns indicate that the spectrum is mostly under-utilized under the current regime of static spectrum allocation [1], [2]. It is widely accepted that the discrepancy between the apparent spectrum shortage and the actual usage is due to the regulatory and licensing rules that limit the flexibility of spectrum utilization. This opens up a new paradigm of secondary spectrum access which stems from the concept of cognitive radio [3], [4]. The secondary spectrum access allows secondary users to share the spectrum allocated to primary (legacy) users provided that the secondary users do not cause harmful interference to the primary users. Potential primary users are not only mobile communication networks but also the systems of various purposes and characteristics, e.g. digital TV, radar, and aeronautical equipments [5].

There have been extensive studies on the secondary spectrum access in recent years. Achievable channel capacity and rate region for secondary users were analyzed in [6], [7]. In [8], the impact of spectrum sharing techniques was evaluated. Temporal aspect of the secondary access was studied in [9]–[11]. A review of spectrum sensing techniques was presented in [12]. A survey describing basic definitions and challenges of opportunistic spectrum access can be found in [13]. However, it is pointed out in [14] that little research has been done

to assess the practical availability and real-life benefit of the secondary access. Quantification of the usable TV spectrum in the UK and the USA was addressed in [15] and [16], respectively. In [17], opportunity of indoor usage was studied considering adjacent channel interference to TV receivers. So far, most of the efforts have been devoted to assessing the value of TV white spaces in 470-790 MHz. This necessitates the investigation on the feasibility and the business opportunity of secondary access to other primary frequency bands

One of the spectrum bands to be examined is 960-1215 MHz primarily allocated to aeronautical navigation systems [18]. This frequency is mostly occupied by distance measuring equipment (DME) system. The DME has been used as the navigation aids of aircrafts for several decades [19], [20]. It operates via long range communications between airborne equipments and ground stations. The susceptibility of DME equipments to interference can be found in [18], [21]. The impact of onboard electronic devices to DME performance was investigated in [21], [22]. In [23], interference from UMTS cellular base stations in nearby frequency band was studied. To our best knowledge, the secondary access to the spectrum allocated to the DME has not been investigated in the literature.

In this paper, we investigate the secondary access to 960-1215 MHz. We consider the aeronautical DME to be the primary system. Since the DME system performs a functionality concerning safety-of-life, the protection of DME from harmful interference is of crucial importance in any potential secondary usage. We choose indoor femtocells attached to a central network as the secondary users because the low transmission power of the femtocells and building penetration loss can provide better protection to the DME compared to outdoor usage. On the other hand, a large number of secondary users spreading in a large area around the DME equipments makes the control of aggregate interference a major challenge of this scenario.

The purpose of this study is to address the following questions:

- What are the requirements for multiple secondary users to protect the DME system?
- How many secondary users can share the spectrum under the requirements?

Answers to the questions will provide a basis of future studies on the viability of the secondary access to DME spectrum.
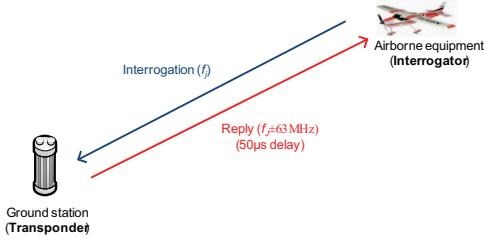
Fig. 1: Basic operating principle of DME

We consider a single DME channel and examine the requirements in terms of the size of exclusion region where the secondary transmissions are not allowed. The relationship between the exclusion region size and the maximum density of the available secondary users in the outside of the exclusion region is also explored. We assume that the secondary users have accurate knowledge of propagation loss to the primary user. This assumption enables us to find out the minimum requirements for the secondary access although it is difficult to realize in practical scenarios. Based on the assumption, a simple interference control scheme is considered that maximizes the number of the secondary users. We adopt simple mathematical models describing the aggregate interference from multiple secondary users to the DME system.

The rest of the paper is organized as follows: In Section II, the system model is described. The operation and protection threshold of DME are explained and the secondary access scenario is introduced. Then, the mathematical models of aggregate interference are derived in Section III. Numerical results are presented in Section IV. Discussions on the challenges and remaining issues are followed in Section V. Finally, conclusions are drawn in Section VI.

## II. SYSTEM MODEL

### A. Basic operation of DME

DME is a secondary radar used for measuring the distance between an airborne equipment (interrogator) and a ground station (transponder). Fig. 1 illustrates the basic working principle of the DME. The airborne equipment sends an interrogation signal down to earth. Then, the ground station responds on a frequency of +63 or -63 MHz from the interrogation frequency after a delay of 50 micro seconds ($\mu$s). The airborne interrogator can determine the slant range between the ground transponder and itself based on the round trip delay of the signal. The interrogator and the transponder exchange short Gaussian pulses with the duration of 3.6 $\mu$s. However, their transmission power reach up to 300 W for the interrogator and up to 2 kW for the transponder [20]. More detailed operation of DME can be found in [19], [20].

The frequency band allocated for DME operation is 962-1213 MHz as shown in Fig. 2. The channel bandwidth of DME is 1 MHz, i.e. there are 252 channels in total. Interrogators

and transponders are allotted 126 channels each. The DME system uses two different operational modes, namely X and Y. Frequency planning according to the mode is illustrated in Fig. 2. The figure also shows that some of frequencies are shared by other aeronautical systems. Upper part of the spectrum (1164-1215 MHz) is planned to be used by the European radio navigation satellite system (RNSS) Galileo. Due to the ubiquitous locations of potential receivers and the low receiver sensitivity, this spectrum is expected to be infeasible for the secondary access. In the rest of the band, the most of the spectrum is allocated solely to DME. Thus, we limit the scope of this study to the portion of spectrum allocated only to the DME system. Secondary spectrum sharing with other systems is not interesting from the business perspective because they account for only a fraction of spectrum which is not enough for broadband services. The bandwidth of interest is then about 180 MHz out of 252 MHz in the frequency band.

Ground transponders are located at fixed locations, mostly near airports. A 1 MHz channel is allocated to each transponder. A ground transponder can serve up to around 100 airplanes at the same time. If it receives too many interrogations, the transponder decreases its sensitivity so that the weakest interrogations get ignored. The theoretical operation range of a DME transponder-interrogator pair can be up to 250 nautical miles [19].

### B. Protection of DME

We define $A_{thr}$ as the maximum aggregate interference power that the DME equipment can tolerate. The value of $A_{thr}$ for the airborne interrogator is specified as -99 dBm/MHz in [18]. It is derived from the carrier to interference ratio (CIR) threshold of 16 dB under the receiver sensitivity of -83 dBm [21]. Notice that this threshold represents the worst case, i.e. the airplane operates at the maximum DME link range. As the airplane gets closer to the ground station, it will be able to tolerate more interference.

Interference tolerance of the ground transponder is not available in literature. We employ 8 dB lower threshold to the transponder because the receiver sensitivity of the transponder is known to be about 8 dB better than that of the interrogator. Unlike the interrogator, the worst case assumption is reasonable to the transponder because it can serve many airplanes at the same time, and thus there is a high probability of having an airplane near the maximum range.

In a previous study about interference from UMTS base stations in 925-960 MHz, additional margin of 12 dB was used by considering a safety margin of 6 dB and by assuming that the UMTS accounts for 25% of total interference, i.e. apportionment margin of 6 dB [23]. We adopt the same amount of the margin. Table I summarizes the protection thresholds of the airborne equipment and the ground station.

Note that the aforementioned thresholds are applied to the co-channel usage. If the secondary users employ adjacent DME channels, higher interference is allowed to the secondary users because the interference power attenuates as it goes through the spectrum mask of the primary user. The impact
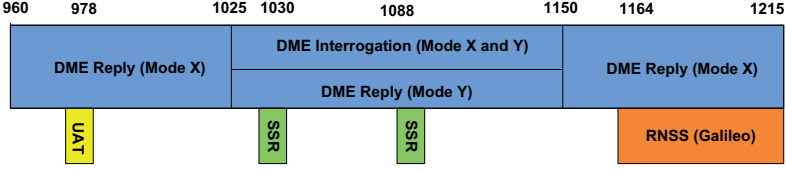
Fig. 2: Frequency allocation to civil aeronautical systems in 960-1215 MHz

TABLE I: Protection threshold of DME

| Parameter | Value |
|---|---|
| Receiver sensitivity of airborne interrogator | -83 dBm/MHz |
| Receiver sensitivity of ground transponder | -91 dBm/MHz |
| Minimum required CIR | 16 dB |
| Safety margin | 6 dB |
| Apportionment of secondary interference | 6 dB |
| $A_{thr}$ for airborne interrogator | -111 dBm/MHz |
| $A_{thr}$ for ground transponder | -119 dBm/MHz |

of the adjacent channel attenuation on the requirements will be examined in Section IV.

Let $I_a$ be the aggregate interference that the primary user receives from the secondary users. The interference is regarded acceptable if

$$\Pr\left(I_a \geq A_{thr}\right) \leq \beta, \tag{1}$$

where $\beta$ denotes the maximum allowed probability of harmful interference [24], [25]. It should be noted that $\beta$ does not necessarily mean DME link failure rate. Instead, it means that the interference exceeds the interference threshold with the probability of $\beta$. In practice, $A_{thr}$ is usually chosen in a conservative manner. Thus, actual interruption to DME will be much lower than $\beta$ depending on the protective margin. A value of 0.01 is used for $\beta$ throughout this paper.

*C. Secondary access scenario*

We consider a secondary use case where indoor femtocells provide short range broadband services. The distance between a mobile station and a femto base station is negligible compared to communication range of the DME pair. Thus, each femtocell network can be regarded as a single secondary user by assuming the same transmission power for the mobile station and the femto base station. It is assumed that the secondary system employs the OFDM technology. Thus, the use of some specific DME channels can be effectively avoided if necessary. For simplicity, the secondary users are assumed to have a fixed transmission power per MHz.

Let us consider a DME channel $k$. We assume that secondary users have an accurate knowledge of propagation loss to the primary user. In order to protect the primary user from detrimental interference, some of the secondary users may not be allowed to use the channel $k$. We consider a simple interference regulation scheme that resembles a mechanism employed by IEEE 802.11h compliant devices for the secondary access to radar spectrum [26], [27]. We introduce an interference threshold $I_{thr}$. The threshold is applied to each individual secondary user such that the access to the channel $k$ is not allowed if the secondary user will generate higher interference than $I_{thr}$.

Let us assume an arbitrary secondary user $j$, and let $\xi_j$ be the interference that the primary user will receive from the user $j$ if the transmission is made regardless of $I_{thr}$. We also define $I_j$ as the interference actually coming from the user $j$. The interference $I_j$ is regulated such that

$$I_j = \begin{cases} \xi_j, & \xi_j \leq I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

The primary user is affected by multiple secondary users spreading in a large area and transmitting simultaneously. Assume that there are $N$ secondary users that want to transmit on the channel $k$. The aggregate interference $I_a$ is given by

$$I_a = \sum_{j=1}^{N} I_j. \tag{3}$$

The aggregate interference should satisfy the condition in (1). Note that $I_a$ depends on $N$ and $I_{thr}$. We assume that the secondary femtocells are connected to a central unit which determines $I_{thr}$ dynamically based on the current number of active femtocells, i.e. $N$.

This study focuses on the interference from the secondary users to the primary user. Interference in opposite path is not considered because the DME signal is bursty and has low temporal occupancy.

## III. Aggregate Interference to Primary System

This section provides a mathematical framework to analyze the aggregate interference. We adopt and modify the interference model proposed in [28]. Since the ground transponder and the airborne interrogator operate in different frequencies, we analyze the impact of the aggregate interference on these components separately. The probability density functions (pdf) of the aggregate interference $I_a$ to a DME ground transponder and an airborne interrogator are derived in Section III-A and Section III-B, respectively.

### A. Interference to DME ground transponder

In this sub-section, first we derive the pdf of $\xi_j$. Then, the distribution of $I_j$ is obtained from the relationship between $\xi_j$ and $I_j$ in (2). Finally, the pdf of $I_a$ is approximated by the method of moments.

Let us assume that $N$ secondary users are uniformly distributed in a circle of radius $R$ where the primary receiver is located at the origin. The distance between the secondary user $j$ and the primary user is denoted by a random variable $r_j$ whose pdf is as follows:

$$f_{r_j}(y) = \frac{2y}{R^2}, \ 0 < y \leq R. \tag{4}$$

Then, $\xi_j$ is given by

$$\xi_j = P_t^{eff} g(r_j) X_j, \tag{5}$$

where $P_t^{eff}$ denotes the effective transmission power of the secondary user including the antenna gain of primary and secondary users and the wall penetration loss. The distance-dependent path loss is modeled as $g(r_j) = Cr_j^{-\alpha}$ where $C$ is a constant and $\alpha$ is an exponent. $X_j$ is a random variable modeling fading effect. Log-normal shadow fading is considered because interference over a large area is investigated. Thus, $X_j$ has the following pdf:

$$f_{X_j}(x) = \frac{1}{x\sqrt{2\pi\sigma_{X_j}^2}} \exp\left[\frac{-(\ln x)^2}{2\sigma_{X_j}^2}\right], \ 0 < x < \infty, \tag{6}$$

where $\sigma_{X_j} = \sigma_{X_j}^{dB} \ln(10)/10$ by denoting the standard deviation of the shadowing by $\sigma_{X_j}^{dB}$ in dB scale.

Note that $\xi_j$ is a function of two random variables, $r_j$ and $X_j$. Since we consider secondary users spreading in a large area, we assume that the location of a secondary user and its shadowing value are independent of each other. Then, it is shown in [28] that the pdf of $\xi_j$ can be expressed by using the Gaussian error function:

$$f_{\xi_j}(z) = \Omega z^{\frac{-2}{\alpha}-1} \left[1 + \text{erf}\left(\frac{\ln(z/Q) - 2\sigma_{X_j}^2/\alpha}{\sqrt{2\sigma_{X_j}^2}}\right)\right], \tag{7}$$

where

$$\Omega = \frac{1}{R^2\alpha} \left(\frac{1}{P_t^{eff}C}\right)^{\frac{-2}{\alpha}} \exp\left[2\sigma_{X_j}^2/\alpha^2\right]. \tag{8}$$

The actual interference $I_j$ is regulated by the parameter $I_{thr}$ as shown in (2). This means a portion of secondary users have the transmission power of zero. That portion is given by $1 - F_{\xi_j}(I_{thr})$, where $F_{\xi_j}(\cdot)$ denotes the cumulative distribution function (CDF) of $\xi_j$. Thus, the pdf of $I_j$ is given by

$$f_{I_j}(z) = \begin{cases} 1 - F_{\xi_j}(I_{thr}), & z = 0, \\ f_{\xi_j}(z), & 0 < z \leq I_{thr}, \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

A cumulant-based approximation is employed to obtain the pdf of $I_a$. The $i$[th] cumulant of the sum of independent random variables is equal to the sum of the individual $i$[th] cumulants [25]. From this property, the cumulant of $I_a$ can easily be calculated from (3) and (9). The pdf of $I_a$ can be approximated as various known distributions by the method of moments [24], [25]. In this study, we found that log-normal and Gaussian distributions show good agreements with the simulation result, while the log-normal distribution provides more accurate description of $I_a$. Let $\kappa_a(1)$ and $\kappa_a(2)$ be the first and second order cumulants of $I_a$, respectively. The pdf of $I_a$ is approximated as the following log-normal distribution:

$$f_{I_a}(z) = \frac{1}{z\sqrt{2\pi\sigma_{I_a}^2}} \exp\left[\frac{-(\ln z - \mu_{I_a})^2}{2\sigma_{I_a}^2}\right], \tag{10}$$

where the parameters $\mu_{I_a}$ and $\sigma_{I_a}^2$ are obtained from the following equations:

$$\kappa_a(1) = \exp\left[\mu_{I_a} + \sigma_{I_a}^2/2\right], \tag{11}$$

$$\kappa_a(2) = \left(\exp\left[\sigma_{I_a}^2\right] - 1\right) \exp\left[2\mu_{I_a} + \sigma_{I_a}^2\right]. \tag{12}$$

### B. Interference to DME airborne interrogator

This sub-section assumes that the primary receiver is an airborne interrogator equipped in an aircraft. The pdf of $I_a$ is derived by taking similar steps described in Section III-A. A major difference from the ground transponder case is that free space propagation loss is considered between the secondary users and the airborne equipment. This means that the fading effect is not taken into account in this sub-section. We assume that the secondary users have an accurate knowledge of the distance from the primary user. It would be difficult to have such a knowledge in practical environment because the airplane usually moves fast. However, we believe that this assumption will provide an indicator of the minimum requirements for the secondary user to share the spectrum with airborne DME equipments.

We assume that $N$ secondary users are uniformly distributed in a circle of radius $R$. Then, we consider an airplane at the origin of the circle with the height of $h$ from the ground. Without fading effect, applying the interference threshold $I_{thr}$ results in a circular exclusion region inside which the secondary users are not allowed to transmit. Let $r_o$ denote the radius of the exclusion region. Fig. 3 illustrates the system model.

Let us consider a secondary user $j$ who is at the outside of the exclusion region with the distance of $r_j$ from the origin $(r_j > r_o)$. Since the secondary users are uniformly distributed, the pdf of $r_j$ is given by

$$f_{r_j}(y) = \frac{2y}{R^2 - r_o^2}, \ r_o \leq y \leq R. \tag{13}$$

Let $d_j$ be the distance from the user $j$ to the primary receiver. Then, $d_j = \sqrt{h^2 + r_j^2}$. The interference from the secondary user $j$ is
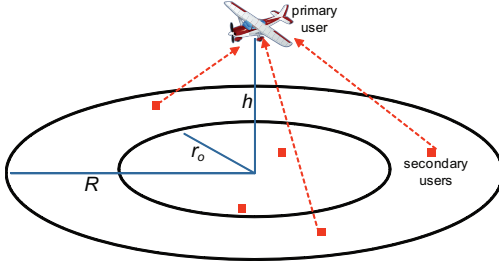
Fig. 3: Interference from secondary users to airborne interrogator

TABLE II: Parameters used for numerical experiments

| Parameters for ground transponder | |
| --- | --- |
| path loss constant ($C$) | $4.5 \times 10^{-13}$ |
| path loss exponent ($\alpha$) | 3.5 |
| Shadowing standard deviation ($\sigma_{X_j}^{dB}$) | 10 dB |
| height of the transponder | 30 m |
| **Parameters for airborne interrogator** | |
| path loss constant ($C$) | $5.7 \times 10^{-10}$ |
| path loss exponent ($\alpha$) | 2.0 |
| height of the interrogator ($h$) | 1 km |
| **Common parameters** | |
| radius of interference aggregation ($R$) | 200 km |
| building penetration loss | 10 dB |
| DME antenna gain | 5.4 dBi |
| secondary user antenna gain | 0 dBi |
| secondary user transmission power | 10 dBm/MHz |
| secondary user height | 1.5 m |

$$I_j = P_t^{eff} g(d_j), \tag{14}$$

where the path loss $g(d_j)$ is given by $C d_j^{-\alpha}$. By applying a transformation of random variable to (14), we get the following pdf of $I_j$:

$$f_{I_j}(z) = \frac{2}{(R^2 - r_o^2)\alpha} \left( \frac{1}{P_t^{eff} C} \right)^{\frac{-2}{\alpha}} z^{\frac{-2}{\alpha} - 1}, \ A \leq z \leq B, \tag{15}$$

where

$$A = P_t^{eff} C \sqrt{h^2 + R^2} \text{ and } B = P_t^{eff} C \sqrt{h^2 + r_o^2}. \tag{16}$$

Let $N_t$ be the number of secondary users that are allowed to transmit, i.e. located at the outside of the exclusion region. It is given by

$$N_t = N \left( 1 - \frac{r_o^2}{R^2} \right). \tag{17}$$

Then, the aggregate interference $I_a$ is

$$I_a = \sum_{j=1}^{N_t} I_j. \tag{18}$$

Since $I_j$ is only affected by the distance based path loss, $I_a$ is well described by a Gaussian distribution. Let $\mathbf{E}[I_j]$ and $\mathbf{V}[I_j]$ be the mean and variance of $I_j$ which are calculated from (15). Then, $I_a$ is approximated as the Gaussian distribution with mean of $N_t \mathbf{E}[I_j]$ and variance of $N_t^2 \mathbf{V}[I_j]$:

$$f_{I_a}(z) = \frac{1}{\sqrt{2\pi N_t^2 \mathbf{V}[I_j]}} \exp \left[ \frac{-(z - N_t \mathbf{E}[I_j])^2}{2 N_t^2 \mathbf{V}[I_j]} \right]. \tag{19}$$

## IV. NUMERICAL RESULTS

The parameters used for the numerical experiments are summarized in Table II. Hata model for suburban area [29] is used for the propagation between the ground transponder and the secondary users, while the free space propagation loss is employed to describe the path loss to the airborne interrogator.

The path loss constants in the table are obtained by considering the center frequency of 1 GHz.

Let $\rho_{su}$ denote the number of secondary users per km$^2$. For the case of the transponder, the secondary access requirement is checked in terms of the individual interference threshold $I_{thr}$ for a given $\rho_{su}$. As for the interrogator, $I_{thr}$ is replaced by the exclusion radius $r_o$. Since the DME system has the stringent protection threshold, the use of DME co-channel may not be possible in some cases. Thus, exploiting adjacent channels is also considered in the analysis. In this regard, the exclusion region is examined as a function of the adjacent channel attenuation characteristics of the DME.

The CDFs of aggregate interference calculated from (10) and (19) are compared with Monte Carlo simulations in Fig. 4 and Fig. 5, respectively. Both figures show that the analytical probability distributions of $I_a$ are in good agreements with the results of simulations. This suggests that the mathematical framework presented in this study can obviate the time consuming simulation efforts in further investigations of the secondary access to the DME spectrum.

The individual interference threshold $I_{thr}$ should be determined to satisfy the condition in (1) for a given $\rho_{su}$. Fig. 6 shows $I_{thr}$ as a function of the adjacent channel attenuation for the case of the ground transponder. Once $I_{thr}$ is determined, each secondary user knows whether it can transmit or not. The opportunity of transmission depends on the distance between the secondary user and the transponder. Recall that this distance is denoted by $r_j$. A probability that the user $j$ can transmit equals to $\text{Pr}(\xi_j \leq I_{thr})$. If $r_j$ is given, $\xi_j$ follows a log-normal distribution due to the shadow fading. The transmission probability of the user $j$ is illustrated in Fig. 7 for some values of $r_j$.

Fig. 6 and Fig. 7 should be examined together since they provide complementary information about the ground transponder case. In Fig. 6, the adjacent channel attenuation of zero dB represents the use of co-channel. For example,
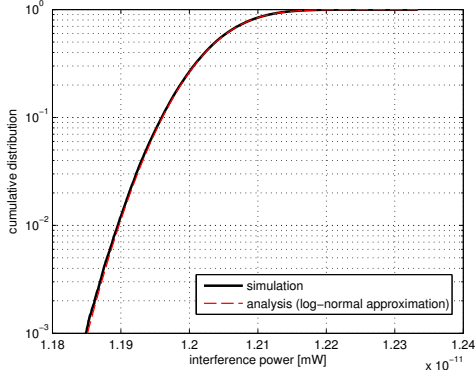
Fig. 4: A comparison between the analytic CDF of $I_a$ and the result of Monte Carlo simulation; the primary receiver is the ground transponder ($I_{thr}$ = -150 dBm and $\rho_{su} = 20/\text{km}^2$).



Fig. 6: $I_{thr}$ as a function of the DME adjacent channel attenuation; the primary receiver is the ground transponder.
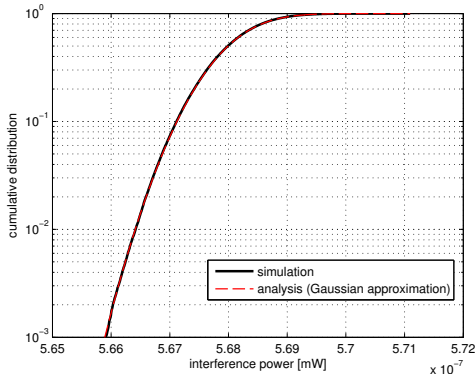


Fig. 5: A comparison between the analytic CDF of $I_a$ and the result of Monte Carlo simulation; the primary receiver is the airborne interrogator ($r_o$ = 20 km and $\rho_{su} = 20/\text{km}^2$).



Fig. 7: $\Pr(\xi_j \leq I_{thr})$, a probability that the secondary user $j$ can transmit, as a function of $I_{thr}$; this is illustrated for some values of $r_j$

$I_{thr}$ of $-140$ dBm is required to access the co-channel when $\rho_{su} = 1/\text{km}^2$. This means that a secondary user can transmit with the probability of 60% if its distance from the primary victim is 5 km as shown in Fig. 7. On the other hand, heavily deployed secondary users ($\rho_{su} = 100/\text{km}^2$) need $I_{thr}$ of $-180$ dBm, which completely forbids the transmission of secondary users 10 km away from the transponder. Thus, the co-channel usage is not promising when the density of the secondary users is high. In Fig. 7, most of the secondary users can have access to DME channel if $I_{thr}$ is above $-100$ dBm. Therefore, it is inferred from Fig. 6 that the use of adjacent channel is the minimum requirement for a dense deployment of the secondary users provided that the adjacent channel attenuation

is larger than 40 dB.

For the case of the airborne interrogator, the absence of fading enables us to replace $I_{thr}$ with the exclusion radius $r_o$. First, we consider a worst case that the airplane is at the boundary of DME coverage. Airplane height of 1 km is employed to ensure the worst case assumption. Fig. 8 shows $r_o$ as a function of the adjacent channel attenuation. Unlike the transponder case, the minimum required $r_o$ for co-channel usage is more than 200 km even when $\rho_{su} = 1/\text{km}^2$. This is because the interference power under the free space propagation does not attenuate significantly even with a large distance from the primary user. However, the exclusion region is not required for accessing adjacent channels as long as the attenuation is higher than 40 dB when $\rho_{su} = 1/\text{km}^2$ and 60 dB
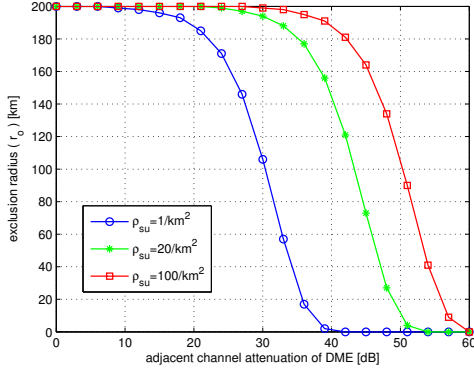
Fig. 8: $r_o$ as a function of the DME adjacent channel attenuation; the primary receiver is the airborne interrogator; $A_{thr}$ of $-111$ dBm is assumed.
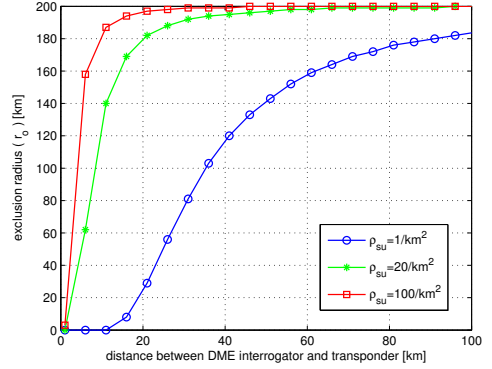


Fig. 9: $r_o$ as a function of the distance between the airborne interrogator and the ground transponder; the primary receiver is the airborne interrogator; co-channel usage is assumed.

when $\rho_{su} = 100/\mathrm{km}^2$. The attenuation value of commercial DME interrogators is shown in [23]. For a DME channel $k$, the attenuation is between 60 and 70 dB for the channels $k \pm 2$. Thus, the separation of two channels (2 MHz) will be the minimum requirement to provide the protection to the primary user when the secondary users heavily access the spectrum.

The interrogator can tolerate more interference as the airplane moves toward the ground station. The impact of DME link distance on $r_o$ is depicted in Fig. 9. We assume that the DME transponder has the transmission power of 1 kW, and calculate $A_{thr}$ as a function of the primary pair distance by considering the CIR threshold of 16 dB and the margin of 12 dB. It is observed that the requirement of secondary access decreases dramatically as the interrogator approaches the transponder when $\rho_{su} = 1/\mathrm{km}^2$. Exclusion region is not necessary for using co-channel if the airplane is within 10 km from the transponder. On the other hand, the requirement for densely deployed secondary users does not change significantly. When $\rho_{su} = 100/\mathrm{km}^2$, the DME link distance of more than 30 km gives the same result as the case that the airplane is at the coverage border. This suggests that the worst case assumption for $A_{thr}$ is reasonable if high density of the secondary users is to be analyzed.

## V. DISCUSSION

### A. Impact of the assumptions and parameters

The objective of the study is to establish the requirement of secondary usage in the spectrum allocated to the DME. We relied on several assumptions and simplifications to enable quantitative analysis. The impact of these assumptions remains as further research questions. It is worth emphasizing that the following questions are not specific to this work but the fundamental issues of secondary spectrum access.

First, the uniform distribution of secondary users was considered in this study. The homogeneity in secondary user distribution is a widely accepted assumption for the aggregate interference modeling in the literature. In practice, the spatial distribution of secondary users is affected by the population density and the mutual interference among the secondary users. Spatial reuse among the secondary users has recently been considered in [30], [31]. The heterogeneous distribution of secondary users due to the population density has not been fully addressed yet.

Second, we employed several parameters to describe the characteristics of secondary users and the protection threshold of primary users. Sensitivity analysis should be done for the parameters used in this study. One of the most important parameters is the protective margin that should be applied to the DME. Since the DME system performs a safety-of-life operation, the importance of providing a proper protection to the DME cannot be overemphasized. Thus, sufficient safety margin and apportionment margin should be put in place. The margin of 12 dB is applied in our analysis. The allowable probability of harmful interference is another important parameter to protect the DME. The impacts of secondary user parameters and environments are also to be investigated such as the transmission power, fading distributions, and path loss.

Finally, we assumed that the protection rule for the primary user is perfectly kept by the secondary users. However, some secondary users may fail to abide by the rule in real environments due to the following reasons: they make a wrong estimation on the propagation loss and/or there are rogue users who deliberately disobey the rule. The former case can be minimized by several technological means such as the use of GPS, collaborative sensing, and the control by a central network. The latter case is a potential problem that may hinder the secondary access in general. Little research has been done

on this issue. A discussion about reinforcing compliance with the rule can be found in [32].

### B. Toward feasibility analysis

It should be noted that the requirement we established does not necessarily guarantee the feasibility of the secondary access, nor it provides the economic worth of the spectrum. The following challenges should be addressed to evaluate the technical viability and the business opportunity.

First, we assumed that the secondary users have perfect knowledge of the path loss to the primary victim. It was the necessary assumption for finding out the requirement for the secondary users that gives the maximum achievable performance of the secondary access. However, the assumption would be unrealistic in actual deployments of the secondary networks. For a practical implementation, a sensing-based estimation can be used for airborne interrogators because they emit interrogation signals on the frequency of $\pm 63$ MHz offset from the reception channel. Geo-location database as in TV white spaces [33] can be employed additionally for ground transponders since their locations are fixed and managed by aviation authorities. These methods are subject to the uncertainty in propagation estimation, which may demand a stringent requirement to the secondary users. Quantitative analysis with the practical schemes remains to be investigated.

Second, our study is limited to a single DME channel. The regional spectrum allocation and occupancy of the DME system is not taken into account. This means that the probability of finding a certain amount of free spectrum at a given location at a specific time has not been addressed in this initial study. The evaluation of the available spectrum should be done on a regional basis, and the result will be different from an area to another. It is also expected that each region has a different requirement for protecting the primary system.

### VI. Conclusion

We investigated the requirements of the secondary spectrum access to 960-1215 MHz band which is primarily allocated to aeronautical systems. Particularly, a scenario was considered where DME equipments for aeronautical navigation operate as primary users and receive aggregate interference from indoor femtocells accessing the spectrum as secondary users. Exclusion region based on propagation loss was applied to the secondary users to prevent harmful interference to the primary users. The requirement for the secondary access was examined in terms of the exclusion region depending on the secondary users density. Since the operation of the DME system is divided into the ground transponder and the airborne interrogator, we considered the impact of the secondary access to these components separately. Simple mathematical models were presented to derive the probability distributions of the aggregate interference.

Numerical experiments were performed with the assumption that the secondary users have accurate knowledge of path loss. The observations from the numerical results are as follows: for the case of the ground transponder, secondary users can have co-channel access if the density of the secondary users is low. The use of adjacent channels is required for dense deployment of the secondary users provided that the adjacent channel attenuation is higher than 40 dB. As for the airborne interrogator, co-channel use is not possible. Adjacent channel attenuation of more than 60 dB is required to accommodate high density of secondary users.

This paper provided an initial result on the requirement of secondary spectrum sharing with the DME system. We envisage that this work can be a stepping stone to various further research. Specifically, studies are needed to assess the technical feasibility and the business viability of this scenario. First, we employed simplified assumptions and models to enable the quantitative analysis. The impact of these assumptions should be investigated. Particular consideration should be taken into the uncertainty in propagation loss. Second, sensitivity of the parameters used in the analysis should be examined further including the interference tolerance and safety margin of the DME system. Finally, the amount of the available spectrum in a certain geographic area should be identified based on the regional spectrum allocation and the occupancy of the DME system.

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## Chapter 9

# On the Feasibility of Indoor Broadband Secondary Access to the 960-1215 MHz Aeronautical Spectrum (Paper 5)

# On the feasibility of indoor broadband secondary access to 960-1215 MHz aeronautical spectrum

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*Abstract*—**In this paper, we analyze the feasibility of indoor broadband service provisioning using secondary spectrum access to the 960-1215 MHz band, primarily allocated to the distance measuring equipment (DME) system for aeronautical navigation. We propose a practical secondary sharing scheme customized to the characteristics of the DME. Since the primary system performs a safety-of-life functionality, protection from harmful interference becomes extremely critical. The proposed scheme controls aggregate interference by imposing an individual interference threshold on the secondary users. We examine the feasibility of large scale secondary access in terms of the transmission probability of the secondary users that keeps the probability of harmful interference below a given limit. Uncertainties in the estimation of propagation loss and DME location affect the feasibility of secondary access. Numerical results show that a large number of secondary users are able to operate in adjacent DME channels without harming the primary system even with limited accuracy on the estimation of the propagation loss.**

## I. INTRODUCTION

The demand for higher data rates in the growing wireless services has made the need for more spectrum evident. This has led to an apparent shortage of the available spectrum. It is generally believed that the spectrum shortage is caused by inefficient spectrum utilization under the existing regulatory and licensing process that only allows static spectrum allocation. Secondary spectrum access has emerged as a promising solution to relieve the apparent spectrum shortage [1], [2]. Secondary access allows secondary users to dynamically access white spaces or unused portions of spectrum licensed to a primary system under non-interfering basis [3].

In spite of extensive theoretical research in the field of cognitive radio and dynamic spectrum access [4], [5], the practical value of the secondary access has not been fully investigated. Most of the efforts to assess the real-life benefit of the secondary spectrum have thus mainly focused on the digital TV broadcasting bands, namely TV white spaces. Quantification of the usable TV white spaces in the UK, the USA and Europe has been investigated in [6]–[8], respectively. In [9], [10], spectrum reuse opportunities for 'WiFi-like' secondary system were analyzed considering adjacent channel interference constraints at the TV receivers. Although a substantial portion of the useful spectrum is primarily allocated to various systems such as radar and aeronautical navigation, the feasibility of secondary access to these frequency bands is mostly unexplored [1].

This work focuses on the 960-1215 MHz band which is allocated to aeronautical systems. In particular, this frequency band is mainly occupied by distance measuring equipment (DME). Since the DME system performs a safety-of-life functionality [11], protection from harmful interference becomes extremely critical. Due to the high sensitivity of DME receivers, aggregate interference should be controlled over a large area, which is the major challenge for secondary access to this spectrum.

### A. Related Work

Little effort has been devoted to assessing the feasibility of large scale secondary usage in the radar and aeronautical bands. As for the secondary sharing with radar, initial feasibility results for 3GPP LTE usage of 2.7-2.9 GHz radar spectrum are presented in [12], where the analysis is based on a single secondary interferer. In [13], the authors assessed the opportunities for secondary access in 5.6 GHz primarily allocated to the meteorological radars. It is reported in [14], [15] that a predictable rotation pattern can further enhance the opportunities for the secondary users.

Compared to a handful of existing work on the radar spectrum, even fewer results are found in literature for the secondary access to aeronautical spectrum. A notable exception is our previous work which first studied the 960-1215 MHz band [16]. As a first step, we investigated the minimum requirements for the secondary users under the ideal assumption that the secondary users have accurate knowledge of propagation loss to the DME receivers. We observed that the secondary usage would be widely available under this particular assumption. However, it is obvious that the requirements to the secondary users will become more stringent if there are uncertainties in the propagation information. In practice, it is difficult to have perfect knowledge of the propagation to the DME system. Thus, it is needed to study the feasibility of secondary access under practical assumptions.

### B. Contribution of this work

In this paper, we investigate the feasibility of secondary spectrum sharing with the DME system. To our best knowledge, it is the first attempt to examine the practical usefulness of 960-1215 MHz with regard to the secondary access. Our contribution can be detailed as follows. First, we propose practical methods by which the secondary users discover opportunities and share the spectrum. They are customized to

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the characteristics of the primary user, i.e. DME receivers, and based on geo-location database and spectrum sensing. Second, we identify the major sources of uncertainties that cause inaccurate estimation of propagation loss to the DME, and analyze the impact of the uncertainties by employing mathematical aggregate interference models in [17], [18].

We consider massive deployment of secondary users that provides high-speed indoor broadband, e.g. WiFi and HeNB. Such a large scale secondary access is deemed *feasible* if the practical sharing methods enable the secondary users to maintain an acceptable transmission probability. Since our analysis accompanies the uncertainties in the propagation loss estimation, we focus on the following research questions:

- Is the massive secondary access feasible in 960-1215 MHz band?
- What is the impact of the uncertainties on the feasibility of secondary access?

The rest of the paper is organized as follows: the system model, primary and secondary systems characteristics are described in Section II. The proposed secondary access scheme and the mathematical models of the aggregate interference for ground transponder and airborne interrogator are introduced in Section III and in Section IV, respectively. In Section V, we present and discuss our numerical results. Finally, the main conclusions of this work and remaining issues for future studies are given in Section VI.

## II. SYSTEM MODEL

### A. DME as the primary system

DME is used for measuring the distance between an aircraft and a ground station. The airborne equipment (interrogator) sends short Gaussian pulses down to earth, and the ground station (transponder) responds on a frequency of $\pm 63$ MHz from the interrogation frequency. The interrogator can calculate the slant distance based on the round trip delay of the signal. The pulses are burst more than 100 times per second by the interrogator and 2500 times by the transponder. Their transmission power reach up to 300 W for the interrogator and up to 2 kW for the transponder. The channel bandwidth of DME is 1 MHz, i.e. there are 252 channels in total. A more detailed description of DME can be found in [16] and references therein.

We consider that the DME receiver can tolerate a maximum interference power of $A_{thr}$, which corresponds to $-119$dBm/MHz and $-111$dBm/MHz for the transponder and interrogator, respectively [16]. The received interference is considered harmful if it exceeds $A_{thr}$. The aggregate interference ($I_a$) is regulated as follows:

$$\Pr[I_a > A_{thr}] \leq \beta_{PU} \tag{1}$$

where $\beta_{PU}$ is the maximum permissible probability of harmful interference at the primary receiver. The nature of DME operation requires $\beta_{PU}$ to be extremely small. A reasonable range of $\beta_{PU}$ has not been discussed well in the literature. We adopt a value used for air traffic control (ATC) radar in

2.7-2.9 GHz, i.e. $\beta_{PU} = 0.001\%$ [12], which also performs a safety service. Notice that the value of $\beta_{PU}$ has been set mainly based on the type of service rather than the operating frequency. Then, the frequency offset between the DME and ATC radar bands should not affect the value of $\beta_{PU}$.

The interference from the DME device to the secondary receiver is, on the contrary, negligible, since the DME generates only short pulses. Although the DME pair exchanges the pulses frequently, the overall channel utilization remains below 1%. Secondary receivers might be saturated if they receive excessively strong DME pulses. Let $I_{sat}$ be the saturation point of the secondary receiver. Then, the following condition should be satisfied:

$$\Pr[I_{PU} > I_{sat}] \leq \beta_{SU} \tag{2}$$

where $\beta_{SU}$ is the maximum saturation probability and $I_{PU}$ is the received primary pulse power. We adopt a value of $\beta_{SU} = 2\%$ and $I_{sat} = -30$dBm which is a typical saturation level of low noise amplifier (LNA) in WiFi receivers [19]. With the adopted values for $A_{thr}$, a simple link budget analysis indicates that (1) is the limiting constraint even before taking the effect of multiple secondary users into account. Therefore, we will focus on the protection of the primary user in the remainder of the paper.

### B. Indoor Broadband as secondary system

Let us consider massive scale deployment of indoor access points and mobiles for high capacity broadband services over a large area. They utilize the spectrum allocated to the DME under the principle of spectrum interweave [20]. In our evaluation, the feasibility of secondary usage depends only on the aggregate interference from the secondary system to the primary victim since the interference from the primary system to secondary system was found to be negligible. Therefore, we investigate a wide range of secondary user density which directly impacts the amount of aggregate interference towards the primary system.

Notice that the DME system does not have a predefined rotating pattern, like the case of rotating radar, which could be employed to further exploit sharing opportunities in the time domain. Therefore, sharing opportunities in the DME band are time-invariant but location-dependent. Based on that, our analysis of the feasibility of large scale secondary access to the DME band will only focus on the spatial domain.

In practical environments, secondary users are deployed according to a heterogenous spatial distribution. Typically, there are zones with different user densities in a large geographical area, e.g. cities, suburbs, and farms. Results in [21] support that a homogeneous secondary user distribution can be assumed when there is a large separation distance between the high density zones and the primary receiver which is generally the case for secondary access to the DME spectrum. Then, secondary users are assumed to be spatially distributed according to a homogeneous Poisson point process in a two dimensional plane $\Re^2$. The primary receiver is located at the

center of the circular region limited by two radii $r_o$ and $R$, which are the minimum and maximum distances from the primary receiver, respectively.

Each secondary user decides whether it can access a particular DME channel or not by estimating the interference it will generate to the primary user. Let $I_{thr}$ denote the interference threshold imposed on the individual secondary users. The value of $I_{thr}$ is given to the secondary users by a central spectrum manager. This ensures that each secondary user makes its own decision without interacting with the others. The interference from a secondary user $i$ is given by

$$I_i = \begin{cases} \xi_i, & \text{if } \tilde{\xi}_i \leq I_{thr} \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

where $\xi_i$ is the interference that the primary user would receive if an arbitrary secondary user were to transmit, and $\tilde{\xi}_i$ is the estimate of $\xi_i$ by the secondary user $i$. Note that $\xi_i = \tilde{\xi}_i$ only when the secondary user has the perfect knowledge of the propagation loss. Considering that there are $N$ secondary users around the primary user, the aggregate interference is

$$I_a = \sum_{i \in N_t} I_i \quad (4)$$

where $N_t$ is the set of transmitting secondary users.

A secondary system with a given user density and transmission power is deemed *feasible* if secondary users at a distance $r_i$ from the primary victim are able to transmit with a minimum transmission probability, $Pr(\tilde{\xi}_i(r_i) \leq I_{thr}) \geq TX_{min}$.

### III. SHARING WITH THE GROUND TRANSPONDER

#### A. Secondary access scheme

The ground transponder is placed at a fixed location and frequently bursts short pulses to the airborne interrogators. Thus, it is possible for the secondary user to detect the existence of the transponder via spectrum sensing. The additional use of a geo-location database enables the secondary users to have prior knowledge about the transponder such as the location, operating frequency, and transmission power. This will significantly improve the performance of the spectrum sensing since the secondary users can have a good expectation about to signal to detect. Given the high transmission power of the ground transponder and the aid of the geo-location database, we assume that the spectrum sensing is reliable enough to ignore missed detection and false alarm. Moreover, the geo-location database can rapidly detect and correct any detection error due to its continuous bidirectional communication with the primary and secondary users.

Fig. 1 depicts the proposed opportunity detection mechanism. Note that the secondary users detect the transponder on the reply (sensing) frequency, while the interference is given on the interrogation (interfering) frequency. In both channels, propagation losses between the DME transponder and the secondary user consist of the distance-based path loss ($L$) and fading[1] ($X$ and $Y$). Although it is reasonable to assume that

[1]Note that the fading here refers to the combined effect of shadowing and multi-path fading

the secondary users accurately estimate the propagation loss of sensing channel ($S = L + X$), it does not necessarily mean that the estimation of interfering channel ($T = L + Y$) is also accurate. With the frequency offset of 63 MHz between the sensing and interfering channels, the shadowing components are typically highly correlated ($\rho_{shadowing} \approx 1$) [22], while the multi-path fading is uncorrelated ($\rho_{fast} = 0$). Therefore, the correlation between the composite fading components, $\rho$, lies between $[0, 1]$. The exact value of $\rho$ depends on the characteristics of different propagation environments. Partial correlation between channels does not allow the secondary user to perfectly estimate its interference to the primary victim. Then, an *uncertainty* in the estimation of fading component of the propagation loss between the secondary user and the ground transponder still remains.

For making the proposed sharing scheme possible, the following technical capabilities are required: good sensing capabilities for the secondary users in order to make a good estimation of the propagation path loss, an upgrade of the primary equipment so it measures and reports the values of $I_a$ to the geo-location database, and backhaul connectivity to assure the communication between the different components of the proposed sharing scheme. Notice that the role of the regulatory entity is particularly important for secondary access to the DME band due to its safety-of-life functionality. Thus, we envisage a close collaboration between the regulatory entity and the geo-location database, providing guarantees on the accuracy of the information and the enforcement of the coexistence rules.

#### B. Aggregate interference modeling

In this section, we model the aggregate interference when there is uncertainty in the fading estimation. Different levels of uncertainty in fading estimation are represented by a correlation coefficient $\rho$. We adopt the mathematical frameworks proposed in [16]–[18] with a slight modification to account for the proposed spectrum sharing mechanism.

Let us consider an arbitrary secondary user $i$ which is distributed according to a homogeneous Poisson point process in a circular area of radius $R$. The path loss between the primary receiver and the secondary user $i$ is modeled as $g(r_i) = Cr_i^{-\alpha}$ where $C$ is a constant and $\alpha$ is the path loss exponent. Then, the user $i$ would cause interference $\xi_i$ to the primary receiver if it were to transmit, which can be expressed as

$$\xi_i = P_t^{eff} g(r_i) Y_i \quad (5)$$

where $P_t^{eff}$ refers to the effective transmission power of the secondary user including antenna gains and bandwidth mismatch. $Y_i$ is a random variable modeling the fading effect. It is generally considered that the fading consists of shadow fading following a normal distribution in dB scale and multi-path fading by which the instantaneous power is varied with an exponential distribution. We use the assumption that the composite fading $Y_i$ follows a log-normal distribution. It is
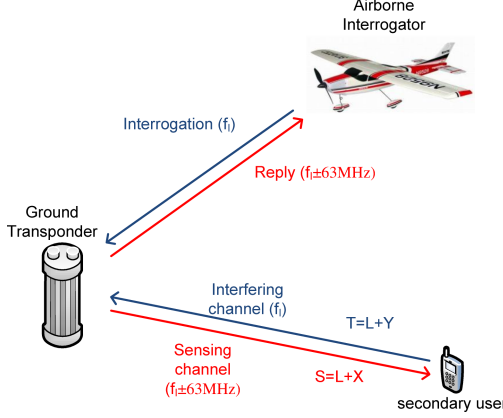
Fig. 1. Uncertainty in secondary sharing scenario with ground transponder as primary victim

known that this assumption works well when the standard deviation of shadowing is higher than 6dB, i.e. when the shadowing is a dominant factor of the composite fading [23]. The user $i$ will decide to transmit if $\tilde{\xi}_i \leq I_{thr}$. Note that $\tilde{\xi}_i$ is affected by the fading on the sensing channel. That is,

$$\tilde{\xi}_i = P_t^{eff} g(r_i) X_i \qquad (6)$$

where $X_i$ is modeled as a log-normally distributed random variable whose parameters are the same as $Y_i$. Therefore, the joint distribution of $X_i$ and $Y_i$ is given by the following bivariate log-normal distribution:

$$f_{X_i,Y_i}(x,y) = \frac{1}{2\pi xy\sigma^2\sqrt{1-\rho^2}} \\ \times e^{-\frac{(\ln x)^2 - 2\rho(\ln x)(\ln y) + (\ln y)^2}{2\sigma^2(1-\rho^2)}} \qquad (7)$$

where $\rho$ is the correlation coefficient of $X_i$ and $Y_i$:

$$\rho = \frac{Cov(\ln X_i, \ln Y_i)}{\sqrt{Var(\ln X_i)Var(\ln Y_i)}}. \qquad (8)$$

We consider that the composite fading components, $X_i$ and $Y_i$, will be partially correlated ($0 < \rho < 1$). The exact value of $\rho$ depends on propagation environments. Note that full correlation ($\rho = 1$) represents an ideal case that the secondary user has an accurate knowledge of interference. On the opposite, zero correlation ($\rho = 0$) stands for a pessimistic assumption that the fading is completely unknown to the secondary user. For simplicity and mathematical tractability, we have adopted the assumption that secondary users in the whole area of study are affected by a homogeneous fading distribution. The feasibility of secondary access under different assumptions, ranging from ideal to pessimistic, will be shown and discussed in Section V.

The aggregate interference $I_a$ can be expressed as:

$$I_a = P_t^{eff} C \underbrace{\sum_{i \in N_t} r_i^{-\alpha} Y_i}_{I_{N_t}}. \qquad (9)$$

Hereafter, we omit the index of secondary user $i$, which is chosen in an arbitrary manner, unless necessary. By applying the Campbell's theorem, the characteristic function of $I_{N_t}$ is as follows:

$$\psi_{I_{N_t}}(jw) = \exp\left(-2\pi\lambda \int_X \int_Y \int_{r_o}^R [1 - \exp(jwyr^{-\alpha})] \\ \times \mathbf{1}_{[0,\hat{I}_{thr}]}(r^{-\alpha}x)f_{X,Y}(x,y)r\mathrm{d}r\mathrm{d}y\mathrm{d}x\right). \qquad (10)$$

where $j = \sqrt{-1}$ and $\hat{I}_{thr} = I_{thr}/(P_t^{eff}C)$. The activity of the secondary users is represented by $\mathbf{1}_{[0,\hat{I}_{thr}]}(r^{-\alpha}x)$, which is a Bernoulli random variable. The indicator function is defined as:

$$\mathbf{1}_{[a,b]}(z) = \begin{cases} 1, & \text{if } a \leq z \leq b \\ 0, & \text{otherwise} \end{cases} \qquad (11)$$

where the value one of the Bernoulli variable denotes that the secondary user is able to transmit. We use (10) to derive exact expressions for the $n^{th}$ cumulant of the aggregate interference in a limited circular region $[r_o, R]$. We consider the case where there is a partial correlation between the two fading effects affecting the sensing and interfering channels, $X$ and $Y$.

For the special cases of full correlation ($\rho = 1$) and zero correlation ($\rho = 0$), the closed-form expressions of cumulants can be found in [17] and [18], respectively. Using the cumulant of $I_{N_t}$ shown in (12), we can obtain the $n^{th}$ cumulant of the aggregate interference $I_a$ as follows:

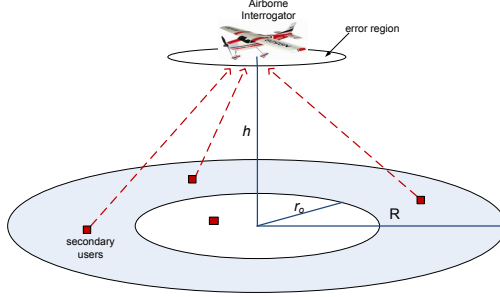$$k_{I_a}(n) = (P_t^{eff}C)^n k_{I_{N_t}}(n). \qquad (13)$$

Fig. 2. Uncertainty in secondary sharing scenario with airborne interrogator as primary victim

$$
\begin{aligned}
k_{I_{N_t}}(n) = \frac{2\pi\lambda}{(n\alpha-2)} \Bigg[ &(r_o^{2-n\alpha} - R^{2-n\alpha}) \int_0^\infty y^n f_Y(y)\Phi(L_i)\mathrm{d}y \\
& - R^{2-n\alpha} \int_0^\infty y^n f_Y(y)[\Phi(L_s) - \Phi(L_i)]\mathrm{d}y \\
& + \hat{I_{thr}}^{\frac{n\alpha-2}{\alpha}} \int_0^\infty y^n f_Y(y) \times \int_{r_o^\alpha \hat{I_{thr}}}^{R^\alpha \hat{I_{thr}}} \frac{x^{\frac{2-n\alpha}{\alpha}}}{\sqrt{2\pi}x\sigma\sqrt{1-\rho^2}} e^{-\frac{(\ln x - \rho \ln y)^2}{2\sigma^2(1-\rho^2)}} \,\mathrm{d}x\mathrm{d}y \Bigg]
\end{aligned}
\tag{12}
$$

where,

$$
L_i = \frac{\ln(r_o^\alpha \hat{I_{thr}}) - \rho \ln y}{\sigma\sqrt{1-\rho^2}},
$$

$$
L_s = \frac{\ln(R^\alpha \hat{I_{thr}}) - \rho \ln y}{\sigma\sqrt{1-\rho^2}}.
$$

The probability density function (pdf) of $I_a$ can be approximated with a known distribution by moment-matching method. In [17], [18], shifted log-normal and truncated-stable distributions are employed to address the skewness of the aggregate interference. In our model, the strong interferers are effectively removed due to the stringent threshold in (3). Therefore, simple log-normal distribution sufficiently describes $I_a$. The pdf of $I_a$ can be approximated with the first and second order cumulants of $I_a$ obtained by (13).

$$
f_{I_a}(y) = \frac{1}{y\sqrt{2\pi\sigma_{I_a}^2}} \exp\left[\frac{-\ln y - \mu_{I_a}}{2\sigma_{I_a}^2}\right], \tag{14}
$$

where

$$
k_{I_a}(1) = \exp[\mu_{I_a} + \sigma_{I_a}^2/2], \tag{15}
$$

$$
k_{I_a}(2) = \exp(\sigma_{I_a}^2 - 1)\exp(2\mu_{I_a} + \sigma_{I_a}^2). \tag{16}
$$

## IV. SHARING WITH THE AIRBORNE INTERROGATOR

### A. Secondary access scheme

Airborne interrogators are equipped in the airplanes, which are moving with a high speed. Therefore, it is not reasonable to assume a reliable detection of the interrogator via spectrum sensing. Instead, we assume that the secondary users are connected to a real-time database where the locations of the airplanes are provided. A living example of such a real-time aircraft location map can be found in [24]. Currently, the database information is updated every 20-60 seconds and has a limited coverage, which means that some airplanes (mostly small ones) do not appear in the map. Since we envision a close interaction between the regulatory body and the geo-location database, we expect that an official database in the future will be able to provide reliable information since it will be maintained/supervised by national authorities, i.e. regulatory body.

Due to the *update delay* in the database, the secondary user could potentially experience *uncertainty* or imperfect information on the location of the airborne interrogator which is changing rapidly. Based on the update delay and the speed of the airplane, we introduce the notion of *error region*, inside which secondary users will assume the worst case scenario that the sky is full of airplanes as shown in Fig. 2. Outside the error region, secondary users will assume that the primary receiver is located at the closest border of the error region. Let $t_u$ be the time of update delay and $v$ be the speed of the airplane. Then, the radius of the error region is given by $t_u v$. For example, the $t_u$ of one minute corresponds to the error

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region of 15 km radius assuming $v = 900$ km/h.

### B. Aggregate interference modeling

For the case of the airborne interrogator, free-space propagation model between the secondary users and the primary receiver is assumed. This means that the fading effect is not taken into account. We adopt this assumption in order to account for the worst case scenario where there exists line-of-sight path between every secondary user and the primary user.

Similar to the ground transponder case, we assume that $N$ secondary users are distributed according to a homogeneous Poisson point process in a circular area of radius $R$. The primary victim is assumed to be located at the center with a height of $h$ from the ground. Since the fading effect is not considered, applying individual threshold $I_{thr}$ will result in a circular exclusion region where secondary users are not allowed to transmit. The radius of exclusion region is denoted by $r_o$.

Let $r_{thr}$ be the exclusion radius under the assumption that the secondary users know the exact location of the primary victim. In the presence of the update delay, each secondary user has to make a conservative decision that the airplane is at the closest possible location. It effectively increases the exclusion radius by $t_u v$. However, if the exclusion region is not needed in the first place ($r_{thr} = 0$), the uncertainty in the primary user location does not make any impact on the feasibility of the secondary users. Thus, $r_o$ is given by

$$r_o = \begin{cases} r_{thr} + t_u v, & \text{if } r_{thr} > 0, \\ 0, & \text{otherwise.} \end{cases} \quad (17)$$

Let $l_i$ be the distance from an arbitrary secondary user $i$ to the primary receiver. Then, $l_i = \sqrt{h^2 + r_i^2}$ and the path loss $g(l_i)$ is given by $C l_i^{-\alpha}$. Then, the aggregate interference $I_a$ is

$$I_a = P_t^{eff} C \underbrace{\sum_{i \in N_t} l_i^{-\alpha}}_{I_{N_t}} \quad (18)$$

where $N_t$ is the number of secondary users that are allowed to transmit, i.e. located at the outside of the exclusion region. Similar to Section III-B, we apply the Campbell's theorem to obtain the characteristic function of $I_{N_t}$. Then, we derive exact expressions for the $n^{th}$ cumulant of $I_{N_t}$ in a limited circular region $[r_o, R]$.

$$k_{I_{N_t}}(n) = \frac{2\pi\lambda}{n\alpha - 2}(B^{(2-n\alpha)/2} - A^{(2-n\alpha)/2}). \quad (19)$$

where $A = h^2 + R^2$ and $B = h^2 + r_o^2$. Since we consider the free-space propagation model ($\alpha = 2$), we employ l'Hopital's rule to calculate the first order cumulant ($k_{I_{N_t}}(1)$).

$$\begin{aligned} k_{I_{N_t}}(1) &= \lim_{M \to 0} \frac{\pi\lambda}{M}(B^{-M} - A^{-M}) \\ k_{I_{N_t}}(1) &= \pi\lambda(\ln A - \ln B) \end{aligned} \quad (20)$$

where $M = (n\alpha - 2)/2$. Using the cumulant of $I_{N_t}$, we can obtain the $n^{th}$ cumulant of the aggregate interference $I_a$ as it is shown in (13). Note that $I_i$ is only affected by the distance-based path loss. Thus, $I_a$ is well described by the central limit theorem. This means that $I_a$ can be approximated as a Gaussian distribution with the first two cumulants as the mean and variance:

$$f_{I_a}(z) = \frac{1}{\sqrt{2\pi k_{I_a}(2)}} \exp\left[\frac{-(z - k_{I_a}(1))^2}{2k_{I_a}(2)}\right]. \quad (21)$$

### V. NUMERICAL RESULTS

The parameters used for our numerical experiments are described in Table I. For the case of ground transponder, we model the propagation loss between the primary victim and the secondary user using Hata model for suburban area. Instead, for the airborne interrogator we employ free-space propagation loss. For the transponder, we investigate the impact of $\rho$ on the requirement and feasibility of secondary access in terms of the individual interference threshold $\tilde{I}_{thr}$ and the transmission probability of the secondary user $i$, $\Pr(\tilde{\xi}_i \leq I_{thr})$, at a given $r_i$. For the interrogator, we analyze the effect of the update delay on the requirements of secondary users. The feasibility of secondary access is given in terms of the exclusion region size $r_o$ imposed on the secondary users.

In both cases, we provide results for co-channel usage and as well as adjacent channel usage. We apply DME selectivity mask given in [25] to determine the adjacent channel rejection (ACR) characteristics. This means that the condition (1) is changed to $\Pr[I_a > (A_{thr} + ACR)] \leq \beta_{PU}$ when we evaluate the adjacent channel usage. The values of ACR will vary according to the frequency separation. For instance, it is between 60dB and 70dB for channels with a frequency separation of 2 MHz. We assume that this applies as well to the channels of more frequency separation. To account for

TABLE I
PARAMETERS USED FOR NUMERICAL EXPERIMENTS

| Parameters for ground transponder | |
|---|---|
| primary user transmission power | 60dBm/MHz |
| path loss constant ($C$) | $4.5 \times 10^{-13}$ |
| path loss exponent ($\alpha$) | 3.5 |
| Fading standard deviation ($\sigma_{X_j}^{dB}$) | 10dB |
| height of the transponder | 30 m |
| **Parameters for airborne interrogator** | |
| primary user transmission power | 55dBm/MHz |
| path loss constant ($C$) | $5.7 \times 10^{-10}$ |
| path loss exponent ($\alpha$) | 2.0 |
| height of the interrogator ($h$) | 1 km |
| **Common parameters** | |
| radius of interference aggregation ($R$) | 200 km |
| building penetration loss | 10dB |
| DME antenna gain | 5.4dBi |
| secondary user antenna gain | 0dBi |
| secondary user transmission power | 1dBm/MHz |
| secondary user height | 1.5 m |
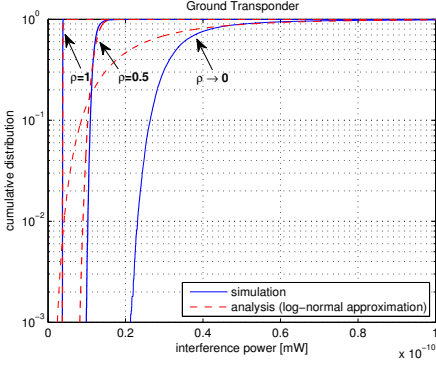
Fig. 3. A comparison between the analytic CDF of $I_a$ and the result of Monte Carlo simulation; primary receiver is the DME ground transponder ($I_{thr} = -150$dBm and $\lambda_{SU} = 20$/km$^2$)



Fig. 5. Impact of different correlation coefficients ($\rho$) on the maximum secondary user transmission power for a given $\lambda_{SU}$ when $Pr(\bar{\xi}_i(r_i) \leq I_{thr}) \geq 90\%$ at $r_i = 5$km; the primary receiver is the DME ground transponder
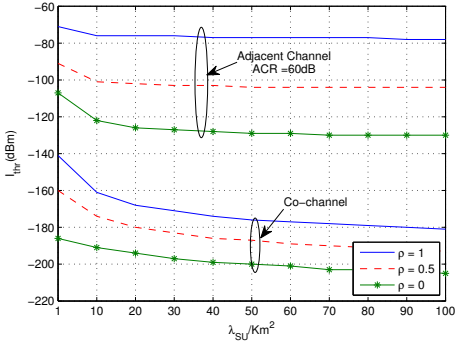


Fig. 4. $I_{thr}$ as a function of secondary network density ($\lambda_{SU}$) for different correlation coefficients($\rho$); the primary receiver is the DME ground transponder

interference aggregation in the spectral domain, we apply a fixed margin of 3dB and 10dB for co-channel and adjacent channel, respectively.

For the case of ground transponder, the cumulative distribution function (CDF) of $I_a$ calculated from (14) for different values of $\rho$ is shown in Fig. 3. A good agreement between analytical CDF of $I_a$ and the simulation results is verified when $\rho > 0$. When the fading is unknown to the secondary user ($\rho = 0$), analytical CDF matches the tails of the simulation-based CDF of $I_a$. Since we are working with $\beta_{PU} = 0.001\%$, it is still possible to employ the log-normal approximation of the probability distribution of $I_a$ to analyze the impact of fading uncertainty on the feasibility of secondary access.

The individual interference threshold $I_{thr}$ required to satisfy (1) is given in Fig. 4. It shows the impact of $\rho$ on the required $I_{thr}$ for accessing a co-channel and an adjacent channel with ACR of 60dB. We observe that the margins to cope with the uncertainty for different values of $\rho$ do not change much when the density of secondary users per km$^2$ ($\lambda_{SU}$) increases. However, the uncertainty margin significantly varies for co-channel and adjacent use cases, i.e. for different $A_{thr}$ values. Considering that secondary users transmit in an adjacent channel with ACR of 60dB, it is observed in Fig. 5 that the impact of fading uncertainty is critical for high-power secondary users (above 10dBm). Fig. 5 also shows that the impact of different propagation environments, i.e. different values of $\alpha$, increases as the secondary network becomes denser. However, the operation of a dense secondary network for indoor coverage is feasible even if the secondary users cannot accurately estimate the propagation loss and an environment with flat terrain ($\alpha = 2.5$) is considered.
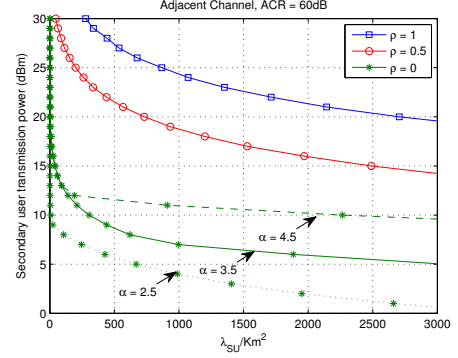
Now, let us consider the airborne interrogator as the primary victim. Recall that the update delay of 5 minutes can lead to the error region of 75 km radius, which is almost equivalent to not having the database. The exclusion region needed to satisfy (1) is shown in Fig. 6. The impact of the update delay is significant only when ACR is lower than 50dB. When ACR is 60dB, no exclusion region is required even if long update delay is experienced in the communication between the secondary user and the real-time database. Fig. 7 shows the combination of secondary users density and transmission power that do not require fast database update, i.e. no requirement for exclusion region. The figure indicates that dense secondary network accessing adjacent channels is feasible when the transmission power is about 0dBm even if no information on the location of the primary victim is provided.

Fig. 6.   Exclusion radius as a function of adjacent channel rejection of DME for different update delays when $\lambda_{SU} = 20/\text{km}^2$; the primary receiver is the DME airborne interrogator
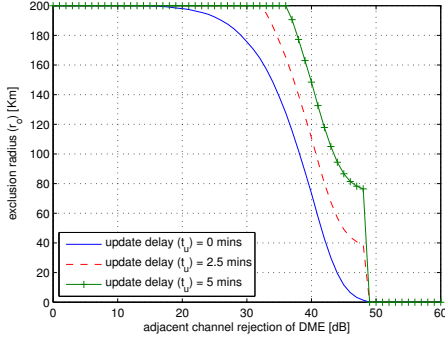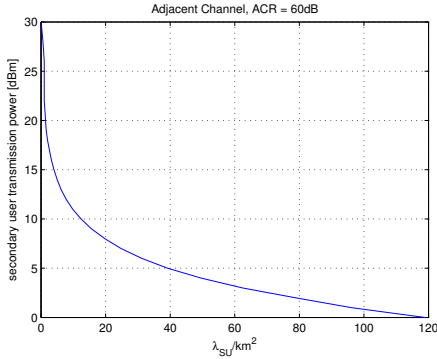


Fig. 7.   Maximum secondary user transmission power for a given $\lambda_{SU}$ when no exclusion region is needed ($r_o = 0$km); the primary receiver is the DME airborne interrogator

## VI.   Conclusions and Future Work

We analyzed the feasibility of large scale indoor broadband secondary access to the 960-1215 MHz spectrum when uncertainties on the fading and the location of the primary receiver are present. Cumulant-based approximations have been employed to derive the probability distribution of the aggregate interference in the presence of uncertainties. The main contributions in this paper are twofold:

- We proposed a practical secondary sharing scheme considering the characteristics of different primary receivers (DME ground transponder and airborne interrogator). Then, we identified uncertainties in the estimation of propagation loss incurring from the proposed sharing scheme.
- The feasibility of large scale secondary access has been

evaluated in terms of the number of secondary users which are able to operate with an acceptable transmission probability and the exclusion region size imposed on the secondary users.

We conclude that massive indoor secondary access to adjacent channels (ACR $\geq$ 60dB) is feasible even if secondary users are not capable of accurately estimating the propagation loss nor have accurate knowledge of the location of the airborne interrogator. Numerical results show that dense secondary users ($\lambda_{SU} > 1000/\text{km}^2$ for ground transponder and $\lambda_{SU} > 100/\text{km}^2$ for airborne interrogator) can have access to adjacent channels with a high transmission probability ($\geq$ 90%) or small exclusion region size.

Since the indoor secondary use of 960-1215 MHz spectrum is identified feasible, the capacity analysis of the secondary system taking self-interference and power control into account remains as an interesting future work. Location-dependent availability of the secondary access and its economic value are also to be investigated.

### Acknowledgment

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# Chapter 10

# Availability Assessment of Secondary Usage in Aeronautical Spectrum (Paper 6)

# Availability Assessment of Secondary Usage in Aeronautical Spectrum

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*Abstract*—In this paper, we provide a quantitative assessment of the *available* spectrum for massive indoor broadband secondary access in the 960-1215 MHz band, primarily allocated to the distance measuring equipment (DME) systems. We employ a practical sharing scheme where the secondary users share the DME spectrum via geo-location database and spectrum sensing. Since the DME system performs a safety-of-life functionality, protection from harmful interference becomes extremely critical. A DME channel is considered *available* in a certain time and location if the secondary users, under the applied sharing scheme, are able to successfully access the channel without violating the primary protection criteria. We analyze the impact of the secondary system parameters and the potential uncertainties in the applied sharing mechanism on the availability in the DME band. Numerical results show that at least 30% of the total DME band (57 MHz out of 190 MHz) can be available for a dense low-power indoor secondary network, even if conservative primary system protection criteria and high levels of uncertainty are considered.

*Index Terms*—Availability, distance measuring equipment, aggregate interference.

## I. INTRODUCTION

The explosive growth in the total mobile traffic demand, which is expected to increase tenfold by 2016, has led us to new capacity requirements [1]. Spectrum is one of the key elements to enhance the capacity of new and existing wireless services. Due to the current regulation and licensing rules which allows only static spectrum allocation, it is difficult to find additional spectrum even though measurements show that spectrum is mostly under-utilized. Secondary access is envisioned as a solution to this discrepancy [2]. Secondary users could potentially access those unused spectrum portions or so called *white spaces* without harming the operation of the primary victim. The improvements on spectrum utilization caused by secondary access were claimed to be significantly large. However, the availability for secondary usage is considerably reduced by the introduction of large safety margins to protect the primary victims against errors in the detection schemes and the effect of the aggregate interference [3]. Therefore, a quantitative analysis of the available spectrum for massive deployment of secondary users is needed to understand the real benefits of secondary access.

Previous works on estimating availability in a large geographical area have mainly focused on the digital TV broadcasting bands [4]–[6]. Although, low spectrum utilization has been reported in the radar and aeronautical bands [7], limited efforts have been made in the investigation of secondary access to these frequency bands [8], [9].

This work focuses on the aeronautical band, specifically the 960-1215 MHz band, which is mainly occupied by the DME system. The major challenge for secondary access to this band is the control of the aggregate interference over a large area due to the high sensitivity levels of the receivers and the extremely low permissible outage probability at the primary system which performs safety-of-life functionality [10]. Despite these challenges, our previous work has shown that secondary access to this band is feasible [11] [12]. Since our previous work was limited to analyzing accessibility to a single DME channel, it is worthwhile to make a quantitative assessment of the availability for massive indoor secondary access considering the total DME band.

In this paper, we develop an assessment methodology for quantifying the availability for large-scale secondary usage in a large geographical area where aggregation of interference in the spatial and frequency domain in considered. In our assessment, a DME channel is considered *available* if the secondary user, under the applied sharing scheme, is able to successfully access the channel without violating the primary protection criteria. By applying our methodology, we examine the practical availability in the DME band for Germany and Sweden considering real-life demographics, i.e. non-uniform population density and actual occupancy of the DME band in both countries. Thus, we aim at addressing the following research question:

- What is the amount of *available* spectrum for massive indoor broadband secondary access to the aeronautical band under practical sharing schemes?

The rest of the paper is organized as follows: the primary and secondary systems characteristics are described in Section II. The applied secondary access schemes are outlined in Section III. The proposed methodology for a quantitative assessment of the availability is presented in Section IV. In Section V, we discuss our numerical results. Finally, the main conclusions of this work are given in Section VI.

## II. SYSTEM MODEL

### A. Basic operation of DME

DME is used for measuring the distance between an airborne interrogator and a ground transponder. The DME basic operation consist of two phases: first, the airborne equipment
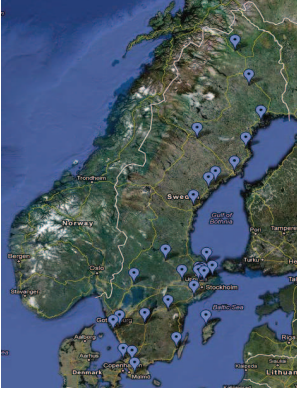
Fig. 1.    Locations of DME ground transponders in Sweden, based on http://worldaerodata.com/nav/. Last update in 2007. Background image from Google Maps.

sends an interrogation signal down to earth; second, the ground transponder responds on a frequency of $\pm 63$ MHz from the interrogation frequency after a delay of 50 $\mu$s. Based on the round trip delay of the signal, the airborne interrogator determines the slant range to the ground transponder. The pulses are burst more than 100 times per second by the interrogator and 2500 times by the transponder. The transmission power reaches up to 300 W for the interrogator and up to 2 kW for the transponder. In the frequency band allocated to the DME system, 962-1213 MHz, there are 252 channels of 1 MHz. The location of a ground transponder is fixed, as it is shown in Fig. 1. Instead the location of the airborne interrogator is rapidly changing. We limit the scope of this study to the portion of spectrum allocated only to the DME system, then the total bandwidth of interest is 190 MHz out of 252 MHz. A detailed description of the DME operation can be found in [11].

### B. Secondary access scenario

We consider a large-scale deployment of indoor access points and mobiles providing high capacity broadband services. For the numerical analysis, the total area of study is divided into rectangular pixels. In each pixel $i$, the density of secondary users $\lambda_{SU}^i$ is determined by the actual population density in that particular geographical area and the activity factor $f_a$. Let us consider an arbitrary secondary user $j$ which is distributed according to a homogeneous Poisson point process in a two dimensional plane $\Re^2$. Let $IT_k^v$ denote the interference threshold imposed on each secondary user accessing channel $k$ to protect the primary receiver $v$. Then, the interference from a secondary user $j$ in channel $k$ is given by

$$I_{k,j}^v = \begin{cases} \xi_{k,j}^v, & \text{if } \tilde{\xi}_{k,j}^v \leq IT_k^v \\ 0, & \text{otherwise} \end{cases} \qquad (1)$$

where $\xi_{k,j}^v = P_t^{eff} g(r_{v,j}) Y_j$ which is is the interference that the primary receiver $v$ would receive in channel $k$ if the secondary user $j$ were to transmit. $P_t^{eff}$ refers to the effective transmission power of the secondary user including antenna gains and bandwidth mismatch, $g(r_{v,j})$ is the path loss between the primary receiver $v$ and the secondary user $j$ and $Y_j$ is a random variable modeling the fading effect. $\tilde{\xi}_{k,j}^v$ is the estimate of $\xi_{k,j}^v$ by the secondary user $j$. Note that $\xi_{k,j}^v = \tilde{\xi}_{k,j}^v$ only when the secondary user has the perfect knowledge of the propagation loss. The aggregate interference from pixel $i$ at the primary victim $v$ in channel $k$ is

$$I_{k,i}^v = \sum_{j \in N_t} I_{k,j}^v \qquad (2)$$

where $N_t$ is the set of transmitting secondary users in pixel $i$. Finally, the aggregate interference at the primary receiver $v$ in channel $k$ is as follows

$$I_{k,a}^v = \sum_{i \in N_p} I_{k,i}^v \qquad (3)$$

where $N_p$ is the set of pixels within the area of aggregation. The mathematical models employed to compute the aggregate interference can be found in [12].

### C. Protection criteria

We consider that an arbitrary DME receiver can tolerate a maximum interference power of $A_{thr}$, which corresponds to -119dBm/MHz and -111dBm/MHz for the transponder and interrogator, respectively [11]. Since we are considering that all channels in the DME band could be simultaneously accessed by the secondary users. Then, not only the aggregate interference in a single channel but also the aggregate interference from multiple channels should not exceed maximum tolerable interference, $A_{thr}$, at the primary receiver [13]. The aggregate interference at a primary receiver, $v$, is regulated as follows

$$\Pr\left[\sum_{k \in N_v} I_{k,a}^v W_k \geq A_{thr}\right] \leq \beta_{PU} \qquad (4)$$

where $N_v$ is the set of channels whose interference aggregate at the primary receiver $v$. The weighting factor, $W_k$, depends on the filter's characteristics and $\beta_{PU}$ is the maximum permissible probability of harmful interference at the primary receiver. Due to the safety-of-life operation of the DME, $\beta_{PU}$ needs to be extremely small. We adopt a value used for air traffic control radar in 2.7-2.9 GHz, $\beta_{PU} = 0.001\%$ [8].

On the other hand, the interference from the DME transmitter to the secondary receiver is negligible since the DME generates only short pulses with sparse channel utilization (below 1%). However, the secondary receiver can be saturated if it receives a strong DME pulse. A secondary user can correctly operate if:

$$\Pr[I_{PU}^v > I_{sat}] \leq \beta_{SU} \qquad (5)$$

where $I_{sat}$ be the saturation point of the secondary receiver, $\beta_{SU}$ is the maximum saturation probability and $I_{PU}$ is the received primary pulse power. We adopt a value of $\beta_{SU} = 2\%$ and $I_{sat} = -30\text{dBm}$ which is a typical saturation level for low noise amplifier (LNA) in WLAN receivers [14]. With the adopted values for $A_{thr}$, a simple link budget analysis indicates that (4) is the limiting constraint even before taking the effect of multiple secondary users into account. Therefore, the remainder of the paper will focus only on the protection of the primary user.

## III. SECONDARY SHARING SCHEME

In this section, we briefly describe the secondary sharing schemes applied to our availability assessment. More detailed description can be found in [12]. Since the DME system is divided into the ground station and the airborne interrogator, different sharing mechanisms are applied to each component.

### A. Sharing with the ground transponder

The secondary users share the DME spectrum via sensing aided by geo-location databases. The reliability of the sensing mechanism is significantly improved by the use of geo-location databases, which provide the prior knowledge of the primary victim such as its transmission power, location and operating frequency. With this information and the fact that the transponders have fixed locations, the sensing mechanism is expected to be good enough to neglect missed detection and false alarm. Moreover, the geo-location database can rapidly detect and correct any detection error due to its continuous bidirectional communication with the primary and secondary users.

In the applied opportunity detection mechanism, notice that the secondary users detect the transponder on the reply (sensing) frequency, while the interference is given on the interrogation (interfering) frequency. Due to the 63 MHz frequency offset between these channels, *uncertainty* in the estimation of the fading component of the propagation loss still remains. The propagation losses between the DME transponder and the secondary user consist of the distance-based path loss and fading[1]. The correlation, $\rho$, between the fading components in the sensing $X$ and the interfering channels $Y$ will depend on the propagation environment.

### B. Sharing with the airborne interrogator

For the interrogators, spectrum sensing is not employed since their locations are rapidly changing. Secondary users share the DME spectrum via a real-time database where the frequency allocation and the locations of the primary victims (airborne interrogators) are provided. A living example of such a real-time aircraft location map can be found in [15]. An official database maintained by national authorities is expected to provide reliable information.

Based on the *update delay* in the communication between the geo-location database and the secondary users, secondary

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[1]Note that the fading here refers to the combined effect of shadowing and multi-path fading

users could potentially experience *uncertainty* or imperfect information on the location of the primary victim. Since the fading effect is not considered, applying individual threshold $IT_k^v$ will result in a circular exclusion region where secondary users are not allowed to transmit in channel $k$. The radius of exclusion region is denoted by $ER_k^v$. We introduce the notion of *error region*, where secondary users will assume the worst case scenario that the sky is full of airplanes. The size of the error region is defined by the time of update delay $t_u$ and the speed of the airplane $s$. Thus, $ER_k^v$ is given by

$$ER_k^v = \begin{cases} ERt_k^v + t_u s, & \text{if } ERt_k^v > 0, \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

where $ERt_k^v$ is the exclusion radius under the assumption that the secondary users know the exact location of the primary victim. Notice that if $ERt_k^v = 0$, then the uncertainty in the primary user location does not make any impact on the feasibility of the secondary users.

## IV. ASSESSMENT METHODOLOGY OF AVAILABILITY

In this section, we propose an assessment methodology for quantifying the *available* channels for indoor broadband secondary access to the aeronautical spectrum. The secondary system applies the sharing mechanisms described in Section III. We consider that the secondary users are indoor broadband devices connected to a geo-location database which controls the aggregate interference according to (4). In order to simplify the computation, we assume that all channels in $N_v$ generate the same amount of interference $M$ at the primary victim $v$. Therefore,

$$W_k I_{k,a}^v = M, \ \forall k \in N_v \tag{7}$$

Then, (4) can be re-written as:

$$\Pr[n(N_v)M > A_{thr}] \leq \beta_{PU} \tag{8}$$

where $n(N_v)$ is number of elements in $N_v$. Then, the aggregate interference in channel $k$ at the primary victim $v$, $I_{k,a}^v$, is regulated as follows:

$$\Pr\left[I_{k,a}^v > \frac{A_{thr}}{n(N_v)W_k}\right] \leq \beta_{PU} \tag{9}$$

By applying (9), the numerical analysis can be performed on single channel basis and the computation complexity is considerably reduced. We compute $I_{k,a}^v$ and determine the minimum requirements to satisfy (9). Both primary receivers, ground station and airborne interrogator, are considered in our calculation. The constraints to protect the primary victim $v$ in channel $k$ are given in terms of the individual interference threshold, $IT_k^v$, or the minimum separation between the DME receiver and the secondary users, $ER_k^v$. Then, a DME channel is considered as *available* in pixel $i$ if

$$D_{k,i} = \begin{cases} 1, & \text{when } \mathbb{E}[\tilde{\xi}_{k,j}^v] \leq IT_k \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

TABLE I
PARAMETERS USED FOR NUMERICAL EXPERIMENTS

| Parameters for ground transponder | |
|---|---|
| primary user transmission power | 60 dBm/MHz |
| path loss constant ($C$) | $4.5 \times 10^{-13}$ |
| path loss exponent ($\alpha$) | 3.5 |
| Fading standard deviation ($\sigma_{X_j}^{dB}$) | 10 dB |
| height of the transponder | 30 m |
| **Parameters for airborne interrogator** | |
| primary user transmission power | 55 dBm/MHz |
| path loss constant ($C$) | $5.7 \times 10^{-10}$ |
| path loss exponent ($\alpha$) | 2.0 |
| height of the interrogator ($h$) | 1 km |
| **Common parameters** | |
| radius of interference aggregation ($R$) | 200 km |
| building penetration loss | 10 dB |
| DME antenna gain | 5.4 dBi |
| secondary user antenna gain | 0 dBi |
| secondary user transmission power | 0 dBm/MHz |
| secondary user height | 1.5 m |

where

$$IT_k = \min(IT_k^1, ..., IT_k^v) \qquad (11)$$

Notice that $IT_k^v$ depends on the transmission power and the density of secondary users. To calculate the number of available channels in a pixel $i$, we simply sum all the channels where the secondary user can fulfil the requirements to protect the primary victim.

$$D(i) = \sum_{k \in K} D_{k,i} \qquad (12)$$

Similarly to the work done in [6], we consider the *average* available channels by *area* in the region.

$$m_a = \frac{1}{A_t} \sum_{i \in I} A_r^i D(i), \qquad (13)$$

where $A_t = \sum_{i \in I} A_r^i$ is the total area of the region. In the same manner, we calculate the *average* available channels by *population* in the region:

$$m_p = \frac{1}{p_0} \sum_{i \in I} P_i D(i). \qquad (14)$$

where $p_0 = \sum_{i \in I} P_i$ is the total population of the region.

## V. NUMERICAL RESULTS

For the case of ground transponder, we model the propagation loss between the primary victim and the secondary user using Hata model for suburban area. Instead, for airborne interrogator we employ free-space propagation loss. We adopt this assumption to account for the worst case scenario where there is line-of-sight path between every secondary user and the aircraft. The parameters used for our numerical experiments are described in Table I.

In our numerical experiments, two countries with different characteristics are considered: Sweden with a large geographical area but rather low population density and a small number of DME ground stations, and Germany with a smaller geographical area but high population density and a large number of DME ground transponders. Basic information about Germany and Sweden is given in Table II.

A country-wide evaluation of the availability in the DME band is shown in Fig. 2. We observe the spatial distribution of the population density has a strong influence in the spatial distribution of the availability. In Germany, we can observe that the availability is almost constant in all the territory same as its population density. On the contrary, the availability in Sweden has a large variance as its population density. For areas with rather low population density, the availability approaches 100% of the total bandwidth in consideration. Instead for dense cities where additional spectrum is actually needed, the availability is considerably lower due to the impact of the aggregate interference and the presence of DME transponders nearby. However, secondary users can anyway access at least 57 MHz bandwidth in any location of Germany or Sweden.

### A. Impact of secondary system parameters: transmission power and activity factor

In this subsection, we illustrate dependencies between the secondary system parameters and the availability. The impact of the secondary user transmission power on the availability is depicted in Fig. 3. A noticeable decrement in the average availability is observed when the transmission power increases to 10dBm/MHz. However, the minimum number of available channels remains constant in both countries, simply because the DME spectrum is sparsely allocated with unallocated 57 MHz throughout these countries.

Fig. 4 shows the impact of secondary user activity factor $f_a$. Note that we consider an extremely massive usage $f_a = 1$, which means that there are as many secondary devices as the whole population transmitting simultaneously. The increase in $f_a$ leads to higher aggregate interference, which can be controlled by lowering $IT_k$ or enlarging $ER_k$. The impact of $f_a$ is mainly observed in Sweden. This effect is not significant in Germany because its population density is more than ten times higher than the population density of Sweden. Thus, the availability in Germany is mostly limited to the unallocated DME channels.

TABLE II
BASIC INFORMATION OF THE COUNTRIES OF STUDY

| | Sweden | Germany |
|---|---|---|
| Population[a] [$\times 10^6$] | 8,886 | 82,250 |
| Area [km$^2$] | 431,704 | 356,027 |
| Number of DME ground transponders[b] | 30 | 79 |

[a] Population density data is an estimated based National Statistics Office (NSO) data in 2002. This can found at http://sedac.ciesin.columbia.edu/

[b] Location and frequency allocation of the DME system is based on http://worldaerodata.com/nav/. Last update in 2007
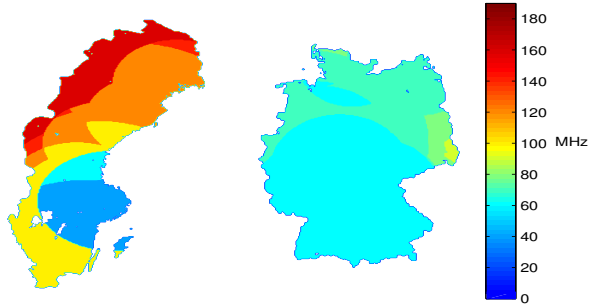
Fig. 2. Availability in Sweden (left) and Germany (right). ($SU_{Ptx} = 0$dBm/MHz, $f_a = 1$, $\rho = 1$ and $t_u = 0$min)
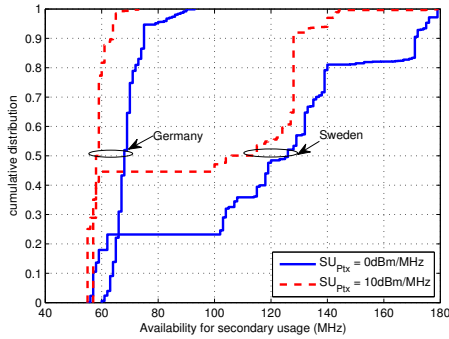


Fig. 3. CDF of the availability for different secondary user transmission power ($f_a = 1, \rho = 1$ and $t_u = 0$min)
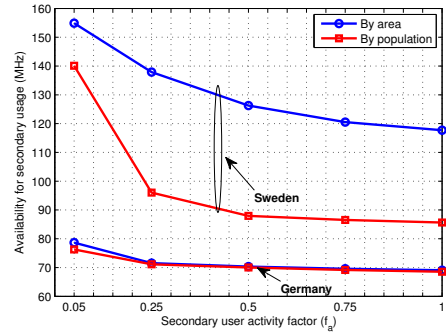


Fig. 4. Average availability for different secondary user activity factor ($SU_{Ptx} = 0$dBm/MHz, $\rho = 1$ and $t_u = 0$min)

### B. Impact of uncertainties in the sharing schemes

Depending on how accurate the fading estimation is or how fast the information is updated in the database, different uncertainty levels could affect the applied opportunity detection schemes. In our numerical experiments, we consider the worst-case scenario which means that uncorrelated fading ($\rho = 0$) is experienced in the interfering and sensing channels. For the airborne interrogator, we also deal with a pessimistic scenario where the update delay ($t_u$) is 150 seconds or 2.5 minutes. Currently, the living example of real-time aircraft location database is updated every 20-60 seconds [15].

In Table III, we show the impact of uncertainty on the fading is stronger for dense secondary network and high density of primary receivers, which is the typical situation for urban areas. This means that accurate sensing becomes more important in urban areas where the probability of harmful interference is higher. Instead, the impact of the update delay becomes more relevant for sparse secondary networks. Even with high levels of uncertainty, the average availability only decreases up to 6% compared to the ideal scenario where uncertainties are not present.

### C. Contiguous Bandwidth

To determine the carrier aggregation capabilities that the secondary user needs to access the available spectrum, we look into the contiguous available spectrum or adjoining available spectrum. In Fig. 5, we observe that despite the fact that there is high availability, most of the available spectrum is non-contiguous. For Sweden and Germany, the median number of contiguous available spectrum is smaller than 10 MHz. Therefore, secondary users need to have good carrier aggregation capabilities in order to fully exploit the availability in the DME band.

TABLE III
AVERAGE AVAILABILITY IN SWEDEN AND GERMANY

| Country | Sharing schemes | Average availability by area (MHz) | Average availability by population (MHz) |
|---|---|---|---|
| Sweden | $\rho$=1, $t_u$=0min | 117.6970 (61.30%) | 85.6323 (44.60%) |
| | $\rho$=1, $t_u$=2.5min | 110.1365 (57.36%) | 81.2953 (42.34%) |
| | $\rho$=0, $t_u$=0min | 114.5914 (59.68%) | 83.0755 (43.26%) |
| Germany | $\rho$=1, $t_u$=0min | 69.0680 (35.97%) | 68.5318 (35.69%) |
| | $\rho$=1, $t_u$=2.5min | 68.7083 (35.78%) | 68.1942 (35.51%) |
| | $\rho$=0, $t_u$=0min | 58.1505 (30.28%) | 57.8966 (30.15%) |



Fig. 5. CDF of the available contiguous spectrum in the DME band. ($SU_{Ptx} = 0$dBm/MHz, $p_a = 1$, $\rho = 1$ and $t_u = 0$min)

## VI. CONCLUSIONS

We investigated the availability of massive indoor broadband secondary access in the 960-1215 MHz band, primarily allocated to the DME system. We applied the practical sharing mechanisms proposed in [12], where the secondary users share the DME spectrum by means of spectrum sensing and geolocation database. We developed a methodology to assess the amount of available of spectrum in a large geographical area.

Our numerical experiments show that availability is location-dependent. For dense cities where additional spectrum is actually needed, the availability is considerably lower compared to rural areas. Th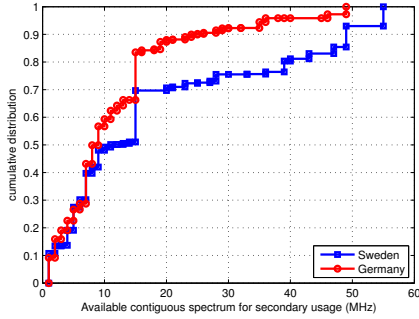is is mainly due to the effect of the aggregate interference and higher density of DME transponders close to the urban areas. Nonetheless, at least 57 MHz is available everywhere in Germany and Sweden. The uncertainties in the propagation loss estimation that accompany the applied practical sharing schemes do not have a critical impact on the average availability, which only decreases up to 6% for high uncertainty. Our results also show that good carrier aggregation capabilities are crucial for the secondary users in order to fully utilize the available spectrum which is mostly non-contiguous. Understanding the economic value of the available DME spectrum for secondary use remains as an interesting future study.

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# Chapter 11

# On the Sharing Opportunities for Ultra-Dense Networks in the Radar Bands (Paper 7)

# On the Sharing Opportunities for Ultra-Dense Networks in the Radar Bands

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*Abstract*—**Finding additional spectrum for indoor networks with very high capacity (ultra-dense networks, UDN) is a prime concern on the road to 5G wireless systems. Spectrum below or around 10 GHz has attractive propagation properties and previous work has indicated that vertical spectrum sharing between indoor users and outdoor wide-area services is feasible. In this paper, we focus on spectrum sharing between UDNs and radar systems. We propose and evaluate regulatory policies that improve sharing conditions/opportunities in areas with large demand (i.e. hot-spots and urban areas). We consider three regulatory policies: area power regulation, deployment location regulation and the combination of these. We address the scenario where secondary users can reliably exploit time and space domain sharing opportunities in the S- and Ku-Bands by means of geo-location databases and spectrum sensing. We evaluate these opportunities in terms of the required time-averaged separation distance between the radar system and the UDN that both protects the radar system as well as guarantees a minimum secondary transmission probability. Our results show that there are ample adjacent channel sharing opportunities for indoor usage in both the S- and Ku-Bands. In the Ku-Band, even outdoor hot-spot use is feasible with very relaxed restrictions. Co-channel usage in the S-band requires large separation distances that makes it practically unfeasible in cities with nearby radar sites. Overall, deployment location regulation seems to be the most effective means to limit interference to the radar system and improve sharing opportunities.**

*Index Terms*—**radar spectrum, spectrum sharing, sharing opportunities, regulatory policy**

## I. Introduction

The increasing popularity of wireless and mobile Internet access, and the proliferation of high-end handsets (e.g. tablets, smartphones) have originated a "data tsunami" in current wireless network [1]. This enormous growth in the global mobile data traffic is expected to continue in the coming years, reaching even 1000-fold increase by 2020 [2], [3]. Mobile broadband has become not only part of our everyday life, but also a big challenge for the mobile operators who need to improve the capacity of their current wireless networks while keeping their business profitable. Traditionally, improving technology has been the main strategy to achieve higher peak rates in a cost-efficient way. However, current capacity demands cannot be satisfied by only improving peak rates, we need to actually improve the average user data rate [1], [4]. This can be achieved by deploying denser networks and finding additional spectrum where the capacity demand is actually high. Approximately, 70% of the current data consumption is generated in indoor locations and "hot spots" [5] followed by urban areas with high user density [1]. Having denser networks represents a big investment for the mobile operators, it is thus crucial to have additional spectrum in these particular locations in order to affordable meet the explosion of traffic demand.

Spectrum sharing has been proposed as a practical solution to quickly open additional, currently underutilized, spectrum for mobile communications [6]. Spectrum sharing is most valuable in frequency bands where spectrum refarming/clearing cannot be done within a reasonable time frame. This paper focuses on vertical spectrum sharing, so called secondary spectrum access. Previous results have shown that the sweetspot for secondary spectrum access lies in short-range and indoor systems with medium to large capacity demands [7]. TV white space (TVWS) steamed as the prime candidate for providing additional spectrum for short-range communication. However, results in [8], [9] showed that TVWS was not suitable for indoor Wi-Fi like system due to the extended coverage range in this frequency band which increases congestion and self-interference, rapidly limiting the system capacity. These previous results raised the need to look for other frequency bands which could provide additional spectrum for short-range communication.

In Europe, the radio spectrum allocated to the radar systems (here denoted as the radar bands) represents a significant portion (approx. 1 GHz) of the allocated spectrum below 6 GHz and exhibits low spectrum utilization [10]. Due to the propagation characteristics of the radar bands, they become ideal candidates for providing additional capacity for indoor and short-range systems. Particularly for indoor systems where the attenuation given by the walls helps to considerably decrease self-interference in the system. Moreover, secondary spectrum access in the radar bands benefits from having prior knowledge of the primary victim location, which allows an accurate estimation of the interference. However, due to the high sensitivity level of the receivers and the extremely low permissible outage probability at the primary system, the control of the aggregate interference over a very large area becomes a challenging task. Secondary spectrum access to the radar bands faces different technical challenges from the ones in the TVWS, leading to different regulatory policies to enable large-scale secondary access which remain still underdeveloped. Technical feasibility of large-scale secondary spectrum access to some portions of the radar bands has been previously demonstrated [11]–[13]. Therefore, it is worthwhile investigating the regulatory policies that would improve shar-

ing conditions/opportunities for large-scale secondary access to the radar bands where the high capacity demand actually is (i.e. hot spots and urban areas).

### A. Related Work

In the last decade, extensive work has been done on addressing the technical, regulatory and business challenges of secondary spectrum access. Most of the technical work has focused on developing spectrum sensing techniques [14], obtaining theoretical capacity limits [15], [16] and identifying desirable system characteristics for different spectrum sharing scenarios [17]. Diverse aggregate interference models [18], [19] have also been proposed to evaluate the scalability of secondary systems [20]. Moreover, the amount of TV white spaces for US and Europe has been quantified with the objective of evaluating the potential real-life benefits of secondary systems [21], [22]. In the regulatory domain, previous work mainly focused on devising new frameworks to support technical requirements of vertical spectrum sharing, such as carrier aggregation [23], fairness between primary and secondary users considering location/time availability of spectrum [24] or the presence of databases [25]. Most of these works considered the TV band as primary system, leaving the evaluation of the potential of other frequency bands (e.g. the radar bands) for spectrum sharing still in early stages.

Spectrum sharing in the radar bands has recently increased its popularity in the international research and regulatory community. In the United States, the National Telecommunications and Information Administration (NTIA) identified a total of 115 MHz of additional spectrum in the radar bands which could be opened up (by means of spectrum sharing) for wireless broadband service provisioning [26]. Making this a reality will require technical and regulatory changes, which are still not clearly defined. Some previous studies addressed mainly technical challenges of spectrum sharing in the radar bands. For instance, initial feasibility results for LTE usage of the 2.7-2.9 GHz radar spectrum are presented in [27] where the analysis is based on a single secondary interferer. Also, sharing opportunities in the 5.6 GHz radar spectrum were assessed in [28]. Moreover, results in [11], [12] showed that a predictable rotation pattern can further enhance the sharing opportunities for the secondary users. Some of these results were employed to identify initial policy reforms needed to facilitate the implementation of vertical spectrum sharing in the radar bands [29]. These previous investigations mainly targeted technical challenges while the regulatory policies to enable large-scale secondary access in the radar bands remains still underdeveloped.

### B. Contribution

In this paper, we analyze regulatory policies that could improve the sharing conditions/opportunities for ultra-dense networks (UDNs) in the radar bands allocated below and above 10 GHz. For that purpose, we consider Air Traffic Control (ATC) radars (2.7-2.9 GHz) and Surveillance Radars (15.7-17.2 GHz) as examples of primary systems operating in the S- and Ku-Bands, respectively. By UDN we refer to a massive scale deployment of indoor/outdoor APs and mobiles providing high capacity broadband services for future scenarios in 2020 and beyond [30]. The UDN shares the spectrum with a rotating radar by means of geo-location databases and spectrum sensing that enables the secondary users to have prior knowledge of the radar rotation pattern, location, operating frequency, and transmission power. Thus, secondary users can reliably exploit sharing opportunities in the time and space domain. In our evaluation, these opportunities are inversely proportional to the required time-averaged separation distance $\bar{r_H}$ between the primary victim and the secondary transmitter in the hot zone that guarantees a minimum secondary transmission probability of $TX_{min}$.

The sharing opportunities in time and space domain will highly depend on the aggregate interference, which is determined by the secondary system characteristics. For instance, if freewheeling transmission and deployment of a very dense secondary system is allowed, we may end up with a required separation distance of several kilometers. This could eliminate the availability of sharing opportunities in cities (where capacity demand is high) that are nearby the radar. Thus, regulatory policies are needed to better exploit the trade-off between the density of active secondary users and the required separation distance. We consider three alternatives: regulation on the area power density, regulation on the deployment and the combination of both of them. In this paper, we aim at answering the following research questions:

- What are the sharing opportunities for indoor/outdoor deployment of ultra-dense networks (UDNs) in the radar bands?
- What regulatory policy should be preferred? How is the selection affected by the radar operating frequency or the spatial distribution of secondary users?

The rest of the paper is organized as follows: the secondary access scenario is described in Section II. The proposed regulatory policies are outlined in Section III. In Section IV, we specify the simulation parameters and discuss our numerical results. Finally, the main conclusions of this work and future directions are given in Section V.

## II. SECONDARY ACCESS SCENARIO

A clear description about the secondary access scenario is the first step towards the evaluation of the sharing opportunities in the radar bands. In [31], the authors identified the key elements that constitute a comprehensive assessment scenario: a primary system and spectrum, a secondary system and usage, and the methods and context of spectrum sharing. These elements will be presented in this section.

### A. Primary system description

Radar is an acronym for Radio Detection And Ranging. The basic operation principle of the radar consists of generating pulses of radio frequency energy and transmitting these pulses via a directional antenna. The radar indicates the range to the object of interest based on the elapsed time of the pulse

traveling to the object and returning to the radar antenna. The most common uses of radar are Ground based Aeronautical Navigation, Marine Navigation, Weather Detection and Radio Altimeters [32]. In this paper, we consider the ground-based rotating radars deployed in the S- and Ku-Bands. Specifically, we are considering Air Traffic Control (ATC) radars operating in the 2.7-2.9 GHz band and Surveillance radars such as Airport Surface Detection Equipment (ASDE) operating in the 15.7-17.2 GHz band as candidate primary systems. Notice that within 15.7-17.2 GHz, the precise allocation of Surveillance radars could vary depending on the country or region. For the ATC radars, the channel bandwidth can vary from 2 MHz to 6 MHz, depending on the radar type [33]. In contrast for Surveillance radars, the channel bandwidth could reach up to 100 MHz [32]. The different radar operating frequencies also impact the radar antenna size and the rotating pattern. For instance, radars operating in the S-Band are typically medium range systems (50 to 100 nm) with medium sized antennas rotating at 12 to 15 rpm in contrast to the radar operating in the Ku-Band which are short range systems ($< 20$ nm) with much smaller antennas and faster rotation of 20 to 60 rpm [32].

*Protection criteria*

In order to guarantee that the detection performance of radar systems is not degraded by harmful interference, a maximum interference-to-noise ratio (INR) threshold is established. The INR value defines the maximum allowable interference level relative to the noise floor at the radar receivers. For radars with safety-related functionality, the INR value is often set to very conservative value (i.e. -10dB) due to the high sensitivity of the radar receivers and very high antenna gain of the typical radar [33].

Due to the random nature of the radio propagation, the protection of the radar is expressed as a interference probability which refers to maximum allowable probability that the aggregate interference exceeds the tolerable interference level. The interference probability is mathematically expressed as follows,

$$\Pr\left[I_a \geq A_{thr}\right] \leq \beta_{PU} \qquad (1)$$

where $I_a$ is the aggregate interference from the UDN or secondary system, $A_{thr}$ is the maximum tolerable interference at the radar and $\beta_{PU}$ is the maximum permissible probability of harmful interference at the primary receiver. Due to the safety-related functionality of the radar, we applied conservative values for $A_{thr}$ and $\beta_{PU}$ which practically implies almost no interference violation. We adopt a very small value for $\beta_{PU}$ that is used for air traffic control (ATC) radar in 2.7-2.9 GHz, $\beta_{PU} = 0.001\%$ [33]. We set $A_{thr}$ based on the INR value, $A_{thr}(dB) = INR + N$, which drops to $A_{thr} = -119$ dBm/MHz for co-channel secondary access.

*B. Secondary system description*

We envisage an UDN as the secondary system in the radar bands. Secondary spectrum access would be the most
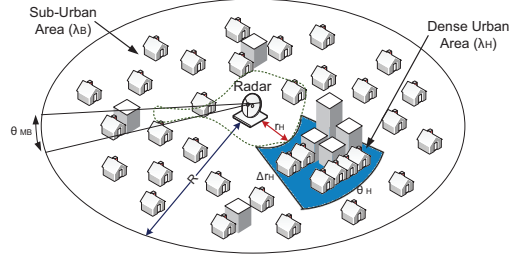


Fig. 1. Secondary Access Scenario. The rotating radar is the primary user with a beam width $\theta_{MB}$. Notice that the exclusion region (dotted line) has an irregular shape.

beneficial and attractive from the commercial point-of-view where we find the highest capacity needs taking into account that it has emerged as a solution to deal with the exploding mobile traffic demand. We consider the scenario where an already cellular network operating in dedicated/licensed spectrum opportunistically expand its network capacity by employing available spectrum in the radar bands. Due to the tremendous number of secondary users simultaneously transmitting over a large geographical area, controlling the aggregate interference with very high reliability becomes a difficult challenge.

In real environments, several zones with different user densities can be found in a large geographical area. For instance, user density in cities is typically higher than in rural areas. In order to reflect the heterogeneity in the spatial distribution of secondary users, we consider the hot zone model previously proposed in [34]. This model is represented by an annulus sector which has three parameters: $r_H$, $\triangle r_H$, and $\theta_H$. As illustrated in Fig. 1, $r_H$ is the distance between the hot zone and the primary user, the length of the hot zone (depth) is $\triangle r_H$, and the central angle (width) is given by $\theta_H$.

For this investigation, we consider circular region with one hot zone representing a highly populated urban area with density $\lambda_H$ surrounded by a less populated sub-urban/rural area or background area with density $\lambda_B$. Within the hot zone and background area, secondary users are assumed to be spatially distributed according to a homogeneous Poisson point process in a two dimensional plane $\Re^2$. The primary receiver is located at the center of the circular region limited by the radius $R$, which is the maximum distance from the primary receiver. Since we are considering a rotating radar with a predefined rotating pattern as the primary victim, secondary users are able to exploit sharing opportunities also in the time domain. Thus, sharing opportunities for secondary users in the radar band will depend not only on the distance $r_j$ to the primary victim, but also on the angle $\theta_j$ from the radar. Let us consider an arbitrary secondary user $j$, the interference that the primary user would receive if it were to transmit at a distance $r_j$ and

at an angle $\theta_j$ from the radar receiver can be expressed as

$$\xi_j(r_j, \theta_j) = G_r(\theta_j) P_t^{eff} g(r_j) Y_j \qquad (2)$$

where $P_t^{eff}$ refers to the effective transmission power of the secondary user including antenna gains and bandwidth mismatch. $Y_j$ is a random variable modeling the fading effect. The path loss between the primary receiver and the secondary user $j$ is modeled as $g(r_j) = C r_j^{-\alpha}$ where $C$ is a constant and $\alpha$ is the path loss exponent. $G_r(\theta_j)$ refers to the radar antenna gain dependent on the position of the secondary user and rotation of the antenna. Thus, $G_r(\theta_j)$ value will be changing in time domain for a secondary user with a fixed location according to

$$G_r(\theta_j) = \begin{cases} G_r^{max}, & \text{if } 0 \le \theta_j \le \theta_{MB} \\ G_r^{min}, & \text{otherwise} \end{cases} \qquad (3)$$

where $\theta_{MB}$ is the radar main beam width, $G_r^{max}$ and $G_r^{min}$ are the antenna gains corresponding to the main beam and side lobes of the radar. Let $I_{thr}$ denote the interference threshold imposed on each secondary user. The value of $I_{thr}$ is given to the secondary users by a central spectrum manager. Each secondary user accesses a particular channel or not by estimating the interference it will generate to the primary user. This ensures that each secondary user makes its own decision without interacting with the others. The interference from a secondary user $j$ is given by

$$I_j(r_j, \theta_j) = \begin{cases} \xi_j(r_j, \theta_j), & \text{if } \tilde{\xi}_j(r_j, \theta_j) \le I_{thr} \\ 0, & \text{otherwise} \end{cases} \qquad (4)$$

where $\tilde{\xi}_j$ is the estimate of $\xi_j$ by the secondary user $j$. Note that $\xi_j = \tilde{\xi}_j$ only when the secondary user has the perfect knowledge of the propagation loss. Considering that there are $N$ secondary users around the primary user, the aggregate interference is

$$I_a = \sum_{j \in N_t} I_j \qquad (5)$$

where $N_t$ is the set of transmitting secondary users. The mathematical models employed to compute the aggregate interference can be found in [13].

*C. Secondary sharing scheme*

In this analysis we consider the sharing mechanism proposed in [13], which is based on three design principles. The first principle states that a central spectrum manager controls the aggregate interference from potentially thousands or millions of secondary users and makes a decision on which user can transmit with what power. Thus, simple interference control functionality at the device level can be implemented for the real-time execution of the transmission decision. A central spectrum manager guarantees that the aggregate interference is reliably controlled, which is particularly important due to the safety related functionality of radar systems.

The second principle requires that secondary users employ the combined use of spectrum sensing and geolocation database for the interference estimation. Even though the hidden node problem is not present in the radar bands, spectrum sensing alone cannot provide the required accuracy because it could be affected by detection errors. Notice that due to the combined use of spectrum sensing and geo-location databases, spectrum sensing is expected to be reliable enough to ignore missed detection and false alarm. Thus, secondary users can reliably exploit sharing opportunities in the time and space domain. If a single detection mechanism is employed, it would be needed to add margins to account for any uncertainty on the interference estimation.

The third principle demands fast feedback loop between the primary user and the spectrum manager, so any violation of the maximum tolerable interference can be rapidly detected. This principle might be redundant in practical deployments given that the application of the second principle guarantees accurate calculation of the aggregate interference. However, we consider this principle to provide additional protection of the radar receivers.

*Performance Metric*

We analyze the sharing opportunities in terms of the time-averaged minimum required separation distance $\bar{r}_H$ between the radar receiver and the hot zone such that an arbitrary secondary user $j$ in the hot zone is able to access the radar bands with a minimum transmission probability, $TX_{min}$. Thus, $\bar{r}_H$ is given by

$$\bar{r}_H = \mathbb{E}_{\theta_i}[r_H] \qquad (6)$$

where $r_H = f(\theta_i)$ which is determined by the following condition

$$\Pr[\tilde{\xi}_j(r_H, \theta_i) \le I_{thr}] \ge TX_{min}, \forall \theta_i \in [0, 2\pi] \qquad (7)$$

Notice that the transmission probability of the secondary users will vary according to the value of $I_{thr}$ determined by the transmission power and number of active secondary transmitters, which will depend on the selected regulatory policy. In our evaluation, we consider $TX_{min} = 95\%$.

### III.  Regulatory Policy Options

In this section, we describe different regulatory policies that impact the trade-off between the density of secondary users and the required separation distance. This consequently also impacts the availability of time and spatial sharing opportunities in the radar bands. Fig. 2 illustrates how the different regulatory policies impact the size of the irregular exclusion region.

*A. Area Power Regulation (APR)*

We consider that secondary system transmissions are based not only on the protection of the radar system or primary, but also on the number of simultaneous transmissions within a contention area. This means that if secondary users are located very close to each other, then only one of them will be able to
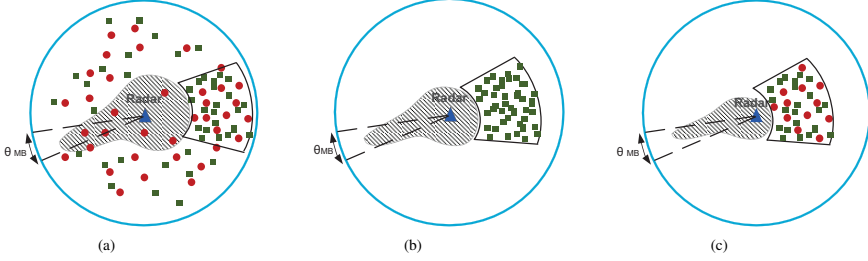
Fig. 2. Regulatory Policy Options: a)Area Power Regulation, b)Deployment Location Regulation and c)Combined Regulation. The radar (blue triangle) is surrounded by transmitting secondary users (green squared), not transmitting secondary users (red circles) and an irregular exclusion region (shadow area).

transmit at a given time. Thus, the area power of the secondary system is regulated to effectively reduce the interference between secondary users and the aggregate interference towards the primary victim. Then, the transmission of a secondary user $j$ will be regulated by the following

$$I_j^{APR} = \begin{cases} \xi_j, & \text{if } \tilde{\xi}_j \leq I_{thr}^{CS} \text{ and } I_{SU} \leq I_{CS} \\ 0, & \text{otherwise} \end{cases} \quad (8)$$

where $I_{thr}^{CS}$ denote the interference threshold imposed on each secondary user to protect the primary system, $\xi_j$ is the interference that the primary user would receive if the secondary user were to transmit, $\tilde{\xi}_j$ is the estimate of $\xi_j$ by the secondary user $j$, $I_{SU}$ is the interference to the nearest secondary user and $I_{CS}$ is the maximum tolerable interference at the secondary user. The aggregate interference at the primary victim can be described as

$$I_a^{APR} = \sum_{j \in N_{APR}} I_j^{APR} \quad (9)$$

where $N_{APR}$ is the set of transmitting secondary users which fulfill (8).

### B. Deployment Location Regulation (DLR)

We consider that secondary system transmissions are only allowed within a specific geographical area (e.g. a city or a town). This means that secondary access to certain frequency band is not allowed outside this area. In contrast to APR, secondary users are able to transmit even if they are very close to each other, meaning that the network density is not regulated within the allowed area. Thus, secondary users regulate its interference according to (10)

$$I_j^{DLR} = \begin{cases} \xi_j, & \text{if } \tilde{\xi}_j \leq I_{thr}^{S_A} \text{ and } D_j \in S_A \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

where $D_j$ refers to the location of the secondary user $j$ and $S_A$ represents the area where secondary user transmissions are allowed. Then, the aggregate interference at the primary victim can be described as

$$I_a^{DLR} = \sum_{j \in N_{DLR}} I_j^{DLR} \quad (11)$$

where $N_{DLR}$ is the set of transmitting secondary users. This regulatory policy aims at enabling and improving sharing opportunities in urban or metropolitan areas where the capacity demand is typically extremely high.

### C. Combined Regulation (CBR)

We consider that secondary system transmissions are only allowed within a specific geographical area (e.g. a city or a town) and the number of simultaneous transmissions within a contention area is also regulated. Notice that this option is a combination of Area Power Regulation and Deployment Location Regulation, thus secondary users regulate its interference by combining (8) and (10).

### IV. NUMERICAL EVALUATION

#### A. Simulation Environment

The parameters used for our numerical evaluation are described in Table I. For the case of sharing in the S-Band, we model the propagation loss between the primary victim and the secondary user using Modified Hata model for suburban area [35]. Instead for the case of sharing in the Ku-Band, we employ the propagation model proposed in [36] combined with the rain attenuation values given in [37]. In both frequency bands, we investigate the impact of the proposed regulatory policies on the sharing opportunities for an UDN and we provide results for co-channel usage and as well as adjacent channel usage. This means that the condition (1) is changed to $\Pr[I_a > (A_{thr} + ACR)] \leq \beta_{PU}$ when we evaluate the adjacent channel usage. The values of ACR will vary according to the frequency separation. In this investigation, we assume a conservative ACR value of 40dB which much lower than typical ACR values given in [32], [38].

As mentioned in Section II-B, we consider the hot zone model to account for the impact of the spatial heterogeneity on the benefits of the proposed regulatory policies. In our evaluation, the typical scenario corresponds to the case when the network density in the suburban/rural area is half of the one in the urban area ($\lambda_H/\lambda_B = 2$). Moreover, we look into

TABLE I
PARAMETERS USED FOR NUMERICAL EXPERIMENTS

| Parameters for S-Band | |
|---|---|
| path loss model SU - PU | Modified-Hata [35] |
| Fading standard deviation ($\sigma_{X_j}^{dB}$) | 9 dB [35] |
| path loss model SU - SU | Keenan-Motley [39] |
| height of the radar | 8 m |
| building penetration loss | 10 dB |
| outdoor secondary user transmission power | 10 dBm/MHz |
| **Parameters for Ku-Band** | |
| path loss model SU - PU | Outdoor Model [36] |
| Fading standard deviation ($\sigma_{X_j}^{dB}$) | 9 dB |
| path loss model SU - SU | Keenan-Motley [39] |
| height of the radar | 8 m |
| building penetration loss | 20 dB [40] |
| outdoor secondary user transmission power | 20 dBm/MHz |
| **Common parameters** | |
| radius of interference aggregation ($R$) | 200 km |
| radar antenna gain ($G_r^{max}, G_r^{min}$) | (41 dBi,12 dBi) |
| radar noise figure | 5 dB [32], [41] |
| indoor secondary user antenna gain | 0 dBi |
| indoor secondary user transmission power | 0 dBm/MHz |
| indoor secondary user height | 1.5 and 30 m |
| outdoor secondary user antenna gain | 10 dBi |
| outdoor secondary user height | 10 m |
| area of the Hot Zone | 245 km$^2$ |
| radar main beam width | 3$^o$ |

the extreme cases: homogeneous scenario ($\lambda_H/\lambda_B = 1$) and very heterogeneous scenario ($\lambda_H/\lambda_B = 10$). Finally, we also take into consideration the impact of above the clutter indoor users which means that 25% of indoor users are located at height of 30 m.

### B. Results

We present our numerical results on the benefits that different regulatory policies could bring in different radar bands. These benefits are evaluated in terms of the required time-averaged separation distance between the primary victim and the hot zone to avoid harmful interference and guarantee $TX_{min}$.

*1) S-Band:* Fig. 3 and Fig. 4 show how the proposed regulatory policies can impact the indoor and outdoor sharing opportunities to the 2.7-2.9 GHz band, respectively. Based on these results, we observe that exploiting indoor/outdoor co-channel sharing opportunities in this band requires challenging sharing conditions (i.e. very large separation distance) if no regulation is applied. Applying the proposed regulatory policies can considerably reduce the required separation distance (around 60% for the highest network density when applying Combined Regulation), but still the exploitation of co-channel sharing opportunities seem quite difficult since at least 40 km separation distance is required to protect the radar receivers. This could potential melt down any possibility of secondary usage in close-by cities.

On the other hand, adjacent channel sharing opportunities are more promising for the indoor and outdoor scenario even though we considered a very conservative ACR value of 40 dB.
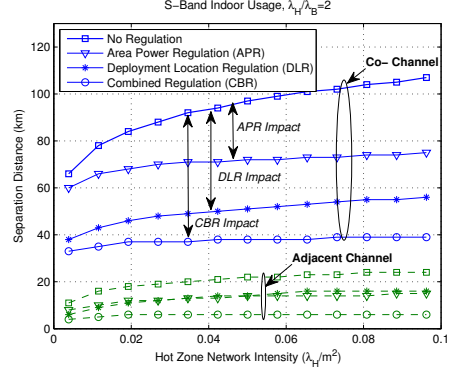


Fig. 3.   S-Band Indoor Usage, $\lambda_H/\lambda_B = 2$
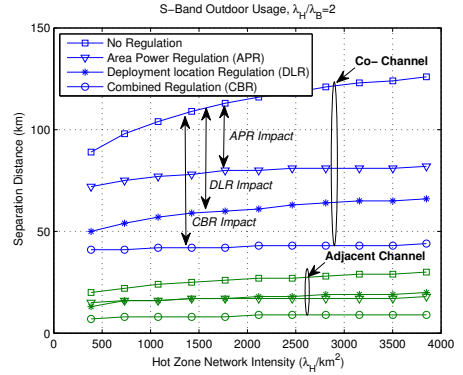


Fig. 4.   S-Band Outdoor Usage, $\lambda_H/\lambda_B = 2$

By applying either APR or DLR, the required separation distance can be reduced 50%, reaching values of 16 km (indoor) and 20 km (outdoor) for extremely high network density. Notice that both regulatory policies have an equivalent impact, opposite to the co-channel case where benefits from DLR were significantly larger. Also, considering CBR makes more sense for exploiting indoor/outdoor adjacent channel sharing opportunities since the required separation distance drops to 6 km (indoor) and 9 km (outdoor), enabling blind deployment of UDNs in cities near the radar.

Previously, we observed that CBR could actually reduce the required separation, therefore improving the sharing opportunities. But, if we could only applied a single option, which *regulatory option* should we choose? In Fig. 5 and Fig. 6, we look into the impact of the spatial heterogeneity on the benefits that different regulatory policies. Based on the results, applying DLR has the strongest impact on the reduction of

S–Band Co–channel Indoor Usage, $\lambda_H = 0.05/m^2$
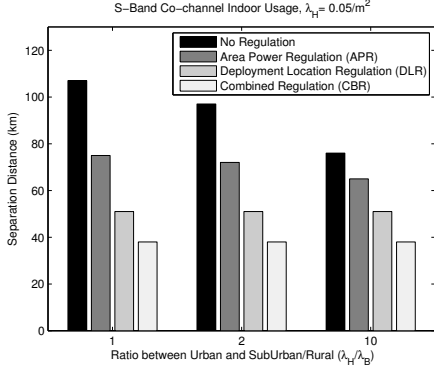


Fig. 5.   Impact of spatial heterogeneity: S-Band Indoor Co-channel Usage

S–Band Adjacent channel Indoor Usage, $\lambda_H = 0.05/m^2$



Fig. 6.   Impact of spatial heterogeneity: S-Band Indoor Adjacent Channel Usage

the required separation distance if only co-channel usage is considered. However, looking at the adjacent channel usage, DLR is still the best regulatory option for the homogeneous scenario ($\lambda_H/\lambda_B = 1$) or when the difference in network density between urban and rural areas is negligible. Instead for very heterogeneous scenario ($\lambda_H/\lambda_B = 10$), APR would be more beneficial.

In Table II, we examine the sensitivity of our results with respect to the protection criteria. Results show that the required separation distance is mostly affected by the INR value, while the value of $\beta_{PU}$ has almost no impact. This can be explained by our model which considers a stringent threshold in (1) and assumes perfect knowledge of the propagation loss, leading to effectively remove strong interferes and considerably reduce the variance of the aggregate interference distribution.

*2) Ku-Band:* We also analyze the sharing opportunities for UDNs in the 15.7-17.2 GHz band. The first observation

TABLE II
SEPARATION DISTANCE FOR DIFFERENT PROTECTION CRITERIA

| No Regulation | | |
|---|---|---|
| | $\beta_{PU} = 0.001\%$ | $\beta_{PU} = 5\%$ |
| INR = 0 dB | 76 Km | 75.2 Km |
| INR =-10 dB | 107 Km | 106.2 Km |
| INR =-20 dB | 146 Km | 145.4 Km |
| **Deployment Location Regulation** | | |
| | $\beta_{PU} = 0.001\%$ | $\beta_{PU} = 5\%$ |
| INR = 0 dB | 42 Km | 41.5 Km |
| INR =-10 dB | 56 Km | 55.3 Km |
| INR =-20 dB | 73 Km | 72.8 Km |

is that even though the propagation characteristics of this frequency band, the deployment of UDNs can lead to a required separation distance of up to 13 km (indoor) and 30 km (outdoor) for co-channel secondary usage. Fig. 7 shows that applying any of the three proposed regulatory policies can almost eliminate the need for a minimum separation distance (around 1 km) in order to exploit indoor co-channel sharing opportunities. For the outdoor case, the aggregate interference can have a larger impact, leading to a required separation distance of up to 30 km, as shown in Fig. 8. However, applying DLR can reduce the separation distance to less than 5 km.

Based on these results, we can conclude that applying any of the proposed regulatory policies can enable blind co-channel deployment of UDNs or exploitation of sharing opportunities in the space domain. Improving co-channel sharing opportunities in the 15.7-17.2 GHz band can be more beneficial than in the 2.7-2.9 GHz band due to the existence of old transmitter technologies with poor filtering characteristics and the more challenging requirements for the exploitation of the time domain sharing opportunities. Therefore, infeasible co-channel secondary usage can significantly decrease total available spectrum for vertical spectrum sharing in the Ku-band. Our results for the case of adjacent channel usage show that the impact of aggregate interference is negligible even with pessimistic assumptions and high secondary user transmission power (20 dBm/MHz). Thus, the benefit of applying any type of regulation is marginal for exploiting adjacent channel indoor/outdoor sharing opportunities since blind deployment of UDNs is feasible without requiring any regulation.

## V. CONCLUSIONS

The "data tsunami" and the large expected increase in the total mobile traffic demand has raised new capacity requirements in current wireless networks. One of the key resources to meet these new requirements in a cost-efficient way is finding additional spectrum where the capacity demand is high (hot spots and urban environments). Spectrum sharing is a practical solution to quickly open additional, currently underutilized, spectrum for mobile communications. In this paper, we analyzed regulatory policies to improve sharing conditions/opportunities for indoor and outdoor ultra-dense networks in the radar bands, specifically the S- and Ku-Bands. These policies have been proposed with the objective of better
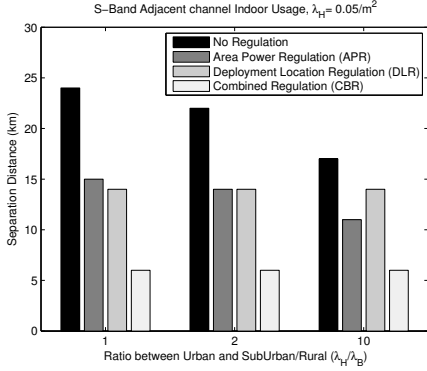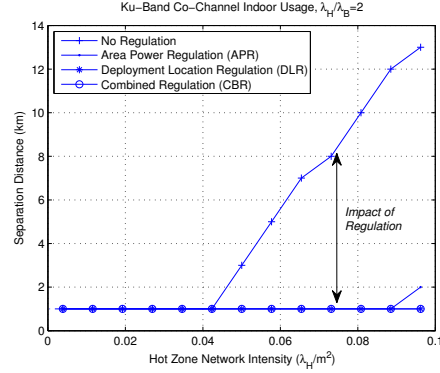
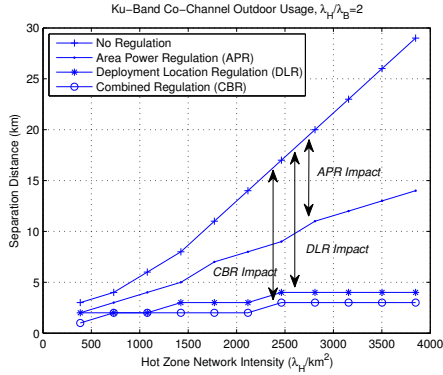Fig. 7. Ku-Band Co-Channel Indoor Usage, $\lambda_H/\lambda_B = 2$



Fig. 8. Ku-Band Co-Channel Outdoor Usage, $\lambda_H/\lambda_B = 2$

exploiting the tradeoff between the density of secondary users and the required separation distance. We consider three regulatory policies: area power regulation, deployment location regulation and the combination of them.

Numerical results showed that indoor and outdoor co-channel sharing opportunities for UDNs in the S-Band are limited for cities near the radar since large separation distances (around 40 km) are required even if CBR is applied. Instead indoor and outdoor adjacent channel sharing opportunities for UDNs seems promising and applying CBR could lead to very small separation distances (less than 10 km) even for very high network density. In the Ku-Band, the impact of interference aggregation is much less critical so exploitation of indoor sharing opportunities in urban areas close-by the radar is possible even if no regulation is applied (13 km separation distance for the highest density). For the outdoor case, adjacent channel sharing opportunities can be fully exploited without

regulation and blind co-channel deployment of UDNs if any of the proposed regulatory policies is applied.

Overall, applying any of the proposed regulatory policies results more beneficial in the S-Band given that the impact of interference aggregation is higher. Instead in the Ku-Band, the benefit of applying any policy was less significant since (almost) blind deployment of UDNs is feasible without requiring any restriction. The heterogeneity in the spatial distribution of secondary user impacts the selection of a regulatory policy: applying DLR has the strongest impact on the reduction of the required separation distance, especially when the difference in network density between urban and rural areas is negligible (homogeneous environment).

In this investigation, we have adopted general and conservative values for characterizing the radar systems and assessing the benefits of the proposed regulatory policies. Further work can focus on analyzing the impact of the proposed regulatory policies on the spectrum availability for a particular country or region where specific frequency allocation and actual usage of radar systems in the S- and Ku-Bands are considered. Moreover, a regulatory framework that could enable the real life implementation of the regulatory policies and sharing mechanism proposed in this paper needs to be determined.

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# Chapter 12

# Secondary Access to the Radar Spectrum Bands: Regulatory and Business Implications (Paper 8)

# Secondary Access to the Radar Spectrum Bands: Regulatory and Business Implications

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## Abstract

The large expected increase in the capacity requirements raises not only technical issues but also regulatory and business challenges. One of the key methods to increase the capacity of mobile networks in a cost efficient way is to find additional frequency spectrum. However, it is a difficult task since most of the spectrum is already allocated in long-term basis. Therefore, innovation in the technical and regulatory domain is needed to make additional spectrum available for mobile communications that not only improve spectrum utilization but also to make long-term investments feasible. Secondary spectrum access was proposed as a technical solution to improve spectrum utilization. However, uncertainties on the regulatory regime have been the main "show-stopper" for long-term investments. This paper has devised techno-regulatory conditions for making large-scale secondary access to the "radar bands" an attractive business scenario from the MNO's perspective. Our numerical results showed that applying regulation on the deployment of secondary users can significantly improve sharing opportunities, especially in lower frequency bands (S-band) where the impact of interference aggregation is higher. We also identified Licensed Shared Access (LSA) as suitable authorization model for secondary access to the "radar bands" since it provides the level of reliability on the protection against harmful interference and it could also motivate long-term investments. Finally, establishing the right spectrum access cost or license fee for secondary access to the "radar bands" is crucial for achieving competitive edge over alternatives indoor solutions.

*Index terms – radar bands, secondary spectrum access, secondary access availability, spectrum opportunities.*

## 1. Introduction

The "data avalanche" in mobile networks caused by the proliferation of high-end handsets and the large expected increase in the average traffic per device brings new capacity requirements to current wireless networks [1]. This does not only give rise to technical issues but also regulatory and business challenges. One of the key methods to increase the capacity of mobile networks in a cost efficient way is to find additional frequency spectrum. Current long-term, exclusive licensing regimes are preferred by Mobile Network Operators (MNOs) since they are guaranteed access to spectrum over long periods of time to match their long-term investments. Finding spectrum for exclusive allocation, however, is a difficult task since most of the spectrum is already allocated existing services on a long-term basis. Therefore, other ways of making additional spectrum available for mobile communications are being investigated, that require innovation in the technical and regulatory domain to not only improve spectrum utilization but also to make long-term investments feasible.

Secondary spectrum access has been proposed as a technical solution to improve spectrum utilization [2]. Extensive previous work has proved that secondary access is technically possible. However, uncertainties on the regulatory regime (i.e. cost, liability, etc.) have been the main "show-stopper" for the MNOs to invest on the commercial roll-out secondary networks. Recently, some of these uncertainties has been addressed for enabling secondary access to the TV broadcasting band, so called TV white spaces (TVWS) [3, 4]. However, these uncertainties have not been investigated in other frequency bands, such as the radar band. In Europe, the spectrum allocated to radars (here denoted the "radar bands") represents a significant portion (approx. 1GHz) of the allocated spectrum below 6GHz and exhibits low spectrum utilization [5].  Previous studies showed that large-scale secondary access to some portions of this band is technically feasible [6, 7]. Therefore, it is worthwhile investigating the regulatory regime and economic potential of secondary access to this band.

Secondary access to the radar band faces different technical challenges from the ones in the TVWS, leading to different regulatory policies to enable large-scale secondary access to the radar bands. In this investigation, we aim at *devising the regulatory policies to make large-scale secondary access to the radar band an attractive business scenario.* Particularly, we consider an incumbent MNO as potential operator because results in [8, 9] showed that it is type of operator which obtains the largest benefits from secondary spectrum access.

Previous works on secondary spectrum access have addressed diverse technical, regulatory and business challenges, mostly related to the TV broadcasting band [3, 10]. The link between technical and regulatory solutions is, however, frequently unclear. A coherent techno-regulatory proposal is needed to minimize uncertainty on business scenarios for operators that could retard the commercial deployment of secondary networks. In [7], the authors identified policy reforms needed to facilitate the implementation of proposed technical solutions for hierarchical spectrum sharing, highlighting the relationship between technical and regulatory challenges. In this paper, we will also analyze the techno-regulatory conditions in the radar band and their impact on the business attractiveness for

existing MNOs. Firstly, the key technical characteristics of secondary access to the different radar bands will be identified. Secondly, the technical findings will be employed to qualitatively evaluate a suitable authorization scheme. Finally, we analyze how the authorization scheme and proposed regulatory policies could benefit the business scenario of the incumbent MNO.

## 2. Spectrum sharing in the "radar bands"

### 2.1. Description and basic operation of radar systems

Radar is an acronym for Radio Detection And Ranging. The basic operation principle of the radar consists of generating pulses of radio frequency energy and transmitting these pulses via a directional antenna. When a pulse imposes on an object in its path, a small portion of the energy is reflected back to the antenna. The radar is in the receiving mode in between the transmitted pulses, and receives the reflected pulse if it is strong enough. The radar indicates the range to the object as a function of the elapsed time of the pulse traveling to the object and returning. In general, the most common uses of radar are: Ground based Aeronautical Navigation, Marine Navigation, Weather Detection and Radio Altimeters. Radar stations may be fixed or mobile, and some are mounted on ships. Mobile radars are often military [11].

Some radar applications such as Air Traffic Control (ATC), Secondary Surveillance Radar (SSR) and Maritime Surveillance are clearly identified as "Safety of Life" services. Other radar applications, such as ground based weather radars, provide a safety-related function. Long range systems (up to 250nm) use L-Band with large antenna rotating at 5 rpm Medium range systems (50 to 100 nm) use S-Band with medium sized antennas rotating at 12 to 15 rpm and short range systems (< 20 nm) use X or Ku-Band and tend to have much smaller antennas and faster rotation (20 to 60 rpm) rates [11]. Therefore, above 10GHz might be challenging to exploit time-domain sharing opportunities.

It is common to define a maximum interference-to-noise ratio (INR) threshold at the radar that defines the maximum allowable interference level relative to the noise floor, such that detection performance of the primary radar system is not unduly compromised. Large INR thresholds mean that the radar has a better interference tolerance capability. For radars with safety-related functionality, the INR value is often set to -10dB [12]. Due to the high sensitivity and low selectivity of the radar receivers and very high gain of the typical radar antenna, the maximum tolerable co-channel interference level could drop to -119dBm/MHz. Therefore, devising policies and sharing mechanisms for an efficient control of the co-channel and adjacent channel aggregate interference over a large geographical area becomes critical for allowing secondary access to the radar bands.

### 2.2. Current regulatory trends

Some portions of the radar bands have been recently allocated to communication services. For instance, the ITU decided to allocate the spectrum between 5150 and 5350 MHz and between 5470 and 5725 MHz on a co-primary basis to "Wireless Access Systems including RLANs" under the condition that RLANs would implement a sharing mechanism called Dynamic Frequency Selection

(DFS) according to ITU-R Recommendation M.1652 [13]. Such a mechanism has the objective of detecting and avoiding causing co-channel interference into radars [14].

In the United States, the National Telecommunications and Information Administration (NTIA) has recently devoted efforts on identifying frequency bands that could be made available for wireless broadband service provisioning. Based on the results of the Fast Track evaluation, a total of 115 MHz of additional spectrum (1695-1710 MHz and 3550-3650 MHz bands) has been identified for wireless broadband implementation [15]. Making this a reality will require changes on the equipment of current systems (e.g. radar systems) and the regulatory rules given by the Federal Communications Commission (FCC). President's Council of Advisors on Science and Technology (PCAST) investigations in [16] suggest that a feasible way to enable broadband deployment on the 3550-3650 MHz (radar) band would be implementing an extension of the White Space system already developed and deployed by the FCC and various third party vendors in the TV Bands. Meanwhile, the Commission just recently proposed sharing with the radar system by means of "licensed-light" basis [17]. To date, the identification of the needed technical and regulatory changes is an open issue.

Secondary spectrum access to the TVWS has been extensively studied during the last decade. From the regulatory viewpoint, the main condition was to avoid harmful interference to the TV receivers and PSME with unknown location. To fulfill this constraint, different methods were proposed and evaluated by a several regulators: geolocation databases, spectrum sensing and beacons. The latter one was discarded due to its costly infrastructure requirements and its lack of guaranteed protection against harmful interference. Instead the use of geolocation databases has been adopted worldwide, i.e. US, UK, Europe, due to its proven technical capability to protect the primary system. Approaches based on spectrum sensing only has been mostly discarded, unless very low transmission power is employed (50mW), since it does not guarantee the protection of passive TV receivers [18]. However, the combination of geolocation databases and spectrum sensing could be beneficial when dealing with aggregate interference or fairness in secondary sharing. This combination could be particularly beneficial in the radar bands since the potential of spectrum sensing could be better exploited given that the hidden node problem[1] is not present in these bands. Moreover, the control of the aggregate interference can be done more accurately so extremely conservative values can be avoided. In the radar bands, the conservative values could be much lower than in the TV bands due to the high sensitivity of the receivers, eliminating the opportunities for secondary access.

The regulatory bodies OFCOM and FCC have considered the licensed-exempt approach for secondary spectrum with the objective of promoting innovation in the use of the TVWS [18]. However, the commercial take-off of mobile networks using the TVWS is retarded mainly due to the lack of incentives for long-term investments on the network deployment and equipment development. Recent studies in [16] suggest that other types of licensing, even though they may not be totally free or may

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[1] The hidden node problem occurs in the wireless networks when a node is not visible to other nodes communicating during the sensing phase. This leads to harmful interference or corrupted data since the transmitter is not aware of the other node's presence.

not allow universal access in space or time domain, could be an incentive for a better economy of scale in the white spaces.

## 3. Secondary Access Availability in the "radar bands"

In this analysis, we explore the fact that having a denser secondary system leads to a larger *exclusion region* due to the higher aggregate interference. By exclusion region, we typically mean a circular area where no secondary user is allowed to guarantee the acceptable level of interference at the primary receiver which is located at the center of this area [19]. Then, if freewheeling transmission and deployment of a very dense secondary is allowed, we may end up with an exclusion region radius of several kilometers. Regulatory policies are needed to better exploit the tradeoff between the density of secondary users and the size of the exclusion region. This work considers three alternatives: regulation on the density of transmitting secondary users (e.g. by means of CSMA), regulation on the deployment of secondary users (e.g. allowed secondary usage in the big cities only) and the combination of both of them. The benefits of these alternatives for the secondary access availability are evaluated in terms of the time-averaged exclusion region radius.

Our analysis mainly focused on the primary-secondary sharing between a radar system and indoor system providing broadband services. The ground-based radar radiolocation systems deployed in the S and Ku band are the candidate primary systems. Particularly, we are considering Air Traffic Control (ATC) radars operating in the 2.7-2.9 GHz band and Surveillance Radar in the 16.7-17.3 GHz. The latter frequency band is also allocated to other services such as earth exploration satellites, space research and defense systems. Considering these two frequency bands with different propagation characteristics will give us insights on how the frequency band can impact the technical and regulatory approach for enabling secondary access in the radar bands. Due to the random nature of the radio propagation, the protection of the radar is expressed as a interference probability which refers to maximum allowable probability that the aggregate interference exceeds the tolerable interference level. The interference probability is mathematically expressed as follows,

$$\Pr(I_a \geq A_{thr}) \leq \beta_{PU}$$

where $I_a$ is the aggregate interference from the secondary system, $A_{thr}$ is the maximum tolerable interference at the radar and $\beta_{PU}$ is maximum probability of harmful interference. Since the two primary systems provide safety related services, we adopt the INR value of -10dB and $\beta_{PU}$ is set to an extremely small value which practically implies almost no interference violation, $\beta_{PU} = 0.001\%$[12].

In the numerical analysis conducted in Section 3.1 and 3.2, we consider multiple secondary users sharing with single rotating radar. We envisage a large-scale deployment of indoor access points and mobiles providing high capacity broadband services as secondary system, which exploits the space and time domain sharing opportunities in the radar band. We consider indoor secondary usage due to the high capacity needs in indoor environments, i.e. 70% of today's total mobile traffic demand [20]. Moreover, the indoor secondary usage would be helpful for mitigating the interference

towards the primary victim because each secondary device would emit very low transmission power with a short coverage requirement. The reliable control of the aggregate interference in the radar band is a critical requirement due to the high sensitivity of the receivers. Therefore, a reliable sharing mechanism is needed to control the interference from a huge amount of secondary user simultaneously transmitting over a large area.

In this analysis we consider the sharing mechanism proposed in [21], which was tailored to the distance measuring equipment (DME) system but can be also adapted to the radar bands in consideration. That mechanism is based on three design principles. The first principle stipulates that *a central spectrum manager* controls the aggregate interference from potentially millions of secondary users and makes a decision on who can transmit with what power. Therefore, simple interference control functionality at the device level can be implemented for the real-time execution of the transmission decision. The second principle requires that secondary users employ the combined use of *spectrum sensing and geolocation database* for the interference estimation. Even though the hidden node problem is not present in the radar bands, spectrum sensing alone cannot provide the required accuracy because it could be affected by detection errors. The third principle demands fast feedback loop between the primary user and the spectrum manager, so any violation of the maximum tolerable interference can be rapidly detected. These design principles has been set mainly considering the primary receiver protection. Therefore, the current analysis aims at devising new principles that could improve the secondary access availability from the secondary system perspective. The parameters employed in our investigation are summarized in Table 1.

**Table 1 Simulation Parameters [11]**

|  | S - Band | Ku - Band |
|---|---|---|
| Antenna main beam gain (dBi) | 35 | 38 |
| Antenna side-lobe attenuation (dB) | 21 | 26 |
| Antenna height (m) | 8 | 8 |
| Out Of Band Attenuation (dB) | 40 | 40 |
| Frequency Accuracy (MHz) | 0.05-10 | 3-40 |
| Propagation Model | Modified Hata | EPM73 |

### 3.1.     S-Band

Secondary access availability in the 2.7 – 2.9 GHz band is evaluated for co-channel secondary access (secondary users access the same frequency channel as the primary user) and adjacent channel secondary access (secondary users access a different frequency channel as the primary system). In Figure 1 and Figure 2, we examine how the exclusion region radius for different secondary system densities varies according to the applied type of regulation. Due to the high antenna gain and high sensitivity of the radar receivers, exploiting sharing opportunities with co-channel secondary access seems extremely difficult since it requires very large exclusion region

radius as shown in Figure 1. Applying regulation on the density does not improve co-channel sharing opportunities in the S-Band. On the contrary, allowing secondary access only in a specific area (a mid-sized city is considered in this evaluation) significantly reduces the size of the exclusion regions. However, exclusion region radiuses of around 27Km are needed even if combined regulation is considered. Regulating the density or the deployment of transmitting secondary users significantly improves secondary access to adjacent channels since practically no exclusion region is required as shown in Figure 2.



**Figure 1 Exclusion Region Radius for co-channel secondary access to the 2.7-2.9GHz band**
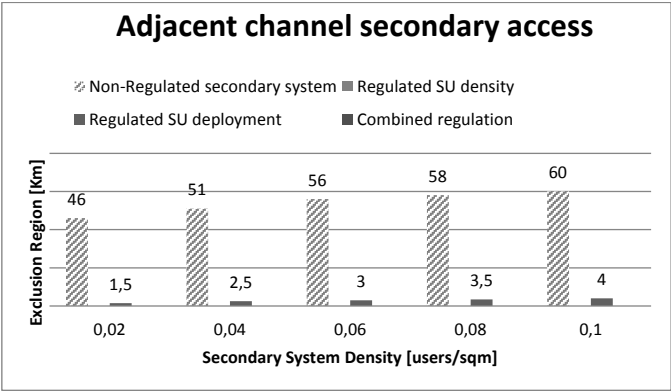


**Figure 2 Exclusion Region Radius for adjacent channel secondary access to the 2.7-2.9 GHz band**

### 3.2.      Ku-band

In this section, we evaluate the secondary access availability in the 17 GHz band. The first observation is that even though the high propagation loss in this frequency band, massive co-channel secondary access can be harmful to the radar operation.  Figure 3 shows that if no regulation on the density or the deployment of secondary user is applied, exclusion regions radius of up to 59Km are needed to protect the radar receiver. On the contrary, regulating the deployment of secondary user can considerably decrease the exclusion region radius for co-channel secondary access, reaching to less than 30Km even for very dense secondary system. In contrast, the benefit of regulating the density of secondary user is marginal for adjacent channel secondary access, where almost blind deployment of very dense secondary network is feasible without requiring an exclusion region radius larger than 4Km.

Improving co-channel sharing opportunities in the 17GHz can be more critical than in the 2.7-2.9GHz because of the existence of 40-year-old transmitter technologies with poor filtering characteristics and the more challenging requirements for the exploitation of the time domain sharing opportunities. Therefore, infeasible co-channel secondary access can significantly decrease total available secondary spectrum in the Ku-band.
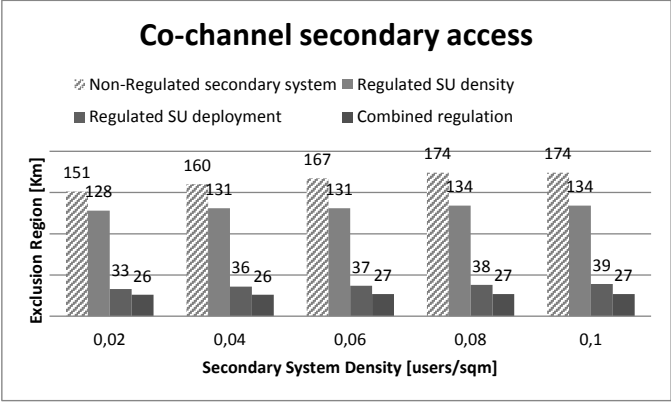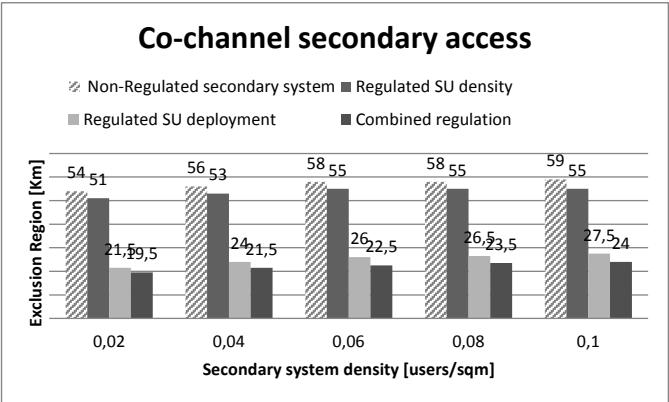


**Figure 3 Exclusion Region Radius for co-channel secondary access to the 17GHz band**
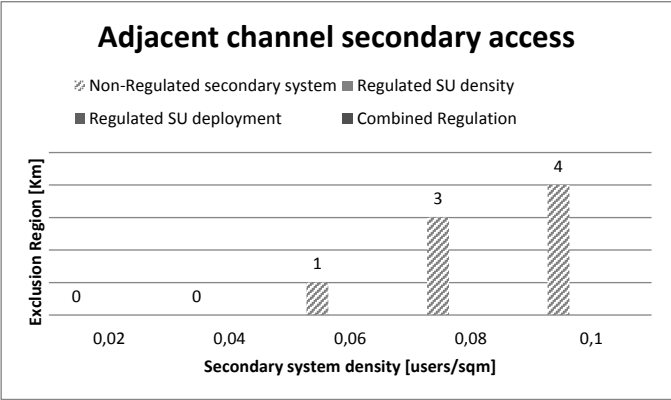
**Figure 4 Exclusion Region Radius for adjacent channel secondary access to the 17GHz band**

## 4. Regulatory and business implications

The regulatory regime for enabling secondary spectrum access to radar bands is still undefined. A key question is: *should we allow universal secondary spectrum access to the radar bands in space or time domain?* This question has been already answered in the TVWS where the licensed-exempt approach was adopted, meaning that any device can access the TVWS anywhere as long as it complies with the sharing rules. However, adopting the same approach in the radar bands may result counterproductive because the radar system characteristics which could require exclusion region radius of up to several hundreds of kilometers to protect the primary system. This could eliminate the possibility of secondary usage in cities close-by the radar, melting down any business opportunity and social benefit since additional spectrum will not be available where the highest demand is.

This paper proposes regulatory policies to better exploit the tradeoff between the density of secondary users and the exclusion region size for co-channel and adjacent channel usage. Our analysis look at three alternatives: regulation on the density of transmitting secondary users (e.g. by means of CSMA), regulation on the deployment of secondary users (e.g. allowed secondary usage in the big cities only) and the combination of both of them. Results showed that applying regulation on the deployment of secondary users can dramatically improve co-channel and adjacent channel sharing opportunities, leading to practically blind or unrestricted deployment of secondary systems *within* the regulated area in adjacent channels and much smaller exclusion region size for dense co-channel secondary access. These improvements are more visible in lower frequency bands, i.e. S-band, where the impact of interference aggregation is higher. Notice that improving co-channel sharing opportunities can significantly increase the amount of available spectrum, especially in frequency bands where the transmitter technology employs 40-year-old magnetron designs that has a increment of 10 times in the occupied -40 dB bandwidth compared with a newer technologies. An

upgrade of the transmitter technology can increase the cost up to 100%, which directly impact the cost-effectiveness and business attractiveness of secondary access. The benefits of the other two regulatory policies were found marginal. This means if the deployment of an extremely dense secondary system is allowed only *within a specific area*, secondary users could access the entire band with a relatively small exclusion region size by exploiting the time domain sharing opportunities. Thus, large secondary access availability in dense cities with high capacity demand would be possible. But, *is it attractive from the business perspective?* The answer will depend on the selected authorization model and the operator type.

The selection of a suitable authorization model that not only considers the protection of the primary system but also the exploitation of sharing opportunities by secondary systems is crucial. Regulators promoted the licensed-exempt approach in the TVWS with the objective of promoting innovation, boosting competition and eliminating barriers for potential new players in the mobiles communication industry. However, the commercial take-off of secondary access to the TVWS is still not happening mainly due to the licensed-exempt approach that does not attract long-term investments from operators. In the radar bands, a key requirement for selecting an authorization model is the establishment of a sharing mechanism that provides reliable protection against the harmful interference due to the safety related systems operating in this band. To achieve the required level of reliability, it is needed an authorization model that guarantees the enforcement of the sharing rules and liability in case these rules are violated. Moreover, the sharing mechanism requires accurate information exchange between primary and secondary systems which involves negotiations with multiple primary systems under different administrative control (e.g. military and civil radar), arising the need of a spectrum manager or regulatory entity and a small number of licensees to ease the complexity of sharing process. Based on those requirements, applying license-exempt authorization model would not be recommendable because of two reasons: the lack of registration and the unlimited number of licensees that would make extremely difficult for providing the required level of enforcement and liability. An interesting alternative is Licensed Shared Access (LSA since it requires *registration* and allows *access for only few* of licensees. Based on the LSA concept given in [22], applying LSA would imply a common agreement between primary system and licensees on the sharing rules. This would lead to almost negligible probability of non-compliant devices, effective correction in case of rules violations and accurate estimation of an economic compensation or a fee for the licensees accessing the radar spectrum. Contrary to the license-exempt approach, LSA would involve *a fee* which could be an incentive for the primary system to enable sharing in its licensed spectrum. However, it can also be a stopper for the potential licensees if it is not carefully established to promote long-term investments.

We consider that the candidate licensee is an incumbent MNO willing to significantly improve its indoor capacity to satisfy customer demands. The MNO is also interested in a cost-effective solution that will help to keep its revenues. Indoor secondary access under LSA model in the radar bands is a potential solution, but there could be other solutions such as indoor Wi-Fi deployment in licensed-exempt spectrum and heterogeneous networks (Het-Nets) operating in licensed spectrum. In

Table 2, we identified different attributes related to spectrum, performance and complexity that could impact the selection of one of these solutions. Based on Table 2, we can identify the advantages and disadvantages that the MNO will face if choose indoor secondary access under LSA model. One of the main disadvantages is the location-based availability of secondary access. However, applying regulation on the deployment of secondary users leads us to talk about area-based or city-based availability make this solution competitive with the other alternatives in the areas with high capacity demand. This solution offers guaranteed quality of service and a level of system complexity that is perfectly manageable for traditional MNO that is used to complex systems. Also, the fact of only few licensees will access the available spectrum makes this option more valuable for competition with other players.

Finally, we identify that spectrum access cost is still an undefined parameters which will directly impact the business attractiveness of this solution for long-term investments. Thus, it should be set according to the potential benefits that could bring for the licensee, which will highly depend on the characteristics of the secondary access availability such as: the amount and the granularity of the available spectrum over space and time domain, the complexity of sharing mechanism and the devices implementation issues. Clearly, a large amount of available spectrum anytime and anywhere with a low complexity is desirable but not always feasible in secondary spectrum.

**Table 2 Comparison between three solutions for indoor offloading**

|  | Wi-Fi deployment | Het-Net deployment | Secondary system deployment |
|---|---|---|---|
| Spectrum availability | Anywhere | Anywhere | Location -based |
| Spectrum management | Distributed | Centralized | Centralized |
| Service performance | Low /Medium | Medium/High | Medium/High |
| Spectrum access cost | Free | Marginal | *Undefined* |
| Service reliability | Best-effort | Guaranteed | Guaranteed |
| System Complexity | Low | High | Medium |
| Spectrum access | Open | Exclusive | Few licensees |

## 5. Conclusions

The large expected increase in the total traffic demand has raised new capacity requirements to current wireless networks. One of the key resources to meet these new requirements is radio spectrum which is inefficiently utilized due to current static spectrum allocation regime. Secondary spectrum access was proposed as a technical solution to improve spectrum utilization. However, making secondary spectrum access a cost efficient solution that attracts long-term investments requires innovation in the technical and regulatory domain. This paper has analyzed how the techno-regulatory conditions of secondary access to the "radar bands" could impact its business attractiveness for incumbent MNOs.

We conducted a coexistence analysis to identify key regulatory policies to better exploit the sharing opportunities in the radar bands. For that, we focused on the tradeoff between the density of secondary users and the exclusion region size. Numerical results showed that applying regulation on the density of secondary users gives marginal improvements in terms of sharing opportunities. Instead, applying regulation on the deployment of secondary users can dramatically improve these opportunities, leading to practically blind deployment of secondary systems *within* the regulated area in adjacent channels and much smaller exclusion region size for dense co-channel secondary access. Therefore, secondary access to the radar bands can be made available in cities or areas with very high data demand.

For assessing the business attractiveness of secondary access to the radar bands from the MNO's perspective, we first selected Licensed Shared Access (LSA) as suitable authorization model since it provides the level of reliability on the protection against harmful interference. This level is achieve mainly because LSA model allows access to a small number of licensees and requires registration. Towards the assessment of business attractiveness, we identified two alternative competitor solutions for indoor deployments (Wi-Fi and Het-Net) and qualitatively compared them against indoor secondary access to the radar bands. Based on this comparison, we confirmed that applying regulation on the deployment of secondary users under LSA model can give competitive edge of secondary access in terms of spectrum availability and spectrum access. We also spotted the importance of establishing the right spectrum access cost or license fee (currently still undefined) for motivating the MNOs to make long-term investments on this solution. Further work can be done on establishing a license fee under LSA model, leading to a quantitative evaluation of business feasibility of large scale secondary access.

## Acknowledgement

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# Chapter 13

# Is Spectrum Sharing in the Radar Bands Commercially Attractive? - A Regulatory and Business Overview (Paper 9)

# Is Spectrum Sharing in the Radar Bands Commercially Attractive? - A Regulatory and Business Overview

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**Abstract**

The avalanche in mobile data consumption represents a big challenge for mobile networks operators (MNOs). Secondary spectrum access is discussed as a potential solution for finding additional spectrum mobile communications in a cost- and time-efficient way. In this paper, we provide a comprehensive assessment of the *commercial viability of secondary access in the radar bands* focused mainly on the case of indoor and hotspots communication in the radar bands offloading mobile traffic demand of incumbent MNO's wireless networks.

A key contribution of this work is a well-defined methodology for dealing with the technical, regulatory and business aspects of deploying large-scale wireless networks with secondary spectrum access in the radar bands. By employing this methodology, we have identified the following criteria for achieving business success: spectrum availability, radio technology availability, low-cost end-user devices, system scalability and guaranteed quality of service. This paper also proposes a sharing mechanism that enables large-scale secondary access in the radar systems based on three design principles: a central spectrum manager controlling the aggregate interference, the combined use of spectrum sensing and geo-location database and a fast feedback between the primary user and the central spectrum manager. As a result of our technical availability assessment, we have identified the geo-location database support as necessary technical enabler and detect-and-avoid mechanism as a beneficial technical enabler for improving sharing conditions. Moreover, Licensed Shared Access (LSA) was found to be the suitable regulatory framework to support the proposed sharing mechanism and regulatory policies in real-life implementation.

Finally, the business feasibility assessment concluded that there is enough spectrum availability for indoor and hotspots communication in urban areas in the radar bands as well as guaranteed quality of service, potential low-cost de-

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vices and proven system scalability. Therefore, it is possible to meet the MNO's needs where it is needed which favors the commercial viability of the large-scale secondary access to the radar bands. However, the commercial viability cannot be fully determined until the uncertainties in the radio technology cost and the spectrum access cost are resolved.

*Keywords:* radar bands, short range communication, regulatory framework, business analysis.

## 1. Introduction

The unprecedented success of mobile services has resulted in the exponential growth of wireless data traffic. The substantial traffic increase is expected to continue in the coming years with the proliferation of high-end handsets (Cisco, 2013). There is a widespread concern about the shortage of available radio spectrum to fulfill the future demand, which is dubbed as spectrum deficit (FCC, 2010). Secondary spectrum access, referring to the sharing of already-licensed but under-utilized radio spectrum while protecting primary systems, has emerged as a practical means to address the perceived spectrum scarcity (Hwang et al., 2012).

Although the concept of secondary spectrum access has been studied extensively from theory to practice in the last few years, most of the practical work has focused on a specific portion of spectrum, i.e., VHF/UHF band primarily allocated to digital terrestrial television (DTT) so-called TV white spaces (TVWS) (Nekovee, 2010; Harrison et al., 2010; Van de Beek et al., 2012; Shi et al., 2012). This means that the vast amount of radio spectrum remains unexplored with regard to the potential of the secondary usage. ITU spectrum allocation table indicates that the majority of frequency bands below 6 GHz are allocated currently to various systems such as aeronautical navigation, radar, satellite, and fixed link. Significant research efforts will have to be spent to investigate the viability of secondary access to those spectrum bands [1]. Our previous work showed that there are ample sharing opportunities for the deployment of ultra-dense networks (UDNs) in the

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[1]Besides the studies on TVWS, only a handful can be found on radar and aeronautical spectrum. See, e.g., (Saruthirathanaworakun et al., 2012; Peha, 2013; Rahman & Karlsson, 2011; Tercero et al., 2013)

radar bands, both above and below 10 GHz (e.g. S- and Ku-Bands). However, as claimed in (Zander et al., 2013), the fact that secondary spectrum access is technically feasible does not necessarily guarantee its commercial success. Whether the deployment of large-scale wireless networks employing secondary spectrum access or vertical spectrum sharing in the radar bands can really happen or not is a multi-dimensional problem which includes technical, regulatory and business aspects. Therefore, we aim at answering the following research questions: *What are the main factors that would facilitate business success for short range communication in the radar bands? Is there a suitable regulatory framework that can ensure the protection of the primary system and still provide enough spectrum for secondary use to make it commercially interesting?*. In this work, *short range communication* refers to indoor and outdoor hotspot communication providing high-capacity broadband services.

We can find substantial literature that studied individual aspects of secondary spectrum access: technical, regulatory, and business aspects. For example, fundamental limits of the secondary sharing were investigated in (Ghasemi & Sousa, 2007; Devroye et al., 2006), the regulatory and policy aspects were discussed in (Medeisis & Minervini, 2013; Forde & Doyle, 2013), and the business side was looked into in (Markendahl et al., 2012; Gronsund et al., 2013). However, it is difficult to find a cross-boundary study. Thus, the main contribution of this paper is to establish a well-defined methodology for dealing with the technical, regulatory and business aspects of deploying large-scale wireless networks with secondary spectrum access. Moreover, this methodology is tailored to the radar bands which had not been clearly addressed.

The remainder of the paper is organized as follows: the methodology for assessing technical, regulatory and business aspects that can make vertical spectrum sharing in the radar bands attractive is explained in Section 2. Section 3 focuses on defining the business case and identifying key factors that impact its business success. In Section 4 and Section 5, we give a detailed technical description of the sharing usage scenario, sharing mechanism and technical enablers; which are essential inputs for selecting the regulatory framework in Section 6. Finally, the business feasibility analysis is provided in Section 7 and our main findings are discussed and summarized in Section 8.

## 2. Methodology

Towards assessing the commercial viability of sharing opportunities in the radar bands, we propose the methodology illustrated in Fig. 1. This methodology

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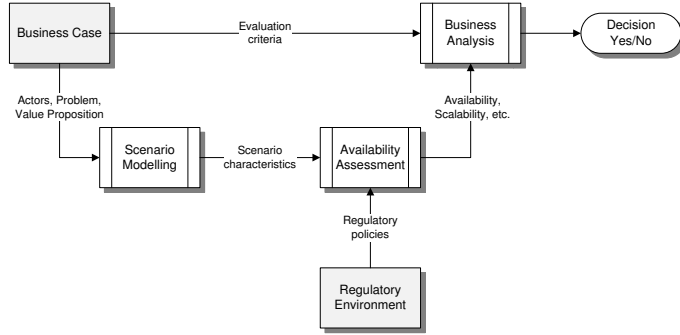


Figure 1: Methodology for Assessing Sharing Opportunities

includes technical, regulatory and business aspects which are needed to make an assessment whether secondary spectrum access in the radar bands can take-off or not from the commercial point-of-view.

We first describe the business case by identifying the main actors, problems and value proposition. Based on a clearly defined business case, we establish the key factors that would facilitate business success. These factors are the evaluation criteria for the business feasibility analysis. Also based on the characteristics of the business case, we model the secondary access scenario modeling that will be employed for technical spectrum availability assessment. Another input to the technical assessment is the regulatory environment, such as sharing mechanism and spectrum etiquettes. Notice that the results of the assessment will depend strongly on the selected regulatory policies,

As a next step, we identify the most suitable regulatory framework (i.e. licensing regime) for enabling vertical spectrum sharing in the radar bands is a sequential approach. This evaluation is made in a systematic manner by employing a spectrum sharing toolbox proposed within the EU FP7 METIS project, which allows to have a direct mapping between technical enablers, spectrum sharing scenarios and regulatory framework. First, we start by defining the secondary access scenario and the sharing mechanism to then identify the tools or enablers that make this scenario feasible from the technical point-of-view. Later, the regulatory framework is chosen to bring the selected policies to real-life implementation. The selection of suitable regulatory policies are based on their impact on the exploitation of sharing opportunities. More detailed explanation on the the different

components of the toolbox can be found in (Irnich et al., 2013).

Finally, we proceed to *qualitatively* assess the business potential of the selected secondary access scenarios by employing the defined evaluation criteria and the results of the availability assessment, which includes technical and regulatory aspects.

## 3. Identifying Factors for Business Success

In this section, we identify and discuss different factors that would facilitate business success for short range communication (i.e. indoor and outdoor hotspot communication providing high-capacity broadband services.) in the radar bands. These factors will depend highly on the particular business case, which is defined by the type of actors that provides the service, their pains or problems and the specific value proposition. We detail the business case in the following:

- Main Actors: An *incumbent MNO* who has a strong incentive to offer significantly higher capacity to satisfy *their customer's* demands in indoor and hotspots locations. We consider the incumbent MNO in this study based on the argument in (Markendahl et al., 2012) that a new entrant does not have a competitive edge over the incumbent MNO for deploying in secondary spectrum.

- Problem: The MNO needs a solution that offers the best cost-performance trade-off since it has already been *challenged by the revenue gap* which refers to a discrepancy between soaring mobile data demand and dwindling revenue increase.

- Value Proposition: Short range communication in the radar bands *offloading mobile broadband traffic demand in indoor and hotspot* environments where the demand is extremely high.

In order to analyze the potential of the business case, we need to identify the different factors that could influence business success or in other words *what should the radar bands offer?*

- **Enough Spectrum Availability** to alleviate the increasing data demand in current MNOs networks in indoor and hotspot locations.

- **Availability of radio technology** is crucial for estimating when the solution can be deployed and the cost it will generate.

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- **Low-cost end-user devices** is crucial for reaching mass adoption. Current alternatives offer low-cost devices, thus it is critical for the proposed solution to also have low-cost end-user devices or being able to use existing devices with minor modifications that will not have a significant impact on the total cost.

- **System Scalability** is also essential for motivating investments. Moreover, given that this solution is proposed for alleviating the high capacity demand, then system scalability is a must.

- **Guaranteed quality of service** should be provided in order to attract investments given that other best-effort alternatives are available for free. Thus, there is a need to establish a regulatory framework that could guarantee quality of service for short range communication in the radar bands.

## 4. Sharing Usage Scenario

In this section, we provide a brief of description of the selected sharing usage scenario which is conformed by the characteristics of the primary system (incumbent) and the secondary system (newcomer).

### 4.1. Radar systems as Incumbent

Radar is an acronym for Radio Detection And Ranging. The basic operation principle of the radar consists of generating pulses of radio frequency energy and transmitting these pulses via a directional antenna. The radar indicates the range to the object of interest based on the elapsed time of the pulse traveling to the object and returning to the radar antenna. The most common uses of radar are Ground based Aeronautical Navigation, Marine Navigation, Weather Detection and Radio Altimeters (Alenia Marconi Systems Limited, 2002).

This paper focuses on the radar systems allocated below and above 10 GHz due to the good propagation characteristics for providing mobile broadband services. Specifically, we consider the ground-based rotating radars deployed in the S- and Ku-Bands: Air Traffic Control (ATC) radars in the 2.7-2.9 GHz band and Surveillance radars such as Airport Surface Detection Equipment (ASDE) in the 15.7-17.2 GHz band, respectively. For the ATC radars, the 3 dB channel bandwidth can vary from 0.5 MHz to 15 MHz, depending on the radar type (International Telecommunication Union (ITU), 2003). In contrast for Surveillance radars, the 3 dB channel bandwidth could reach up to 100 MHz (Alenia Marconi

Systems Limited, 2002). Notice that within 15.7-17.2 GHz, the precise allocation of Surveillance radars could vary depending on the country or region.

*Protection criteria*

A maximum interference-to-noise ratio (INR) threshold is established to guarantee that the detection performance of radar systems is not degraded by harmful interference. The INR threshold defines the maximum allowable interference level relative to the noise floor at the radar receivers. This threshold is often set to very conservative value (i.e. -10dB) for radars with safety-related due to the high sensitivity of the radar receivers and very high antenna gain of the typical radar (International Telecommunication Union (ITU), 2003).

Due to the random nature of the radio propagation, the protection of the radar is expressed as a interference probability which refers to maximum allowable probability that the aggregate interference exceeds the tolerable interference level. The interference probability is mathematically expressed as follows,

$$\Pr\left[I_a \geq A_{thr}\right] \leq \beta_{PU} \tag{1}$$

where $I_a$ is the aggregate interference from the UDN or secondary system, $A_{thr}$ is the maximum tolerable interference at the radar and $\beta_{PU}$ is the maximum permissible probability of harmful interference at the primary receiver. Due to the safety-related functionality of the radar, we applied conservative values for $A_{thr}$ and $\beta_{PU}$ which implies practically almost no interference violation. We adopt a very small value for $\beta_{PU}$ that is used for air traffic control (ATC) radar in 2.7-2.9 GHz, $\beta_{PU} = 0.001\%$ (International Telecommunication Union (ITU), 2003). We set $A_{thr}$ based on the INR value, $A_{thr}(dB) = INR + N$, which drops to $A_{thr} = -119$ dBm/MHz for co-channel secondary access for a noise figure (N) of 5 dB.

### 4.2. Ultra-Dense Networks as Newcomer

Various types of secondary usage were described in (Hwang et al., 2012). Secondary spectrum access or vertical spectrum sharing would be the most beneficial and attractive from the commercial point-of-view where we find the highest capacity needs taking into account that it has emerged as a solution to deal with the exploding mobile traffic demand. Approximately, 70% of the current data consumption is generated in indoor locations and "hotspots" (Ericsson, 2012) followed by urban areas with high user density (Zander & Mahonen, 2013). Thus, it

is natural to assume that the secondary system provides high-capacity broadband services for customers located in these locations.

We envisage a scenario where an UDN as the secondary system in the radar bands, which is employed to expand the network capacity of a cellular network already operating in dedicated/licensed spectrum. The extremely high density of active UDN transmitters over a large geographical area raises the need of controlling the aggregate interference with very high reliability, which is a challenging task. Moreover, the secondary APs must be much cheaper than traditional outdoor base stations in order to make the massive deployment affordable. Thus, a simple interference control functionality is desired at the device level. A detailed description of the sharing mechanism and functionality of the different involved entities will be provided in Section 5.

## 5. Sharing Mechanism and Technical Enablers

### 5.1. Sharing Mechanism

In this section, we introduce a spectrum sharing mechanism that enables vertical spectrum sharing between the radar systems and the UDN. The key requirements for designing this mechanism are: guaranteed reliable protection of the primary system as well as good sharing opportunities for the secondary users. Moreover, it is desirable to implement a simple interference control functionality at the device level so the price of secondary APs can be kept below traditional outdoor base stations. Thus, large-scale investments can become attractive from the economic point-of-view. The design principles of the sharing mechanism are:

- *First principle: the aggregate interference should be controlled by a central spectrum manager*. This entity should external and independent of the incumbent's and newcomer's interest , guaranteeing the fair enforcement of sharing rules. The central spectrum manager communicates and supervises constantly the correct operation of the geo-location databases, which collects all relevant information of the system. Given that the radar receiver can potentially receive interference from millions of UDN transmitters, thus each UDN user is unable to know whether its own transmission would cause a interference violation to the primary user. It is essential that the central unit estimates aggregate interference and makes a decision on who can transmit with what power based on the information provided by the geo-location databases. A real-time execution of the decision (whether to transmit *now* or not) may be delegated to the individual secondary users,

but the guideline for the decision must be provided and updated constantly by the spectrum manager.

- *Second principle: the combined use of spectrum sensing and geo-location database should be employed by the secondary users for the interference estimation.* For the central spectrum manager to calculate the aggregate interference, each secondary user must be able to estimate the interference it would inflict to the radar and report it to the spectrum manager through the databases.

- *Third principle: the establishment of a fast feedback loop between the primary user and the spectrum manager.* It requires that the primary user be attached to the spectrum manager and provides a feedback when it receives the interference above a certain level. This feedback loop might turn out to be redundant in practical secondary access situations because the application of the second principle is expected to produce an accurate estimation of the aggregate interference. However, it will contribute to the guaranteed protection to the safety-of-life functionality of the primary user.

Our proposed spectrum sharing mechanism is illustrated in Fig. 2, which shows the basic architecture and communication links between the different entities, i.e. the primary system, the secondary system, the geo-location database and the regulatory entity. Communication links 1, 2 and 3 are employed to fulfill the first design principle. The second design principle is illustrated by the communication links 2 and 3, while Communication link 1 illustrates the third design principle. Notice that the existing radars cannot measure the interference nor have a back-haul connection. Thus, an upgrade of primary equipment is necessary for establishing the feedback loop. Finally, communication link 4 shows the close collaboration between the geo-location database and the regulatory entity that aims at monitoring the correct operation of the geo-location database and enforcing the coexistence rules.

*5.2. Technical Enablers*

Based on the proposed sharing mechanism, we have identified technical enablers within the METIS toolbox that would enable vertical spectrum sharing in the radar bands, which are the combination of geo-location database support and Detect-and-avoid mechanisms.
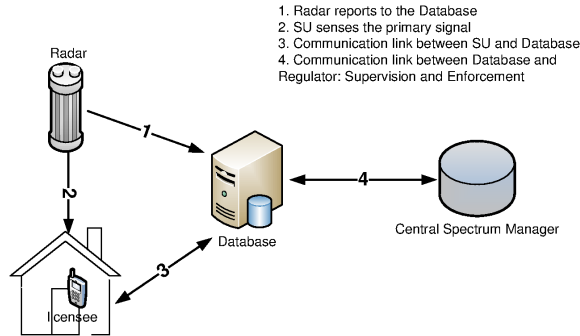
Figure 2: Sharing mechanism

The support of geo-location databases is required to guarantee the reliable control of the aggregate interference, crucial for enabling vertical spectrum sharing in the radar bands. With the help of geo-location databases, the central unit can reliably estimate the aggregate interference from a huge number of secondary users deployed in a very large geographical area. Moreover, the central unit can make the decisions on who can transmit with what power and constantly update them based on the geo-location database information. It is important to notice that this database support is required mainly for the protection of the primary system. However, it could also be employed to manage interference between multiple secondary systems (e.g. postal address licensing).

We also consider the detect-and-avoid mechanisms (i.e. spectrum sensing) as a beneficial enabler that should be employed by the secondary users for the interference estimation. Thus, each secondary user must be able to estimate the interference it would inflict to the primary receiver and report it to the geo-location databases or spectrum manager. Spectrum sensing is considered unreliable in many scenarios of commercial interest (Zander et al., 2013) since it does not tell us the whereabouts of the primary receiver which should be protected [2]. In radar systems, the secondary user can actually detect the presence of the primary receiver since the hidden node problem is not an issue. This will bring more re-

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[2]A typical example is the DTT spectrum where thousands of passive TV receivers are kilometers away from a TV transmission tower.
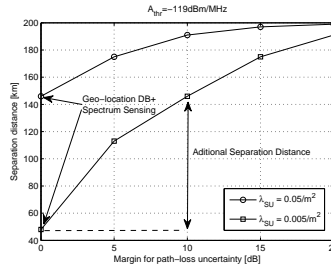
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Figure 3: Benefit of applying geo-location databases and spectrum sensing

liability and precision for calculating the aggregate interference, making sharing conditions less rigid. For instance, if only geo-location databases are employed, the need for additional interference margins arises in order to cope with the uncertainty on the interference estimation. Fig. 3 shows how the minimum required separation distance increase with different margins.

Notice that the combination of these two enablers is not necessary but beneficial for improving sharing conditions. This means that geo-location databases could potentially be employed alone. However, the spectrum sensing, if used alone, cannot provide the required accuracy because it could be affected by detection errors. Any missed detection in the vicinity of the primary user could be critical to the radar operation.

## 6. Regulatory Framework

The objective of this section is to identify the most suitable regulatory framework (i.e. licensing regime) that can support the above-discussed sharing mechanism in real life implementation. Various options can be envisaged under the umbrella of vertical spectrum sharing. Based on the METIS toolbox, two potential regulatory framework alternatives for vertical coexistence are license-exempt (countless licensees) and licensed shared access (LSA) (only a few licensees). One of the key factors that distinguishes these different frameworks is the number of entities who are granted usage rights.

From the incumbent point of view, reliable protection against harmful interference is critical. This becomes an essential requirement when choosing the regulatory framework. In the same way, the newcomer is willing to have guaranteed

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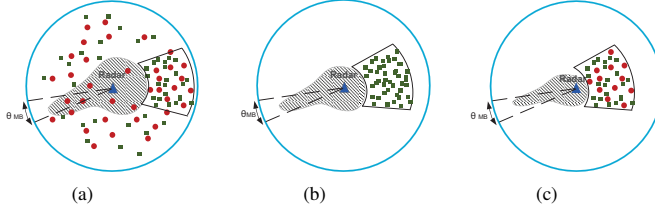OVERVIEW (PAPER 9)*

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Figure 4: Regulatory Policy Options: a)Area Power Regulation, b)Deployment Location Regulation and c)Combined Regulation. The radar (blue triangle) is surrounded by transmitting secondary users (green squared), not transmitting secondary users (red circles) and an irregular exclusion region (shadow area).

access to the available spectrum and manageable sharing conditions so long-term investments can be justified. Based on these two point-of-views, our previous work investigated regulatory policies that improve sharing conditions for the newcomers in areas with high capacity demand (i.e. indoor and urban hotspots) while keeping the incumbent protection criteria fulfilled (Obregon et al., 2014). We evaluated three regulatory policies: area power regulation, deployment location regulation and the combination of them. Sharing opportunities were inversely proportional to the required time-averaged separation distance between the radar receiver and the UDN that guarantees a minimum transmission probability for the UDN user.

Our results showed that applying any of the regulatory policies improves sharing conditions, particularly for radars allocated below 10 GHz. Overall, deployment location regulation was the most effective means to limit interference to the radar system and improve UDN's sharing opportunities, in particular when the difference in network density between urban and rural areas is dramatic. This means that not only traditionally regulated transmission power level and operating frequency, but also location of the UDN needs to be strictly regulated to fulfill primary protection criteria and to make sharing conditions less rigid. Based on these requirements, we consider that LSA[3] would be the suitable regulatory framework

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[3]Notice that LSA concept is still under development. Hence, our discussion is based on the definition by CEPT: *"A regulatory approach aiming to facilitate the introduction of radio communication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users. Under the LSA framework, the additional users are allowed to use the spectrum (or part of the*
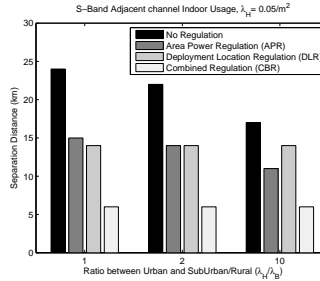
Figure 5: Impact of spatial heterogeneity: S-Band Indoor Adjacent Channel Usage

that could allow the real-life implementation of the selected regulatory policies enabling UDN deployment in the radar bands. We ruled out license-exempt vertical coexistence given that it does not required to obtain a specific decision or permission before users exercise their right coming from a *general authorization*, which basically defines basic sharing conditions. For instance, license-exempt use of TVWS in the USA is applied since 2008 (FCC, 2008b,a). This model allows the white space devices (WSDs) to have access to the DTT spectrum without an individual license but subject to technical restrictions, allowing the access of an unlimited number of WSDs who provide different applications. This however cannot be employed in the radar bands since it cannot guarantee that sharing conditions and regulatory policies are *enforced to all* the UDN devices without exception. This does not allow to reliably protect the primary system and apply regulation on the deployment of UDN users, which requires an individual authorization instead.

Customizing the general LSA concept to the context of radar spectrum would be a challenge to be addressed. One of the most important aspects to address this challenge would be the terms of the LSA contract between the primary system and the licensees, which should contemplate mainly the following: the potential changes or variations in the radar system that could negatively impact the secondary licensees and the technical and economic conditions in case of evacuation

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*spectrum) in accordance with sharing rules included in their rights of use of spectrum, thereby allowing all the authorized users, including incumbents, to provide a certain QoS"* (ECC Report 205, 2013).

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request from the primary system, e.g. request frequency, time period, time response, economic compensations, etc.

### 7. Business Feasibility Analysis

In this section, we revisit the evaluation criteria and discuss what the radar bands offer with respect to them. Moreover, we identify the existing alternatives or competitors and analyze how indoor and hotspot communication in the radar bands is positioned with respect to other alternatives.

**Enough Spectrum Availability** can significantly impact business viability in the radar bands. However, there is no a single answer and availability can significantly vary between different countries. For instance, there is a single civilian ATC radar in Macedonia while there are around 77 ATC radars between civilians and military type in the UK. Here, we will give an estimate of the availability in Europe based on our previous work in the aeronautical and radar bands (Obregon et al., 2013a, 2014), and current European allocation table. Results in (Obregon et al., 2013a) found that at least 30% of the Distance Measuring Equipment (DME) band was available for secondary usage and results in (Obregon et al., 2014) showed that applying regulation on the deployment of secondary users could be further improve availability in the urban areas. Considering that below 10 GHz there is around 1.2 GHz allocated to radar systems, then up to 400 MHz could be available for secondary access in the radar bands assuming that similar results to the ones in the DME (30% availability) will be obtained given the technical similarities. However, availability in the radar bands would be very much fragmented and with large separation in the frequency domain. This means that a equipment would be able to access at most 100 MHz at a given location, even if it has advanced carrier aggregation capabilities. It is important to notice that the availability in the radar spectrum has low spatial granularity, which means that the available amount of spectrum is spatially uniform for large geographical areas. Therefore, the availability in a city will be most likely constant in space and time domain, which is a key difference from the availability in the TV bands.

**Availability of radio technology** will depend on the selected radar band. Here, we are mainly discussing the bands below 10 GHz (i.e. L-Band and S-Band) which are located close to already available radio technology dedicated to mobile communications. Moreover, filter characteristics, sensing capabilities and carrier aggregation functionalities, which are extremely relevant due to the non-contiguous availability, are already quite advanced in their development. Thus, adaptation to the radar bands below 10 GHz can be done within a reasonable time

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period and cost. In contrast, the radar bands above 10 GHz would require much more time to make radio technology available since currently there is no radio technology for mobile communication in these bands.

**Low-cost end-user devices** is an essential requirement for mass adoption. Devices operating in the radar bands below 10 GHz will require additional spectrum sensing capability, which could increase their production cost but not significantly.

**System Scalability** in the radar bands has been previously demonstrated in (Obregon et al., 2013b,a, 2014) where a system with a very high network density can share the radar bands with reasonable requirements (i.e. small exclusion region size), especially for adjacent channel access. Moreover, complex cross-layer interference management between the cellular networks and short range network will not be required in order to provide quality of service since they operate in different frequency bands.

**Guaranteed quality of service** is feasible in the radar bands due to the selected regulatory framework, LSA, which allows access to few licensees so that the sharing rules are effectively enforced and quality of service can be guaranteed for all licensees.

As a next step, we identify the alternatives that are currently available in the market:

- **Unlicensed Option**: Indoor offloading in the license-exempt ISM bands (2.4 GHz or 5 GHz band) by employing Wi-Fi technology.

- **Licensed Option**: Indoor offloading in frequency band exclusively licensed to the MNO by employing LTE technology.

We compare these options with our value proposition, short range communication in the radar bands, which will be called **LSA option** given that this is the selected regulatory framework. Table 1 shows this comparison by identifying the advantages and disadvantages that the MNO will face if LSA option is chosen. One of the main disadvantages is the location-based availability of the radar bands. However, applying regulation on the deployment of secondary users leads us to talk about area-based or city-based availability making this solution competitive with the existing alternatives in the areas with high capacity demand. The LSA option offers guaranteed quality of service and a level of system complexity that is perfectly manageable for traditional MNO that is used to complex systems. Also, the fact of only few licensees will access the available spectrum makes this option more valuable for competition with other players.

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Table 1: Comparison between three solutions for indoor offloading

|  | **Unlicensed** | **Licensed** | **LSA** |
|---|---|---|---|
| Spectrum availability | Anywhere (538 MHz) | Anywhere (100 MHz) | Location-based (approx. 100 MHz) |
| Technology | Available | Available | Near-Term Available |
| System Scalability | Poor | Good | Good |
| Quality of Service | Best-effort | Guaranteed | Guaranteed |
| Spectrum access cost | Free | Marginal | Undefined |
| Spectrum access | Open | Exclusive | Few Licensees |

Finally, we identify that spectrum access cost is still an undefined parameters for the LSA option which will directly impact the business attractiveness of this solution for long-term investments. Thus, it should be set according to the potential benefits that could bring for the licensee, which will highly depend on the characteristics of the secondary access availability such as: the amount and the granularity of the available spectrum over space and time domain that strongly depend on the region or country where the evaluation is made. Establishing the right spectrum access cost or license fee is critical for motivating the MNOs to make long-term investments on this solution.

## 8. Discussion

This paper has provided a comprehensive qualitative assessment of the *commercial viability of secondary access in the radar bands* mainly focused on the case of indoor and hotspots communication in the radar bands offloading mobile traffic demand of incumbent MNO's wireless networks. For that, this work has proposed a well-defined methodology for dealing with the technical, regulatory and business aspects of deploying large-scale wireless networks with secondary spectrum access in the radar bands.

By employing this methodology, we have identified the necessary conditions or *criteria for achieving business success* the deployment of high-capacity wireless system with secondary spectrum access in the radar bands, which are the following: spectrum availability, radio technology availability, low-cost end-user devices, system scalability and guaranteed quality of service. In oder to understand what the radar bands can offer with respect to these criteria, this paper conducted a technical availability assessment where we proposed sharing mechanism that enables vertical spectrum sharing between the radar systems and the UDN

based on three design principles: the aggregate interference should be controlled by a central spectrum manager, the combined use of spectrum sensing and geo-location database for the interference estimation and a fast feedback loop between the primary user and the central spectrum manager.

Based on the proposed sharing mechanism, we have identified the combination of geo-location database support and detect-and-avoid mechanisms as necessary technical enablers. Notice that the combination of these two enablers is not necessary but beneficial for improving sharing conditions. Moreover, we also identified that applying regulation on the deployment of the UDN could also improve sharing conditions. LSA was found to be the suitable regulatory framework to support the above-discussed sharing mechanism and proposed regulatory policies in real-life implementation. License-exempt was ruled out since it cannot guarantee the enforcement of sharing conditions and regulatory policies to all UDN devices, which is critical for radar bands with many safety-related services.

Finally, we conducted a business feasibility assessment based on the devised technical and regulatory conditions. In this assessment, we compared short range communication in the radar bands (LSA option) with two existing alternatives, Unlicensed and Licensed options, by employing the identified evaluation criteria for business success. We conclude that there is enough spectrum availability for indoor and hotspots communication in urban areas in the radar bands, therefore meeting the MNO's needs where it is needed. This is a crucial characteristic for long-term investments as well as guaranteed quality of service, potential low-cost devices and proven system scalability that also favor the commercial viability of the LSA option. However, the commercial viability is still not clearly determined given the remaining uncertainties in the radio technology cost and the spectrum access cost. These uncertainties need to be resolved to proceed to quantitative evaluation of the business viability, leading to more explicit conclusions the commercial viability of indoor and hotspots communication in the radar bands.

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