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Low-Power Secondary Access to the TV and Aeronautical Bands

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Abstract

The avalanche in mobile data consumption represents a big challenge for mobile operators. The efficient use of radio resources, e.g. technology, infrastructure and spectrum, is needed to meet the new capacity requirement in the mobile networks. This thesis aims at quantifying the real-life spectrum opportunities for deploying a massive low-power indoor secondary system. Our studies have mainly focused in two frequency bands: the digital TV and the aeronautical band. Indoor secondary access to these bands presents different technical challenges: Limited adjacent channel rejection capabilities and no information about the location of the primary receivers are key challenges in the digital TV band. Instead for the aeronautical band, the control of the aggregate interference over a large area due to the high sensitivity levels and the extremely low permissible outage probability at the primary system are the key issues for secondary access.

We have proposed a research methodology for determining the availability of spectrum opportunities in both frequency bands: digital TV and aeronautical band. Our methodology mainly emphasizes on establishing the realistic limits of tolerable interference at the primary, devising practical sharing schemes and determining the operational conditions and constraints for the secondary system. Based on our numerical results and measurement campaigns, we conclude that there is significant amount of spectrum opportunities for the deployment of massive low-power indoor secondary access in the digital TV and aeronautical band. The availability of spectrum opportunities highly depends on the sharing mechanisms, the primary protection criteria and the secondary system parameters. Future work should consider how the secondary users share the available spectrum in order to optimize the performance of secondary system in realistic scenarios. Another interesting investigation is the business viability assessment of secondary access in both frequency bands.

Acknowledgements

These years of graduate studies have been an enriching experience that has helped me grow as a professional and as a person. I would like to thank many people who have, directly or indirectly, contributed to this experience. My sincere gratitude goes to my advisor, Prof. Jens Zander for offering me the opportunity to take this challenge and providing very valuable feedback on my work. I am very thankful to Dr. Ki Won Sung for being a great co-advisor, who always encourages me to keep going with a good attitude. I am grateful to Prof. Lars K. Rasmussen for reviewing and providing valuable comments to improve the quality of my Licentiate thesis. I am also grateful to Dr. Jonas Kronander for accepting the role of opponent on my defense.

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Part I

Chapter 1

Introduction

1.1 Background

In 2011, the global mobile data traffic growth rate was 133%, more than doubling for the fourth consecutive year. The overall mobile data traffic is expected to increase 15-fold between 2010 and 2017 as it is shown in Fig. 1.1 [1]. The main reasons for the data consumption avalanche in mobile networks are the proliferation of high-end handsets and the exponential growth in average traffic per device [2]. 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 current networks while keeping their business profitable.

Traditionally, improving technology and infrastructure have been the main strategies for increasing the mobile network capacity. However, the spectral efficiency[1] of current technologies is already close to the theoretical bounds. Then, new technologies will require high complexity and cost in order to significantly raise the mobile network capacity. Deploying denser networks represents a big investment for the mobile operators, who are fighting to keep their business profitable. Therefore, an efficient utilization of not only technology and infrastructure, but also additional spectrum for mobile networks is needed to meet the explosion of traffic demand [3].

There is a common agreement that additional spectrum will certainly bring economic benefits for the operators because the network capacity is proportional to the spectrum bandwidth. However, apparently there is a shortage of spectrum since it has been almost fully allocated to the existing communication services. In Fig. 1.2, the allocation of frequencies in the United States radio spectrum is shown as an example.

Measurement campaigns indicate that most of the allocated spectrum lies actually idle at a given time and location [4,5]. The discrepancy between the apparent spectrum shortage and the measurement results is caused by the current static spectrum allocation regime[2]. Dynamic spectrum access (DSA) is proposed to resolve this discrepancy [6, 7]. DSA allows secondary systems to dynamically access already allocated but under-utilized fre-

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

[2] Spectrum is owned in spatial and time domain.

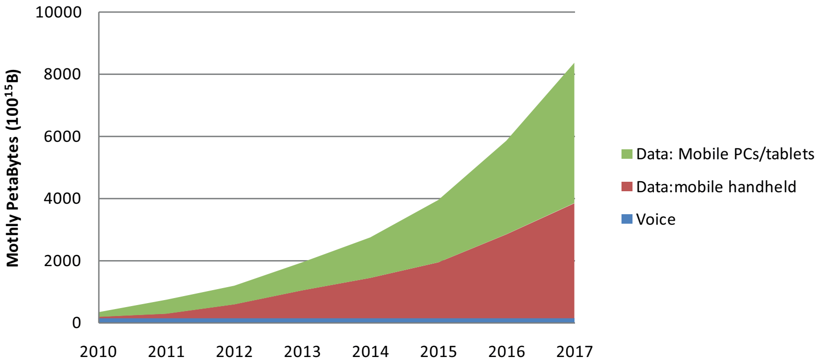


Figure 1.1: Mobile traffic: voice and data, 2010-2017 [1].

quency bands under non-interfering basis. Different DSA models have been proposed, ranging from open-sharing model to hierarchical models, where a secondary system needs to meet interference constraints [6–9]. Only hierarchial models of DSA are considered in our study, specifically interweaved approach where tight collaboration between the primary and secondary system is not needed.

In this thesis, indoor low-power system offloading the existing mobile networks is envisioned as secondary system. The main reasons for that are the following:

- Mobile operators need to improve the network capacity especially in indoor locations where approximately 70% of the current data consumption is generated [10].
- Low-power secondary systems could provide better protection of the primary system against harmful interference.
- Low infrastructure and deployment cost since secondary user equipment is expected to be inexpensive.

The gains in spectrum utilization due to secondary access were claimed to be significantly large. However, the constraints for the primary protection and practical implementation issues considerably limit the opportunities for large-scale commercial deployment of secondary systems [11].

1.2 Previous Work

One of the main concerns for allowing the operation of secondary system is the protection of the primary receivers. Most of the previous research in this topic had mainly focused on the protection from co-channel interference (CCI) [12]. However, adjacent channel interference (ACI) becomes also critical when the primary receiver's filter characteristics are not ideal. In this thesis, we have particularly focused on assessing the impact of ACI on the

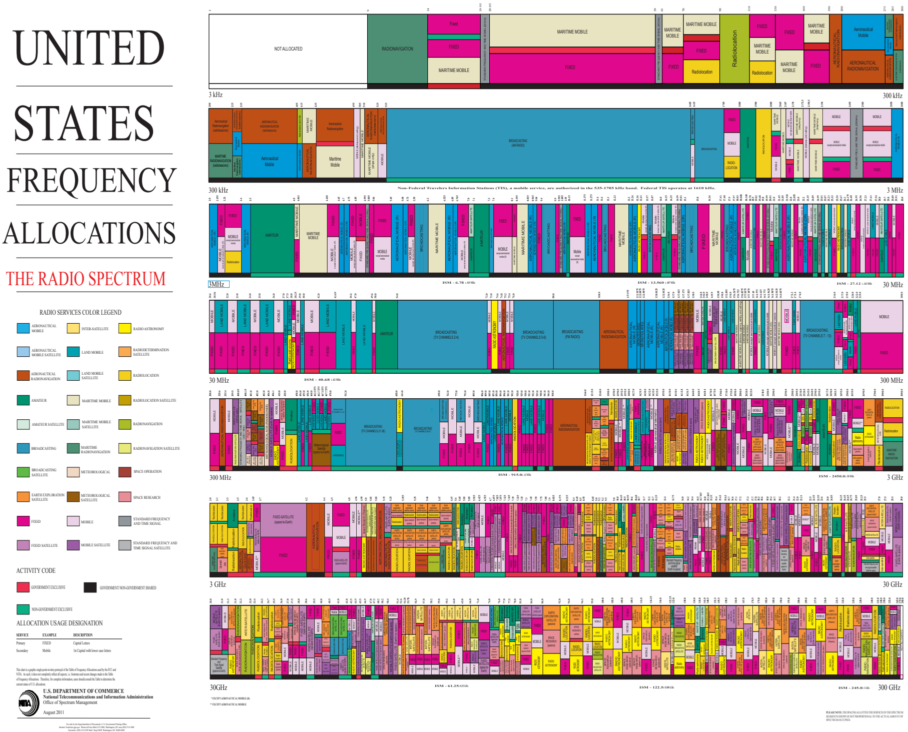


Figure 1.2: United States Frequency Allocations. Source:http://www.ntia.doc.gov/files/ntia/ publications/2003-allochrt.pdf

DTV reception under realistic scenarios, which was not previously addressed. In realistic scenarios, low-power indoor secondary users can be located in the close proximity of the DTV receiver whose location is unknown. Then, secondary access to the TV white space (TVWS) could harm the DTV reception even if CCI is avoided. Different measurement campaigns have been conducted to characterize the ACI rejection capabilities of DTV receiver and to quantify the opportunities of low-power indoor secondary user when ACI is considered. The ACI limitations have been incorporated in recent academic and regulatory work on determining the maximum transmission power of the secondary users [13, 14].

So far, most of the studies have addressed diverse challenges of secondary access considering the TV band as primary system [15, 16]. Although low spectrum utilization has been detected in the radar and aeronautical band, little work has been devoted to quantify the commercial opportunities of secondary access to these bands. In our studies, we assess secondary access to the 960-1215 MHz spectrum which is primarily allocated to distance measuring equipment (DME) systems. As opposed to the DTV receivers, the location of DME receivers is known. However, the high sensitivity of the DME receivers makes challenging to control the aggregate interference of the secondary system over a large geographical area.

In our work, we have particularly investigated how the aggregate interference impacts the requirements of secondary access, which has a direct impact on the availability of secondary spectrum for large scale deployments.

1.3 Problem Formulation

A significant amount of unlicensed secondary spectrum will certainly decrease the operator's cost for deploying more capacity. In the United States, the National Broadband Plan recommended the Federal Communications Commission (FCC) to make 300 MHz available for mobile services by 2015 to cope with the data avalanche consumption. In Europe, the need for additional spectrum is also critical. Therefore, feasibility of secondary access in different frequency bands with low spectrum utilization must be assessed. In this thesis, two different under-utilized frequency bands are considered as primary systems [4]: digital TV and aeronautical band. We apply the interweaved approach, which allows the secondary user to opportunistically access "spectrum holes" or unused portions of spectrum in time, spatial and frequency domain. We have focused our investigation on the spatial and frequency domain.

Secondary access to the digital TV and aeronautical band presents different technical challenges. For the case of digital TV band, limited adjacent channel rejection capabilities and unknown location of the primary receivers are key challenges for secondary access. Instead, the control of the aggregate interference over a large area due to receiver with high sensitivity levels and the extremely low permissible outage probability at the primary system are the key issues for secondary access to the aeronautical band.

In our work, *spectrum opportunity* refers to the available spectrum portion or *channel* where secondary access is feasible while meeting the primary protection criteria. The main overall objective of this thesis is to:

- Determine the amount of spectrum opportunities for deploying a large scale low-power indoor secondary system in the digital TV and the aeronautical band when practical scenarios are considered

For assessing the secondary opportunities in both primary systems, we propose a research methodology with the following steps:

1. *Analyze the impact of low-power indoor secondary user transmission on the primary receiver*. We focus on establishing the limits of tolerable interference at the primary victim by considering not only co-channel, but also adjacent channel interference.

2. *Propose a practical sharing scheme*. For enabling secondary access, we devise sharing schemes customized to the characteristics of the primary system. The uncertainties that accompany our proposed sharing schemes are identified and included in the interference analysis.

3. *Determine the requirements of secondary access*. Operational conditions and constraints for the secondary system, such as minimum distance between the primary receiver and secondary transmitter, maximum secondary transmission power and individual interference threshold, are given for single and multiple secondary user scenario.

4. *Estimate the available spectrum opportunities for low-power indoor secondary systems*. The final output is given in terms of the number of available channels for secondary access in a certain geographical area.

Most of the previous works have determined the availability for secondary access under ideal scenarios. Little efforts were devoted to investigate the real life limitations and benefits of secondary access. The main contribution and novelty of our proposed methodology is that special emphasis is given to determine the interference constraints at the primary victim and to propose sharing schemes for realistic scenarios.

1.4 Overview of Contributions

In this section, we briefly describe the contribution of each publication. This thesis is a compilation of six publications: five conference papers and one journal article.

Chapter 2

Chapter 2 focuses on the secondary access to the TV band. Our contribution to this topic has been presented in the following papers:

- **Paper 1**. 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.

- **Paper 2**. 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 3**. 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 1 investigates the characteristics and interference rejection capabilities of the primary receiver in the presence of multiple secondary users. The paper proposes a model for the maximum aggregate adjacent channel interference that the DTV receiver can tolerate without experiencing any distortion or quality degradation. The proposed model and assumptions were validated by measurement campaigns. Paper 2 determines if there is an opportunity for low-power indoor single secondary user when adjacent channel interference to the TV receivers is considered. In this paper, the importance of adjacent channel interference is shown. The models and assumptions were validated through measurement campaigns that were presented in Paper 3.

The author of this thesis proposed the original problem formulation and acted as leading author of these papers. The measurement campaigns were designed and conducted jointly with Lei Shi and Javier Ferrer. The proposed model in Paper 1 was jointly elaborated by all the authors of the paper. Professor Jens Zander provided directions and valuable insights in all papers. The author of this thesis was the main contributor in the writing process of all papers.

Chapter 3

Chapter 3 assesses the feasibility and availability of secondary access in the aeronautical band. Different findings in this investigation are shown in:

- **Paper 4**. 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**. E.Obregon, K. W. Sung, and J. Zander, "On the Feasibility of Indoor Broadband Secondary Access to the 960-1215 MHz Aeronautical Spectrum," *submitted to the IEEE Transactions on Vehicular Technology (under review)*, 2012.
- **Paper 6**. E.Obregon, K. W. Sung, and J. Zander, "Availability Assessment of Secondary Usage in Aeronautical Spectrum," *to be submitted*, 2012.

Paper 4 investigates the requirements of secondary access to avoid harmful interference to the primary victim. A practical sharing scheme based on geo-location databases and spectrum sensing and mathematical models to compute the aggregate interference are proposed in Paper 5. The impact of uncertainties on the feasibility of secondary access is also evaluated in Paper 5. An assessment methodology for a country-wide evaluation of the availability of spectrum opportunities in the aeronautical band is presented in Paper 6. This methodology incorporates the mathematical models and sharing schemes proposed in the previous papers.

Dr. Ki Won Sung was the main contributor in 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 are 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 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 papers.

1.5 Thesis Outline

The remainder of this thesis is organized in two parts:

- The first part contains from Chapter 2 through 4. Chapter 2 presents our contributions related to secondary access to the TV white space. In this chapter, we give special focus to Step 1 and Step 3 of our methodology. Different measurement campaigns were conducted to verified our interference models. Also, operational conditions for single secondary user were presented. In Chapter 3, we describe the models and results obtained on the large-scale low-power secondary access to the aeronautical band. Considering a multiple secondary user scenario, we emphasize on addressing Step 2 and Step 4. Chapter 4 draws the main conclusions of the thesis. Limitations and possible future directions of this work are also described.
- The second part contains *verbatim* copies of the papers included in this thesis.

Chapter 2

Secondary Access to the Digital TV Band

2.1 Introduction

The analogue broadcasting system for TV transmission was replaced by Digital Television Broadcasting (DVB-T) by which the existing TV channels were reallocated to spectrum portions with less bandwidth. In Sweden, the last analogue TV broadcast station was switched off on October 15th 2007. Currently, 320 MHz in the VHF and UHF bands are dedicated to over-the-air TV transmissions. However, most of the TV spectrum lies idle in a given time and location. Even in dense urban areas, multiple TV channels are vacant or unused. The presence of under-utilized spectrum is not discussed considering that the average number of TV channels occupied in a local market is between six to eight channels [17].

Radio transmissions in TV bands are done at high power to guarantee reliable reception in the complete coverage area. The TV broadcast sites do not change their location nor their operation frequencies, which simplifies identification of vacant TV channels. Potentially, secondary users could access those vacant TV channels without degrading the quality of the TV reception. However, the lack of information about the location and the filter characteristics of the TV receiver make controlling the interference at the primary receivers a key challenge for secondary access to this band. Due to the poor adjacent channel rejection capabilities of the TV receivers, co-channel and adjacent channel interference need to be considered when assessing the interference at the TV receiver. Fig. 2.1 shows the required Desired-to-Undesired (D/U) power level ratios at the TV receiver, which can be seen as the TV receiver filter characteristics. The values of the D/U ratios (γ_k) indicate the maximum tolerable interference ($\hat{I}_{N+k}$) that a typical commercial TV receiver can tolerate at a given channel $N + k$ when a single interferer is considered.

$$\gamma_k = \frac{S_N}{\hat{I}_{N+k}} \tag{2.1}$$

where S_N is the received TV signal power in channel N. Notice that the DVB-T system uses the 470-862 MHz which is divided in 49 channels of 8 MHz each. According to Fig. 2.1, even secondary access in adjacent channels with frequency offset larger than 40 MHz could disturb the operation of TV receivers.

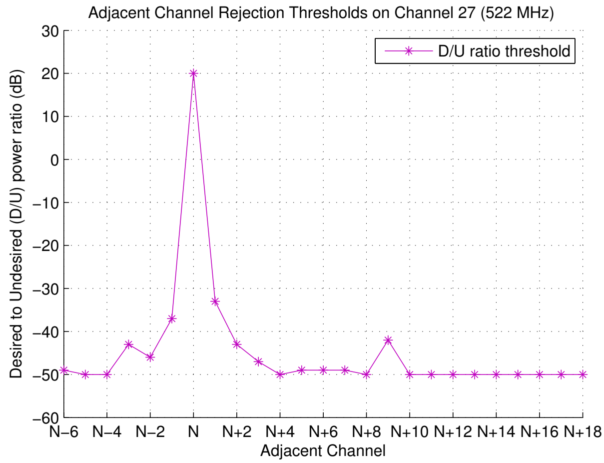


Figure 2.1: Adjacent Channel Rejection Thresholds on Channel 27 (522 MHz) or threshold D/U ratios (γ_k) for a particular DTV receiver

In the following sections, our contributions to the characterization of the primary receivers and to determine the spectrum opportunities for secondary access to the TV band are described.

2.2 Related Literature

Previous measurement campaigns have quantified the effect of a single 3G or WiMAX interferer signal on typical commercial TV receivers. These measurements have focused on characterizing the ACI rejection capabilities of the TV receiver in terms of the required D/U power level ratios to avoid harming the TV reception [18–20].

In [15, 21], the authors show the impact of ACI in the available TV white spaces. The main scenario considered is single secondary user accessing one vacant TV channel. According to [22], multiple low-power secondary users operating in the same frequency behave as a single high-power user. In [12], an analysis of the effect of the aggregate interference and a general formula for the keep-out region is introduced. However, only CCI had been considered and limitations regarding the ACI to the primary receivers were not clearly detailed in [12].

In realistic scenarios, low-power indoor secondary users can be placed in the close proximity of the TV receiver whose location is unknown. Therefore, secondary user could harm the TV operation even if CCI is avoided. Moreover, multiple secondary users can simultaneously access different adjacent channels, which could have a cumulative effect on the interference in the frequency domain. Then, ACI from the secondary system becomes extremely relevant when evaluating the interference at the primary victim. A better understanding of the required thresholds or protection ratios for the ACI in more realistic scenarios with multiple simultaneous secondary transmissions is needed.

2.3 Aggregate Adjacent Channel Interference Model for TV white space (Paper 1)

We propose a multi-ACI scenario with multiple secondary users simultaneously accessing multiple adjacent channels $(N + k, N + j)$. Fig. 2.2 illustrates the multi-ACI scenario. In this scenario, we have assumed that the basic information of the primary system is obtained through a geo-location database. This information refers to the occupied TV channels and the received primary signal level at the location of the secondary user.

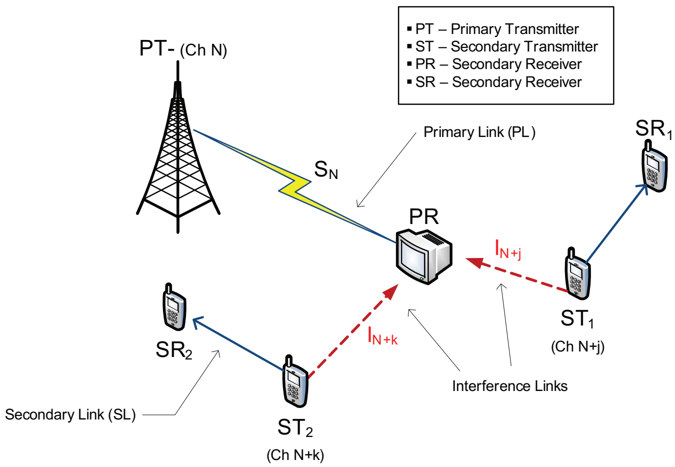


Figure 2.2: Multi Adjacent Channel Interference scenario

In this work, we present a characterization of the aggregate adjacent channel interference (AACI) when the multi-ACI scenario is considered. We assume that there is an aggregate effect from the interference received from multiple adjacent channels[1].

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

$$\frac{S_N}{\hat{I}} \geq \gamma_0 \tag{2.2}$$

[1]This assumption is based on the measurement results where a linear decrement is observed in the maximum tolerable interference in a particular adjacent channel when the number of secondary users is increased.

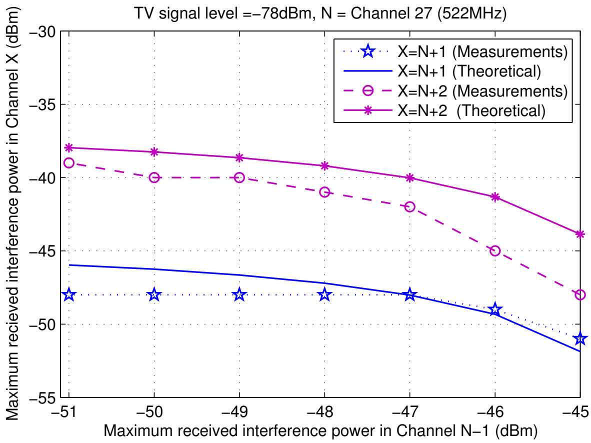


Figure 2.3: Relation between the maximum received interference power level in two different TV channels.

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

$$\hat{I} = \sum_{k\neq 0}^{m} I_{N+k}\frac{\gamma_k}{\gamma_0} \qquad (2.3)$$

where γ_k values are considered as a weighting factor for the aggregate interference generated by m different adjacent channels. Values of γ_k are taken as a linear approximation of the TV filter's characteristics.

Based on (2.3) and (2.2), we proposed an analytical expression to approximate the tolerable AACI at the TV receiver:

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

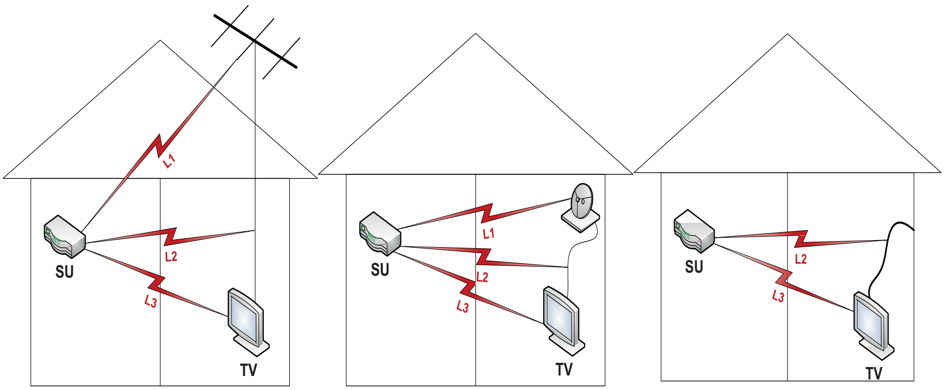
Our model states that not only the interference received in each adjacent channel should stay below the corresponding threshold for that particular channel, but also the weighted sum of the total ACI should be kept below a certain threshold. Measurement campaigns were conducted to verify our assumptions and our proposed model for the maximum tolerable AACI.

Fig. 2.3 shows the relation between the maximum tolerable received interference power in two adjacent channels when they are simultaneously accessed by secondary users. We observe that if the interference power increases in one channel, then the interference power in the other channels in used must be reduced. Therefore, we verified that ACI cannot be treated separately since there is a cumulative effect of the interference in the frequency domain. A good agreement between the theoretical model and the measurement results can be clearly seen in Fig. 2.3.

2.4 Indoor TV white space opportunity for single secondary user (Paper 2, Paper 3)

A realistic assessment of spectrum opportunities for indoor environments must take into account not only CCI caused by the secondary user operation, but also the CI at the TV receiver. The close proximity between secondary user and the primary victim makes the ACI a severe problem.

We consider a scenario where the secondary user is connected to a geo-location database where basic information about the primary system is provided. This information refers to the occupied TV channels and the received primary signal level at the location of the secondary user. For the single secondary user scenario, we consider a low-power indoor secondary user accessing a single adjacent channel $N + k$ and the primary signal is received in channel N. The secondary user has the same channel bandwidth as the TV signals, and ideal filtering is assumed for its output signal. The secondary user is randomly deployed in the indoor environment, e.g. home or office.



(a) (b) (c)

Figure 2.4: TV reception scenarios: a)Rooftop Antenna, b)Set-top Antenna and c)Cable Antenna.

Three different TV reception scenarios are examined: rooftop, set-top and cable TV reception. Then, the interference is assumed to reach the primary receiver over three different paths as it is shown in Fig. 2.4. L_1 represents the propagation loss[2] to the TV receiver antenna, L_2 represents the propagation loss to the cable and L_3 represents the propagation loss to the TV receiver equipment. Then, the total interference at the primary victim or TV receiver in channel N+k (I_{N+k}) is calculated as:

$$I_{N+k} = P_{SU}G_{SU}(\frac{G_{TV}(\theta)}{L_1} + \frac{G_2}{L_2} + \frac{G_3}{L_3}) \qquad (2.5)$$

[2]Propagation loss represents the combined effect of distance-based path loss and shadowing.

where P_{SU} and G_{SU} are the transmit power and the antenna gain of the secondary user, respectively. $G_{TV}(\theta)$ is the gain of the TV receiving antenna, which depends on the incidence angle of the interference, θ. The TV cable attenuation and TV receiver isolation are G_2 and G_3, respectively.

A TV channel was considered as *available* for secondary transmissions if

$$\frac{S_N}{I_{N+k}} \geq \gamma_k \tag{2.6}$$

In our study, typical γ_k from measurements in [19] were used. Based on our assumptions, we found that there is plenty of available channels for low-power indoor secondary users, also called White Space devices (WSD). Secondary users are able to access the majority of the vacant channels without harming the TV reception. Depending on the type of TV reception, the number of available channels for secondary transmissions can significantly vary as it is shown in Fig. 2.5 and Fig. 2.6. For indoor set-top TV reception, ACI becomes critical due to the short separation distance between the TV receiver and the secondary user. Therefore, a separation distance larger than 2 meters is needed to find available spectrum opportunities for secondary users. In the case of rooftop or cable TV reception, secondary users can always find at least one available channel despite short separation distances. For these scenarios, the impact of ACI is not significant even if the number of occupied TV channels is increased.

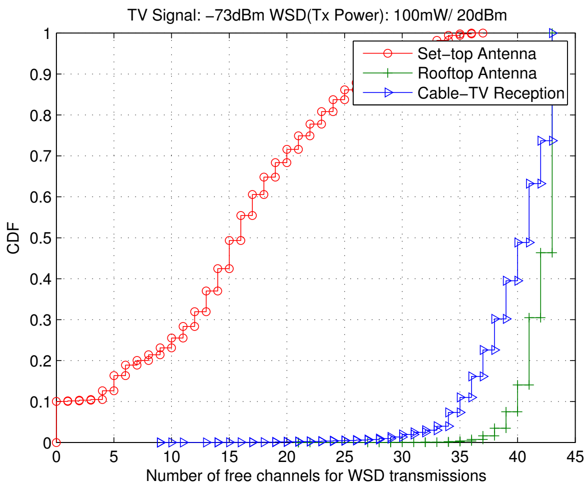


Figure 2.5: CDF of the number of free channels for WSD transmission, Weak TV signal.

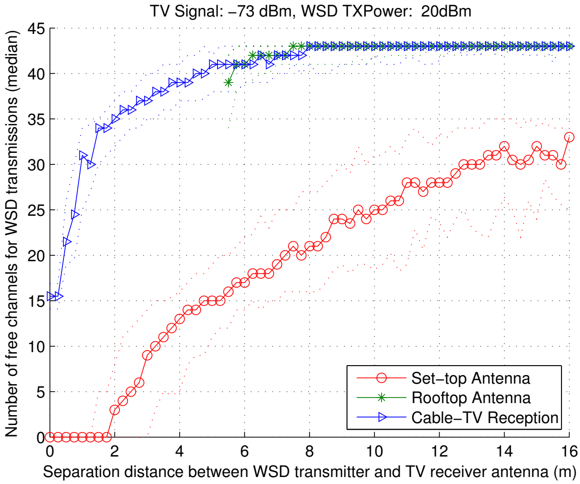


Figure 2.6: Median number of free channels for WSD transmissions depending on the separation distance between the WSD and the TV receiver antenna. WSD transmit power: 100 mW/ 20dBm. 90 and 10- percentiles are shown for each scenario.

Experimental Verification

We assess the impact of low power indoor secondary user on the TV reception quality in a real indoor environment. In our measurement campaign, we aim at verifying our previous assumptions and the proposed interference model given in (2.5). The following questions were proposed to verify the validity of our assumptions:

- Is the D/U ratio (γ_k) a good reference for estimating the spectrum opportunities for secondary users in TVWS?
- Is the direct radiation in the TV receiver significant enough to influence the separation distance?

Our measurement campaign has been carried out in two different locations: laboratory environment and home environment. Fig. 2.7 shows the basic measurement setup employed in the home environment. For the home environment, we conducted our measurements in two apartment of approximately 70 m^2 located in the city of Gävle. In Fig. 2.8, we observe the measurement results when we employed an indoor set-top antenna with high directivity (G_{TV}=8 dBi) to receive the DVB-T signal.

Our measurement results show the importance of the ACI when evaluating the real number of opportunities for short-range secondary system. We have confirmed that the direct radiation from secondary users into cables and the TV receiver set-top box can be neglected. For cable-TV or rooftop antenna reception, ACI was not severe and low-power

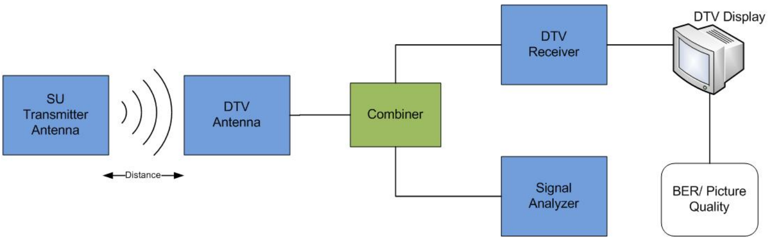


Figure 2.7: Measurement setup in a home environment

indoor secondary users can operate in the majority of vacant TV channels without any noticeable effects on the TV reception quality. However, ACI can significantly reduce the number of available channels for secondary transmissions for indoor set-top antenna reception as it is demonstrated in Fig. 2.8. Also, we observe a good agreement between the simulation-based and measurement results on the available channels for secondary access. Even though the simulation-based results are slightly pessimistic compared to the measurement-based results, the assumptions and overall performance predicted by the theoretical models are reasonable and can be used as lower-bound reference.

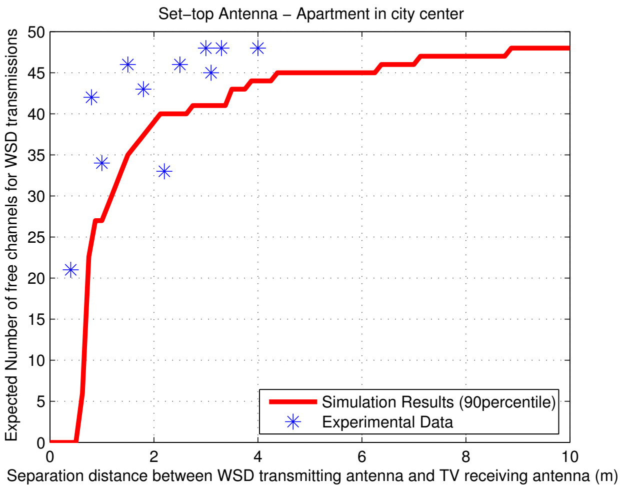


Figure 2.8: Expected Number of available channels for WSD transmissions (high directivity set-top antenna)

2.5 Summary

We analyzed the impact of low-power secondary transmissions on the TV receiver in realistic scenarios. We considered the multi-ACI scenario where low-power secondary users simultaneously access multiple adjacent channels. For that scenario, we proposed a mathematical model for AACI which states that ACI cannot be treated separately in each channel. Instead, the weighted sum of the total ACI in different channels should be kept below a certain threshold.

We incorporated the impact of ACI when assessing the number of spectrum opportunities for indoor secondary access to the TV bands. The limited adjacent channel rejection capabilities of the TV receivers and the close proximity between the secondary transmitter and the TV receivers make the impact of ACI a critical limiting in the set-top scenario. Considering the single secondary user scenario, we identified necessary practical conditions or constraints for the deployment of a secondary user without harming the TV receivers. Our assumptions and models were verified by measurement campaigns. The impact of AACI in the limitations for the deployment and performance of low-power indoor secondary users for a multiple secondary users scenario has not been addressed in our contributions.

Chapter 3

Secondary Access to the Aeronautical Band

3.1 Introduction

Several measurement campaigns have shown low spectrum utilization not only in the digital TV broadcasting band, but also in the radar and aeronautical band. Recent works have demonstrated that the gains in spectrum utilization in the TV bands are not as large as it was claimed. Therefore, there is a need to look for other frequency bands with low spectrum utilization which could be accessed by large-scale low-power secondary networks. The aeronautical band is a good candidate for secondary usage since the location of the primary victim is known, which allows a better control of the interference from the secondary users. 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 interference over a large area becomes challenging. In this chapter, we focus on the 960-1215 MHz spectrum, which is primarily allocated to distance measuring equipment (DME) systems. We investigate the requirements, feasibility and availability for large-scale secondary usage in the DME band.

3.2 Related Literature

In spite of the apparently low spectrum utilization of the radar and aeronautical frequency bands, few studies have been made to determine the requirements and feasibility of secondary spectrum access in these bands. In [23, 24], the authors assessed the opportunities for secondary access in 5.6 GHz primarily allocated to the meteorological radars. Initial feasibility investigation for 3GPP LTE usage of 2.7-2.9 GHz radar spectrum has been presented in [25]. The analysis is based on a single secondary interferer. Specifically in the DME band, the impact of onboard electronic devices to DME performance was investigated in [26, 27]. In [28], 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.

To determine the business viability of secondary access in a particular frequency band, a technical availability assessment is needed. Prior work in estimating the amount of available white spaces has mainly focused on the digital TV bands. In [15], the amount of white spaces in the continental USA is quantified considering two different aspects: the interference from the primary system to the secondary system and viceversa. This work has been extended in [16] to provide the capacity of the secondary users operating in the TV white space of the USA. The self-interference among secondary users, the non-uniform distribution of the population density and the expected transmission range of the secondary users were also incorporated. Following a similar methodology as in [15], the authors in [29] quantified the amount of TV white space in Europe. So far, single secondary user has been considered and the aggregation of the interference in spatial and frequency domain has not been fully addressed in [30].

3.3 System Model

Basic Operation of DME

DME is a radar used for measuring the distance between an airborne equipment (interrogator) and a ground station (transponder). Fig. 3.1 illustrates the basic working principle of the DME. The basic operation of DME consists of two steps: first, the airborne equipment sends an interrogation signal down to 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 (μs). Based on the round trip delay of the signal, the airborne interrogator determines the slant range to the ground transponder. The DME system exchanges gaussian pulses with a short duration of 3.6 μs, but very high transmission powers of 300 W for the interrogator and 2 kW for the transponder. More detailed operation of DME can be found in [31, 32].

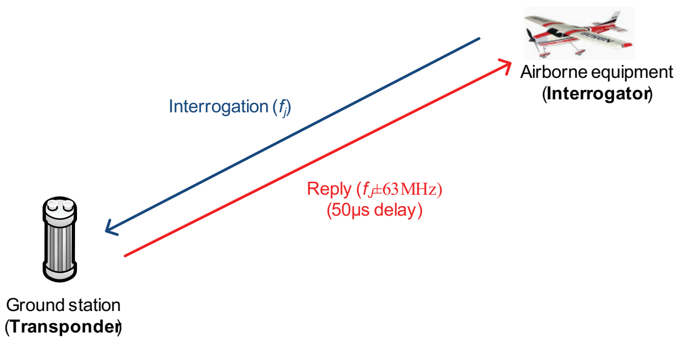


Figure 3.1: Basic operating principle of DME

The DME system is allocated in the 962-1213 MHz frequency band as shown in

Fig. 3.2. 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. 3.2. Some of the frequencies are shared with other aeronautical systems. However, our studies only consider the spectrum exclusively allocated to the DME system. Thus, the bandwidth of interest is about 180 MHz out of 252 MHz in the frequency band.

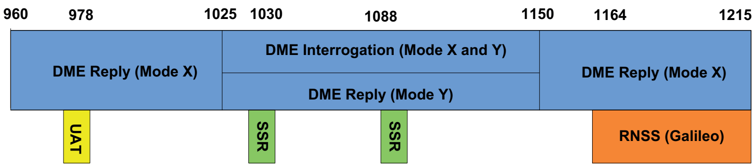


Figure 3.2: Frequency allocation to civil aeronautical systems in 960 -1215 MHz

DME Protection Criteria

We consider that a primary receiver can tolerate a maximum interference power of A_{thr}. The values of A_{thr} for the transponder and the airborne are determined based on their respective sensitivity level. Table 3.1 describes the protection thresholds for ground transponder and airborne interrogation.

Table 3.1: 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

These values correspond to co-channel usage and they represent the worst case scenario, i.e. the airborne interrogator and the ground transponder are at the limit of the DME coverage. For adjacent channel usage, we apply higher interference thresholds since the interference is attenuated by the receiver filter.

The received interference exceeding A_{thr} is considered as harmful interference. Therefore, the aggregate interference (I_a) is regulated as follows:

$$\Pr[I_a > A_{thr}] \leq \beta_{PU} \tag{3.1}$$

where β_{PU} is the maximum permissible probability of harmful interference at the primary receiver. Since the primary system performs a safety-of-life operation, β_{PU} needs to be extremely small. A reasonable range of β_{PU} has not been discussed well in the literature. We adopt a value used for air traffic control radar in 2.7-2.9 GHz, i.e. $\beta_{PU} = 0.001\%$ [25].

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. Let I_{sat} be the saturation point of the secondary receiver. Then, the following condition should be satisfied:

$$\Pr[I_{PU}^{v} > I_{sat}] \leq \beta_{SU} \tag{3.2}$$

where β_{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 for low noise amplifier (LNA) in WLAN receivers [33]. With the parameters in Table 3.1, a simple link budget analysis indicates that (3.1) 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.

Secondary Access Scenario

We consider that secondary users are indoor femtocells which provide indoor broadband services. 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 in the spectrum they use.

Each secondary user decides whether it can access the DME spectrum or not by estimating the interference it will generate to the primary user. Let I_{thr} denote the interference threshold imposed on each secondary user. Then, the interference from a secondary user j is given by

$$I_j = \begin{cases} \xi_j, & \text{if } \tilde{\xi}_j \leq I_{thr} \\ 0, & \text{otherwise} \end{cases} \tag{3.3}$$

where ξ_j is the interference that the primary user would receive if the secondary user were to transmit, and $\tilde{\xi}_j$ is the estimate of ξ_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. The aggregate interference at the primary victim can be described as

$$I_a = \sum_{j \in N_t} I_j \tag{3.4}$$

where N_t is the set of transmitting secondary users.

3.4 Requirements of Secondary Access to the Aeronautical Band (Paper 4)

In this section, we determine the requirements of secondary access to the DME band under the assumption that secondary users have perfect knowledge of the propagation loss to the primary victim ($\xi_j = \tilde{\xi}_j$). The requirements are given in terms of the individual interference threshold (I_{thr}) and the exclusion region (r_o) around the primary user.

We consider that N secondary users are uniformly distributed in a circular area where the primary victim is located at the origin. The secondary users regulate their interference at the primary victim according to (3.3). A cumulant-based approximation is employed to obtain the probability distribution of I_a for a given I_{thr} or r_o. The interference model proposed in [34] is taken as a reference for our mathematical framework. The impact of aggregate interference is analyzed separately for the ground transponder and the airborne interrogator because they operate in different frequencies.

Aggregate Interference to the Ground Transponder

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

$$f_{r_j}(y) = \frac{2y}{R^2},\ 0 < y \leq R. \tag{3.5}$$

Then, ξ_j is given by

$$\xi_j = P_t^{eff} g(r_j) X_j, \tag{3.6}$$

where P_t^{eff} denotes the effective transmission power of the secondary user including the bandwidth difference between the primary and secondary users, antenna gain of primary and secondary users, and wall penetration loss. The distance-dependent path loss is modeled as $g(r_j) = C{r_j}^{-\alpha}$, where C is a constant and α is an exponent. Since we investigate the interference over a large area, a log-normal random variable (X_j) is used to model the fading effect.

We consider that the location of a secondary user and its shadowing value is independent of each other. By using the relationship between r_j and X_j, the pdf of ξ_j can be expressed by the Gaussian error function:

$$f_{\xi_j}(z) = \Omega z^{\frac{-2}{\alpha}-1} \left[1 + \mathrm{erf}\left(\frac{\ln(z/Q) - 2\sigma_{X_j}^2/\alpha}{\sqrt{2\sigma_{X_j}^2}}\right)\right], \tag{3.7}$$

where

$$\Omega = \frac{1}{R^2\alpha}\left(\frac{1}{P_t^{eff}C}\right)^{\frac{-2}{\alpha}} \exp\left[2\sigma_{X_j}^2/\alpha^2\right]. \tag{3.8}$$

According to the interference rule given in (3.3), some secondary users will have zero transmission power. That portion of secondary users is given by $1 - F_{\xi_j}(I_{thr})$, where $F_{\xi_j}(\cdot)$ denotes the cumulative distribution function (CDF) of ξ_j. Thus, the pdf of I_j is given by

$$f_{I_j}(z) = \begin{cases} 1 - F_{\xi_j}(I_{thr}), & z = 0, \\ f_{\xi_j}(z), & 0 < z \leq I_{thr}, \\ 0, & \text{otherwise}. \end{cases} \tag{3.9}$$

The i^{th} cumulant of the sum of independent random variables is equal to the sum of the individual i^{th} cumulants [35]. From this property, the cumulant of I_a can be easily calculated from (3.4) and (3.9). The pdf of I_a can be approximated by a log-normal distribution which provides good accuracy and reduced computational load. The pdf of I_a is approximated as follows:

$$f_{I_a}(z) = \frac{1}{z\sqrt{2\pi\sigma_{I_a}^2}} \exp\left[\frac{-(\ln z - \mu_{I_a})^2}{2\sigma_{I_a}^2}\right], \tag{3.10}$$

where the parameters μ_{I_a} and $\sigma_{I_a}^2$ are obtained from $\kappa_a(1)$ and $\kappa_a(2)$ which are the first and second order cumulants of I_a, respectively.

$$\kappa_a(1) = \exp\left[\mu_{I_a} + \sigma_{I_a}^2/2\right], \tag{3.11}$$

$$\kappa_a(2) = \left(\exp\left[\sigma_{I_a}^2\right] - 1\right) \exp\left[2\mu_{I_a} + \sigma_{I_a}^2\right]. \tag{3.12}$$

Aggregate Interference to the Airborne Interrogator

For the case of airborne interrogator, we consider an airplane at the origin of the circle with the height h from the ground. To account for the worst case scenario, free space propagation loss and no fading are assumed. 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.

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

$$f_{r_j}(y) = \frac{2y}{R^2 - r_o^2}, \; r_o \leq y \leq R. \tag{3.13}$$

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

$$I_j = P_t^{eff} g(d_j), \tag{3.14}$$

where the path loss $g(d_j)$ is given by $Cd_j^{-\alpha}$. By applying a transformation of random variable to (3.14), we get the following pdf of I_j:

$$f_{I_j}(z) = \frac{2}{(R^2 - r_o^2)\alpha} \left(\frac{1}{P_t^{eff} C} \right)^{\frac{-2}{\alpha}} z^{\frac{-2}{\alpha}-1}, \; A \leq z \leq B, \tag{3.15}$$

where

$$A = P_t^{eff} C \sqrt{h^2 + R^2} \text{ and } B = P_t^{eff} C \sqrt{h^2 + r_o^2}. \tag{3.16}$$

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

$$N_t = N \left(1 - \frac{r_o^2}{R^2} \right). \tag{3.17}$$

Since I_j is only affected by the distance based path loss, I_a is well described by the central limit theorem. Let $\mathbf{E}[I_j]$ and $\mathbf{V}[I_j]$ be the mean and variance of I_j, which are calculated from (3.15). Then, I_a is approximated as a Gaussian distribution with mean of $N_t \mathbf{E}[I_j]$ and variance of $N_t^2 \mathbf{V}[I_j]$:

$$f_{I_a}(z) = \frac{1}{\sqrt{2\pi N_t^2 \mathbf{V}[I_j]}} \exp \left[\frac{-(z - N_t \mathbf{E}[I_j])^2}{2N_t^2 \mathbf{V}[I_j]} \right]. \tag{3.18}$$

Results

The main observations from the numerical results shown in Fig. 3.3 and Fig. 3.4 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 rejection (ACR) or attenuation is higher than 40dB. As for the airborne interrogator, co-channel usage is not possible. Adjacent channel attenuation of more than 60dB is required to accommodate high density of secondary users.

3.5 Feasibility of Secondary Access to the Aeronautical Bands (Paper 5)

We propose a practical sharing scheme where the different characteristics of the two primary receivers, ground transponder and airborne interrogator, are taken into account. In the proposed sharing scheme, the secondary users are low-power indoor devices connected to a central geo-location database which provides basic information about the primary system, i.e. locations and frequency allocation. We identify the uncertainties in the propagation loss incurring from the proposed sharing scheme.

The ground transponder is stationary in location, and thus we consider spectrum sensing aided by the geo-location database. The secondary user detects the transponder on the reply (sensing) frequency, while the interference is given on the interrogation (interfering)

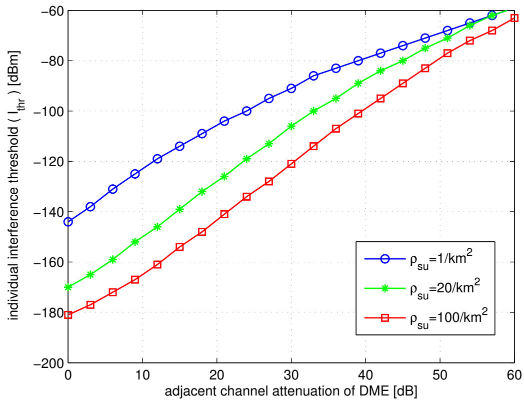


Figure 3.3: I_{thr} as a function of the DME adjacent channel attenuation; the primary receiver is the ground transponder.

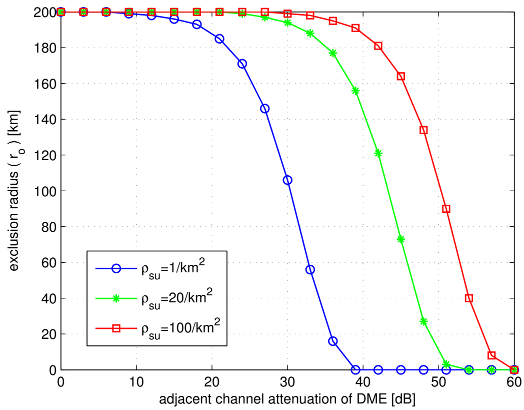


Figure 3.4: r_o as a function of the DME adjacent channel attenuation; the primary receiver is the airborne interrogator.

frequency. The propagation losses between the primary user and the secondary user consist of the distance-based path loss (L) and fading[1](X and Y). Even if the secondary user accurately estimates the propagation loss ($S = L + X$) of the sensing channel, it does not imply that the estimation of interfering channel ($S = L + Y$) is also accurate. Due to the 63 MHz frequency offset between the sensing and interfering channels, *uncertainty* in the estimation of the fading (X and Y) component of the propagation loss between the secondary users and the ground transponder still remains. The correlation, ρ, between the composite fading components, X and Y, will depend on the propagation environment.

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

Fig. 3.5 shows the proposed sensing-based spectrum sharing mechanism.

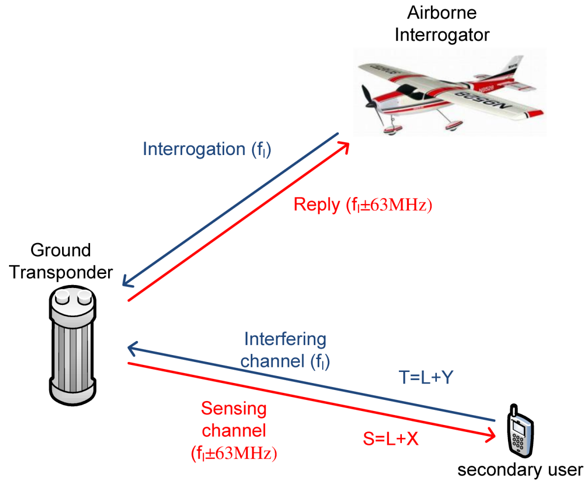


Figure 3.5: Uncertainty in secondary sharing scenario with ground transponder as primary victim

The location of airborne equipment is rapidly moving, then the secondary users could potentially experience *uncertainty* or imperfect information on the location of the primary victim. We employ a real-time location database of airplanes. The level of *uncertainty* will depend on the *update delay* (t_u) in the communication between the geo-location database and the secondary users. Based on the update delay and the speed of the airplane, we introduce the notion of *error region*. Inside this region, secondary users will assume the worst case scenario that the sky is full of airplanes as shown in Fig. 3.6.

Aggregate Interference Modeling under the proposed sharing scheme

We incorporate the identified uncertainties in the mathematical models to compute the aggregate interference. Based on the mathematical framework proposed in [36–38], we employ a cumulant-based approximation to obtain the probability density function (pdf) of I_a. Note that the I_a depends on the level of uncertainty (ρ, t_u). The aggregate interference I_a can be expressed as:

$$I_a = P_t^{eff} C \underbrace{\sum_{j \in N_t} r_j^{-\alpha} Y_j}_{I_{N_t}} . \tag{3.19}$$

where P_t^{eff} refers to the effective transmission power of the secondary user including antenna gains and bandwidth mismatch, C is a constant and α is the path loss exponent. Y_j is a random variable modeling the fading effect which follows a log-normal distribution. It is

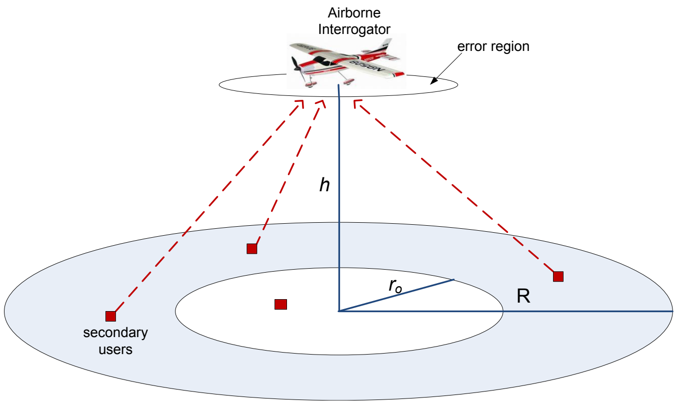


Figure 3.6: Uncertainty in secondary sharing scenario with airborne interrogator as primary victim

known that this assumption works well when the standard deviation of shadowing is higher than 6 dB, i.e. when the shadowing is a dominant factor of the composite fading [39].

The mathematical expressions when there is partial correlation ($0 < \rho < 1$) between the composite fading components, X and Y, can be found in [40]. For the cases of full correlation ($\rho = 1$) and zero correlation ($\rho = 0$), the closed-form expressions of cumulants can be found in [37] and [38], respectively. Using the cumulant of I_{N_t}, we can obtain the n^{th} cumulant of the aggregate interference I_a as follows:

$$k_{I_a}(n) = (P_t^{eff} C)^n k_{I_{N_t}}(n). \tag{3.20}$$

For the ground transponder case, the aggregate interference I_a can be approximated by a known probability distribution with the cumulants obtained in (3.20). We found that log-normal distribution provides a good description of I_a. The pdf of I_a can be approximated with the first and second order cumulants of I_a.

$$f_{I_a}(y) = \frac{1}{y\sqrt{2\pi\sigma_{I_a}^2}} \exp\left[\frac{-\ln y - \mu_{I_a}}{2\sigma_{I_a}^2}\right], \tag{3.21}$$

where

$$k_{I_a}(1) = \exp[\mu_{I_a} + \sigma_{I_a}^2/2], \tag{3.22}$$

$$k_{I_a}(2) = \exp(\sigma_{I_a}^2 - 1)\exp(2\mu_{I_a} + \sigma_{I_a}^2). \tag{3.23}$$

For the airborne interrogator case, the I_j 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 is approximated as a Gaussian distribution with the first two cumulants which are the mean and variance:

$$f_{I_a}(z) = \frac{1}{\sqrt{2\pi k_{I_a}(2)}} \exp\left[\frac{-(z - k_{I_a}(1))^2}{2k_{I_a}(2)}\right]. \tag{3.24}$$

Results

The feasibility of large scale secondary access is evaluated in terms of the number of secondary users which are able to operate with an acceptable transmission probability and the exclusion region imposed to the secondary users.

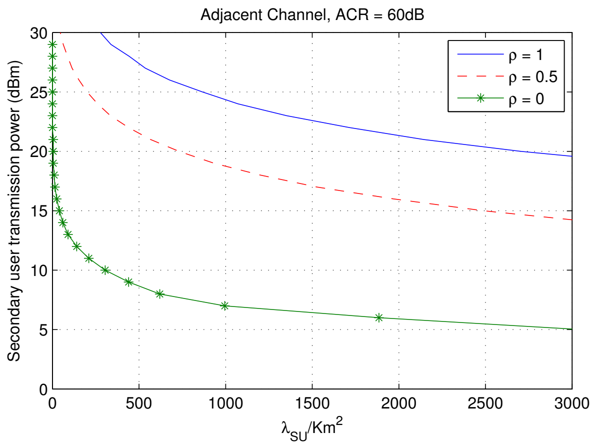


Figure 3.7: Impact of different correlation coefficients(ρ) on the feasibility of the secondary access when $Pr(\tilde{\xi}_j \leq I_{thr}) \geq 90\%$ at $r_j = 5$km, the primary receiver is the DME ground transponder. Secondary user transmission power vs. density of secondary user(λ_{SU}).

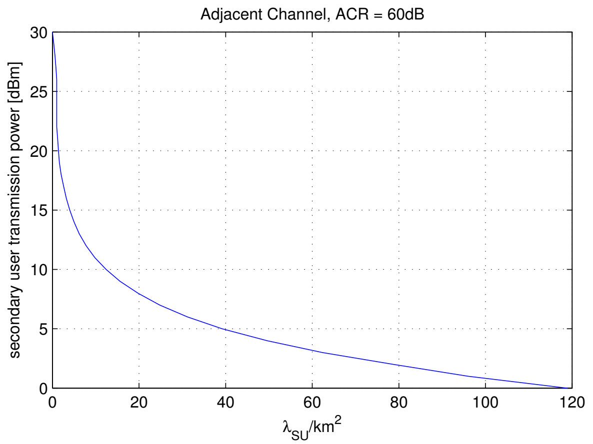


Figure 3.8: Maximum secondary user transmission power for a given λ_{SU} when no exclusion region is needed ($r_o = 0$km), the primary receiver is the DME airborne interrogator. Secondary user transmission power vs. density of secondary user(λ_{SU}).

From our numerical results presented in Fig. 3.7 and Fig. 3.8, we conclude that low-power indoor secondary access to an adjacent channel 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. For the case of the ground transponder channels and airborne interrogator channels, our results show that propagation loss uncertainty and the update delay will not have significant impact on the performance of secondary user when the secondary users operate with low-transmission power and they access an adjacent channel with ACR higher than 60dB.

3.6 Availability Assessment of Secondary Usage in the Aeronautical Band (Paper 6)

We investigate the availability of spectrum opportunities for large-scale low-power secondary access in the 960-1215 MHz band, primarily allocated to DME systems. We develop a methodology that takes into account real-life demographics such as regional spectrum allocation of the DME band, location of the DME ground transponders and population density. In our assessment, a DME channel is considered as an *available* channel if the secondary user, under the applied sharing scheme, is able to successfully access the channel without violating the primary protection criterion.

The total area of interest is divided in two dimensional rectangular pixels. Within the pixel, we consider that secondary users are distributed according to a homogeneous Poisson point process (PPP) and the density of secondary users is proportional to the population density. Since we are considering a scenario where multiple DME channels could be simultaneously accessed by the secondary users, not only the aggregate interference in a single channel but also the aggregate interference from different channels should not exceed maximum tolerable interference, A_{thr}, at the primary victim [30]. The protection criterion given in (3.1) is modified to account for aggregate multi-channel interference. Then, the interference at a primary receiver, *v*, is regulated as follows

$$\Pr\left[\sum_{k\in N_{ch}^{v}}\sum_{i=1}^{N_p} I_{k,i}^{v} W_k \geq A_{thr}\right] \leq \beta_{PU} \tag{3.25}$$

where N_p is the total number of pixels, N_{ch}^{v} is the set of channels which interference aggregate at the primary victim *v*. The total interference from pixel i that the primary victim v receives in channel k is denoted as $I_{i,k}^{v}$ and β_{PU} is the maximum permissible probability of harmful interference at the primary receiver. The weighting factor, W_k, depends on the DME filter's characteristics. For our numerical evaluations, we employ the values of W_k given in [28].

Assessment Methodology of Availability

In our methodology, we assume that all channels in N_{ch}^{v} generate the same amount of interference at the primary victim v. Then, (3.25) can be re-written as:

$$\Pr\left[N_{ch}^{v} W_k \underbrace{\sum_{i=1}^{N_p} I_{k,i}^{v}}_{I_{k,a}^{v}} > A_{thr}\right] \leq \beta_{PU} \tag{3.26}$$

Then, the aggregate interference in channel k at the primary victim v, $I_{k,a}^{v}$, is regulated as follows:

$$Pr[I_{k,a}^{v} > \frac{A_{thr}}{N_{ch}^{v} W_k}] \leq \beta_{PU} \tag{3.27}$$

By applying (3.27), the numerical analysis can be performed on channel basis. We compute the aggregate interference in channel k at the primary victim v, $I_{k,a}^{v}$, and determine the minimum requirements to satisfy (3.27). Both primary receivers, ground transponder and airborne interrogator, are considered in our calculations. The constraints to protect the primary victim v in channel k are given in terms of the individual interference threshold, $I_{thr}(k)^{v}$, or the minimum separation between the DME receiver and the secondary users, $r_o(k)^{v}$. Then, a DME channel is considered as *available* in pixel i if

$$C_{k,i} \equiv \begin{cases} 1, & \text{when } \mathbb{E}[\tilde{\xi}_{k,j}^{v}] \leq I_{thr}(k) \\ 0, & \text{otherwise} \end{cases} \tag{3.28}$$

where

$$I_{thr}(k) \equiv \min(I_{thr}(k)^{1}, ..., I_{thr}(k)^{v}) \tag{3.29}$$

where $\mathbb{E}[\tilde{\xi}_{k,j}^{v}]$ is the expectation of the estimated interference from the secondary user j at the primary victim v. Notice that the interference threshold will be set depending on the level of uncertainty, the transmission power and 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.

$$C(i) \equiv \sum_{k \in K} C_{k,i} \tag{3.30}$$

Results

This methodology is applied to examine the availability of spectrum opportunities in Germany and Sweden as it is shown in Fig. 3.9. In Table 3.2, we also show how the uncertainties in the applied sharing schemes impact the availability in both countries.

Our numerical experiments showed that the available channels for large-scale low-power secondary usage is at least 50 MHz in any location of Germany and Sweden. The spatial distribution of the available channels highly depends on the distribution of the population. The availability is strongly influenced by the parameters and requirements of the secondary system. For a dense deployment of secondary users, it is recommended to adopt low transmission power in order to have a larger number of available channels. The potential uncertainties in the estimation of propagation loss have a negative but not critical impact on the availability. For high levels of uncertainty, the availability only decreases up to 6%. Most of the available channels are, however, non-contiguous. Therefore, good carrier aggregation capabilities are crucial for the secondary users in order to fully utilize the available channels.

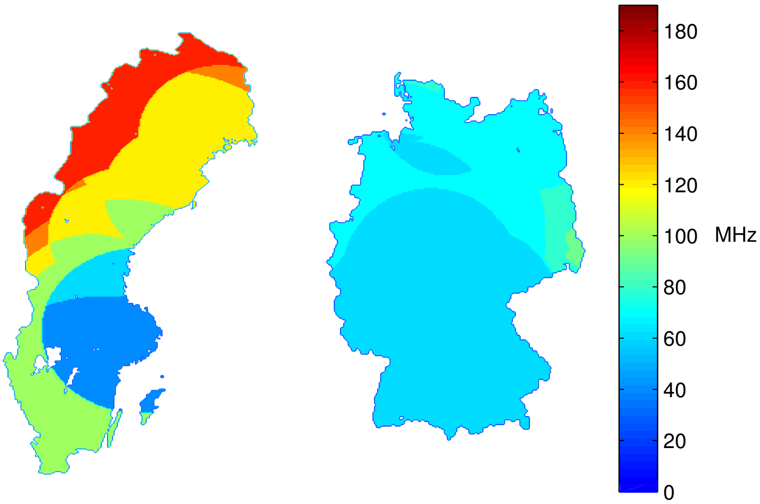


Figure 3.9: Availability by area(MHz) in Sweden (left) and Germany (right). (SU_{Ptx}=0dBm/MHz, f_a=1, $\rho = 1$ and t_u=0min)

Table 3.2: The average available channels

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

3.7 Summary

In this section, we have investigated the feasibility and availability of secondary access to the aeronautical band. Particularly, we focused on the spectrum allocated to the DME system.

As an initial study, the requirements of secondary access to the DME band were established under the assumption that secondary users have perfect knowledge of the propagation loss to the primary victim. Since this assumption is unrealistic, those requirements do not guarantee the feasibility of secondary access in this band. Our results can be taken as theoretical minimum requirements which give the maximum achievable performance of the secondary users.

Later, we proposed a practical sharing scheme customized to the DME characteristics. We assessed the impact of imperfect knowledge of the propagation loss on the requirements of secondary access, which became stricter to guarantee the protection of the primary victim. Although the impact of uncertainty on the requirements was significant, the feasibility of secondary access to adjacent channels was still possible.

Finally, our work was extended to a multi-channel scenario where the interference aggregation not only in the spatial domain but also in the frequency domain was considered. In order to evaluate the economical benefits of secondary access to the DME band, regional availability assessment was introduced. Real demographic data, such as population density, was incorporated into our models. In our assessment methodology, we assumed that the interference equally divided into the DME channels. Therefore, the maximum achievable availability with the optimum allocation of the interference power budget in spatial and frequency domain remains an interesting further study. The accuracy of the demographic information and the operational facts about the primary system can also be improved to provide more precise assessment.

Chapter 4

Conclusions and Future Work

4.1 Conclusions

The explosive growth in mobile data consumption represents a big challenge for mobile operators. The efficient use of radio resources, e.g. technology, infrastructure and *spectrum*, is needed to meet the new capacity requirement in mobile networks. In this thesis, we have proposed a research methodology which aims at quantifying the real-life spectrum opportunities for deploying a massive low-power indoor secondary system in two different frequency bands: digital TV and aeronautical band.

In the first part of this thesis, we mainly investigate the impact of interference from a single and multiple secondary user at the TV receiver. We verified, through measurement campaigns and simulations, that not only CCI but also ACI needs to be taken into account when determining the maximum tolerable interference at the primary victim. Especially for indoor low-power secondary access to the TV band, ACI becomes the limiting factor of the real-life spectrum opportunities. This is mainly caused by the limited adjacent channel rejection capabilities and the lack of information about the location of the TV receivers. The impact of ACI becomes even more critical when different frequencies are simultaneously accessed by secondary users, principally because the interference aggregates not only in the spatial but also in the frequency domain. The suitable selection of the physical placement, the channel allocation scheme and the transmission power of the secondary users will increase the number of spectrum opportunities.

The second part of this thesis focuses on the aeronautical band, which presents different challenges from the ones in the TV band. Despite the locations of the primary victims are mostly known and spectrum sensing can be applied in a practical scenario, the high sensitivity of the DME receiver makes the control of the aggregate interference over a large area a challenge for secondary access in this band. We proposed a practical sharing scheme based on geo-location databases and sensing, which was customized to the characteristics of realistic DME systems. Under the propose sharing scheme, the deployment of large scale low-power indoor secondary system in adjacent channels was shown to be feasible. Imperfect knowledge of the propagation loss and imperfect information of the primary victim location do not have a significant impact on the country-wide availability of spectrum opportunities for secondary access in the aeronautical band.

Based on our results, we conclude that there is significant amount of spectrum opportunities for secondary access in the digital TV and the aeronautical band. The practical availability of secondary spectrum highly depends on the sharing mechanisms, the primary protection criteria and the secondary system parameters.

The findings in this thesis show the technical viability of secondary access to the TV band and the aeronautical band. These results are directly beneficial for spectrum policy makers and industry players worldwide to foresee the deployment of new or existing wireless services, which will ultimately benefit the consumers.

4.2 Future Work

In our studies, we have mainly focused on the protection of primary victim. Future work should consider how the secondary users share the available spectrum. Therefore, the self-interference in the secondary system should be taken into account when analyzing the performance of secondary systems under realistic scenarios, e.g. imperfect knowledge of the environment. Further investigations on the impact of level of knowledge on the maximum achievable secondary system performance could identify the most critical parameters which give the main losses or degradation.

We have developed interference models to account for fading uncertainty in the aeronautical band. In future studies, these models can be refined to be applied when the primary victims have different characteristics from the DME receivers, also when the secondary user applies power control or different access protocols.

Finally, we have provided an assessment methodology for a country wide evaluation of availability for secondary access in the aeronautical band. However, business viability cannot be claimed even if a significant availability was shown. Therefore, further work should develop business viability assessment methodology where technical and economical aspects are taken into account.

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