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 function, protection from harmful interference becomes extremely critical. A DME channel is considered *available* in a certain location if the secondary users, under the applied sharing scheme, are able to successfully access the channel without violating the primary protection criterion. 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 dense deployment of low-power secondary network even with conservative parameters for primary system protection and high levels of uncertainty.**

***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, but they are actually limited by the protection of the primary victims. Due to potential errors in the detection schemes and the effect of the aggregate interference in massive deployments, large safety margins are introduced to protect the primary victims. These margins considerably decrease the availability for secondary usage [3]. A quantitative analysis of the availability 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. In [4], 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 [5] to provide the capacity of the secondary users operating in the TV white space of the USA. Following a similar methodology as in [4], the authors in [6] quantified the amount of TV white space in Europe. So far, the aggregation of the interference is spatial and frequency domain [7] has not been fully addressed.

Although low spectrum utilization has been reported in the radar and aeronautical bands [8], limited efforts have been made in the investigation of secondary access to these frequency bands [9], [10]. This work focuses on the aeronautical band, specifically the 960-1215 MHz band, which is mainly occupied by 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 [11]. Despite these challenges, our previous work has shown that secondary access to this band is feasible [12] [13]. Therefore, a quantitative assessment of the availability for the deployment of a massive secondary network in the DME band is worthwhile to be investigated.

In this paper, we investigate the availability for massive indoor broadband secondary access to the 960-1215 MHz band, primarily allocated to DME systems. Our main contributions are the following: first, we develop an assessment methodology for quantifying the spectrum availability for secondary usage in a large geographical area; second, we examine the practical availability in Germany and Sweden by taking into account real-life demographics. 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 criterion. Thus, we focus on 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. We briefly outline the applied secondary access schemes in Section III. The proposed methodology for 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.

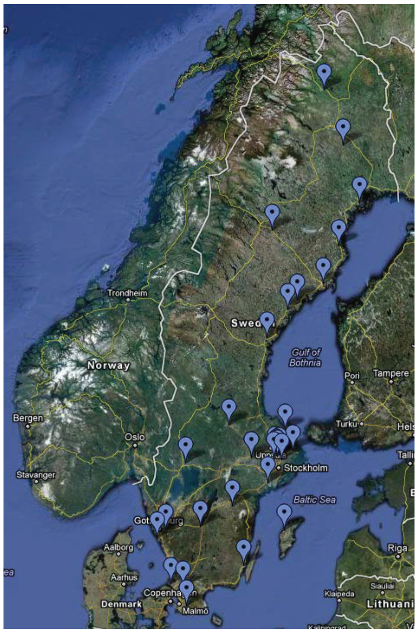

Fig. 1. Locations of DME ground transponders in Sweden, based on http://worldaerodata.com/nav/. Last update in 2007. Background image from Google Maps.

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 sends an interrogation signal down to earth; second, the ground transponder responds on a frequency of ± 63 MHz from the interrogation frequency after a delay of 50 μs. 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 more detailed description of the DME operation can be found in [12].

B. Secondary access scenario

We consider a large-scale deployment of indoor access points and mobiles providing high capacity broadband services. The total area of study is divided into rectangular pixels, where the density of secondary users λ_{SU}^i in a pixel i is proportional to the population density in that particular area. The secondary users are spatially distributed according to a homogeneous Poisson point process (PPP) in a two dimensional plane $\Re^2$. An arbitrary secondary user j decides whether it can access a particular DME channel or not by estimating the interference it will generate to the primary user. Let $I_{thr}(k)^v$ denote the interference threshold imposed on each secondary user accessing channel k to protect the primary victim v. Then, the interference from a secondary user j in channel k is given by

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

where $\xi_{k,j}^v$ is the interference that the primary user v would receive in channel k if the secondary user j were to transmit, and $\tilde{\xi}_{k,j}^v$ 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

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

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

$$I_{k,a}^v = \sum_{i=1}^{N_p} I_{k,i}^v \quad (3)$$

where N_p is the total number of pixels.

C. Protection criteria

We consider that the 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 [12]. Since we are considering a multi-channel scenario where multiple DME channels could be simultaneously accessed by the secondary users. Then, 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 [7]. The aggregate interference at a primary receiver, v, is regulated as follows

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

where N_{ch}^v is the set of channels whose interference aggregate at the primary victim v. The weighting factor, W_k, depends on the filter's characteristics and β_{PU} is the maximum permissible probability of harmful interference at the primary receiver. Due to the safety-of-life operation of the DME, β_{PU} needs to be extremely small. We adopt a value used for air traffic control radar in 2.7-2.9 GHz, $\beta_{PU} = 0.001\%$ [9].

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:

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

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 $I_{sat} = -30\text{dBm}$ 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, we will focus on the protection of the primary user in the remainder of the paper.

III. Secondary sharing scheme

In this section, we briefly describe the secondary sharing schemes proposed in [13], which are applied to our availability assessment. Since the DME system is divided into the ground station and the airborne equipment, different sharing mechanisms are applied to each element.

A. Sharing with the ground transponder

The secondary users share the DME spectrum via sensing aided by geo-location databases. The geo-location databases provide the basic information of the transponder such as transmission power, location and operating frequency. With this information, the reliability of the spectrum sensing is expected to be good enough to neglect missed detection and false alarm since the location of the transponder is fixed as depicted in Fig. 1.

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 the sensing and interfering channels, *uncertainty* in the estimation of fading component of the propagation loss between the secondary users and the transponder still remains. The correlation, ρ, between the composite fading components in these frequencies will depend on the propagation environment. More details can be found in [13].

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 users could potentially experience *uncertainty* or imperfect information on the location of the primary victim. 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 update delay and the speed of the airplane. For additional details, the readers can be referred to [13].

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. We consider that the secondary users are indoor broadband devices connected to a central database which provides basic information about the primary system. The secondary users apply the sharing mechanisms described in Section III. The secondary users have a fixed transmission power and their density in pixel i (λ_{SU}^{i}) is proportional to the population density in that particular location and their activity factor (f_a). The mathematical models described in [13] are employed to compute the aggregate interference in the spatial and frequency domain at the primary victim, which is regulated by (4).

In order to simplify the computation, we assume that all channels in N_{ch} generate the same amount of interference at the primary victim. Then, (4) can be re-written as:

$$\Pr\left[N_{ch}^{v} W_k I_{k,a}^{v} > A_{thr}\right] \leq \beta_{PU} \tag{6}$$

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

$$Pr[I_{k,a}^{v} > \frac{A_{thr}}{N_{ch}^{v} W_k}] \leq \beta_{PU} \tag{7}$$

By applying (7), the numerical analysis can be performed on channel basis and computation complexity is considerably reduced. We compute $I_{k,a}^{v}$ and determine the minimum requirements to satisfy (7). 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, $I_{thr}(k)^{v}$, 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

$$C_{k,i} \equiv \begin{cases} 1, & \text{when } \mathbb{E}[\tilde{\xi}_{k,j}^{v}] \leq I_{thr}(k) \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

where

$$I_{thr}(k) \equiv \min(I_{thr}(k)^{1}, ..., I_{thr}(k)^{v}) \tag{9}$$

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 $I_{thr}(k)^{v}$ depends on 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.

$$C(i) \equiv \sum_{k \in K} C_{k,i} \tag{10}$$

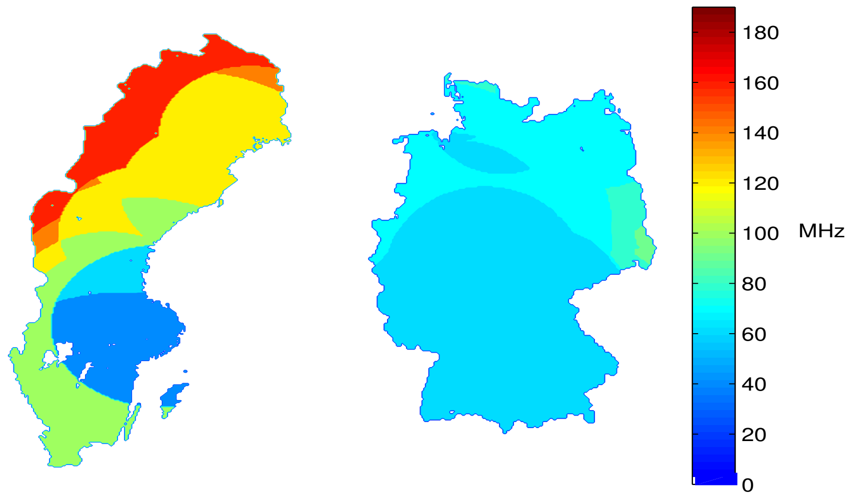

Fig. 2. Availability in Sweden (left) and Germany (right). ($SU_{Ptx} = 0$dBm/MHz, $f_a = 1$, $\rho = 1$ and $t_u = 0$min)

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

$$m_a \equiv \frac{1}{A_t} \sum_{i \in N_p} A_R^i C(i), \tag{11}$$

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

$$m_p \equiv \frac{1}{p_0} \sum_{i \in N_p} P_i C(i). \tag{12}$$

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

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 airborne interrogator we employ free-space propagation loss is assumed. We adopt this assumption to account for the worst case scenario where there is line-of-sight path between every secondary user and the airborne.

We assess the availability by area in the DME spectrum in two countries with different characteristics: 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 by area in the DME band is shown in Fig. 2. For the case of Germany, we can observe that the availability is almost constant in all the country, mainly because the spatial distribution of the population density has a small variance. On the contrary, the availability in Sweden has a large variance as well as the spatial distribution of 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 considerably decreases. This is mainly due to higher aggregate interference from the secondary users and higher density of DME transponders close to the urban areas as it is shown in Fig. 1. However, secondary users can still access at least 57 MHz bandwidth in any location of Germany or Sweden.

TABLE I
Parameters used for numerical experiments

Parameters for ground transponder	
primary user transmission power	60 dBm/MHz
path loss constant (C)	4.5×10^{-13}
path loss exponent (α)	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)	5.7×10^{-10}
path loss exponent (α)	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

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 by area is depicted in Fig. 3. A noticeable decrement in the 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. Then, there are at least 57 MHz that are not allocated to the DME system throughout these countries.

Fig. 4 shows the impact of secondary user traffic intensity which is represented by the activity factor f_a. Note that we consider an extremely massive usage because the activity factor of one 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 I_{thr} value or enlarging the exclusion region. A higher f_a causes the diminishing availability as observed in Sweden. However, this effect is not visible in Germany because its population density is more than ten times higher than the population density of Sweden. The availability in Germany is mostly limited to the unallocated DME channels.

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 uncertainties 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 both the interfering and sensing channels. In the case of airborne interrogator, uncertainty on the location of the primary victim is present due to the high speed of the airplanes. Currently, the living example of real-time aircraft location database is updated every 20-60 seconds [15]. In our experiments, we deal with a pessimistic scenario where the update delay (t_u) is 150 seconds or 2.5 minutes.

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 low density of secondary networks. Even with pessimistic levels of uncertainty, the availability only decreases up to 6% compared to the ideal scenario where uncertainties are not present.

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

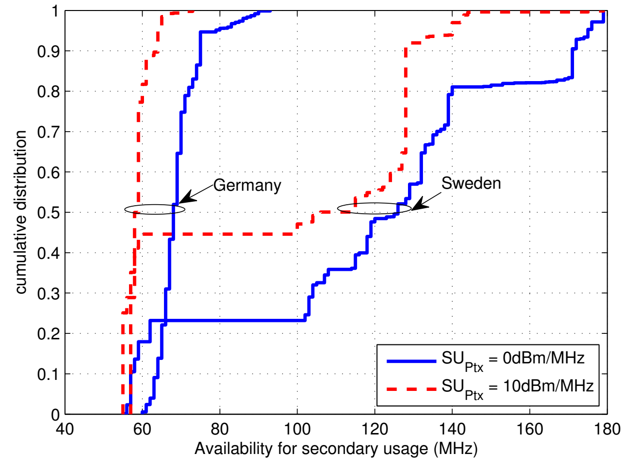

Fig. 3. CDF of the availability for different secondary user transmission power ($f_a = 1$,$\rho = 1$ and $t_u = 0$min)

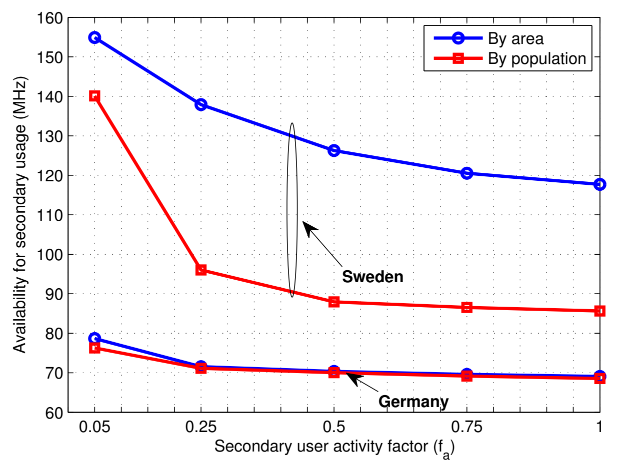

Fig. 4. Average availability for different secondary user activity factor ($SU_{Ptx} = 0$dBm/MHz, $\rho = 1$ and $t_u = 0$min)

C. Contiguous Bandwidth

In order to estimate 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 are non-contiguous. In both countries of study, the median number of contiguous 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	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%)

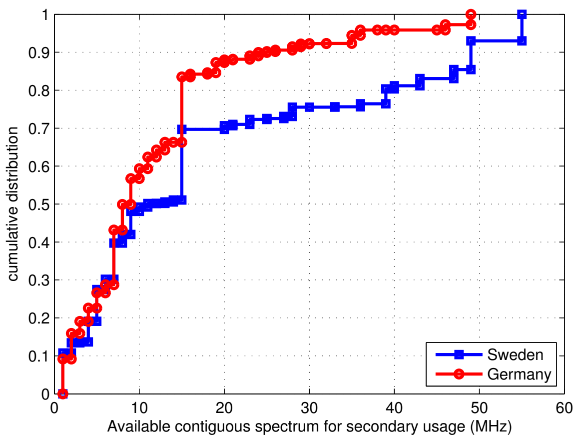

Fig. 5. CDF of the available contiguous spectrum in the DME band. (SU_{Ptx} = 0dBm/MHz, $p_a = 1$, $\rho = 1$ and t_u = 0min)

VI. CONCLUSIONS

We investigated the availability of massive indoor broadband secondary access in the 960-1215 MHz band, primary allocated to the DME systems. We applied the practical sharing mechanisms proposed in [13], where the secondary users share the DME spectrum by means of spectrum sensing and geolocation database. We developed a methodology to assess the available amount 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. This is mainly due to higher aggregate interference from the secondary users 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 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 since most of it is non-contiguous. Understanding the economic value of the available DME spectrum for secondary use remains as an interesting future study.

ACKNOWLEDGMENT

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