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

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

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

I. Introduction

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

There have been extensive studies on the secondary spectrum access in recent years. Achievable channel capacity and rate region for secondary users were analyzed in [6], [7]. In [8], the impact of spectrum sharing techniques was evaluated. Temporal aspect of the secondary access was studied in [9]–[11]. A review of spectrum sensing techniques was presented in [12]. A survey describing basic definitions and challenges of opportunistic spectrum access can be found in [13]. However, it is pointed out in [14] that little research has been done to assess the practical availability and real-life benefit of the secondary access. Quantification of the usable TV spectrum in the UK and the USA was addressed in [15] and [16], respectively. In [17], opportunity of indoor usage was studied considering adjacent channel interference to TV receivers. So far, most of the efforts have been devoted to assessing the value of TV white spaces in 470-790 MHz. This necessitates the investigation on the feasibility and the business opportunity of secondary access to other primary frequency bands

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

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

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

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

Answers to the questions will provide a basis of future studies on the viability of the secondary access to DME spectrum.

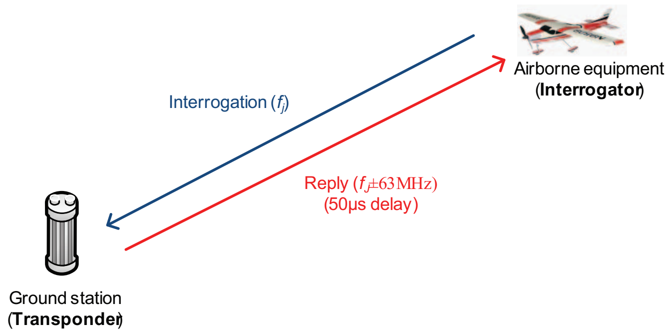

Fig. 1: Basic operating principle of DME

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

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

II. System Model

A. Basic operation of DME

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

The frequency band allocated for DME operation is 962-1213 MHz as shown in Fig. 2. The channel bandwidth of DME is 1 MHz, i.e. there are 252 channels in total. Interrogators and transponders are allotted 126 channels each. The DME system uses two different operational modes, namely X and Y. Frequency planning according to the mode is illustrated in Fig. 2. The figure also shows that some of frequencies are shared by other aeronautical systems. Upper part of the spectrum (1164-1215 MHz) is planned to be used by the European radio navigation satellite system (RNSS) Galileo. Due to the ubiquitous locations of potential receivers and the low receiver sensitivity, this spectrum is expected to be infeasible for the secondary access. In the rest of the band, the most of the spectrum is allocated solely to DME. Thus, we limit the scope of this study to the portion of spectrum allocated only to the DME system. Secondary spectrum sharing with other systems is not interesting from the business perspective because they account for only a fraction of spectrum which is not enough for broadband services. The bandwidth of interest is then about 180 MHz out of 252 MHz in the frequency band.

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

B. Protection of DME

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

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

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

Note that the aforementioned thresholds are applied to the co-channel usage. If the secondary users employ adjacent DME channels, higher interference is allowed to the secondary users because the interference power attenuates as it goes through the spectrum mask of the primary user. The impact

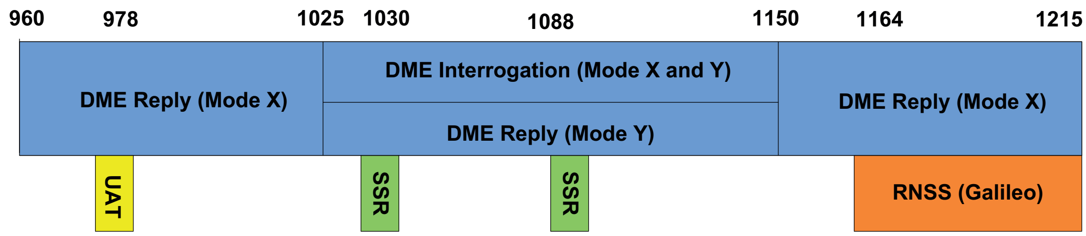

Fig. 2: Frequency allocation to civil aeronautical systems in 960-1215 MHz

TABLE I: Protection threshold of DME

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

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

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

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

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

C. Secondary access scenario

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

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

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

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

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

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

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

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

III. Aggregate Interference to Primary System

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

A. Interference to DME ground transponder

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

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

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

Then, ξ_j is given by

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

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

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

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

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

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

where

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

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

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

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

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

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

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

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

B. Interference to DME airborne interrogator

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

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

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

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

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

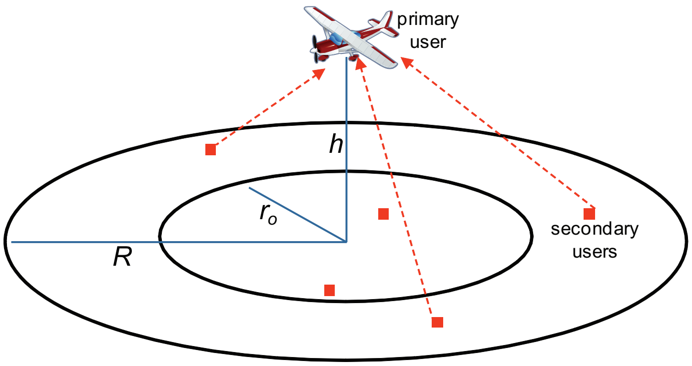

Fig. 3: Interference from secondary users to airborne interrogator

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

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

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

where

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

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

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

Then, the aggregate interference I_a is

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

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

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

IV. Numerical Results

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

TABLE II: Parameters used for numerical experiments

Parameters for ground transponder	
path loss constant (C)	4.5×10^{-13}
path loss exponent (α)	3.5
Shadowing standard deviation ($\sigma_{X_j}^{dB}$)	10 dB
height of the transponder	30 m
Parameters for airborne interrogator	
path loss constant (C)	5.7×10^{-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	10 dBm/MHz
secondary user height	1.5 m

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

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

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

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

Fig. 6 and Fig. 7 should be examined together since they provide complementary information about the ground transponder case. In Fig. 6, the adjacent channel attenuation of zero dB represents the use of co-channel. For example,

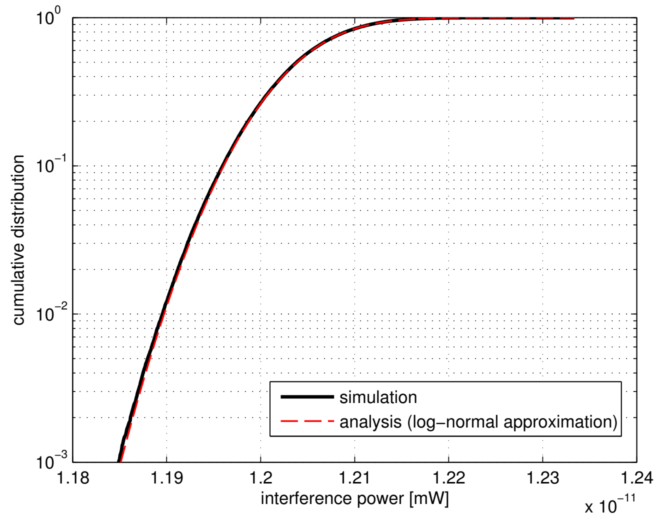

Fig. 4: A comparison between the analytic CDF of I_a and the result of Monte Carlo simulation; the primary receiver is the ground transponder (I_{thr} = -150 dBm and $\rho_{su} = 20/\text{km}^2$).

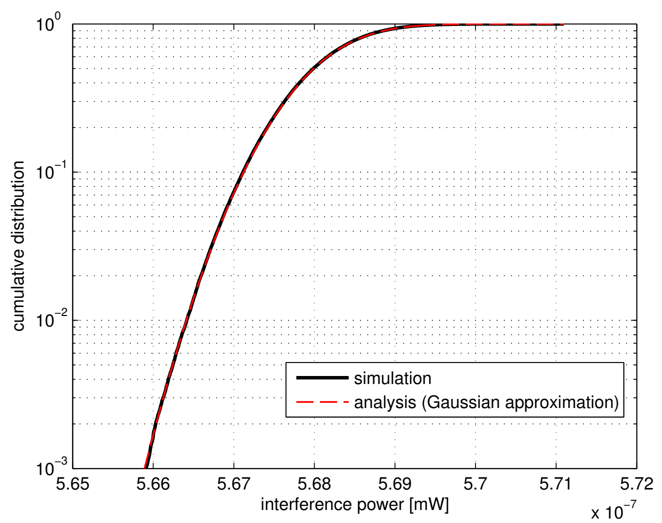

Fig. 5: A comparison between the analytic CDF of I_a and the result of Monte Carlo simulation; the primary receiver is the airborne interrogator (r_o = 20 km and $\rho_{su} = 20/\text{km}^2$).

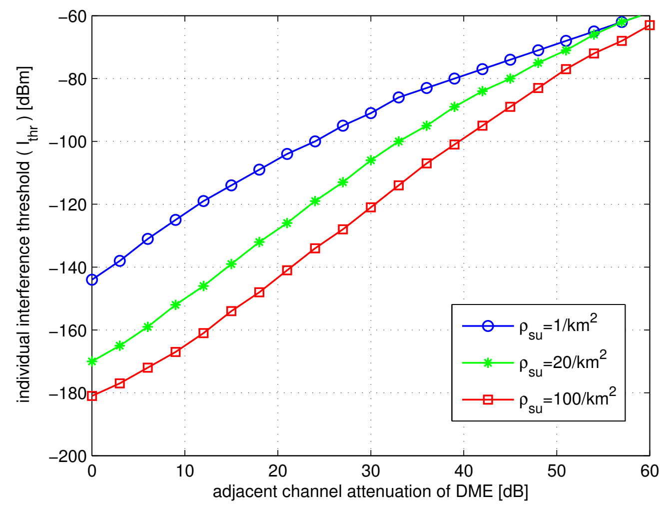

Fig. 6: I_{thr} as a function of the DME adjacent channel attenuation; the primary receiver is the ground transponder.

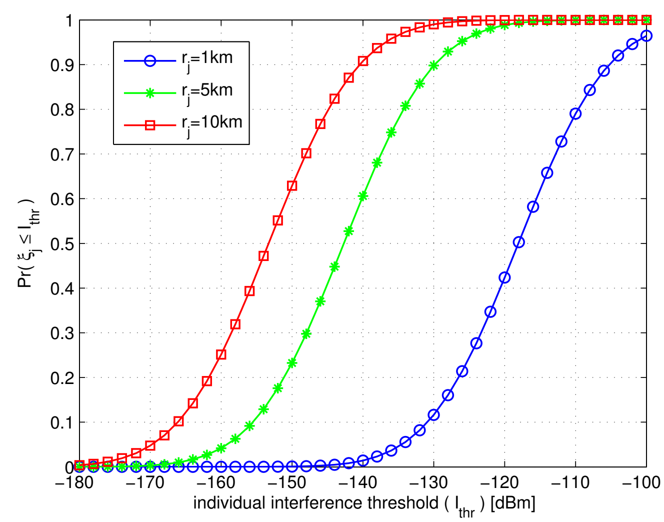

Fig. 7: $\Pr(\xi_j \leq I_{thr})$, a probability that the secondary user j can transmit, as a function of I_{thr}; this is illustrated for some values of r_j

I_{thr} of -140 dBm is required to access the co-channel when $\rho_{su} = 1/\text{km}^2$. This means that a secondary user can transmit with the probability of 60% if its distance from the primary victim is 5 km as shown in Fig. 7. On the other hand, heavily deployed secondary users ($\rho_{su} = 100/\text{km}^2$) need I_{thr} of -180 dBm, which completely forbids the transmission of secondary users 10 km away from the transponder. Thus, the co-channel usage is not promising when the density of the secondary users is high. In Fig. 7, most of the secondary users can have access to DME channel if I_{thr} is above -100 dBm. Therefore, it is inferred from Fig. 6 that the use of adjacent channel is the minimum requirement for a dense deployment of the secondary users provided that the adjacent channel attenuation is larger than 40 dB.

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

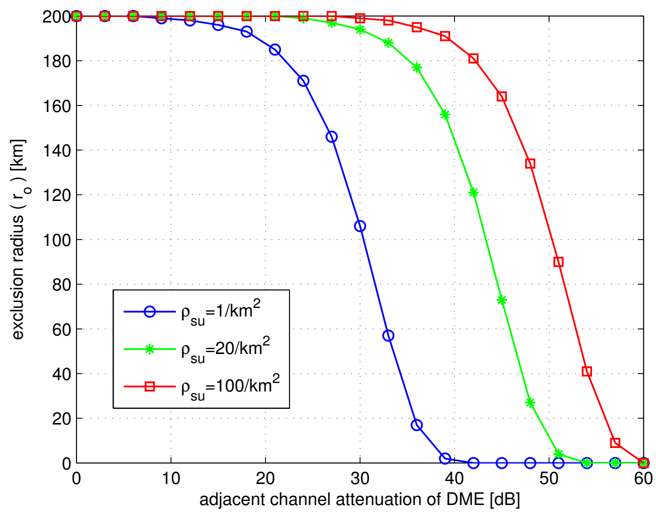

Fig. 8: r_o as a function of the DME adjacent channel attenuation; the primary receiver is the airborne interrogator; A_{thr} of -111 dBm is assumed.

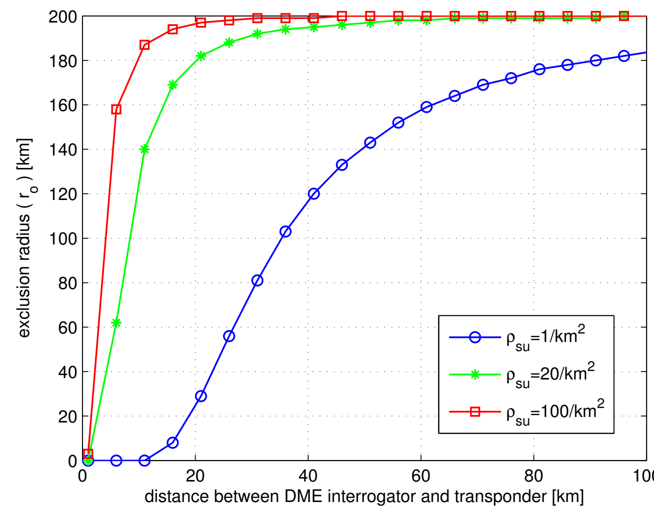

Fig. 9: r_o as a function of the distance between the airborne interrogator and the ground transponder; the primary receiver is the airborne interrogator; co-channel usage is assumed.

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

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

V. Discussion

A. Impact of the assumptions and parameters

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

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

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

Finally, we assumed that the protection rule for the primary user is perfectly kept by the secondary users. However, some secondary users may fail to abide by the rule in real environments due to the following reasons: they make a wrong estimation on the propagation loss and/or there are rogue users who deliberately disobey the rule. The former case can be minimized by several technological means such as the use of GPS, collaborative sensing, and the control by a central network. The latter case is a potential problem that may hinder the secondary access in general. Little research has been done on this issue. A discussion about reinforcing compliance with the rule can be found in [32].

B. Toward feasibility analysis

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

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

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

VI. Conclusion

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

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

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

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