Strategies for the Calculation of Location Specific Power Limits for Secondary Devices Operating on TV White Spaces

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***Abstract*—The use of TV white spaces as an alternative to overcome the spectrum scarcity is a huge opportunity for new telecommunication systems and services. While being attractive for its desirable propagation characteristics, this part of the spectrum imposes a major difficulty from design and regulatory perspectives: how to optimize the use of spectrum and to ensure the protection of primary users, TV systems for example, at the same time. This paper discusses new strategies that can be adopted by geo-location database operators to calculate adaptive maximum permitted power levels for secondary devices, according to permissible levels of interference into the digital terrestrial television (DTT) primary system.**

***Index Terms*—Cognitive radio, white spaces, unlicensed devices.**

I. Introduction

Spectrum is a valuable and limited resource shared among a large number of wireless communication systems. The increase on the use of wireless technologies as well as the current - fixed - model of spectrum usage have motivated what is called spectrum scarcity, i.e., the available spectrum may not be enough to accommodate the expected traffic demand for the next years.

In the past few years, a new model for the use of spectrum has been proposed: the dynamic spectrum access. In this model, instead of fixed assignment of spectrum for specific services, frequency bands are assigned to services or systems according to the demand. In this sense, cognitive radio has emerged as the enabling concept for more efficient utilization of spectrum, since it is capable of changing emission characteristics of systems (transmission frequency, for example), according to the spectral availability at its location.

The switch off from analog to digital television has freed up a large amount of frequencies in the ultra-high frequency (UHF) band, which has motivated the use of this spectrum - known as TV white spaces - on a secondary basis. Regulatory authorities in different countries are defining the rules and requirements for secondary usage in this frequency band. In the United States, for example, the Federal Commission Comitee (FCC) launched the rules for white spaces in the end of 2010. In Europe, the European Conference of Postal and Telecommunications Administrations (CEPT), through SE43 project team (responsible for dealing with cognitive radio matters) finalized its ECC Report 159 in January 2011, specifying technical and operation requirements for cognitive radio systems operating on the frequency band 470-790 MHz, and determining issues that require further studies.

Two aspects of the operation of white space devices (WSDs) are crucial to the protection of primary systems, and highly dependent on the regulatory requirements: the accuracy of the technique for identification of free channels and the maximum permitted transmission power. Two techniques are well known for the identification of spectral opportunities: spectrum sensing and the geo-location database. With spectrum sensing, WSDs try to detect the presence of incumbent services and determine the potentially available channels. On the other hand, with geo-location database, the WSDs need to be aware of their location and consult a geo-location database in order to determine which frequencies are available in that location, as well as the maximum permissible transmission powers. Initial studies have shown that spectrum sensing techniques alone cannot guarantee a reliable identification of available channels; therefore the geo-location database assisted operation is preferred to provide protection to primary systems.

The geo-location database contains relevant information about the DTT system planning (location of transmitters, used frequencies and propagation characteristics, for example) for the determination of the channel availability in different locations. The database matches the location provided by the WSD with the information previously available in order to determine if there is a transmission opportunity, or not. If there are available channels, the database must inform the WSD with the frequency and the maximum permissible power at that location, so that harmful interference to the primary system is avoided.

CEPT and FCC recommend the geo-location database as the main method to protect the primary system. However, the implementation of this database differs in each case. The FCC, for example, defined fixed emission limits of those secondary devices based on their type (fixed or portable) and location regarding the DTT transmitter: inside or outside its coverage contour [1]. Besides, FCC does not permit the use of fixed WSDs on the first adjacent channel inside the coverage area. Some companies are already providing databases based on FCC rules, like Spectrum Bridge [2].

On the other hand, CEPT is still discussing the WSD emission limits [3]. The approach proposed on ECC Report 159 [4] describes a flexible method for the calculation of maximum permitted power, i.e, the database implementation is much more flexible than the implementation proposed by FCC. In CEPT methodology, the maximum permitted power varies within the coverage area according to the quality of the DTT signal.

This paper addresses new strategies to be considered at the geo-location database for the calculation of WSD transmission power. These strategies are in accordance with the CEPT methodology [4], respect protection criteria and interference limits. Section II introduces important parameters used in planning of broadcasting services in the band 470-790 MHz. Protection criteria to DTT service used to set maximum permitted interference are discussed in Section III. Different database strategies to calculate the WSD maximum permitted emission limits are presented in Section IV. Finally, simulation results and conclusions are presented in Sections V and VI.

II. Broadcasting service in the band 470-790 MHz

When planning DTT systems, a number of relevant parameters must be taken into account in order to guarantee appropriate coverage and avoid mutual interference. Recommendation ITU-R BT. 1368-8 [5] defines a set of those parameters and planning criteria for digital terrestrial television technologies in the VHF/UHF bands, the digital video broadcasting - terrestrial (DVB-T) included.

Usually, DTT systems are planned as a function of a minimum electric field strength, E_{min}, according to the regulatory authority and characteristics of reference receivers, like the minimum required signal-to-noise ratio (SNR) and noise figure. Using E_{min} and considering appropriate propagation models and transmitter characteristics, it is possible to calculate the coverage contour where DTT receivers would operate correctly with a target probability known as location probability (LP) [4] defined in Eq. (1):

$$LP = \Pr\left\{ E_w \geq E_{min} + \sum_{k=1}^{K} PR_{U_k} E_{i_{U_k}} \right\} \tag{1}$$

where $\Pr\{A\}$ is the probability of event A, E_w is the wanted electric field strength at the DTT receiver antenna input, $E_{i_{U_k}}$ is the field strength of the interfering signal, and PR_{U_k} is the protection ratio. For fixed outdoor and portable outdoor reception, an area is considered covered if $LP \geq 95\%$ [6]. Figure 1 shows an example of the variation of the location probability with the wanted median field strength E_{wmed} at the DTT receiver in the absence of interference from other DTT transmitters, i.e. $\sum_{k=1}^{K} PR_{U_k} E_{i_{U_k}} = 0$.

In the presence of other DTT transmitters located nearby using the same or adjacent frequencies, it is necessary to consider this interference in the calculation of location probability. In this case, the field strength of the interfering signal, $E_{i_{U_k}}$, and reference values of protection ratio for a given frequency offset between the wanted signal and the unwanted signal, PR_{U_k}, are also considered.

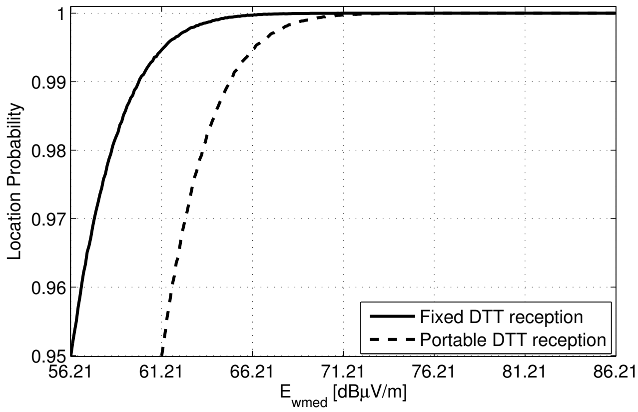

Fig. 1. Location Probability in the absence of unwanted emissions from the DTT service.

The radio frequency protection ratio is defined as the minimum value of wanted-to-unwanted signal ratio at the receiver input, usually expressed in decibels, for the achievement of a target quality, which for digital systems is usually measured in terms of bit error rate (BER). For DVB-T systems, the protection ratio is measured before the Reed Solomon decoding, considering a 2×10^{-4} BER [6], [7]. The protection ratio for a given frequency offset considers the adjacent channel leakage ratio (ACLR) of the interfering transmitter, as well as the adjacent channel selectivity (ACS) of the interfered receiver [4].

In general, protection ratios are not dependent on the wanted signal level. However, this is not true if the interference at the DTT receiver input reaches a level over which the receiver assumes a non-linear behavior. This level of interference is known as the overloading threshold (O_{th}), defined as the interference level, expressed in dBm, above which the receiver begins to lose its ability to discriminate against interfering signals at frequencies differing from that of the wanted signal, i.e. the receiver has a non-linear behavior [7]. The combination of different types of transmitter and receiver leads to different values of overloading threshold.

III. Protection criteria to DTT service

Previous section presented some parameters related to the operation of DTT systems and its protection against interference. These parameters must be considered on the definition of criteria to protect DTT receivers from harmful WSD interference. Such criteria will define the maximum permitted transmit power, i.e. the effective isotropically radiated power (EIRP) of WSDs for non-harmful interference to DTT receivers.

When assessing the interference caused by a WSD into the DTT service, two quantities are important:

- The degradation of the coverage quality of DTT service;
- The degradation of the ability of DTT receiver in discriminating the desired signal from interference signals.

Coverage quality of DTT service is directly related to the location probability. WSD transmission will reduce the DTT location probability LP described in Eq. (1), which becomes LP_{WSD} given below [4]:

$$LP_{WSD} = \Pr\left\{E_w \geq E_{min} + \sum_{k=1}^{K} PR_{U_k} E_{i_{U_k}} + PR_{WSD} E_{i_{WSD}}\right\}, \quad (2)$$

where PR_{WSD} is the WSD-to-DTT protection ratio for a given frequency offset, and $E_{i_{WSD}}$ is the field strength of the interference generated by the WSD, which depends on the transmit power and losses between interferer and interfered. Hence, a straightforward protection criteria is defined by an acceptable degradation in the location probability due to the presence of WSD interference. The location probability degradation is expressed as:

$$\Delta LP = LP - LP_{WSD}. \quad (3)$$

In ECC Report 159 three values of ΔLP are considered: 0.1%, 0.5%, and 1%. For each value of E_{wmed} a different value of E_{imed} (median interfering field strength) is necessary to cause a given degradation in location probability ΔLP. The degradation of LP with E_{imed} is illustrated in Figure 2 for different values of E_{wmed}.

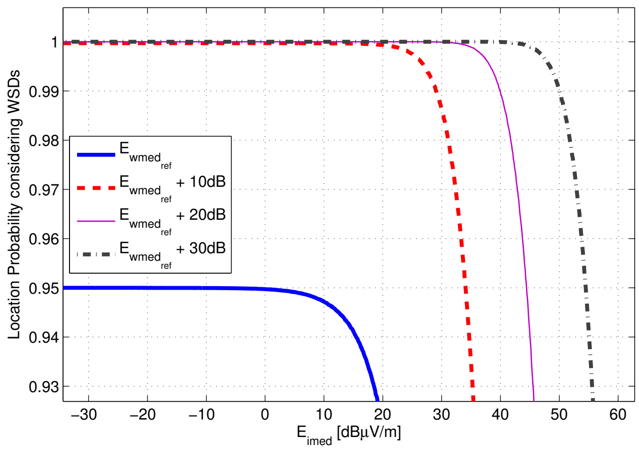

Fig. 2. Location probability in the presence of WSD interference, considering fixed DTT reception, for different values of E_{wmed}. $E_{wmed_{ref}}$ represents the median field strength of the wanted DTT signal at the edge of the coverage area, and E_{imed} is calculated considering co-channel protection ratio, $PR(0)$.

The DTT service is protected threefold: by the definition of a minimum level of signal at the DTT receiver, by the definition of acceptable signal to interference ratios, represented by protection ratios, and by respecting the maximum accepted interference. The relevance of each protection parameter in the determination of WSD emission limits is discussed in [8].

A. Upper limits of the ΔLP

Considering the protection criteria presented above, upper limits for the degradation of location probability can be defined. In DTT service planning, wanted and interference field strengths at the DTT receiver are modeled as log-normal random variables with specific mean and standard deviation.

- E_w [dBμV/m] $\sim \mathcal{N}(E_{wmed}, \sigma_w^2)$: field strength of the wanted signal at the DTT receiver antenna, with mean E_{wmed} [dBμV/m] and standard deviation σ_w [dB].
- E_i [dBμV/m] $\sim \mathcal{N}(E_{imed}, \sigma_i^2)$: field strength of the interfering signal at the DTT receiver antenna, with mean E_{imed} [dBμV/m] and standard deviation σ_i [dB].

The respect of the first protection parameter, PR, consists in guaranteeing that the signal-to-interference ratio at the DTT receiver antenna is higher than or equal to the protection ratio for a percentage X of locations in a pixel. Therefore, the maximum interference median field strength imposed by the protection ratio may be written as:

$$E^{PR}_{imed_{max}} = E_{wmed} - PR + \mu_X \sqrt{\sigma_w^2 + \sigma_i^2}, \quad (4)$$

where $\mu_x = Q^{-1}(X)$, $Q^{-1}(\cdot)$ denotes the inverse of the Q-function. Following similar analysis for the second protection parameter, the respect of $\mathrm{O_{th}}$ consists in guaranteeing that the mean interference field strength at the DTT receiver antenna is lower than or equal to the overloading threshold for a percentage X of locations in a pixel. The maximum E_{imed} imposed by overloading threshold is written as:

$$E^{\mathrm{O_{th}}}_{imed_{max}} = \mathrm{O_{th}} + \mu_X \sigma_i + POL - G_a - 20\log_{10}(f_{MHz}) + 77.2, \quad (5)$$

where POL[dB] represents antenna polarization discrimination and G_a[dBi] is the DTT receiver antenna gain. The maximum interference mean field strength is then written as:

$$E_{imed_{max}} = min\left(E^{PR}_{imed_{max}}, E^{\mathrm{O_{th}}}_{imed_{max}}\right). \quad (6)$$

By replacing the value of $E_{i_{WSD}}$ by $E_{imed_{max}}$ in (2) it is possible to find the maximum ΔLP in (3) for each value of E_{wmed} and consequently for each location within the DTT service coverage area.

IV. Strategies to Calculate Maximum WSD EIRP

Section III-A presented upper technical limits for the degradation in ΔLP. However, different strategies may be adopted by National Administrations in order to set the location specific WSD EIRP. In this Section we present three strategies for the calculation of the permitted interference field strength, and consequently, the calculation of the maximum permitted WSD EIRP.

Strategy 1 proposes the division of the coverage area in layers, defined by the value of the DTT median field strength at its edges, as in Figure 3. This means that E_{wmed} is inside the i^{th} layer if $E_{wmed_{ref}} + (i-1)\Delta \leq E_{wmed} < E_{wmed_{ref}} + i\Delta$, where Δ may be determined by Administrations, based on the accuracy of information present at the geo-location database. For each WSD that queries the database for a channel, the database will match the location provided by this device with the planned value of E_{wmed} for that location. Then, the database maps this location in a layer, and returns the maximum permitted EIRP for that layer to the WSD. This strategy is expected to increase the protection of DTT receivers against errors at the geo-location database due to uncertainties associated with the information about the DTT planning, or lack of accuracy of location information given by the WSD, since the level of E_{wmed} taken for calculations is the one estimated to the external edge of the layer, i.e the lowest one at that location. Besides, the computational effort is proportional to the number of layers defined by the database. This strategy also uses a fixed value of ΔLP in all layers and may be summarized in the following:

1) WSD sends its location to the geo-location database.
2) The geo-location database maps the received location in a value of planned E_{wmed} and the corresponding layer, which leads to a $E_{wmed_{layer}}$.
3) Using the value of $E_{wmed_{layer}}$, and ΔLP, the database calculates the the maximum $E^{st_1}_{imed_{layer}}$, so that $E^{st_1}_{imed_{layer}} \leq E_{imed_{max_{layer}}}$.

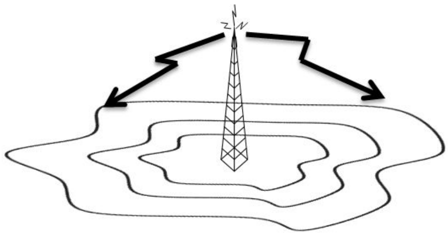

Fig. 3. Division of the coverage area in layers, according to the received E_{wmed}. The same value of ΔLP is used in all layers.

Strategy 2 (Figure 4) also divides the coverage area in layers, as in Strategy 1, but proposes the use of different values of ΔLP in each layer. The value of ΔLP inside each layer must respect the maximum permitted degradation that leads to $E_{imed_{max}}$, in Eq. (6). Albeit giving more flexibility to the maximum WSD EIRP, this strategy maintains protection of DTT receivers, since the division of the DTT coverage area in layers is still present. Strategy 2 is summarized in the following:

1) WSD sends its location to the geo-location database.
2) The geo-location database maps the received location in a value of planned E_{wmed} and the corresponding layer, which leads to a $E_{wmed_{layer}}$.
3) Using the value of $E_{wmed_{layer}}$, and the maximum value of ΔLP for the median field strength considered in that layer, the database calculates the the maximum $E^{st_2}_{imed_{layer}} \leq E_{imed_{max_{layer}}}$.

Strategy 3 (Figure 5) is the most flexible strategy. Instead of splitting the coverage area in layers, as in Strategies 1 and 2, this strategy uses the exact value of planned E_{wmed} for the location provided by a WSD. For each value of E_{wmed} this strategy uses the maximum permitted ΔLP. This strategy is summarized in:

1) WSD sends its location to the geo-location database.

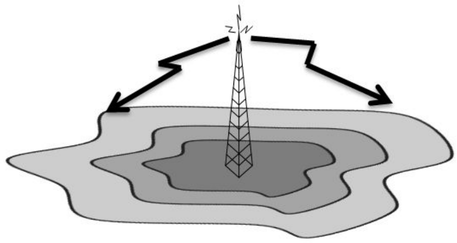

Fig. 4. Division of the coverage area in layers, according to the received E_{wmed}. Each layer uses different values of ΔLP.

2) The geo-location database maps the received location in a value of planned E_{wmed}.
3) The database matches the E_{wmed} with the maximum permitted ΔLP and calculates $E^{st_3}_{imed} = E_{imed_{max}}$.

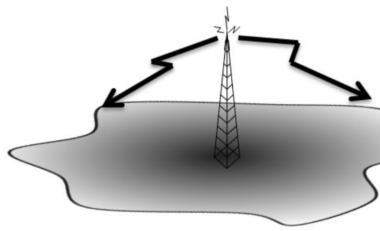

Fig. 5. The value of permitted ΔLP varies within the coverage area.

With the value of $E^{st_i}_{imed}$ calculated for each one of the presented strategies, the database needs to calculate the maximum permitted interference, I^{st_i}, accepted at the DTT receiver antenna. This interference is calculated as:

$$I^{st_i} = E^{st_i}_{imed} - 20\log_{10}(f) - 77.2 + (PR(0) - PR(\Delta f)) \quad (7)$$

in which f is the WSD emission frequency, in MHz, $PR(0)$ is the co-channel protection ratio and $PR(\Delta f)$ is the adjacent channel protection ratio. With the maximum interference, the database can inform WSDs with the maximum permitted EIRP:

$$EIRP^{st_i} = I^{st_i} + LOSS, \quad (8)$$

where LOSS represents a total loss in a reference geometry between the interfering WSD and the interfered DTT-Rx. For every type of WSD (fixed or portable), the geo-location database must consider reference geometries provided by Administrations. Examples of reference geometries can be found in [4].

V. Simulation Results

Based on upper limits of ΔLP presented on section III-A and the strategies described in section IV, we now present examples of maximum emission limits based on a reference scenario. In this paper we present results for the fixed WSD and fixed DTT receiver scenario. Table I summarizes parameters for this reference scenario [4], [8]. In a real situation, these parameters would be loaded by the geo-location database every time a device queries for a transmission opportunity, based on the WSD type provided to the database. The purpose of using reference geometries at the geo-location database is to overcome the lack of spatial information about DTT receivers. Therefore, those geometries represent, in general, worst case situations between DTT receivers (DTT-Rxs) and WSDs, either for the small distance or alignment of antennas.

TABLE I
REFERENCE GEOMETRY: FIXED WSD - FIXED OUTDOOR DTT RECEIVER

Parameter	Value
DTT-Rx height [m]	10
WSD height [m]	10
DTT-Rx antenna gain [dBi]	9.15
Distance between DTT-Rx and WSD [m]	20
Polarization discrimination [dB]	3
Total loss [dB]	57.72

Besides having information about the interference scenario to be considered, for every type of DTT-Rx and WSD considered, the database will also have information about protection ratio and overloading thresholds in order to calculate the permitted degradation in the DTT system. For the case considered in this work, Table II summarizes the protection parameters [7].

TABLE II
PROTECTION PARAMETERS FOR FIXED WSD - FIXED OUTDOOR DTT RECEIVER

Parameter	Value
$E_{wmed_{ref}}$ [dBμV/m]	56.21
Co-channel $PR(0)$ [dB]	21
1^{st} adj. channel $PR(1)$ [dB]	-30
2^{nd} adj. channel $PR(2)$ [dB]	-40
1^{st} adj. channel O_{th} [dBm]	-13
2^{nd} adj. channel O_{th} [dBm]	-7

After defining the scenario and protection parameters, the limits of ΔLP in (3) can be calculated for the protection of the DTT receiver for X percent of the locations. Figure 6 shows the ΔLP limits for protection of 99.9%, 99.5% and 99% of locations. Besides, for each case, curves of the resulting LP considering the interference from a fixed WSD are also shown.

It is important to stress that the presented results depend on the set of considered parameters, i.e. reference characteristics of DTT receivers and WSDs, as well as the percentage of locations to be protected. As expected, as the percentage of protected locations increases, the permitted degradation decreases. The limits found on Figure 6 will serve as guidance for the calculation of the maximum permitted EIRP by each strategy presented on Section IV. The absolute power limits for the second adjacent channel and protection parameters mentioned in this work are shown in Figure 7. Next results show the power limits of each strategy considering the protection of DTT-Rx for 99.9% of locations.

Strategy 1 divides the coverage area in layers, and considers the same ΔLP in all of them. The value of this degradation

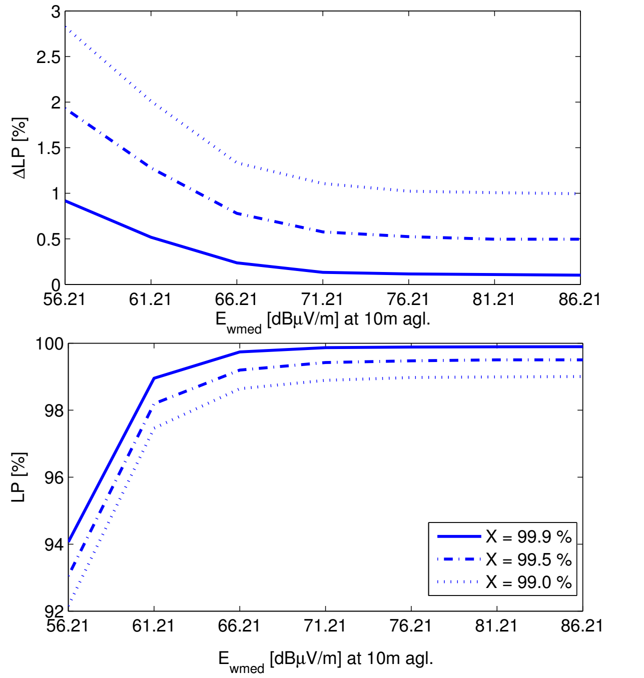

Fig. 6. ΔLP limits and resulting LP for the 2^{nd} adjacent channel considering the selected scenario for protection 99.9%, 99.5% and 99.0% of locations.

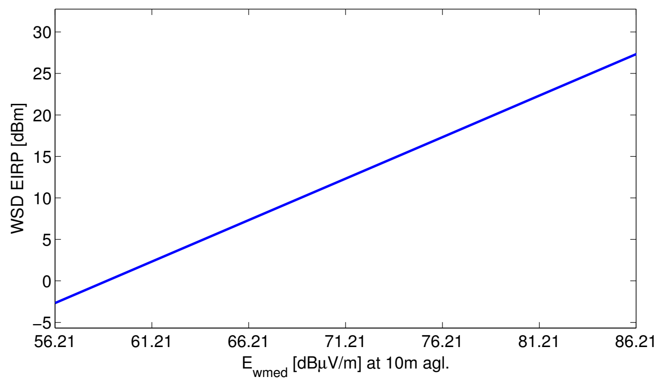

Fig. 7. Maximum permitted EIRP for the reference scenario, considering protection of 99.9% of locations.

has to be below the limit in all locations within the coverage area. Therefore, ΔLP of strategy 1 has to be selected as the minimum of the ΔLP curve. In our example, this value equals $\Delta LP = 0.109\%$ and the layers are selected with $\Delta = 5$ dB. Depending on the quality of information available at the database, Δ can be increased or decreased.

From Figure 8, strategy 1 may be considered very conservative in comparison to the upper limit, since the permitted degradation is the same in all layers. At the edge of the coverage area, for example, the resulting maximum EIRP obtained with this strategy is far from the upper limit. On the other hand, this strategy protects the DTT-Rx located near the edge of the coverage area.

In opposition to strategy 1, strategy 2 considers different

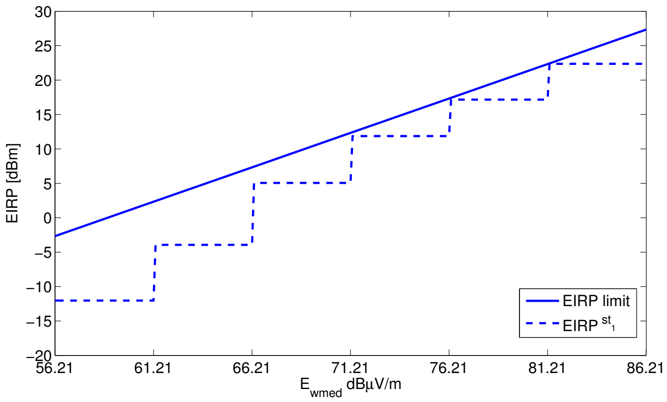

Fig. 8. Maximum permitted EIRP given by Strategy 1.

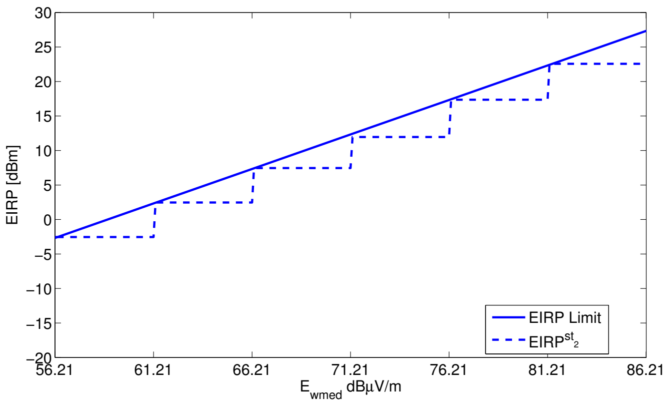

Fig. 9. Maximum permitted EIRP given by Strategy 2.

values of ΔLP in each layer. Any value of ΔLP below the upper limit can be used in this strategy. Figure 9 shows the case where the ΔLP are equal to the upper limits shown in Figure 6 in each layer. Increasing the number of layers in this strategy, the maximum WSD EIRP becomes closer to the upper limits. Albeit being less conservative than strategy 1, strategy 2 continues providing protection of DTT-Receivers, since the value of E_{wmed} considered in each layer is the expected at the edge of the layer, i.e is the lowest inside that layer.

As expected, strategy 3 is the most flexible strategy presented in this work. It does not proposes the division of the coverage area in layers as strategies 1 and 2, neither proposes fixing the value of ΔLP. This strategy can reach the upper limit, if the values of ΔLP are chosen accordingly. In Figure 10, three examples of EIRP values are shown according to the percentage of locations protected. This strategy is more susceptible to errors in the geo-location database due to lack of accuracy of location information provided by WSDs. If the location informed by the WSD has a higher planned value of E_{wmed} than the real location of this WSD, the database will inform a higher EIRP for the selected channel.

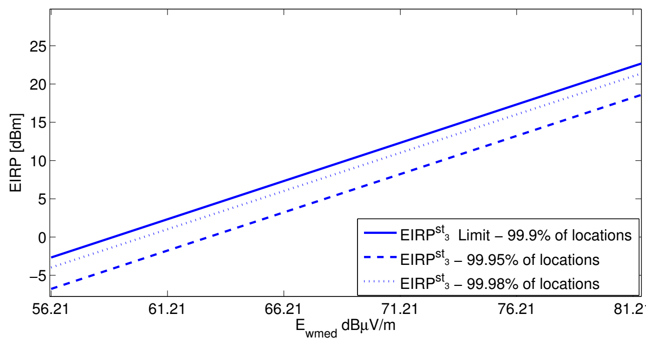

Fig. 10. Maximum permitted EIRP given by Strategy 3.

VI. Conclusions

In the definition of WSD emission limits, there is a trade-off between the maximum permitted WSD EIRP and the protection of DTT receivers. In Europe, although the methodology to calculate the maximum power is defined in ECC Report 159, the database implementation and the upper emission limits are still open issues. This paper presents viable solutions for database implementation of the CEPT methodology, respecting upper limits and reference geometries. Three strategies are proposed in this work, ranging from a conservative and less complex approach to a more flexible one, closer to the upper limit. Moreover, all strategies presented in this work ensure the required protection. Next steps of this work could include trial implementation of those strategies and comparison between them.

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