White space device emission limits in alternative DTT planning strategies

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***Abstract*—This paper deals with the co-existence of terrestrial digital television (DTT) networks and White Space Devices (WSD) on the same frequency band, assisted by a geolocation database. The database evaluates and provides to the WSD the local emission power. The common approach adopted in Europe to estimate such limits is expanded to the case of Single-Frequency-Network (SFN) planning of DTT networks. Also, the criterion for setting the allowable DTT quality degradation is discussed and a novel approach is proposed, based on local DTT quality. The complete procedure to evaluate WSD emission limits is applied to a real Italian DTT scenario. We compare different DTT planning strategies over the same set of transmitters and the same area, from the point of view of potential WSD presence. This comparison highlights the advantage of SFN planning both in terms of DTT coverage and allowed WSD emissions.**

***Index Terms*—White space device, geolocation database, location probability degradation function, SFN, MFN.**

I. Introduction

In recent years the UHF TV band between 470 and 790 MHz has been considered, at international level, a suitable candidate for employing cognitive radio technology, due to its local under-utilization and its favourable propagation proprieties [1], [2], [3]. In Europe, the coordinating body for European Union telecommunications and postal organizations, CEPT, within the ECC Working Group (WG) SE43 has published report 159 that defines the technical and operational requirements that should be applied to exploit the unused spectrum, i.e. white spaces (WS), of this frequencies band by the so called white space device (WSD) [3], [4]. The WSDs are then opportunistic users of the UHF WSs, subject to the constraint of producing no harmful interference to the incumbent service [1]. The WSs can be accessed through different techniques such as spectrum sensing, beacons and geolocation database. As stated in ECC report 159, at present only the approach based on geolocation databases appears to be feasible, whereas spectrum sensing is considered only in support to geolocation database and the beacon approach presents inherent problems. The WG SE43 has also published the ECC report 186 that specifically addresses the technical requirements for the operation of WSDs under geolocation approach [5]. In this report a model suitable to be implemented in a geolocation database to estimate the WSD emission limits is defined. The method is based on the definition of a maximum permitted degradation of DTT quality service that guarantees appropriate protection of the service itself. Analytical expressions for the calculation of the maximum permitted WSD power according to this approach were derived in [6], [7], [8]. The expressions derived in [7] and [8] were based on the approximation that is accurate only in noise-limited environments. In [6], we derived a new efficient methodology for the calculation of such limits that provides accurate results both in noise-limited and in interference-limited environments. Considering that DTT planning strategies manage interference in different ways, the WSD opportunities can vary depending on the DTT network scheme. Digital UHF terrestrial TV networks can be planned as MFN (Multi-Frequency-Network), consisting in transmitters each using an individual channel, or SFN (Single-Frequency-Network), which allocates the same frequency to all transmitters carrying the same multiplex programme [9]. Broadcasting networks can also be planned as k-SFN networks, which include features of both MFN and SFN planning techniques [10].

In this paper we aim at comparing MFN and SFN planning strategies in terms of WSD emission levels. We use the methodology presented in [6], extending the applicability to SFN deployment. We also complement previous work, proposing a different approach to define the allowable degradation of DTT quality. In [6] and [11] a fixed value of acceptable degradation of DTT quality is considered, independently of DTT coverage over the territory while in [5] a variable acceptable degradation is proposed under specific conditions and scenarios. Here we suggest a general and complete approach, flexible for every scenarios by considering a variable value depending on the local DTT quality. In our analysis we use real transmitters data of a DTT network of the Italian region of Friuli-Venezia Giulia. We show that the WSD emission limits are quite sensitive to the definition of the constraints on the DTT quality degradation and that the SFN planning strategy provides advantages both from the point of view of DTT quality and of the WSD usage. The paper is organized as follows. In section II we briefly outline the adopted methodology to estimate the maximum permitted WSD EIRP (Equivalent Isotropic Radiated Power) that follows the approach developed

[1]It has to be noted that in Europe the incumbent services of 470-790 MHz band that have to be protected include DTT broadcasting, Program Making and Special Event (PMSE), Radio Astronomy Service (RAS), Aeronautical Radionavigation Service (ARNS), although this paper focuses only on DTT systems.

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in [6]. Firstly we introduce the concept of location probability as the quality measure of the DTT coverage. We then present the concept of considering variable values of tolerable degradation of quality of the DTT service according to the local quality itself. In section III we summarize the main characteristics of the DTT planning strategies highlighting how to combine the signals in order to calculate the location probability and the related WSD emission levels. In section IV we present the operations to be performed to carry out the analysis in a real scenario. Real transmitters data of a DTT network in the Italian region of Friuli-Venezia Giulia are employed to construct the scenario for the simulations. We end the paper in section V presenting the numerical results comparing WSD emission limits in different DTT planning strategies.

II. Estimation of maximum permitted WSD power

In this section we briefly outline the methodology for assessing the maximum permitted WSD power, following the approach adopted in Europe by CEPT within the ECC WG SE43 [3]. We provide a detailed analytical development of this methodology in [6].

The involved scenario assumes the coexistence of two systems: a DTT network, i.e. the incumbent service to be protected, and a cognitive radio system, represented by WSDs. This coexistence is managed through a pre-calculated geolocation database. When an unlicensed WSD requests permission to transmit in the DTT frequency band, the database shall return indications about the best channel, if any, and the maximum EIRP that the WSD can transmit from its location without damaging the DTT system.

Given a certain deployment of DTT service, the process of estimating the local WSD emission limits for constructing the database requires three steps:

A. characterization of the DTT coverage quality over the territory;
B. selection of a criterion for defining the constraint on allowable degradation of DTT quality compatible with the protection of the DTT service;
C. derivation of a practically feasible methodology for calculating the local WSD emission limits.

In the following, we adopt the location probability as the quality measure of the DTT service, in accordance with SE43 approach.

A. Evaluation of Location Probability

The *Location Probability* (LP) characterizes the DTT coverage and is defined as the probability that a DTT receiver would operate above a defined quality threshold at a specific location and on a specific DTT channel. It is generally calculated for each unit area, fragmenting the national territory in regular pixels (e.g. square pixels), taking into account interference from other DTT transmitters.

In the absence of other sources of interference, the general expression of LP can be written (in the linear domain) as [5]:

$$q_1 = Pr\left\{P_S \geq P_{S,min} + P_V\right\} \tag{1}$$

where $Pr\{A\}$ is the probability of event A, P_S is the received power of the wanted signal, $P_{S,min}$ is the DTT receiver's (noise-limited) reference sensitivity level, P_V is the power sum of unwanted DTT signals $P_{U,k}$, each multiplied by its relevant value of DTT-to-DTT protection ratio $r_{U,k}$ (co- and adjacent-channel), i.e.:

$$P_V = \sum_{k=1}^{K} r_{U,k} P_{U,k} \tag{2}$$

Note that P_S and each term $P_{U,k}$ are lognormal random variables, due to the statistical nature of received power, particularly for the phenomenon of shadow fading, while $P_{S,min}$ is a constant. Under the commonly held assumption that the sum of lognormal variables is approximately still a lognormal variable P_V can be modelled as lognormal variables as well. The derivation of q_1 has been developed and explained in detailed in [6]. The derived closed form expression can be written as:

$$q_1 = \frac{1}{2}\,\mathrm{erfc}\left\{\frac{1}{\sqrt{2}}\frac{m_X}{\sigma_X}\right\} \tag{3}$$

where m_X and σ_X are the median value and standard deviation of the Gaussian random variable $X_{(dB)}$, resulting from the sum of lognormal random variables; in our model implementation, m_X and σ_X are evaluated via successive applications of the Schwartz-Yeh algorithm [12], [13], which provides both a good approximation and is a computationally efficient technique. The expression (1) can be readily extended to account for the effects of additional interference from WSDs [6], as will be briefly outlined in section II-C.

B. Criterion for maximum DTT quality impairment

It is commonly assumed that a WSD can be allowed to transmit on DTT frequencies only if the ensuing degradation of the DTT quality (in terms of LP) does not exceed a small, predetermined value. The maximum reduction of LP, Δq, is considered a suitable measure for specifying regulatory emission limits for WSDs operating in DTT frequencies, as outlined in [4]. The value of tolerable Δq is generally set as a fixed percentage value, e.g. 1% [6], [11]. In this work, we adopt a different approach, since targeting a fixed Δq independently of the local actual DTT quality may have a twofold unsatisfactory consequence: it may lead on one hand to unacceptable degradation of DTT service in area with high LP, on the other hand to excessive restriction of WSD transmission in areas with lower values of LP. In fact, the implementation costs of a DTT network is highly related to the mean LP value guaranteed over the territory. Particularly in territories like Italy characterised by wide mountain and hilly areas, the number of necessary DTT sites and thus the cost tend to increase virtually exponentially with the LP. An incremental 1% of LP is much more expensive to achieve when the LP is already high. Moreover, the DTT broadcasting systems are usually planned to guarantee high values of LP in most populated pixels. A 1% LP degradation in such pixels would most probably cause a loss of the DTT service to a greater number of households than in pixels with lower LP. Therefore, we propose an approach for the allowed quality degradation according to which the target Δq is locally selected as a function of the LP value, q_1, in each individual pixel. This approach is described in section IV.

C. WSD emission levels

The maximum permitted WSD in-block (i.e. within the bandwidth of the particular channel) EIRP in a pixel is calculated as the value that produces the maximum tolerable reduction, Δq, of the DTT LP, q_1.

Consider a WSD which transmits with in-block EIRP of P_{IB} over a DTT channel bandwidth, i.e. 8 MHz, at the frequency $f_{WSD} = f_{DTT} + \Delta f$, where f_{DTT} is the DTT carrier frequency and Δf represents the frequency offset of the WSD. The presence of this WSD will cause additional interference, reducing the DTT LP to a value q_2 lower than q_1. Extending the definition (1), q_2 can be written (again in the linear domain) as:

$$q_2 = Pr\left\{P_S \geq P_{S,min} + P_V + \ r(\Delta f, m_S) G P_{IB}\right\} \qquad (4)$$

where m_S is the median value of the Gaussian random variable $P_{S_{(dBm)}}$, G is the coupling gain between the WSD and the DTT antenna receiver and the product GP_{IB} represents the WSD interfering power at the DTT receiver. The protection ratio $r(\Delta f, m_S)$ is defined as the ratio of the received wanted DTT signal power to the received WSD interfering power at the point of failure of the DTT receiver. It depends on the frequency separation, Δf, between the WSD and the DTT signal and on the wanted signal level m_S (taking into account non-linear effects for high power levels) as shown in [15]. The coupling gain G includes path loss, receiver antenna gain, as well as receiver angular polarization discrimination. Taking into account the shadow fading, G can be modelled as a lognormal variable, i.e. $G_{(dB)}$ can be modelled as a Gaussian random variable, with median value m_G and standard deviation σ_G.

The maximum permitted value of P_{IB} is obtained by setting $q_2 = q_1 - \Delta q$ and inverting equation (4), necessarily by means of an iterative algorithm. The same approach of section II-A for the sum of lognormal variables (analytical Schwartz-Yeh approximation) is applied for efficient calculation.

III. MFN and SFN planning strategies

There are two fundamental types of terrestrial digital broadcasting networks:

(i) Multi-Frequency Networks (MFN), the traditional planning technique in which each individual transmitter of the network operates independently of the others on its allocated channel; and
(ii) Single Frequency Networks (SFN), which provide the coverage through multiple transmitters operating on the same frequency and carrying the same multiplex of programmes.

The features of both MFN and SFN are present in k-SFN networks, which are made of $k > 1$ SFN "sub-networks", each using a different channel from the adjacent ones; the overall coverage of the territory is given by the sum of the coverage of all k sub-networks [10]. SFN allows for much greater spectrum efficiency, at the cost of planning efforts to avoid significant echoes producing auto-interference. Signals delayed by more than the guard interval with respect to the main signal contributes to interference, while those arriving within a guard interval contributes to the wanted signals. While for MFN the wanted power, P_S in (1) and (4), is normally considered as a single signal, in case of SFN P_S is generally given by the sum of several contribution. In equation (1) both P_S and P_V can be approximated as lognormal variables given by the sum of several lognormal signals. Assuming that all DTT signals are characterised by the same standard deviation, the k-LNM technique is an efficient and easy method to evaluate the median and standard deviation of P_S and P_V [14].

IV. WSD in real DTT networks

In order to compare different DVB-T planning strategies, i.e. SFN, MFN and k-SFN, from the point of view of allowing the presence of in-band WSDs, we have selected a real scenario considering the data of an Italian TV network in the region of Friuli-Venezia Giulia. This network is composed of 35 transmitting sites. To this set of DTT transmitters, assuming the real powers and antenna diagrams, we have applied three different frequency plans: that is, under the same hypothesis of three available channels for the network coverage, we have allocated the channels to the sites according to a 3-MFN, a 1-SFN and a 3-SFN plan. Figure 1 shows the considered DTT transmitters (specifically, the figure refers to the case of 3-SFN, each colour representing a distinct frequency channel). Performance have been evaluated over the whole territory of Friuli-Venezia Giulia, dividing the territory in pixels of size 400 m x 400 m. The parameters values used for performance evaluations are selected according to typical DTT values.

A. Scenarios description

It is assumed that three channels are available with a frequency offset between them of 16 MHz, i.e. f_{DTT_1} = 594 MHz, f_{DTT_2} = 610 MHz and f_{DTT_3} = 626 MHz (that correspond to DTT channels 36, 38, 40 respectively). The following configurations for broadcasting a single multiplex signal have been considered in the analysis:

- SFN using channel 38;
- MFN using the three available frequencies;
- k-SFN using the three available frequencies (i.e. $k = 3$).

In case of MFN and k-SFN, frequencies have been allocated to transmitting sites applying coverage optimisation criteria, in order to emulate realistic networks as far as possible. We set at 70% the LP minimum value for a pixel to be considered inside the network coverage area (if on all channels the LP in a pixel is below 70%, the pixel is not considered covered and no protection of DTT service from WSD transmission in that pixel is taken into account). In case of MFN and k-SFN planning, coverage areas for different channels can be

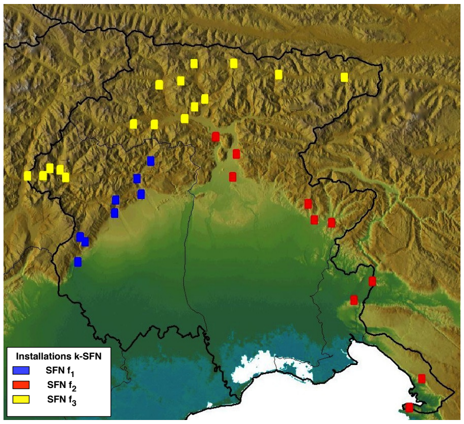

Fig. 1. DTT installations (k-SFN plan).

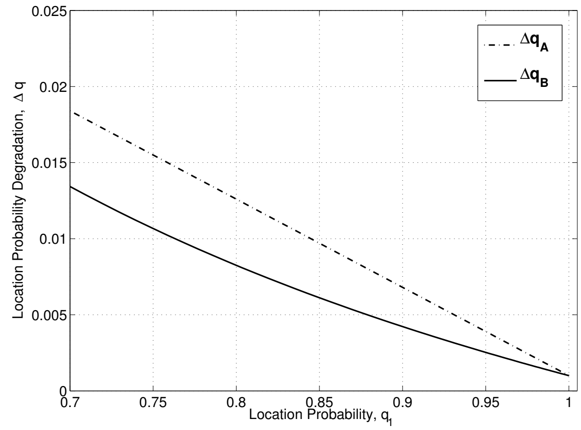

Fig. 2. Location probability degradation functions, Δq_A and Δq_B.

overlapping, i.e. the LP can be over 70% on more than one channel. In our present evaluations, in each pixel protection of DTT service has been considered only for the best-quality channel (in terms of LP). At the borders of the coverage areas, considering the variability and the uncertainty of predictions, protections for more than one channel may be envisaged.

B. Evaluation of Location Probability q_1

The calculation of the LP expressed by (1) for each pixel is performed as follows:

- the median field strength levels of all signals coming from DTT transmitters in the area is evaluated using a proprietary prediction tool that implements the ITU-R Recommendation P.526 propagation model [16]; all DTT signals are considered lognormally distributed with standard deviation equal to 5.5 dB;
- in case of SFN and k-SFN, signals contributing to wanted signal and those contributing to interference are discriminated considering a guard interval of 224 μs;
- the DTT interference from other transmitters is evaluated considering only co-channel signals from the network itself (DTT adjacent channel interferer signals are not considered);
- the co-channel protection ratio ($r_{U,k_{(dB)}}$ in (2)) is assumed equal to 21 dB (according to ITU standards) for all DTT interfering signals;
- the value of LP is evaluated using the methodology described in section II-A. The reference sensitivity level, $P_{S,min}$ is assumed to be -74.2 dBm.

Note that the considered values to estimate the location probability are typically used in DTT planning.

C. Definition of Location Probability maximum degradation

According to the principles outlined in II-B, the maximum allowed degradation caused by a WSD has been considered both as a fixed value, i.e. 1% (common approach), and as a decreasing function of the LP local value. Specifically, a linear and a hyperbolic trends for Δq have been tested in our analysis, shown in Figure 2 and defined respectively as Δq_A and Δq_B:

$$\Delta q_A = -0.058 \cdot q_1 + 0.059; \tag{5}$$
$$\Delta q_B = \frac{0.029}{q_1} - 0.028.$$

Coefficients for Δq_A and Δq_B are obtained by fixing the same two targets for both trends:

- a degradation of 3% for LP equal to 50%;
- a degradation of 0.1% for LP equal to 100%.

D. Calculation of WSD EIRP

The maximum allowed EIRP for a WSD located inside each pixel is evaluated by applying the methodology described in section II-C, within the following guidelines:

- no transmission is allowed on the frequency if the DTT service in the pixel is provided on the frequency itself (no co-channel use is allowed within the DTT coverage area);
- no more than the maximum LP degradation to the DTT service can be inflicted by WSD adjacent-channel interference in the pixel itself and towards other pixels;
- no more than the maximum LP degradation can be inflicted to the DTT service by WSD co-channel interference towards other pixels.

The maximum allowed EIRP results as the tightest EIRP value derived by satisfying each of the above constraints.

In order to perform the calculations, two interferer-victim coexistence geometries have been defined: *A. Reference geometry <u>inside</u> the covered pixel*, considered in case of WSD interferer and DTT victim receiver located in the same pixel (or in immediately adjacent pixels); *B. Reference geometry <u>outside</u> the covered pixel*, considered in case of WSD interferer and DTT victim receiver located multiple pixels apart. Both geometries consider a fixed WSD and a fixed DTT receiver located at 10 m a.g.l. (above the ground level); the nominal distance between them is assumed equal to 20 m for geometry A and equal to the actual distance

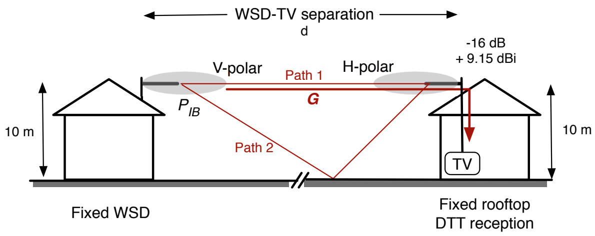

Fig. 3. Reference geometry for fixed WSDs.

between the WSD and the potentially interfered pixel for geometry B, as is depicted in Figure 3. The coupling gain G is calculated using the free-space propagation model for geometry A and a two-ray propagation model for geometry B. In all cases, it is assumed that: the different polarization between the DTT receiver antenna and the WSD transmitter antenna provides a discrimination of 16 dB; there is no receiving antenna angular discrimination; the net TV aerial gain is equal to 9.15 dBi [2]. These values are taken from [7]. From [6] and [17], for Δf = 16 MHz the adjacent-channel protection ratio is taken as:

$m_S(dBm)$							
-80	-70	-60	-50	-40	-30	-20	-12
$r(\Delta f, m_S)(dB)$							
-32	-32	-28	-24	-19	-13	-10	-8

The dependence from the received median wanted DTT signal power, implicitly characterizes the non-linear behaviour (including hard overload) of the DTT receiver. In our simulations the same values for the protection ratio are used also for frequency offset, Δf, of 32 MHz.

V. Numerical Results

In this section we provide some numerical results obtained by simulating the scenarios described in section IV, focusing on the comparison among the performance of different DTT planning strategies. Figure 4 shows the network coverage prior to the presence of WSD for SFN, k-SFN and MFN frequency plans, in terms of complementary cumulative distribution function (CCDF) per population of the LP value, q_1. As can be noted, the network provides very good coverage with all frequency plans, although the k-SFN plan provides a slightly better coverage than the MFN plan: for instance, the population in pixels with LP higher than 95% increases from 93% in the MFN case to 98% in the k-SFN case. k-SFN provides slightly better coverage than SFN as well, which is not surprising since in case of single-channel SFN the distance between the DTT sites can be larger (the sites of Figure 1 are all planned on the same frequency in case of 1-SFN), therefore self-interference (i.e. signals delayed by longer than the guard

[2]This is equivalent to an aerial gain of 12 dBd and 5 dB cable loss.

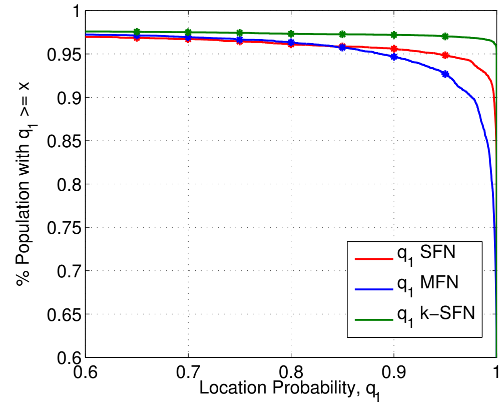

Fig. 4. CCDF of the LP per population for the three planning strategies.

interval) is more likely to occur; on the other hand, single-channel SFN has a three-times greater spectral efficiency, since only one channel is used in place of three.

Then, the methodology to evaluate WSD possible emissions as described in previous sections is applied in each pixel; as a performance measure, we consider the maximum WSD EIRP allowed for transmission *on at least one frequency channel*. As an example, Figure 5 shows the maximum WSD EIRP on at least one channel over the considered area for our k-SFN frequency plan. Figure 6 shows the cumulative distribution function (CDF) of this EIRP value per population in case of 3-SFN plan comparing three different LP degradation functions, i.e. Δq = 1 %, $\Delta q = \Delta q_A$ and $\Delta q = \Delta q_B$. Since the great majority of population is located in pixels where the DTT quality is very high, the curves relevant to Δq_A and Δq_B are virtually overlapping (showing that for high values of q_1 the two trends in (5) are equivalent). Thus, hereafter only Δq_A is considered. Moreover, the curves corresponding to $\Delta q_{A/B}$ are above the one for Δq = 1 %. This means an overall reduction of WSD EIRP with respect to 1% degradation, in the order of 5 dB, since $\Delta q_{A/B}$ provides stricter protection for high quality coverage. Similar results have been obtained considering the other planning schemes as well.

The better protection to DTT service provided by $\Delta q_{A/B}$ compared to Δq = 1 % can be seen in our scenario in terms of overall population losing coverage due to the presence of a transmitting WSD. Assuming the population covered in a pixel as the population in the pixel multiplied by the location probability in that pixel, it is possible to calculate the overall covered population prior and after the WSD presence, for the different location probability degradation functions. In case of the MFN plan, for instance, in our scenario the total population covered amounts to 1134000 without the presence of the WSD, i.e. the 99% of the population living in the coverage area (pixel with LP $\geq$ 70%); when our WSD model is applied to each pixel, the loss of coverage due to the presence of a WSD is significantly reduced from 1% to less than 0.2% adopting $\Delta q = \Delta q_{A/B}$ in place of Δq = 1%. Similar results are obtained for the SFN and k-SFN plans.

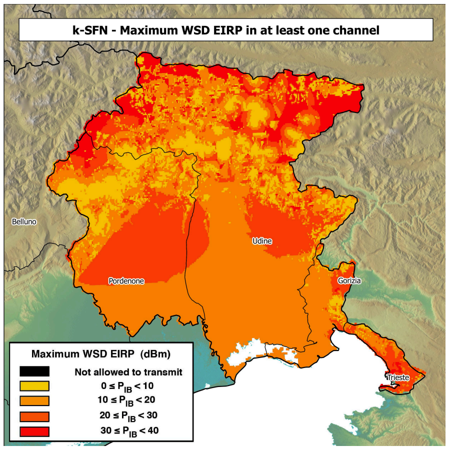

Fig. 5. Maximum WSD EIRP in at least one channel in k-SFN plan.

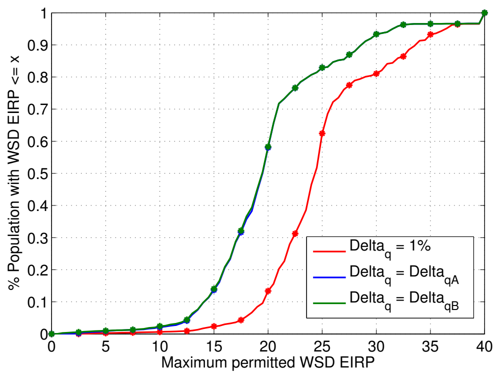

Fig. 6. CDF of the maximum WSD EIRP in at least one channel per population for SFN considering Δq = 1 %, $\Delta q = \Delta q_A$ and $\Delta q = \Delta q_B$.

Finally, Figure 7 shows a comparison between MFN, k-SFN and SFN planning configurations for $\Delta q = \Delta q_A$, again in terms of CDF of WSD EIRP per population. The performance of the SFN plan are virtually identical to k-SFN; as a matter of fact, possible interference from outside the considered region of Friuli-Venezia Giulia - i.e. from distant sources - has not been considered in this evaluation, while it may be expected that analysis over bigger areas would show greater impairment in case of 1-SFN planning. The curves for k-SFN and SFN lie well below the one for MFN, which means higher allowed WSD EIRP in case of SFN. For instance, in case of SFN more than 85% of population lives in pixels where allowed WSD EIRP is at least 15 dBm, while this value reduces to only about 25% in case of MFN . The separation between the curves is in the order of 10 dB; this value can be taken as a broad measure of the gain of the SFN plan in terms of allowed WSD transmissions in this scenario.

VI. Conclusion

The approach adopted in the European regulatory context to assess emission limits for WSDs coexisting with DTT networks is based on the definition of the maximum permitted degradation of DTT quality in terms of location probability.

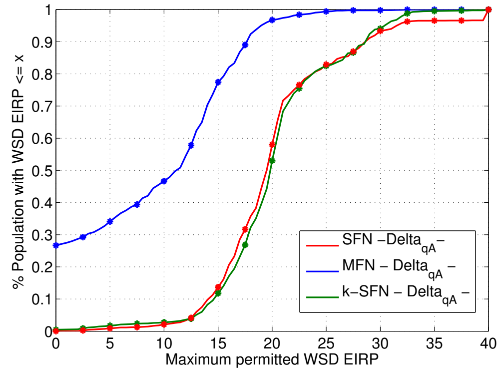

Fig. 7. CDF of the maximum WSD EIRP in at least one channel per population for SFN, MFN and k-SFN planning strategies.

In this paper, we expanded this approach, proposing and discussing a criterion for setting the maximum LP degradation as a function of the local DTT quality. Moreover, we extended the common model to the case of SFN planning of the victim DTT network. Performance analysis has been carried out in a real scenario, considering the transmitters of a DTT network in the Italian region of Friuli-Venezia Giulia. Three DTT planning strategies, i.e. SFN, k-SFN and MFN, have been compared in terms of potential WSD transmission. The results show that, for a high quality network such as the one examined, the WSD emission limits are quite sensitive to the constraint on LP degradation, which therefore should be carefully defined. Setting a fixed valued of 1% allowable degradation, independently of the actual local quality, may result in over-estimation of appropriate WSD emission limits. The comparison between MFN and SFN frequency plans provides some insight of the advantages of SFN planning from the point of view of allowing the presence of WSD. The robustness of the SFN technique, in fact, results in considerable expansion of the areas where a WSD can be allowed to transmit with power levels of practical interest. Naturally, our results refer to a single, albeit typical, example of DTT network deployment, nevertheless the considered methodology has general and flexible characteristics allowing to deal with all different DTT coverage situations.

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