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Planning Large Single Frequency Networks for DVB-T2

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Abstract—**The final coverage and associated performance of an SFN is a joint result of the properties of all transmitters in the SFN. Due to the large number of parameters involved in the process, finding the right configuration is quite complex. The purpose of the paper is to find optimal SFN network configurations for DVB-T2. Offering more options of system parameters than its predecessor DVB-T, DVB-T2 allows large SFN networks. However, self-interference in SFNs gives rise to restrictions on the maximum inter-transmitter distance and the network size. In order to make optimum use of the spectrum, the same frequency can be reused over different geographical areas - beyond the reuse distance to avoid co-channel interference. In this paper, a methodology based on theoretical network models is proposed. A number of network architectures and network reference models are considered here for different reception modes in order to study the effects of key planning factors on the maximum SFN size and minimum reuse distance. The results show that maximum bitrate, network size and reuse distance are closely related. In addition, it has been found that the guard interval is not the only limiting parameter and that its impact strongly depends on the rest of DVB-T2 mode parameters as well as on the network characteristics (Equivalent Radiated Power, effective height, inter-transmitter distance). Assuming that the C/N requirements are in the vicinity of 20 dB and bitrates over 30 Mbps, it has been found that the network can be as large as 360 x 360 km (delivering 39.2 Mbps) or even 720 x 720 km (delivering 37.5 Mbps). The reuse distance will also have a complex dependency on the DVB-T2 mode and especially the network parameters, ranging from below 100 to 300 km.**

Index Terms—**maximum size, reuse distance, DVB-T2, SFN, LPLT, HPHT**

I. INTRODUCTION

Compared to Multiple Frequency Networks (MFN), Single Frequency Networks (SFN) have many advantages for the distribution of broadcast services, such as high spectrum utilization and power reduction [1]-[3]. Reduced electricity consumption will lead to low carbon emission and green network deployment [4].

When an SFN is deployed, it is expected to provide services using a single channel within the whole service area. In some cases, this service area can be as large as an entire country. Unless a region shows particular topographic characteristics, the SFN area is limited by self-interference (SI) effects that are related to the Guard Interval (GI) choice, but, as it will be shown in further sections of this paper, this is not the only limiting factor.

For DVB-T, the first generation digital terrestrial broadcast system [5]-[7], in an 8 MHz channel using the 8k carrier mode and a guard interval fraction of 1/4, the maximum inter-transmitter distance is limited to roughly 70 km. In addition, depending on the sensitivity of the chosen transmission mode, the guard interval length limits the total size of the SFN.

The second generation digital terrestrial broadcast system (DVB-T2) [8] has adopted different techniques to overcome the potential limitations of its predecessor DVB-T. DVB-T2 includes additional FFT sizes of 1k, 4k, 16k and 32k as well as more GI values: 1/128, 19/256 and 19/128. This wider range of GIs enables larger inter-site distances and large scale SFNs. In DVB-T2, the maximum inter-transmitter distance can be up to about 160 km [9], [10].

Spectrum is a scarce resource. In order to make full use of the spectral resource, new digital terrestrial television broadcasting standards are being developed to improve the capacity and to increase spectral efficiency [11]-[13]. Apart from that, the same channel has to be reused in different service areas with a certain separation to avoid co-channel interference. The minimum separation distance is called re-use distance (RUD), which is defined as the minimum required separation distance between two co-channel service areas in order to keep the mutual interference at an acceptable level. This parameter has a significant influence on the number of channels required to provide coverage to a larger area containing several countries or regions, each one having its own TV contents.

Planning an SFN network for a specific service area involves a series of external planning factors such as the existing available infrastructure, the population distribution, terrain databases, building and other clutter layers, etc [14]-[16]. All these considerations add to the planning factors associated to the DVB-T2 standard parameter choice [8], [9]. The final solution in a service area will be highly influenced by those factors specific to that area and not applicable in other cases.

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Investigating SFN architectures based on such specific cases would lead to configurations that would not have generic applicability.

In consequence, an alternative approach is required in order to gain insight and knowledge of generic properties of DVB-T2 SFN. For this purpose, theoretical SFN models represent a useful tool to analyze the performance limits of DVB-T2 networks.

Additionally, different network topologies will require different DVB-T2 parameters and will exhibit different maximum coverage size limits and minimum reuse distances. There are currently discussions about the pros and cons of two approaches: High-Power–High-Tower (HPHT) and Low-Power–Low-Tower (LPLT) topologies [17]-[19].

SFN theoretical models have been used in the past as a tool to propose optimal planning configurations and parameters applicable to a wide range of coverage scenarios. These reference planning configurations and parameters are required not only for national frequency allocations and attributions but also for complex international coordination agreements such as GE06 [20], [21].

The definition of these planning models has been restricted to reports from international broadcast coordination and stakeholder bodies, mainly ITU, EBU and CEPT [20]-[24]. Their use requires interpretation of some of the procedures, algorithms and input values involved, which can lead to very different coverage estimations. This aspect has been investigated in [25].

This paper presents quantitative results for maximum coverage area extent and minimum frequency reuse distances in large and very large SFNs using the DVB-T2 standard. The study analyzes the impact of planning parameters such as the DVB-T2 mode, the effective antenna height h_{eff} and the effectively radiated power (ERP) on the size of the service area. There is also an increasing interest in evaluating different network structures, namely HPHT versus LPLT topologies. This paper proposes a formal definition for those structures and evaluates the maximum size of an SFN in DVB-T2 with each option. The conclusions address the performance limits and optimal configurations of a generic DVB-T2 SFN for delivering television services for fixed, portable (indoor and outdoor) and mobile reception.

The paper is organized as follows. The next section describes the general methodology associated to the theoretical SFN model. Section III discusses coverage calculation aspects and section IV describes the involved planning factors. The results of the study are given in section V. Section VI presents the results of a case study for large SFN. Section VII contains the conclusions.

II. METHODOLOGY

The study is based on a theoretical hexagon SFN network model as shown in Fig. 1. The network has seven transmitters (Tx) situated at the center and at the vertices of a hexagonal lattice. All the transmitters in this model have the same h_{eff} and ERP characteristics. All the transmitters are synchronized in time and frequency. All the transmitting antenna systems are assumed to be omnidirectional thus targeting the worst case from inter-site distance (ISD) and reuse distance. Polarization discrimination techniques to minimize interferences have not been considered in this study, and all simulations are carried out assuming horizontal polarization for every DVB-T2 transmitter. There is not any static delay optimization and in consequence, the relative delays at each receiving location are those associated to the line of sight propagation path.

The network can be open or closed. The service area of a closed network is restricted to the area inside the solid line inter-connecting all the peripheral transmitters. The area within the dashed red line is an open network service area, which is also hexagonal and the service diameter D exceeds that of the closed case by 15%.

This basic network configuration is used to determine minimum required ERP values and serves as a starting point for the subsequent investigations.

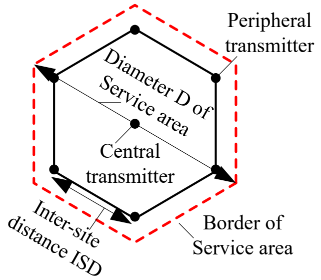


Fig. 1. Theoretical hexagon SFN network.

For digital broadcasting systems, the coverage probability should be high enough to overcome the rapid degradation of signal quality from perfect to full drop-out. A minimum required coverage probability of 99% is used for mobile reception and of 95% for the fixed, portable indoor and portable outdoor receptions.

A. Maximum SFN Size

It is assumed that the ISD is a fixed parameter of the network and thus, for a maximum SFN size calculation, the network transmitter topology is based on additional hexagon rings, as shown in Fig. 2.

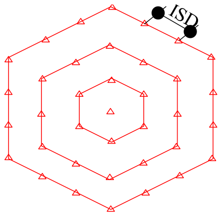


Fig. 2. Maximum SFN size calculation model.

The coverage condition will be that the receiving locations within the service area have a coverage probability above the required minimum value to achieve the satisfied reception quality. The maximum size has been calculated adding successive rings and checking that the coverage probability is kept above the threshold for all the service area. A closed network was used for this kind of coverage calculations.

B. Minimum Reuse Distance

In order to calculate the minimum reuse distance, the model defines six interfering SFNs, symmetrically situated around the wanted SFN, as shown in Fig. 3. All the unwanted networks are identical to the wanted network, which is considered to be open.

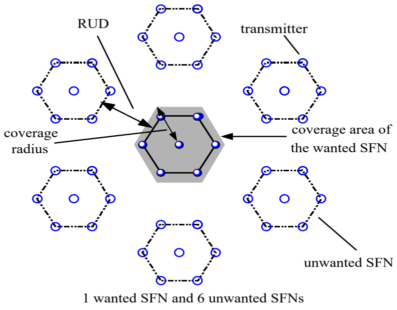


Fig. 3. Reuse distance calculation model.

Besides the self-interference of the wanted SFN, the six unwanted co-channel SFN networks will generate undesired interference levels inside the central wanted SFN network. The goal is to find the minimum required distance between the center SFN and the six peripheral SFNs maintaining mutual interference below the appropriate protection ratio. To do so, the six interfering SFNs are moved towards the wanted SFN until the coverage probability at any location within the wanted SFN area falls below the minimum threshold. This is regarded to be representative of the worst case and more realistic for real planning when mutual interference between networks is investigated.

III. COVERAGE CALCULATION ASPECTS FOR DVB-T2 SFN

The procedure for broadcast service coverage estimation involves different models. The main components of the planning method are: the field strength prediction model, the DVB-T2 receiver model, the signal summation model and the coverage probability calculation model.

A. Field Strength Prediction Model

In order to calculate the coverage probability, the SFN service area is decomposed into a large number of small area elements (pixels) in such a way that the receiving locations are in the center of each pixel. Due to the generic nature of the results, the calculations have been carried out over a flat earth homogeneous terrain using a path-general method, the ITU-R Rec.P.1546-4 propagation model [26].

Within each small area, the field strength P exhibits random variation with location due to shadow fading [27] and is assumed to be a log-normal random variable (RV) with mean $\overline{P}_i$ and standard deviation σ[28]–[30]. $\overline{P}_i$ is calculated according to the ITU-R Rec.P.1546-4 propagation model. Regarding the standard deviation, for outdoor reception σ_o = 5.5 dB is usually applied in digital broadcasting [20]. For indoor reception, the standard deviation σ is the combined result of the outdoor variation and the variation factor due to building penetration attenuation. As these distributions are expected to be uncorrelated, the value of σ for the indoor field strength distribution can be calculated as

$$\sigma = \sqrt{\sigma_o^{\ 2} + \sigma_I^{\ 2}}\ , \tag{1}$$

where σ_o and σ_I are the standard deviations of shadow fading and building penetration loss, respectively. In UHF, the mean value of the building penetration loss is 11 dB and its standard deviation σ_I is 6 dB [10].

In view of the very rapid transition from satisfactory reception to complete reception failure and due to the high Quality of Service (QoS) requirements in digital broadcasting, digital television planning is based on 99% time protection against interference. So field strength values exceeded for 1% of time are used for the unwanted signal ($E_{\text{interfering}}^{1\%}$), which is close to a 99% time protection, and field strength values exceeded for 50% of time for the wanted signal ($E_{\text{useful}}^{50\%}$). The impact of using different time percentages for field strength prediction on the coverage probability calculations has been analyzed in [25].

B. DVB-T2 Receiver model

Assuming that the SFN service area is composed of N transmitters denoted by $\{Tx_1, Tx_2, ...Tx_N\}$, the field prediction model described in section III-A is used to predict the local mean power $\{\overline{P}_1, \overline{P}_2, ...\overline{P}_N\}$ and propagation times $\{t_1, t_2, ...t_N\}$ from N transmitters at each receiving location.

At the receiver, the Fast Fourier Transform (FFT) window to demodulate the signal has to be correctly positioned. In an SFN, many potential useful signals are available to the receiver, making the task of the FFT window synchronization a complex process. Various strategies can be applied in order to optimize the receiver performance. In [31] five different strategies for FFT window synchronization are described. In this work, the FFT window is synchronized to the first received signal, whose arriving time is denoted by t_o.

Assuming that the wanted SFN is composed of N transmitters, the relative propagation delay $\Delta\tau_i$ of the signal from the i-th transmitter is equal to $\Delta\tau_i = t_i - t_0$. Depending on $\Delta\tau_i$, the received signal may contribute completely or partially to the useful part or the interfering part of the combined signal. The ratio between the useful and interfering contribution is modeled by the weighting function, as shown in (2) and depicted in Fig. 4 [10].

$$w(\Delta\tau_i) = \begin{cases} 0, & \Delta\tau_i \notin EI \\ \left(\dfrac{T_u + \Delta\tau_i}{T_u}\right)^2, & \Delta\tau_i \in EI \ \&\ \Delta\tau_i < 0 \\ 1, & \Delta\tau_i \in EI \ \&\ 0 \le \Delta\tau_i \le T_g \\ \left(\dfrac{(T_u + T_g) - \Delta\tau_i}{T_u}\right)^2, & \Delta\tau_i \in EI \ \&\ \Delta\tau_i > T_g \end{cases} \tag{2}$$

where:

$w(\Delta\tau_i)$ is the weighting coefficient for the i-th component

T_u is the useful symbol length

T_g is the guard interval length

EI is the equalization interval during which signals can be correctly equalized and therefore can usefully contribute.

In Fig. 4, T_P is the length of *EI*. The length and position of *EI* is pilot pattern dependent. For network planning purposes, it can be assumed that T_P is 57/64 of the Nyquist time limit, which is calculated as a fraction of the useful symbol length T_u and is also pilot pattern dependent [10].

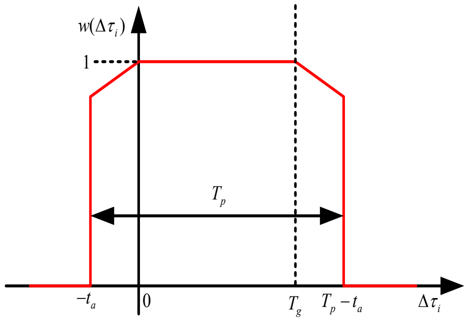


Fig. 4. Weighting function $w(\Delta\tau_i)$ for DVB-T2.

Eight different scattered pilot patterns (PP1-PP8) are available in DVB-T2. Pilot patterns can be selected according to the intended transmission channel type or payload requirement. However, only a subset of pilot patterns is permitted for each FFT size and GI combination. In large area SFNs, where long guard intervals are required, only PP1, PP2 or PP3 are available.

For a given receiving location, the useful power U_i and interfering power I_i of the i-th signal are calculated as follows:

$$U_i = w_i P_i \tag{3}$$

$$I_i = (1 - w_i) P_i \tag{4}$$

Since P_i is a log-normal RV and $w(\Delta\tau_i)$ can be assumed to be constant over an area element, U_i and I_i are also log-normal RVs. The mean values and standard deviations of the logarithms of U_i and I_i are respectively

$$m_{U_i} = \bar{P}_i + 10\log_{10} w(\Delta\tau_i) \qquad \sigma_{U_i} = \sigma \tag{5}$$

$$m_{I_i} = \bar{P}_i + 10\log_{10}(1 - w(\Delta\tau_i)) \qquad \sigma_{I_i} = \sigma \tag{6}$$

C. Signal Summation model

The received signal in an SFN can be seen as a mixture of multiple delays of the transmitted signal. The total useful power U and the total interfering power I are the sum of the individual components and are calculated as

$$U = \sum_i U_i = \sum_i w_i P_i \tag{7}$$

$$I = \sum_i I_i = \sum_i (1 - w_i) P_i \tag{8}$$

U and I are the sum of several log-normal components and can be well approximated by log-normal RVs [32], [33]. Among the approximation methods for the summation of log-normal distributions, t-LNM [22] has the highest accuracy and is used in the simulation in this paper.

The QoS at a given receiving location depends on the Carrier to Interference and Noise Ratio (CINR), denoted by γ. If the interference introduced by external neighboring networks is ignored and only the SFN self-interference is considered, γ can be written as

$$\gamma = \frac{U}{I + N_0} = \frac{\sum_{i=1}^{N} U_i}{\sum_{i=1}^{N} I_i + N_0} = \frac{\sum_{i=1}^{N} P_i w(\Delta\tau_i)}{\sum_{i=1}^{N} P_i [1 - w(\Delta\tau_i)] + N_0} \tag{9}$$

where P_i is the power received from the i-th transmitter from the wanted SFN coverage area, N is the number of transmitters in the network and N_0 is the background noise level of the receiver.

When interference from other co-channel SFNs is also considered, and assuming that the overall number of transmitters in the interfering networks is N_I, γ can be written as (10)

$$\gamma = \frac{U}{I + N_0} = \frac{\sum_{i=1}^{N} U_i}{\sum_{i=1}^{N} I_i + \sum_{k=1}^{N_I} \tilde{I}_k + N_0} = \frac{\sum_{i=1}^{N} P_i w(\Delta\tau_i)}{\sum_{i=1}^{N} P_i [1 - w(\Delta\tau_i)] + \sum_{k=1}^{N_I} \tilde{P}_k + N_0} \tag{10}$$

where $\tilde{P}_k$ is the power received from the k-th interfering transmitter.

D. Coverage Probability Calculation

An appropriate quality of service criterion implies that CINR should be higher than a certain Protection Ratio (PR) that is imposed by the system parameters, including the used modulation scheme, code rate and channel type. Since interference by an OFDM signal is noise-like, PR can be taken equal to the required Carrier to Noise Ratio (C/N) of the system under consideration.

The coverage probability P_c for a pixel around the receiving location is defined as

$$P_c = \mathrm{P}\{\gamma > PR\} = \mathrm{P}\{\gamma_{\mathrm{dB}} > (PR)_{\mathrm{dB}}\} \tag{11}$$

Considering that the effects of interference and noise are independent, in a well-established approximation [22], the coverage probability can be written as

$$\begin{aligned} P_c(x_j, y_j) &= \mathrm{P}\{(\frac{U}{I})_{\mathrm{dB}} > (PR)_{\mathrm{dB}}\} \times \mathrm{P}\{(\frac{U}{N_0})_{\mathrm{dB}} > (PR)_{\mathrm{dB}}\} \\ &= Q(\frac{PR_{\mathrm{dB}} - (m_U - m_I)}{\sqrt{\sigma_U{}^2 + \sigma_I{}^2}}) \times Q(\frac{PR_{\mathrm{dB}} - (m_U - N_0)}{\sqrt{\sigma_U{}^2}}) \end{aligned} \tag{12}$$

where $Q(\cdot)$ is the Complementary Cumulative Distribution Function (CCDF) of a standard normal distribution variable. In (12), the correlation between U and I introduced by SI in SFNs is ignored.

IV. PLANNING FACTORS

A. Transmission and Reception Parameters

Four different reception types are considered in this paper: fixed, portable indoor, portable outdoor and mobile reception.

The planning factors associated to receiver aspects, system parameters [10], [34] and propagation prediction are given in Table I.

TABLE I
PLANNING PARAMETERS

Parameters	Fixed	Portable Outdoor	Portable Indoor	Mobile
Frequency f [MHz]	650			
Bandwidth B [MHz]	7.77			
Noise Figure NF [dB]	7			
Background Noise P_n [dBW]	$P_n=NF+10\log(k\times T_0\times B)$			
Rx sensitivity P_{min} [dBW]	$P_{min}=P_n+C/N$			
σ_0 (Shadow Fading) [dB]	5.5			
Building penetration loss L_b [dB]	N/A	N/A	11	N/A
σ_I (Penetration Loss) [dB]	N/A	N/A	6	N/A
Rx Antenna Gain G_r [dBd]	11	0	0	0
Rx Antenna Height h_r [m]	10	1.5	1.5	1.5
Feeder Loss L_f [dB]	4	0	0	0
Man Made Noise P_{mnn} [dB]	0			
Coverage probability P_c [%]	95	95	95	99
Height Loss L_h [dB]	0	17.1	17.1	17.1

The receiving antenna for fixed reception [35] is assumed to point to the transmitter which has the strongest field strength at the receiving location, while a simple non-directional receiving antenna is used for the other cases (portable and mobile).

B. DVB-T2 Transmission Modes

The selection of the best suitable transmission mode is an important aspect of the planning decisions in DVB-T2 networks. Different configurations (modulation scheme, code rate and pilot pattern) involve different required C/N receiver thresholds, which will affect the SFN coverage performance. A categorization in terms of bitrate and C/N range is given in Table II.

TABLE II
C/N AND BITRATE RANGES FOR EACH RECEPTION MODE

Reception mode	Bitrate range [Mbit/s]	C/N range [dB]
Fixed	18.3=<Rate<=36.9	13.3<=C/N<=23.2
Portable outdoor	16.9=<Rate<=30.1	15.1<=C/N<=23.4
Portable indoor	11.3=<Rate<=22.6	10.2<=C/N<=18.3
Mobile	5.6=<Rate<=20.3	9.5<=C/N<=21.9

Accordingly, Table III provides a range of representative DVB-T2 transmission modes selected for the four different reception modes in the simulation cases of this paper. These DVB-T2 modes are a subset of the potential candidates for use as described in recommended practice and guidelines documents [9], [10]. Some of them are already in use in some European countries.

In order to calculate the required C/N for each transmission mode, the static Rayleigh channel is applied for portable reception, the time-variant Rayleigh channel for mobile reception and the Rician channel for fixed reception [10].

So far there are no measured values of the required C/N for mobile reception of DVB-T2 in hand. In order to calculate the mobile reception coverage the time-variant Rayleigh C/N value is assumed to be 5 dB higher than the static Rayleigh value.

TABLE III
DVB-T2 TRANSMISSION MODES

DVB-T2 Transmission Modes-Fixed Reception

[FFT size/modulation/code rate/GI/PP]		C/N [dB]	Data rate [Mbit/s]
Mode1	32k ext,64QAM-1/2,19/128,PP2	13.3	18.3
Mode2	32k ext,64QAM-3/5,19/128,PP2	15.2	22.0
Mode3	32k ext,64QAM-2/3,19/128,PP2	16.5	24.5
Mode4	32k ext,256QAM-1/2,19/128,PP2	17.4	24.5
Mode5	32k ext,256QAM-3/5,19/128,PP2	19.6	29.4
Mode6	32k ext,256QAM-2/3,19/128,PP2	21.3	32.8
Mode7	32k ext,256QAM-3/4,19/128,PP2	23.2	36.9
Mode8	32k ext,256QAM-4/5,19/128,PP2	24.8	39.3

DVB-T2 Transmission Modes-Portable Outdoor and Indoor Reception

[FFT size/modulation/code rate/GI/PP]		C/N [dB]	Data rate [Mbit/s]
Mode1	16k ext,16QAM-1/2,1/4,PP1	10.2	11.3
Mode2	16k ext,16QAM-3/5,1/4,PP1	11.8	13.5
Mode3	16k ext,16QAM-2/3,1/4,PP1	13.3	15.1
Mode4	16k ext,64QAM-1/2,1/4,PP1	15.1	16.9
Mode5	16k ext,64QAM-3/5,1/4,PP1	16.9	20.3
Mode6	16k ext,64QAM-2/3,1/4,PP1	18.3	22.6
Mode7	16k ext,256QAM-1/2,1/4,PP1	19.5	22.5
Mode8	16k ext,64QAM-3/4,1/4,PP1	20.4	25.4

DVB-T2 Transmission Modes-Mobile Reception

[FFT size/modulation/code rate/GI/PP]		C/N [dB]	Data rate [Mbit/s]
Mode1	16k ext,QPSK-1/2,1/4,PP1	9.5	5.6
Mode2	16k ext,QPSK-3/5,1/4,PP1	11	6.7
Mode3	16k ext,QPSK-2/3,1/4,PP1	12.4	7.4
Mode4	16k ext,QPSK-3/4,1/4,PP1	13.7	8.4
Mode5	16k ext,16QAM-1/2,1/4,PP1	15.2	11.2
Mode6	16k ext,16QAM-3/5,1/4,PP1	16.8	13.5
Mode7	16k ext,16QAM-2/3,1/4,PP1	18.3	15.1
Mode8	16k ext,16QAM-3/4,1/4,PP1	20.0	16.9

C. Network types and ERP requirements

There are two major models for the network topology under discussion [17]-[19]. The first one is associated to HPHT infrastructure, which is the usual configuration in traditional broadcast networks. The sites for other radiocommunication services, such as mobile and broadband data networks, have lower height and the ERP is much lower. This network model is known as LPLT and the ISD is usually much shorter. The exact definition of both categories is yet a matter of discussion. Table IV presents a proposal for classifying HPHT-LPLT networks. The ERP definition of the network is directly related to the ISD and h_{eff}. In the case of HPHT networks the sites are 40 to 100 km away from each other. The transmitter effective height is 150 m or higher.

TABLE IV
DEFINITION OF HPHT, MPMT AND LPLT NETWORKS

Parameters	HPHT	MPMT	LPLT
ERP [dBW]	>=46 and <=53	>36 and <46	<= 36
$h_{eff/}$ [m]	>= 150	>60 and <150	<= 60

In fact, the ISD strongly depends on the surrounding environment, as well as the coverage scenario. In order to guarantee a certain coverage probability and QoS, the ISD is usually denser for the indoor portable scenarios in comparison to fixed rooftop reception scenarios. It is difficult though to define a clear limit between HPHT and LPLT. A third range of values could be regarded as Medium-Power-Medium-Tower (MPMT), as described in Table IV. ERP values between 36 dBW and 46 dBW can be considered MP and h_{eff} larger than 60 m but less than 150 m could be regarded as MT.

In this study, different HPHT, MPMT and LPLT network architectures are investigated for the four reception modes. For these, minimum required ERP values are calculated as well as maximum achievable SFN coverage areas and minimum required reuse distances between co-channel service areas.

V. RESULTS

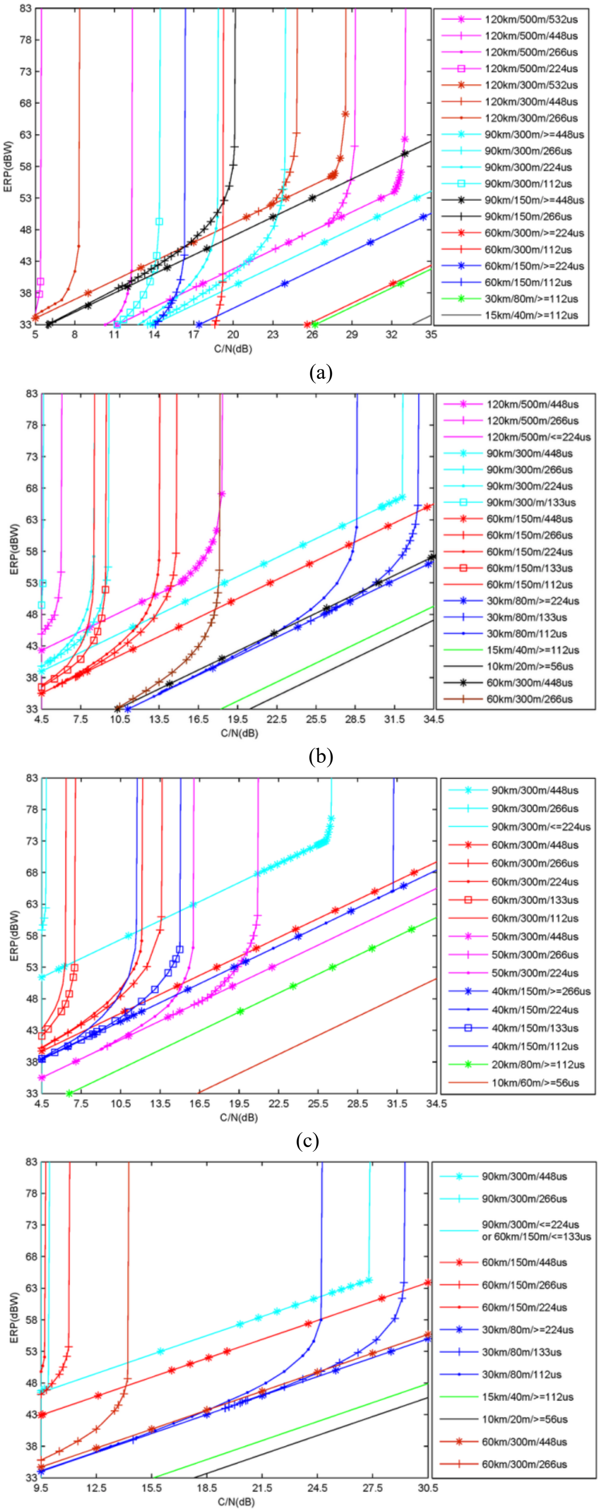
A. Analysis of the minimum required ERP and the limitation by SI degradation

In this section, the general behavior of SFNs is investigated with regard to the minimum required ERP as a function of the robustness of the applied DVB-T2 mode, i.e. its required C/N, and the network topology, as well as the limitation by SI degradation. As an example the 7-Tx hexagon network is used, as shown in Fig. 1. The coverage has been simulated using two different tools. The first one is an SFN planning tool that implements the methodology described in Section III, developed specifically by the Beihang University and the UPV/EHU for the studies in this paper. The second tool is IRT's professional planning tool FRANSY. The results of both tools were cross-checked continuously during the research activities described in this paper.

Looking at a particular scenario with given h_{eff}, ISD, GI, C/N and – as a starting point – arbitrarily chosen ERP three different regimes of behavior can be encountered. In the first regime, the ERP of the Tx is too low to cover the whole service area. This can be overcome by an increase of the ERP, thus also finding the minimum required ERP. In the second regime, the self-interference level in the SFN is so high that no full coverage can be achieved. This cannot be overcome by a change (increase or decrease) of the ERP. If a combination of the two cases is found, the second prevails. In practice there may exist cases where the SI degradation can be mitigated by tuning of individual Tx characteristics like static time delay. Since we are looking for general aspects of SFN planning this is not dealt with here. In the third regime, full coverage of the service area is found. Then the ERP can be decreased to the minimum required ERP. For this regime, a change of C/N can be compensated by a corresponding change of the ERP.

This evaluation is made for each network architecture, transmission mode and reception category (fixed, portable indoor, portable outdoor and mobile). The results are presented in Fig. 5 where the minimum required ERP is shown as a function of the required C/N.

The impact of the three regimes can be identified: There is an upper bound for the required C/N beyond which no coverage can be achieved; there is a range where the minimum ERP scales linearly with the required C/N; and, obviously, no coverage is possible below the minimum required ERP. Finally, there is a transition region, from linear behavior to reaching the upper bound C/N, with non-linear behavior where a significant ERP increase is required to allow for a slightly higher C/N requirement.



(a)

(b)

(c)

(d)

Fig. 5. Link Budget as a function of C/N values for different network structures and different GIs [ISD/h_{eff} /GI]. (a) Fixed reception. (b) Portable outdoor reception. (c) Portable indoor reception. (d) Mobile reception.

The behavior can be explained with the coverage probability calculation formula given by (12). The first term in (12) describes the effect of SI and the second term accounts for the effect of noise.

Under the regime where SI is small, the coverage probability will be associated to the second term in (12), because the first term is close to 1 due to $m_U - m_I >> \text{PR}$. The second term is dominating where m_U compares with noise. Any increment in the C/N threshold (i.e. PR) can be compensated with an equivalent ERP increase being reflected by the linear behavior of the graphs.

Under the regime where SI dominates, the first term in (12) governs the coverage probability. An increment in C/N cannot be compensated by an ERP increase since the difference $m_U - m_I$ remains constant. From a certain required C/N, specific to each scenario, no solution at all can be found beyond this value. The non-linear region is characterized by the transition of the predominance of the first to the second term in (12).

The GI duration governs the amount of SI and therefore the maximum echo delay admissible by the system and accordingly the maximum possible distance between two transmitters in an SFN. The spacing between two transmitters in an SFN should not be significantly larger than the distance permitted by the GI, unless a very robust transmission mode is chosen. This can be seen, as an example, from the scenario with {ISD=60 km; h_{eff}=300 m; GI=133 µs, corresponding to 40 km GI distance} in Fig. 5(c). Only a very low required C/N allows a successful operation of the network. The upper bound for the maximum possible required C/N is the lower the more the ISD exceeds the GI distance.

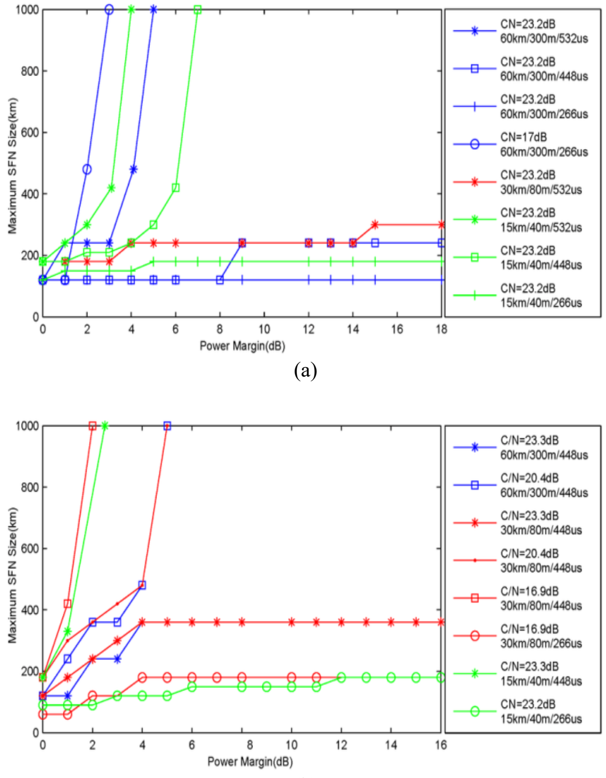
On the contrary, in the case that the ISD is remarkably shorter than the limit associated with the GI value, the coverage is governed by noise. Any C/N increase as a consequence of selecting a less robust DVB-T2 configuration can be overcome with an equivalent ERP increase, as can be seen, for example, from the scenario with {ISD=60 km; h_{eff}=300 m; GI=448 µs, corresponding to 134 km GI distance} in Fig. 5(c).

The minimum ERP found above for a specific scenario is not an exact, universally valid figure but pertains to some extent to the particular characteristics of the 7-Tx hexagon network. Larger SFNs may require a higher ERP or may suffer from more SI such that no full coverage is possible. However, the results found in this section may serve as indicative values for the minimum required ERP and the limitations introduced by SI, thus giving guidance for practical network implementation.

Examples of how the results are impacted by a larger SFN size are investigated in the next section.

B. Analysis of the maximum SFN size

Fixed and portable outdoor reception cases are taken as an example to study the maximum possible size of an SFN for a given scenario (network type and system mode). In the previous section the basic SFN size (7-Tx) was investigated. Now the size is increased by adding further transmitters, i.e. further rings of transmitters, as described in section II-A, Fig. 2. The effect on coverage is that the overall ratio of U/I changes. In most cases the ratio U/I decreases since many transmitters beyond the GI distance are added which lets SI increase in the network. Three cases may be encountered which are related to the regimes described in section V-A. Examples of the three cases can be seen in Fig. 6(a) for fixed reception and in Fig. 6(b) for portable outdoor reception.



(a)

(b)

Fig. 6 Maximum size as function of the ERP increment for different C/N and ISD/h_{eff}/GI combinations. (a) Fixed reception. (b) Portable outdoor reception.

The maximum possible size of the SFN is given as a function of the additional required ERP, termed power margin, beyond the minimum power found in section V-A in order to achieve full coverage.

The first case is that where the system mode is robust enough and the minimum ERP as derived in section V-A is high enough to compensate for the increased SI by only a small amount of additional power, then the SFN may be extended without any further change to the network parameters, maybe even unlimited, i.e. theoretically to infinity. The scenario {ISD=60 km; h_{eff}=300 m; GI=266 µs; C/N=17 dB} in Fig. 6(a) is an example of this first case. The network can be extended to a total area wider than 1000 km with an ERP very close to the minimum value calculated in the previous section V-A.

In fact, as a special case, there are configurations robust enough to enable very large SFN sizes (theoretically unlimited) even with the minimum required ERP as derived for the single ring scenario. However, these have unreasonably large GI such that they would not be implemented in practice for capacity reasons.

A second case is found if the system mode is still robust enough to cope with the additional SI, but the ERP has to be increased remarkably in order to get full coverage again. Then a certain extension of the SFN by one or two or even more tiers of

T_x is possible. This case is represented by the scenario {ISD=30 km; h_{eff}=80 m; GI=532 µs; C/N=23.2 dB} in Fig. 6(a). An increase in ERP allows the extension of the SFN by a certain, however limited amount.

Finally, in third place, the increase of SI in the network by the additional Tx is so large that no full coverage can be achieved any longer, even despite an increase of the ERP. The scenario {ISD=60 km; h_{eff}=300 m; GI=266 µs; C/N=23.2 dB} in Fig. 6(a) is an example of this case. Even with a large increase of the ERP no extension of the SFN is possible since SI would become too large with additional Tx in the network.

Again, this behavior can be explained by (12). With an increase of the ERP, the first term in (12) keeps unchanged. As long as this term remains reasonably large, i.e. fulfills the QoS coverage criterion for itself, an increase of ERP allows for the extension of the SFN since with increasing ERP the second term in (12) becomes larger. The coverage probability will increase and the maximum possible size will become larger; the smaller the C/N value, the larger is the possible increment in the SFN size. As soon as the first term falls below the QoS coverage criterion because too much SI is in the SFN, an ERP increase cannot compensate any longer for the loss of coverage and an extension of the SFN with additional transmitters is not possible.

An interesting aspect of SFN planning is indicated by the fourth example scenario in Fig. 6(a). This HPHT scenario {ISD=60 km; h_{eff}=300 m; GI=532 µs; C/N=23.2 dB} allows for the extension of the SFN to very large sizes, whereas the MPMT scenario {ISD=30 km; h_{eff}=80 m; GI=532 µs; C/N=23.2 dB} with its denser Tx topology allows only for a moderate extension with, in addition, much higher required power margin. This result is not immediately expected since denser networks are usually regarded less sensitive to SI. The performance in this example is limited by the ERP increase requirement and shows the delicate balance of the network planning parameters ISD, h_{eff}, GI and C/N.

In Fig. 6(b) the three configurations with {ISD=30 km; h_{eff}=80 m; GI=448 µs} reflect the impact of the required C/N. For a low C/N = 16.9 dB a large extension of the SFN is possible with only a small amount of additional ERP; for C/N = 20.4 dB already 3dB more power margin is required to achieve this result, whereas for an even higher C/N = 23.3 dB only a limited extension of the SFN is possible. The related scenario with the smaller GI=266 µs does only allow for an even more limited extension of the SFN.

For all the reception modes the maximum possible SFN size decreases with the increase of the C/N value due to the SI effect. There is a trade-off between higher data rate and smaller network size since a higher C/N value is associated with a higher data throughput.

There is an upper bound on the required C/N beyond which only a limited extension of the SFN size or even no extension at all is possible. This upper bound is specific to the network topology, the GI and reception mode. It is lower for HPHT than for LPLT structures, it is lower for fixed reception than for portable and mobile reception and it is lower for smaller GI.

C. *Reuse Distance*

The reuse distance (RUD) is the minimum distance which co-channel service areas have to respect in order to avoid undue interference. In section II-B a model to evaluate RUD is described. In the present section the effect of C/N, ERP, h_{eff} and ISD on the reuse distance is studied for four reception modes. The results are given in Fig. 7 and Fig. 8.

In Fig. 7 the reuse distance is shown as a function of the C/N threshold. ISD is chosen to be 60 km for fixed and portable outdoor reception and 30 km for portable indoor and mobile reception; ERP is chosen such that even for the highest C/N threshold the power budget is high enough to achieve full coverage.

With increasing C/N requirements, the transmission mode becomes more sensitive to self- and co-channel interference. The co-channel interference is in any case higher than the self-interference effect. In order to compensate the co-channel interference, the distance between the wanted and the interfering networks has to be increased in order to decrease the interference power.

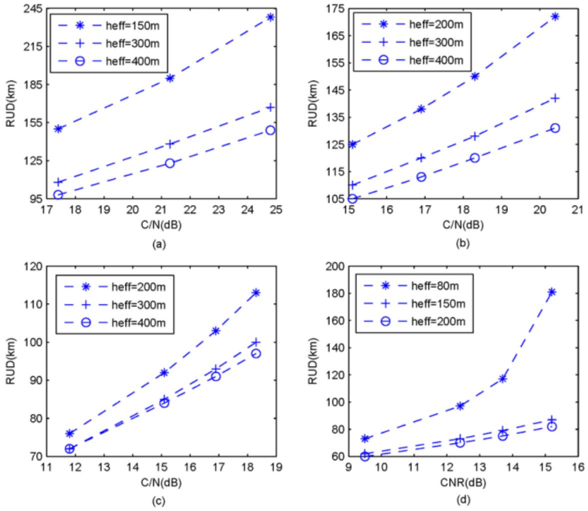


Fig. 7. RUD as a function of C/N thresholds (and h_{eff} values). (a) Fixed reception, ERP=44dBW, ISD=60km. (b) Portable outdoor reception, ERP=53dBW, ISD= 60km. (c) Portable indoor reception, ERP=50dBW, ISD=30km. (d) Mobile reception, ERP=41dBW, ISD=30km.

As a consequence, an increase of the ERP in the networks will decrease the RUD as long as the networks are operated close to the noise limit. The useful and interfering field strengths have the same increment at the same time and the first term in (12) remains the same while the second term increases. Then, a higher coverage probability can be obtained, which will decrease the RUD. This effect shows saturation and for higher ERP, there will be a smaller change in the reuse distance. In general, a trade-off between RUD and robustness of the transmission modes is found. More sensitive transmission modes would offer higher data capacity at the cost of having larger reuse distances.

The RUD increases with the increase of the C/N threshold value. This increase is roughly linear as long as the ERP is high enough to provide everywhere in the service area a link budget which is well above the noise level. If the link budget approaches the noise limit the behavior becomes nonlinear. An example of these changes can be seen in Fig. 7(d) for h_{eff}=80 m.

Fig. 8 shows the RUD for four system/reception modes as a function of the Tx density. A strong dependency on the ISD is found. For a given reception mode, networks with smaller ISD have smaller reuse distances than those with larger ISD. More general, as can be obtained from Tables V and VI, LPLT networks have smaller reuse distances than HPHT configurations.

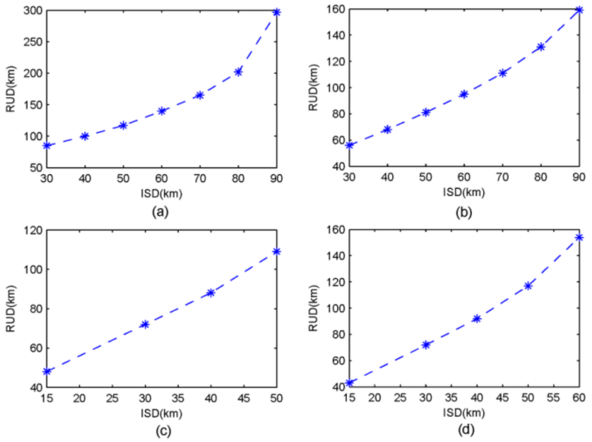


Fig. 8. RUD as a function of ISD. (a) Fixed reception, ERP=41dBW, h_{eff} =300m, C/N=21.3dB. (b) Portable outdoor reception, ERP=50dBW, h_{eff} =300m, C/N=11.8d. (c) Portable indoor reception, ERP=50dBW, h_{eff} =300m, C/N=11.8dB. (d) Mobile reception, ERP=50dBW, h_{eff} =150m, C/N=12.4dB.

The RUD decreases with the increase of the effective antenna height h_{eff}. According to the propagation curves in the ITU-R Rec. P.1546 model [26], the impact of the differentiation of field strength between the curves of different antenna heights is higher on the shorter distance range than on longer distances from the transmitter. Therefore, when the useful field strength increases with the antenna height the interfering field strength increases less rapidly allowing for a lower reuse distance for higher antenna heights.

If further rings are added to the network, as described in section II-A, the reuse distance will increase only slightly as can been seen from Table V and Table VI for several combinations of network scenarios and transmission modes. This means that the ratio between reuse distance and service area diameter decreases. In the comparison shown in Table V and Table VI minimum ERP values as derived for the 7-Tx SFN are used, increased by 3 dB in order to cope with the additional co-channel interference.

In a frequency planning context the ratio of reuse distance and service area diameter is an indicator for the efficiency of spectrum usage: a smaller ratio, i.e. a larger SFN diameter relative to the RUD, indicates a better frequency reuse. Thus, the reuse distance will have an impact on the number of channels needed to cover a region or country with the required service areas.

TABLE V
RUDS FOR FIXED RECEPTION

C/N: (Mode1:17.4dB/Mode2:21.3dB/Mode3:24.8dB)

ISD[km]/ h_{eff} [m]	Number of Rings	RUD [km]
60/150	1/1/1	176/213/247
60/300	2/1/1	140/163/192
30/80	2/2/2	131/165/197
30/80	3/3/3	139/175/208
15/40	4/4/4	99/133/167
15/40	11/7/6	108/147/175

TABLE VI
RUDS FOR PORTABLE OUTDOOR RECEPTION

C/N: (Mode2:15.1dB/Mode4:18.3dB/Mode5:20.4dB)

ISD[km]/ h_{eff} [m]	Number of Rings	RUD[km]
60/150	1/1/1	140/166/185
60/300	1/1/1	111/130/144
30/80	2/2/2	89/110/126
30/80	3/3/3	89/112/129
15/40	4/4/4	54/72/86
15/40	X/8/6	X/75/89
10/20	6/6/6	40/57/71
10/20	X/13/10	X/60/75

Note: “X” values stand for theoretical unlimited SFN sizes and in those cases the reuse distance is not calculated.

VI. USE CASES: MAXIMUM POSSIBLE BITRATE FOR A LARGE AND VERY LARGE SFN NETWORK

This section studies two of the important boundaries for a single frequency network. Firstly, it is the maximum possible size of an SFN for a specific network and operational mode which guarantees a complete coverage of the service area and secondly, the maximum possible throughput of such an SFN.

Using a theoretical hexagon network, the coverage of ‘large’ and ‘very large’ SFN with 360 and 720 km diameters are analyzed in this section. The size of the SFNs is chosen according to the total area of the Bavarian region for ‘large’ and Germany for ‘very large’. Table VII shows the parameters used for the calculations of three reception scenarios. The network transmitter topology is identical to the one in Fig. 2.

The transmitting frequency is 626 MHz. The h_{eff}, ERP and ISD are identical within an SFN for all calculated scenarios. The ISD of 60 km is a rough estimation of average ISDs in German broadcasting networks and it is in line with values in other countries with SFN networks. The h_{eff} and ERP are respectively 300 m and 50 dBW. The coverage target probabilities in this practical example are 95% for fixed and portable and 99% for mobile reception.

TABLE VII
PLANNING PARAMETERS

	Mobile reception	Portable outdoor reception	Fixed roof-top reception
R_x antenna height h_r [m]	1.5	1.5	10
coverage probability P_c [%]	99.0	95.0	95.0
R_x Antenna gain G_r[dB]	0	0	11
R_x Antenna diagram	Omni	Omni	Directional*
T_x antenna height h_{eff}[m]	300	300	300
ERP [kW]	100	100	100
ISD [km]	60	60	60

* ITU-R BT.419-3-Band IV/V

Starting from the highest possible C/N value in DVB-T2, the C/N requirement is reduced gradually down to a point where 100% of the service area is covered with the coverage probability of 99% for mobile and 95% for portable and fixed reception. The chosen modes and the corresponding maximum data rates are shown in Table. VIII.

TABLE VIII
DVB-T2 MODES WITH MAXIMUM DATA RATE WHILE ALLOWING FOR A FULL SFN COVERAGE

	Large SFN (Diameter=360 km)	Very large SFN (Diameter=720 km)
Fixed reception	32k-ext, 256QAM-3/4 PP2 GI 19/256 (266 µs) Data rate: 39.2 Mbit/s	32k-ext, 256QAM-3/4 PP2 GI 1/8 (448 µs) Data rate: 37.5 Mbit/s
Portable reception	16k-ext, 256QAM-2/3 PP1 GI 1/4 (448 µs) Data rate: 30.0 Mbit/s	16k-ext, 64QAM-3/4 PP1 GI 1/4 (448 µs) Data rate: 25.2 Mbit/s
Mobile reception	16k-ext, 64QAM-3/5 PP1 GI 1/4 (448 µs) Data rate: 20.1 Mbit/s	16k-ext, 64QAM-1/2 PP1 GI 1/4 (448 µs) Data rate: 16.8 Mbit/s

According to our results there is always a trade-off between the maximum size of an SFN and the maximum throughput. If the size of the SFN increases from ‘large’ to ‘very large’ the total coverage is guaranteed only if the C/N and consequently the throughput decrease. In other words, the SFN size could be theoretically increased as much as desired, though the data rate will then be compromised.

Using a directional receiving antenna in the fixed reception case minimizes the self-interference problems. This is the main reason for the smaller possible GI for large SFN in fixed reception mode. In all other scenarios, whether the receiving antenna is non-directional or the SFN service area is very large, the guard interval with the duration of 448 µs is inevitable.

In addition to the maximum size and throughput of an SFN, it is interesting to observe the amount of coverage loss when the system throughput is increased beyond the potential maximum as given in Table. VIII. Fig. 9 illustrates the coverage loss in the mobile reception scenario for the large SFN when the system throughput is increased beyond 20.1 Mbit/s.

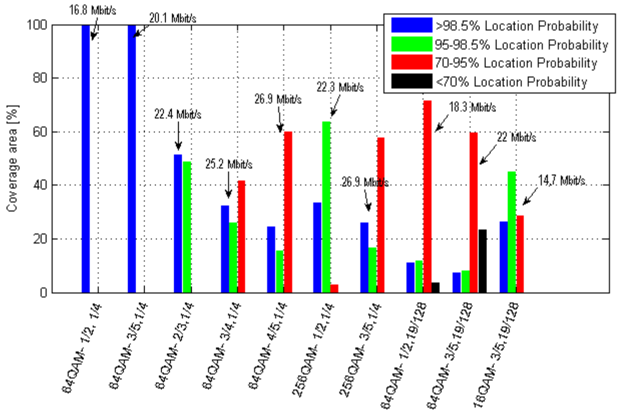


Fig. 9. Percentage of coverage locations in the large SFN (360 km x 360 km) for different DVB-T2 mobile reception modes ordered according to four coverage probability classes.

Except from C/N, all other system and network parameters for the different coverage predictions remain unchanged. If the C/N requirement is too high, some of the locations in the coverage area cannot reach the minimum QoS criterion and the percentage of coverage locations of the service area decreases.

In addition, in Fig. 9 the coverage loss is shown when a smaller guard interval of 266 µs is chosen. The two rightmost colored bars in Fig. 9, with 19/128 GI fraction, show the influence of the smaller GI on the coverage. The original GI of 448 µs corresponds to a GI distance of 134 km. Though it is smaller than the network size, the overall ratio of wanted to interfering field strengths is high enough that full coverage of the service area is achieved. When the GI is reduced to 266 µs the interfering field strength increases, and as a result the coverage area decreases. Increase of robustness by choosing a lower modulation scheme with lower data rate will compensate the loss of coverage.

VII. CONCLUSION

This paper investigates the maximum size and the minimum frequency reuse distance for SFN networks delivering DVB-T2 services. Four reception cases have been studied, namely fixed, portable indoor, portable outdoor and mobile reception. The paper aims at evaluating the relation between the operating mode, useful bitrate, system thresholds and network architecture, characterizing the impact of these factors into the SFN size and frequency reuse pattern.

The analysis has been carried out using theoretical hexagon networks in order to avoid the influence of specific factors associated to terrain, population distribution and other factors not directly related to the parameters of the DVB-T2 standard or the network architecture: ERP, h_{eff} and ISD.

A close relationship has been found between the network ERP, the maximum inter-transmitter distance and the system C/N threshold, that in turn, will define the maximum delivered bitrate. To this respect, it has been discovered that the coverage probability associated to a specific mode (C/N, GI) and network parameters (ISD, h_{eff}) features three different behavior regimes, each one with a different dependency with transmitter ERP values. An interesting finding is the existence of a certain required C/N, specific to each scenario, where the coverage target cannot be achieved no matter the potential ERP increase available.

Very different results have been obtained for the maximum size of the SFN achievable depending upon the specific mode (C/N and GI) and network parameters (ISD, h_{eff}). Again, three cases may be encountered which are related to the three regimes describing the ERP, C/N, ISD and coverage relationship. For certain network structures, if the required C/N threshold is low enough, the network can be extended with additional rings with relatively low ERP increases. As the C/N increases, the maximum achievable size becomes shorter, up to a point where the SI does not enable additional rings within the network, and the maximum size is two times the ISD. It has been found that the GI is a key parameter but in close relation with the rest of DVB-T2 and network parameters. This fact has been proven with two use cases: large SFN (360 km) and very large SFN (720 km). Extending an SFN from 360 km to 720 km would imply around 5% of bitrate reduction for fixed services and 16% for mobile and portable reception.

In general, a trade-off between RUD and robustness of the transmission modes has been identified. More sensitive transmission modes would offer higher data capacity at the cost of having larger reuse distances. For a given reception mode, LPLT networks have smaller reuse distances than HPHT configurations.

If the size of the SFN increases from 'large' to 'very large' the total coverage is guaranteed only if the C/N and consequently the throughput decrease. In other words, the SFN size could be theoretically increased as much as desired, though the data rate will then be compromised.

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