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SFN FREQUENCY PLANNING AND NETWORK IMPLEMENTATION WITH REGARD TO T-DAB AND DVB-T

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Guide on SFN Frequency Planning and Network Implementation with regard to T-DAB and DVB-T

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Content

1. Introduction

The Stockholm 1961 (ST61) agreement[1] and the Geneva 1989 (GE89) agreement[2] allocated VHF and UHF frequencies for analogue television throughout the European Broadcasting area and the African Broadcasting area, respectively. The ITU[3] decided to convene a Regional Radiocommunications Conference (RRC) to revise ST61 and GE89, in two sessions. The first session of the RRC took place in May 2004. The second session will be held in May/June 2006. The aim of the RRC is to establish an agreement and associated frequency plan for the digital terrestrial broadcasting service in the VHF/UHF bands.

The DVB-T and Eureka 147 T-DAB standard have been chosen for the digital terrestrial broadcasting service. These DVB-T and T-DAB are both OFDM systems, which allow the possibility of single frequency network (SFN) operation, through OFDM's multi-path immunity.

In principle, these digital networks can be implemented as multi-frequency networks (MFN) which allow the same or different programmes to be carried by individual transmitters using different frequencies; or as SFN which use multiple transmitters operating on the same frequency and carrying the same programmes; or as a mixture of MFN and SFN.

This report is a guide on SFN planning with regards to the frequency planning and implementation of DVB-T and T-DAB services. It has been produced by the EBU's BCP group and contains sections on the technical elements of digital broadcasting and OFDM, the definition and types of SFN, SFN coverage, SFN models, implementation of SFN and coordination aspects. Case studies of simulated SFN networks in various European countries are also included.

In section 2 technical elements of the DVB-T and T-DAB systems are given, as far as they are relevant for SFN frequency and network planning, i.e. characteristics of the broadcast transmission channel, system properties, inter-symbol and inter-carrier interference, receiver modelling for network planning etc.

Section 3 gives a definition of single frequency networks, classifies the types of SFN according to different criteria, discusses the impact of transmission parameters on the network performance and highlights the spectrum saving potential of the SFN approach.

In section 4 the definition and evaluation of network coverage is discussed in detail. In particular it deals with network gain as a fundamental feature of the SFN technique, limiting factors to the SFN performance and mathematical methods to calculate coverage. Annex A contains the details of the mathematical treatment.

Section 5 deals with theoretical SFN models. These are used to learn about general properties of SFN, as for example self-interference degradation or sensitivity with regard to external interference. Some of the theoretical models and an application in allotment planning – namely the use of reference networks - are described in more detail.

Section 6 deals with some general SFN implementation aspects. However, the report focuses on the frequency planning and theoretical network planning aspects of SFNs. Practical aspects of implementation are covered only to a restricted extent since these will not be the major issues at the RRC04/06. They will be dealt with at a later stage in a separate report or a second edition of the present report.

Section 7 describes coordination aspects and how SFN are handled in a frequency plan synthesis. Allotment planning as the natural planning approach for SFN and, as an example,

[1] Regional Agreement for the European Broadcasting Area Concerning the use of Frequencies by Broadcasting Service in the VHF and UHF Bands, Stockholm, 1961 [1]

[2] Final Acts of the Regional Administrative Conference for the Planning of VHF/UHF Television Broadcasting Area and Neighbouring Countries, Geneva, 1989 [2]

[3] ITU Council Resolutions 1180 (rev.2002) and 1185

the Maastricht 2002 frequency plan for T-DAB is discussed. Also the treatment of SFN in the Chester 97 agreement is described.

Section 8 gives a short overview on some case studies that have been undertaken in Europe relating to SFN implementations. In Annex B these studies are documented in full length.

Section 9 gives a list of documents referred to in the report. In these documents the reader may also find further information on the SFN technique.

Much of the material presented in the report can be found in already published documents of the EBU or other organisations. It was, however, felt useful to gather the available material on SFN from the various sources and collect it into one volume. Much of the text taken from these sources has been left unchanged or only editorially altered in order to fit into the structure of the sections. This explains the heterogeneous character of the report and also the fact that numerous repetitions will be found. The reader is invited to judge this aspect graciously.

2. Technical Elements

2.1. The broadcast transmission channel

In general, the transmission channel forms the physical link between the communicating parties: a transmitter and a receiver. The broadcast concept means that although a return path might be available, it is not required. Content is received without being requested. A radio or television terrestrial broadcast is a program that is transmitted over airwaves for public reception by anyone with a receiver tuned to the right signal channel.

Noise is a fundamental and unavoidable cause of signal distortion. It arises from various processes encountered by transmitted waves on their way from the transmitter antenna to the receiver antenna. Among these processes are the directional characteristics of both the transmitter and receiver antenna; reflection from the smooth surfaces of walls and hills; absorption by walls, trees and by the atmosphere; scattering from rough surfaces such as the sea, rough ground and leaves and branches of trees; diffraction from edges, such as building rooftops and hilltops; refraction due to atmospheric layers and layered or graded materials.

Three mutually independent, multiplicative propagation phenomena taking place in the transmission channel can usually be distinguished: (large-scale) path loss, shadowing (or slow fading) and multipath fading (or fast fading), which appear as time-varying processes between the antennas. They are schematically shown in Figure 2.1.

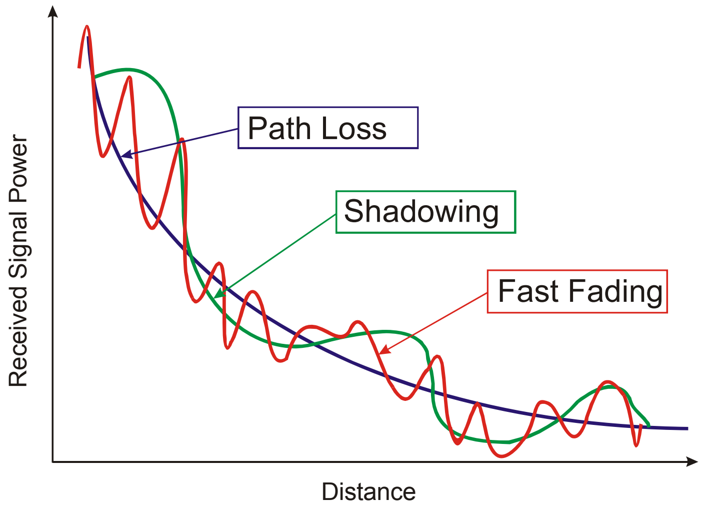


Figure 2.1: Multiplicative processes in the transmission channel

The path loss is an overall decrease in field strength, as the distance between the transmitter and the receiver increases. Superimposed on the path loss is the shadowing, which changes more rapidly, with significant variations over distances of hundreds of meters and generally involving variations of up to around 20 dB. This phenomenon is affected by prominent terrain contours (e.g., hills, forests, billboards, clumps of buildings, etc.) between the transmitter and receiver. The receiver is often represented as being “shadowed” by such prominences. The statistics of slow fading provides a way of computing an estimate of path loss as a function of distance.

Measurements indicate that the mean path loss closely fits a log-normal distribution, that is, the signal measured in decibels has a normal distribution (Figure 2.2). The standard deviation of the shadowing (log-normal) distribution is known as the location variability, σ_L. It varies with frequency and depends on the environment in which the receiver is located. A standard deviation of 3 – 6 dB is typical.

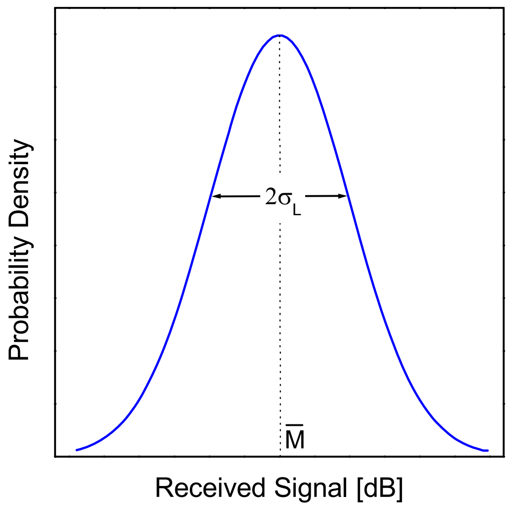


Figure 2.2: Probability density function of shadowed signal. $\overline{M}$ is the mean value of the signal

Fast fading involves variations on the scale of a half-wavelength (50 cm at 300 MHz, 17 cm at 900 MHz) and frequently introduces variations as large as 20 dB. It results from the constructive and destructive combinations of randomly delayed, reflected, scattered, and diffracted signal components. This type of fading is relatively fast and is therefore responsible for the short-term signal variations. Depending on the nature of the radio propagation environment, there are different models describing the statistical behaviour of the multipath fading envelope:

Ricean channel. In this channel, one of the channel paths between the transmitter and the receiver is a line-of-sight path. Other paths have more attenuation and longer delays than the main path. The frequency response of such channels is not constant and has ripples in it. Such a channel will normally apply to directional receiving antennas at roof top level. In the SFN case the delayed signals may also come from other transmitter sites.

The Ricean probability density function is shown in Figure 2.3.

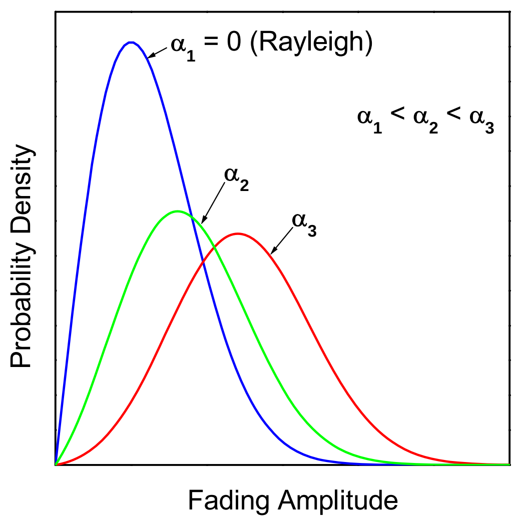


Figure 2.3: Ricean probability density function. α is the magnitude of the line-of-sight component

Rayleigh channel. In this model only reflecting paths exist and the line-of-sight path no longer exists. In this case the channel response versus frequency is not flat. Ripples in frequency response in a Rayleigh channel are greater and deeper than in a Ricean channel. Such a channel will occur at low heights, in built-up areas and inside buildings, where there will be reflections from man-made obstacles and the ground. In the case of an SFN, the delayed signals may also come from other transmitter sites.

The Rayleigh probability density function is shown in Figure 2.4.

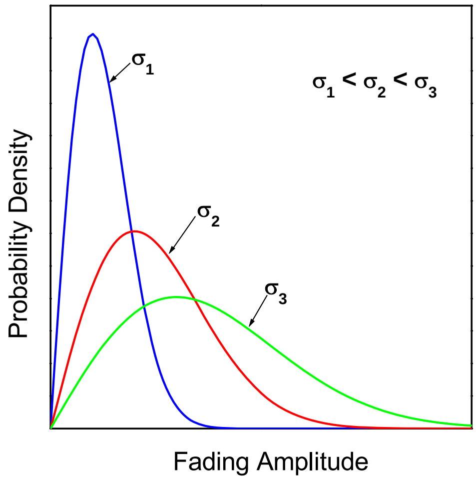


Figure 2.4. Rayleigh probability density function. σ is the standard deviation

Mobile channel. When a receiver moves, channel parameters vary rapidly. So, we have Doppler shifting and spreading. In this case the channel model is a multipath model with variable parameters. The situation corresponds to a Rayleigh channel but with a moving receiver (i.e. several statistically independent incoming signals affected by Doppler shift/spread, with different delay times, none of which dominates, together with thermal noise). There will be rapid and severe variations in the received signal caused by multipath propagation. However, the main degradation to the received signal is caused by the movement of the vehicle carrying the receiver, the speed of which corresponds to a given Doppler frequency. Reception will normally be achieved by using a non-directional antenna situated at no less than 1.5 metres above ground level, on moving vehicles or trains, where there will be reflections from man-made obstacles and the ground. In the case of an SFN, the delayed signals may also come from other transmitter sites.

Portable channel (slow time variation). Not only the mobile channel shows a time variance, also the broadcast transmission channel for portable reception has to be regarded as (slowly) time variant. This time variance is caused by moving objects in the vicinity of the (static) portable receiver which produce a time dependence of the echoes reflected by these objects. Although this mechanism does not introduce a remarkable Doppler degradation, measurements show that receivers have a worse performance in a slowly time-varying Rayleigh as compared to a static Rayleigh channel (probably) because of synchronisation effects.

More information about the broadcast transmission channel can be found, e.g., in [3, 4].

2.2. OFDM features

DVB-T and T-DAB use the Orthogonal Frequency Division Multiplexing modulation scheme (OFDM). Since it is not the task of this report to give an introduction into this modulation technique, the present chapter is restricted to a short description of those OFDM features that are relevant for SFN planning.

Frequency multiplex and orthogonality

The OFDM concept is based on spreading the data to be transmitted over a large number of carriers, each being modulated at a low bit rate. In a conventional frequency division multiplex the carriers are individually filtered to ensure there is no spectral overlap.

There is therefore no inter-carrier interference between carriers but the available spectrum is not used with maximum efficiency. If, however, the carrier spacing is chosen in such a way that the carriers are orthogonal over the symbol period, then symbols can be recovered without interference even with a degree of spectral overlap. For maximum spectral efficiency, the carrier spacing equals the reciprocal of the symbol period (see Figure 2.5). The multiplex of carriers may be conveniently generated digitally using the inverse Fast Fourier Transform (FFT) process.

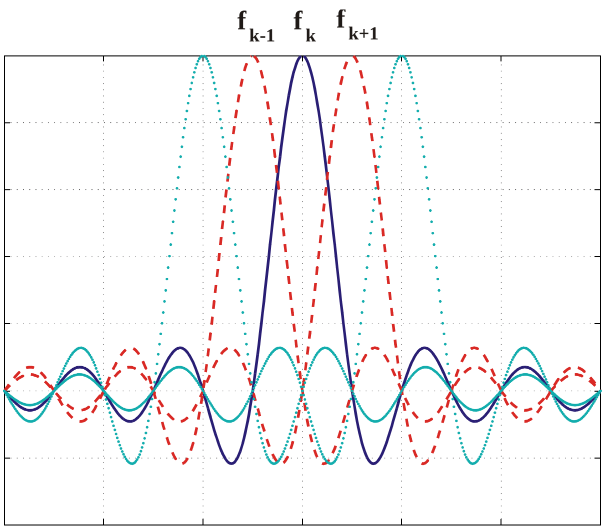


Figure 2.5: Schematic presentation of carrier orthogonality in an OFDM signal (after windowing)

All carriers added together give a noise-like power density over the bandwidth of the OFDM signal. Figure 2.6 shows the sum of the power spectral density of all carriers for the DVB-T system with an 8 MHz channel. Figure 2.7 shows the sum of the power spectral density of all carriers for the T-DAB system.

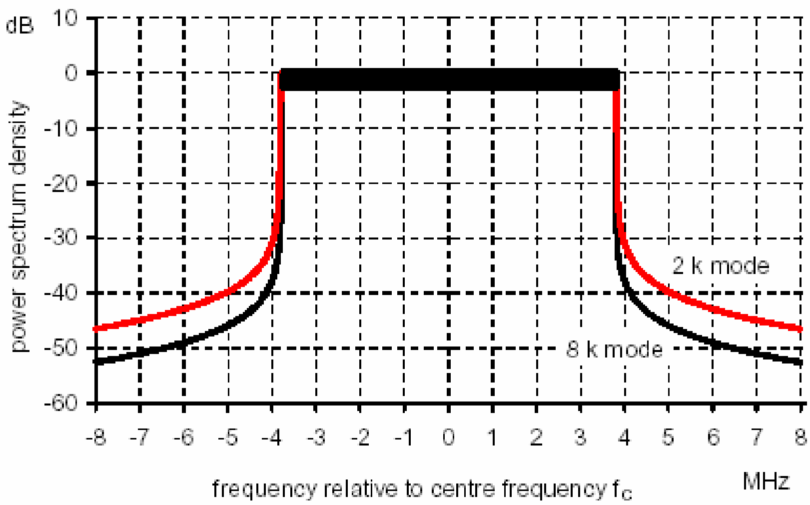


Figure 2.6 : DVB-T transmission signal spectrum (8 MHz channel) (from ETSI Standard EN 300 744 [5])

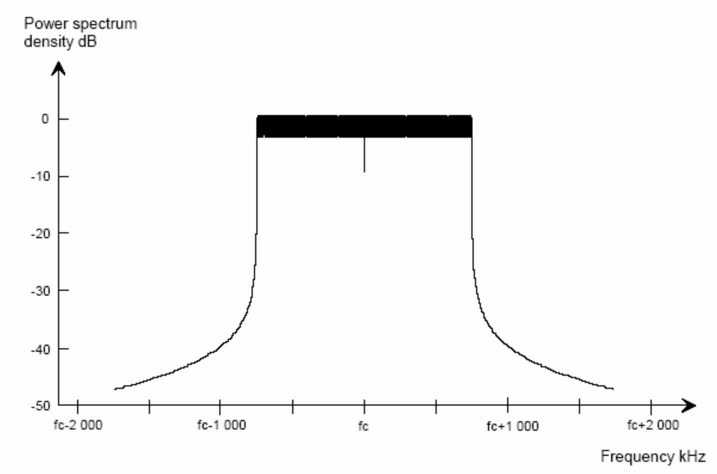


Figure 2.7: T-DAB transmission signal spectrum (1.536 MHz channel) (from ETSI Standard EN 300 401 [6])

Carrier structure DVB-T

Preferred implementations of the FFT tend to be based on radix 2 or radix 4 algorithms, or some combination of radix 2 and 4. This preference leads to the number of carriers generated in practical OFDM systems being some power of 2. The specified systems are based on 2048 (2K) carriers and 8192 (8K) carriers. However, the number of actual carriers transmitted is always smaller than the maximum number possible, as some carriers at either end of the spectrum are not used. These unused carriers provide a frequency guard band which allows practical IF filtering. The number of active carriers is 1705 for the 2K mode and 6817 for the 8K mode. The active carriers carry either data or synchronisation information. Any n-QAM digital modulation scheme may be used to modulate the active carriers; where n is commonly 4, 16 or 64. Roughly 10% of the carriers are used to transport reference information which is known to the receiver and which serves for synchronisation, channel estimation, transmission parameter signalling, etc. These carriers are called pilots and are transmitted at a higher ("boosted") power level than the data carriers. An overview of the carrier structure in time and frequency is given in Figure 2.8.

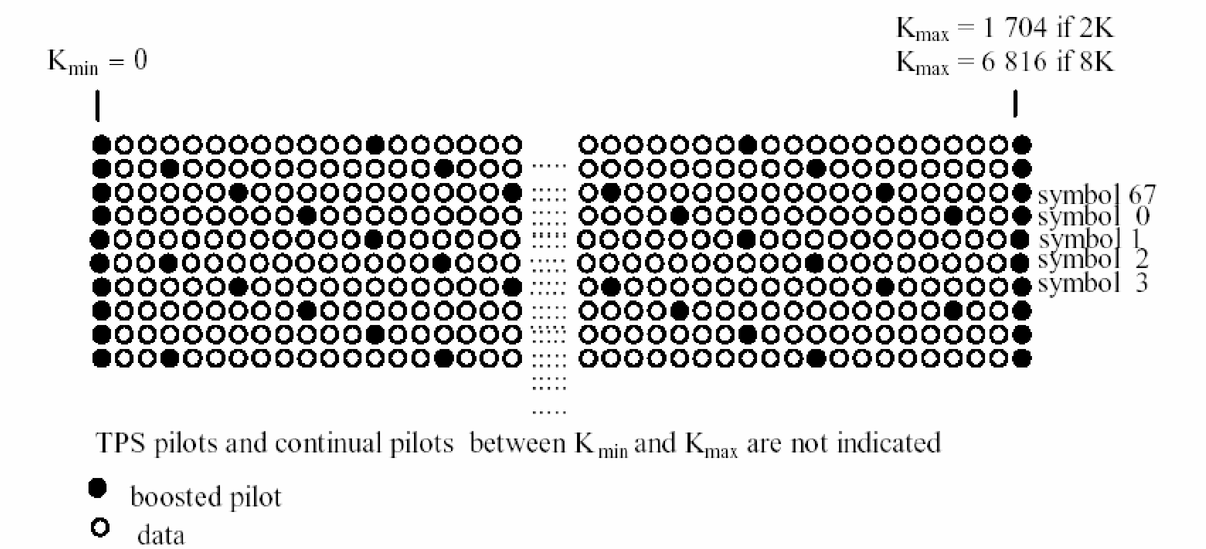


Figure 2.8: DVB-T carrier structure (from ETSI Standard EN 300 744 [5])

Carrier structure T-DAB
Mode I T-DAB is generally used for Band III in Europe and uses a convolutionally coded D-QPSK OFDM signal. The system is based on the use of 1,536 active carriers with a frequency spacing of 1 kHz. All carriers are transmitted at the same power level. Four T-DAB blocks fit into a single 7 MHz television channel, identified by the letters A, B, C and D, with a 176 kHz guard band between blocks A-B, B-C and C-D. Between blocks D and A there is a wider guard band of 320 or 336 kHz in order to align with a 7 MHz television raster.

Frequency interleaving
The decoding algorithm performs poorly when confronted with bit errors that are all bunched together in the data stream, and because the carriers are subject to fading, bit errors usually do occur in groups when a carrier is in a deep fade. To protect against this, DVB-T and T-DAB use frequency interleaving. This mechanism randomly spreads the information across all carriers and thus across the whole bandwidth. This avoids the bundling of bit errors caused by selective fading and significantly improves the performance of the decoder.

Multipath immunity
OFDM, when coupled with appropriate channel coding (error correction coding), can achieve a high level of immunity against multipath propagation and against co-channel interference from, e.g., DVB-T, PAL, SECAM, NTSC. This aspect is dealt with in more detail in chapter 2.3.

Variety of operation modes
OFDM systems also offer the broadcaster great flexibility in the transmission as bit rate can be traded against level of protection depending on the nature of the service. For example, mobile reception of the OFDM signal is possible given due consideration to factors including vehicle speed, carrier spacing, data rate and modulation scheme, whereas, for a service with fixed reception, high order modulation schemes and consequently high bit rates could be used.

Single frequency networks
OFDM signals also allow the possibility of single frequency network (SFN) operation. This is due to OFDM’s multi-path immunity. SFN operation is possible when exactly the same signal, in time and frequency, is radiated from multiple transmitters. In this case, at any reception point in the coverage overlap between transmitters, the weakest received signals will act as post or pre-echoes to the strongest signal. This aspect is dealt with in chapter 2.3.

The choice of the main parameters for the OFDM system is determined by the requirement for the DVB-T or T-DAB service.

2.3. Multipath capability of DVB-T and T-DAB

2.3.1. General

In OFDM the information is carried via a large number of individual carriers in a frequency multiplex. Each carrier transports only a relatively small amount of information and high data capacities are achieved by using a large number of carriers within a frequency multiplex. The individual carriers are modulated by means of phase shift and amplitude modulation techniques. Each carrier has a fixed phase and amplitude for a certain time duration during which a small portion of the information is carried. This unit of data is called a symbol; the time it lasts is called the symbol duration. After that time period the modulation is changed and the next symbol carries the next portion of information.

A DVB-T or T-DAB receiver has to cope with the adverse conditions of the broadcast transmission channel. In general, signals arriving at a receiver by different paths show different time delays which result in inter-symbol interference (ISI), a degradation in reception. An OFDM system with a multipath capability allows for the constructive combination of such signals. This is achieved by inserting a guard interval, a cyclic prolongation of the useful symbol duration of the signal. The FFT-window, i.e. the time period for the OFDM demodulation, is then positioned in such a way that a minimum of inter-symbol interference occurs.

2.3.2. Inter-symbol interference

In order to demodulate the signal - and looking at only one carrier - the receiver has to evaluate the symbol during the symbol duration. Three consecutive symbols in time, denoted by n-1, n and n+1, and the setting of the FFT-window such that symbol n is evaluated by the receiver, are shown in Figure 2.9. No guard interval is used in this example, and the FFT-window has the same duration as the symbol.

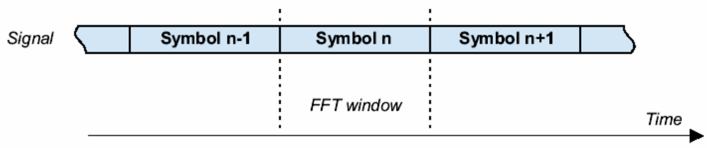


Figure 2.9: OFDM symbol duration and FFT-window (no guard interval)

In an environment where several useful signals – either from multipath echoes or from other transmitters in an SFN - are available to the receiver, things become more complex. Usually, the signals arrive at different times at the receiver which, in the absence of a guard interval, makes correct synchronisation to all of the signals impossible. Such a situation with two signals as an example is depicted in Figure 2.10. Synchronisation to symbol n of signal 1 leads to an overlap of the FFT-window with the preceding symbol n–1 of the delayed signal 2. Since this symbol n–1 carries different information from symbol n, the overlap acts as interference to the evaluation of symbol n. The degradation of the reception caused by this mechanism is called inter-symbol interference (ISI).

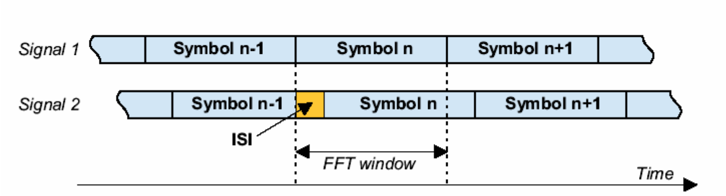


Figure 2.10: Inter-symbol interference with a delayed signal (no guard interval)

2.3.3. Guard interval

In order to overcome the inter-symbol interference problem in DVB-T and T-DAB, part of the symbol is copied from the beginning of the symbol to the end, increasing its duration by a certain amount of time called the guard interval. This cyclic prolongation of the original symbol is shown in Figure 2.11. The guard interval is denoted by Δ.

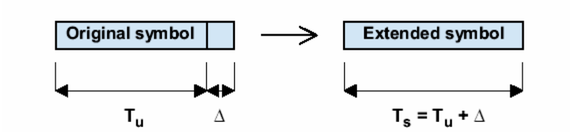


Figure 2.11: Increase of the symbol duration by the guard interval

The new increased symbol duration is denoted by T_s and the original symbol duration is often called useful symbol duration T_u. The duration of the FFT-window during which the symbol is evaluated is kept at the original value T_u. The orthogonal relationship is kept with the original symbol duration T_u, not the extended T_s.

The improvement that is achieved by the insertion of the guard interval can be seen from Figure 2.12 with two signals as an example. The guard interval now allows for the FFT-window to be positioned so that there is no overlap with a preceding or subsequent symbol, thus avoiding ISI.

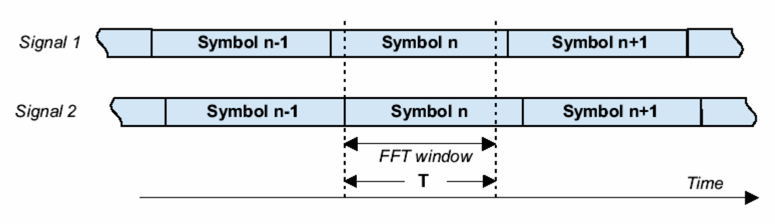


Figure 2.12: Guard interval utilisation

The fact that the duration of the FFT-window is now smaller than the symbol duration allows for a variety of different possible FFT-window positions for the evaluation of a symbol. This is indicated in Figure 2.13 for the simple case of synchronisation to a single signal. Three possible FFT-window positions are indicated as examples. Here, all positions are equivalent with regard to evaluation of the symbol because all the FFT-window positions shown include samples from only one symbol.

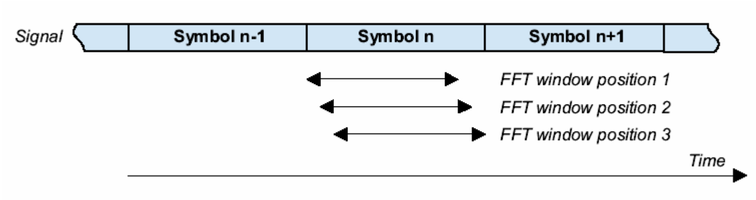


Figure 2.13: Three possible FFT-window positions

The insertion of the guard interval reduces the data capacity because not all of the symbol duration T_s is used for "useful" data.

In a multipath or SFN environment, where many potentially useful signals are available to the receiver, the choice of the FFT-window position becomes more complex. A number of different strategies that can be applied are discussed later in chapter 2.4.

All signals with time delays that cannot be absorbed by the guard interval in the way described above introduce a degradation of reception, similar to that shown in Figure 2.10. Any part of each of these received signals that falls outside the guard interval has an interfering characteristic, which will be dealt with in more detail in chapter 2.3.4.

OFDM, due to its multicarrier nature, exhibits relatively long symbols. This long symbol period already provides a certain degree of protection against inter-symbol interference caused by multipath propagation. However, as described above, this protection is greatly enhanced by use of the guard interval. The guard intervals for the 2K and 8K DVB-T systems are given in Table 2.1 below.

Mode	**8K mode**				**2K mode**			
	Guard Interval							
	1/4	1/8	1/16	1/32	1/4	1/8	1/16	1/32
8 MHz channel	224 µS	112 µS	56 µS	28 µS	56 µS	28 µS	14 µS	7 µS
7 MHz channel	256 µS	128 µS	64 µS	32 µS	64 µS	32 µS	16 µS	8 µS
6 MHz channel	*298.667 µS*	*149.333 µS*	*74.667 µS*	*37.333 µS*	*74.667 µS*	*37.333 µS*	*18.667 µS*	*9.333 µS*
NOTE: values in italics are approximate values								

Table 2.1: Guard interval durations (from ETSI EN 300 744 [5]).

As the proportion of the symbol used to make the guard interval is increased, the transmission capacity decreases. However, if a system with a greater number of carriers were used, the symbol period would increase and therefore the same proportion of guard interval would give a greater protection in terms of absolute time. However, increasing the number of carriers has also some drawbacks:

- higher complexity (FFT performed on a higher number of samples and more memory)
- higher sensitivity to tuner phase noise.

The guard interval for T-DAB Mode I (generally used for Band III in Europe) is ¼ of the symbol period (246 μs).

2.3.4. Contributing and interfering signal components with inter-symbol interference

For network planning, the power of all the echoes received within a window of duration Δ (guard interval width) is considered as useful, and contributes positively to the total available signal power. Outside the guard interval, a part of the echo power is associated with the same OFDM symbol as the primary signal, and which therefore contributes positively to the total useful signal power.

Another part of the echo power is associated with the previous or subsequent OFDM symbol and produces ISI, which has a similar effect to uncorrelated Gaussian noise interference. Therefore, as the echo delay is progressively increased beyond the guard interval, the useful contribution decreases and the ISI increases with a quadratic law. The echo power becomes fully interfering (i.e. it contains no useful power) when the delay is larger than or equal to one OFDM symbol.

DVB-T

Moreover, with DVB-T there is a further degradation mechanism effective: The channel estimation process in the receiver, for constellation equalisation and coherent detection, is based on a frequency domain interpolation filter, which allows recovering of the channel response from the scattered pilot carriers. The pass-band T_p of this filter is designed to be larger than the guard interval (Δ=T_u/4) ([4]), but, because of theoretical limitations, cannot exceed T_u/3 (practical figures are up to T_p= (7/24)T_u for a sophisticated receiver). The following cases can take place:

- the echo is within the guard interval Δ: its power adds to the “useful” signals;
- the echo is outside Δ, but within T_p: it is correctly equalised, but is split into a useful component (relevant to the actual OFDM symbol) and an interfering component (relevant to the previous OFDM symbol), as described in the formula below;
- the echo is outside T_p: it is to be considered as pure interference, with the same effect as an equal-power Gaussian noise.

The situation for DVB-T is depicted in Figure 2.14.

[4] For smaller guard intervals (e.g. Δ=T_u/8,..., T_u/32), it can be assumed that the interpolator filter bandwidth remains the same as for T_u/4.

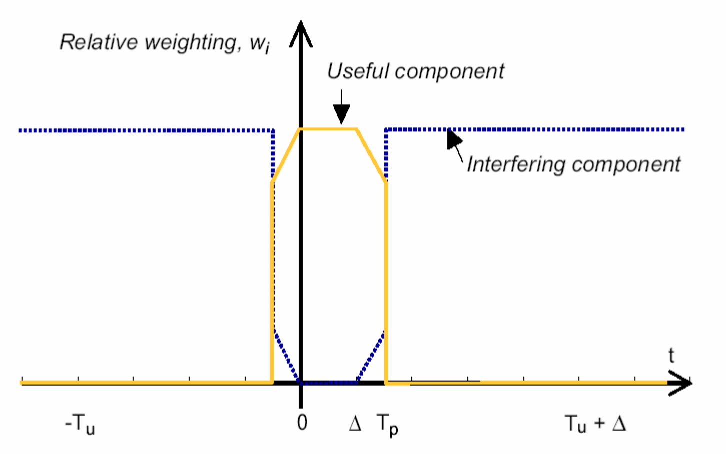


Figure 2.14: DVB-T model **-** Splitting of the signal power into contributing and interfering components.

Mathematically, the rule for splitting the signal power into a useful component and an interfering component is expressed as follows:

$$w_i = \begin{cases} 0 & \text{if} \quad t \le \Delta - T_p \\ \left(\dfrac{T_u + t}{T_u}\right)^2 & \text{if} \quad \Delta - T_p < t \le 0 \\ 1 & \text{if} \quad 0 \le t \le \Delta \\ \left(\dfrac{(T_u + \Delta) - t}{T_u}\right)^2 & \text{if} \quad \Delta < t \le T_p \\ 0 & \text{if} \quad T_p < t \end{cases}$$

$$C = \sum_i w_i C_i$$

$$I = \sum_i (1 - w_i) C_i$$

Where:

C_i is the power contribution from the i-th signal at the receiver input

C is the total power of the effective useful signal

I is the total effective interfering power

w_i is the weighting coefficient for the i-th component

T_u is the useful symbol length

Δ is the guard interval length

t is the signal arrival time

T_p is the interval during which signals usefully contribute

It should be remembered that I, the total effective interfering power, is weighted by the appropriate DVB-T-to-DVB-T protection ratio when being regarded as a source of interference in a coverage calculation.

As already mentioned, a value of $T_u/3$ is regarded as a theoretical limit for T_p, and would require an interpolation filter with an infinite number of taps. The formula $T_p = 7T_u/24$ is often quoted and this gives a sensible practical limit given real filter design. At the present time, many DVB-T receivers do not even reach this performance.

T-DAB

T-DAB uses differential demodulation. Therefore, the restrictions arising from the interpolation filter for the channel estimation do not exist for T-DAB and the degradation function looks slightly different. It is depicted in Figure 2.15.

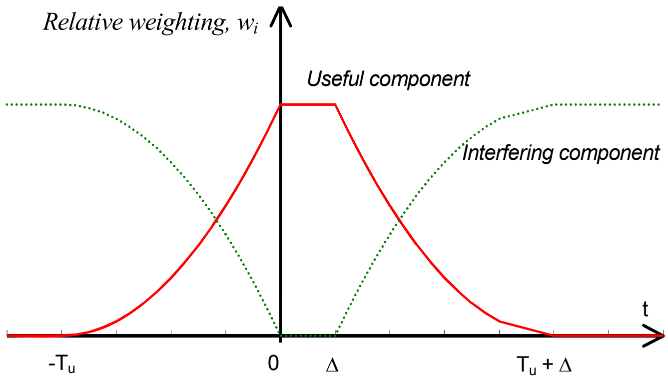


Figure 2.15: T-DAB model **-** Splitting of the signal power into useful and interfering components.

For T-DAB, the rule for splitting the signal power into a useful component and an interfering component is expressed as follows:

$$w_i = \begin{cases} 0 & \text{if} \quad t \le -T_u \\ \left(\dfrac{T_u + t}{T_u}\right)^2 & \text{if} \quad -T_u < t \le 0 \\ 1 & \text{if} \quad 0 < t \le \Delta \\ \left(\dfrac{(T_u + \Delta) - t}{T_u}\right)^2 & \text{if} \quad \Delta < t \le T_u + \Delta \\ 0 & \text{if} \quad t > T_u + \Delta \end{cases}$$

$$C = \sum_i w_i C_i$$

$$I = \sum_i (1 - w_i) C_i$$

Where:

C_i is the power contribution from the i-th signal at the receiver input

C is the total power of the effective useful signal

I is the total effective interfering power

w_i is the weighting coefficient for the i-th component

T_u is the useful symbol length

Δ is the guard interval length

t is the signal arrival time.

It must be borne in mind that *I*, the total effective interfering power, is weighted by the established T-DAB-to-T-DAB protection ratio when being regarded as a source of interference in a coverage calculation.

2.4. FFT-window synchronisation

2.4.1. General

The synchronisation of an OFDM receiver is performed in two stages: the initial synchronisation in which the receiver is aligned with the symbol rate, and the secondary synchronisation in which the receiver positions the FFT-window to demodulate the signal.

The initial synchronisation is normally done by correlating samples taken T_u apart in time. When the waveform repeats, as shown in Figure 2.16, the correlator output exceeds a threshold value. From this the receiver can detect the start of a new symbol period.

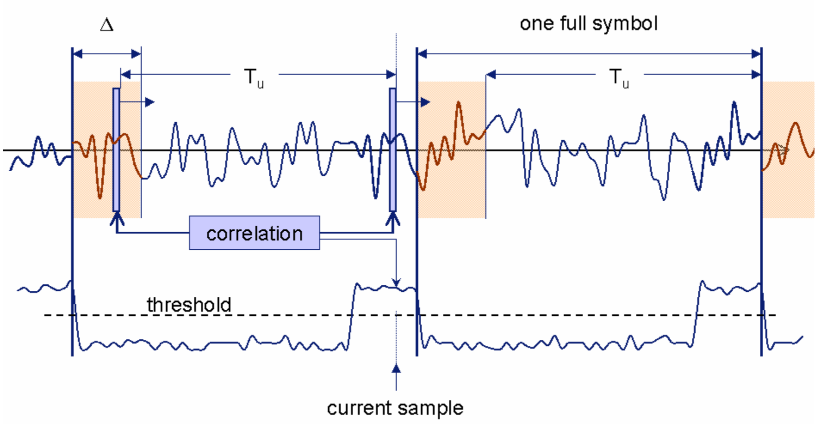


Figure 2.16: Initial Receiver Synchronisation
(image courtesy of Philips Ltd)

In a real multipath environment, the receiver encounters a multitude of echoes that make the second-stage synchronisation process, i.e. finding the “best” position for the FFT-window, a complex task. As a consequence, various strategies can be applied in order to optimize the receiver performance.

For coverage calculations a model is needed to describe the synchronisation performance of real receivers. A natural way to describe the reception situation in planning simulation tools would be to model real receiver behaviour. Unfortunately, the receiver FFT-window positioning is not prescribed in detail in the DVB-T or T-DAB system specifications. This means that all manufacturers have their own solutions and, moreover, regard these various solutions as confidential, making a single description of receiver FFT-window positioning difficult.

A detailed consideration of the difference between direct signals and echoes is relevant at this stage. In an MFN, where each transmitter acts independently on its own frequency, the receiver may get one direct signal and a number of scattered echoes. The direct signal is not necessarily the strongest signal nor is there necessarily a direct signal at all, particularly in the case of portable or mobile reception. On the other hand, there are also cases where there is only the direct signal present. In a SFN, all transmitters in the network use the same channel. In this case, the receiver gets a number of direct signals and a number of scattered echoes.

The difference between direct signals and echoes becomes important in the computer simulation of a coverage calculation.

Most coverage prediction methods use two dimensional (2-D) prediction models taking into account only the direct path. Therefore in an MFN, the modelling of the FFT-window positioning is simple and unique since there is only one direct path present. In an SFN, receiver synchronisation modelling is no longer unique since there are usually several direct path signals present.

In some three-dimensional (3-D) prediction models a multipath propagation environment for each transmitter is considered. Therefore, the FFT-window positioning for an MFN becomes as complex as that for an SFN when 3-D prediction models are used.

A further difference arises from the fact that real receivers have to account for the time variation of the transmission channel, whereas software modelling of the receiver FFT-window positioning usually assumes a static reception situation. This, to some extent, is justified by the different time scales of successive synchronisation instants and the time variation of shadow fading in a transmission channel. But it means that a real receiver will not show exactly the same synchronisation behaviour as that described in the simple model cases below.

2.4.2. Synchronisation strategies

This chapter describes five different strategies for second-stage synchronisation (i.e. positioning of the FFT-window) that are commonly used in receiver modelling. Four of them are relatively simple, straightforward strategies, while the fifth is an idealised, optimal strategy.

FFT-window synchronisation is of particular importance for mobile and portable reception, when the receiver will need to be able to synchronise in a rapidly changing environment and in the presence of pre- and post-echoes.

The strategy employed by a receiver determines which peak in the time-domain impulse response of the received signal is used by the receiver uses for synchronisation, and where the receiver sets the FFT-window relative to this peak.

In a single signal environment, the synchronisation configuration is simple and clear. The principle was already explained in chapter 2.3 and can be seen from, e.g., Figure 2.13. When two or more signals are involved various approaches are possible.

2.4.3. Strongest signal

A natural approach for the FFT-window positioning is to synchronise to the strongest signal. In order to demonstrate the principle, a configuration with four signals is chosen as an example. Figure 2.17 shows the channel response function for the configuration, where the peaks represent a characteristic time instant of the signals, such as the start of symbol *n*.

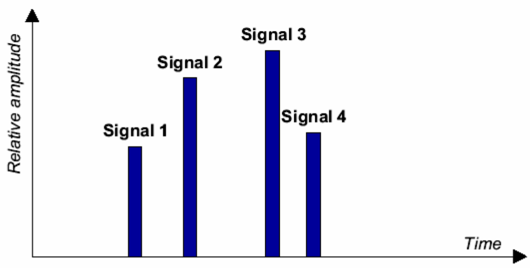


Figure 2.17: Synchronisation to the strongest signal (signal 3); time-domain impulse response

Signal 3 is the strongest signal. Accordingly, the FFT-window is synchronised to signal 3. Since relevant contributions of further signals may be found preceding signal 3 or following signal 3, it seems reasonable to locate the centre of the FFT-window at the centre of symbol *n* of signal 3. This is depicted in Figure 2.18. In the example, signals 3 and 4 contribute fully to the evaluation of symbol *n*, whereas the FFT-window exhibits an overlap with symbol *n+1* of signals 1 and 2, which results in a certain amount of ISI.

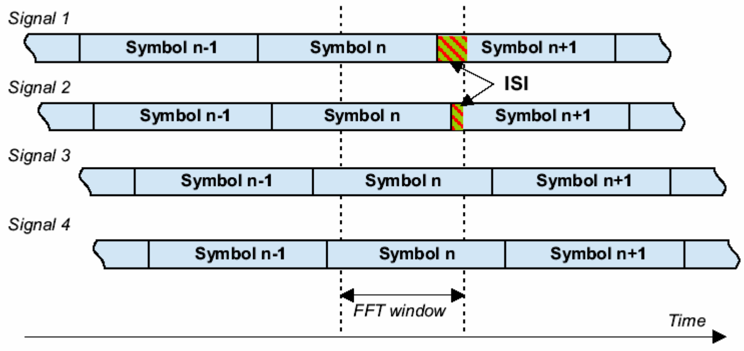


Figure 2.18: Synchronisation to the strongest signal (signal 3)
FFT-window position

A more sophisticated synchronisation strategy based on the strongest signal approach would not be fixed to the centre of the symbol duration but would check for better positions within the symbol duration of the strongest signal. E.g., in the chosen example it would be advantageous to move the FFT-window a little bit backwards in time to avoid the small amount of ISI arising from the overlap with symbol *n+1* of signal 2. Also the inter-symbol interference from signal 1 would be reduced.

2.4.4. First signal above a threshold level

This strategy takes the first signal of the time impulse response as a reference for the FFT-window. Normally, a minimum threshold level is necessary for a signal in order to be accepted as a trigger. Again the 4-signal configuration of the previous chapter is taken as an example. The impulse response is given in Figure 2.19 with the threshold value indicated by a horizontal dashed line.

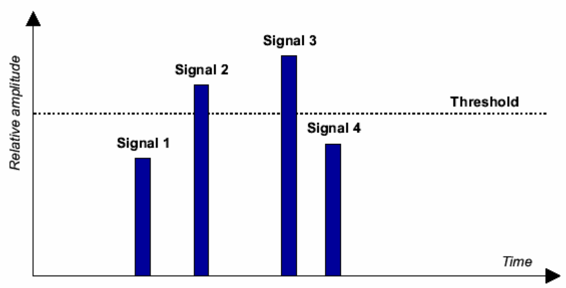


Figure 2.19: Synchronisation to the first signal above a threshold (signal 2);
impulse response

The first signal above the threshold is signal 2. It serves here as the trigger for the FFT-window. If the threshold is chosen reasonably it can be expected that there is no significant signal preceding signal 2, therefore it is logical to align the end of the FFT-window with the end of the symbol n of signal 2. This is indicated in Figure 2.20.

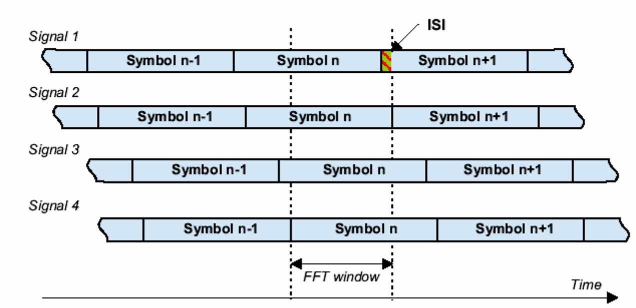


Figure 2.20: Synchronisation to the first signal above a threshold (signal 2); FFT-window position

With this synchronisation strategy, in this example, signals 2, 3 and 4 contribute fully constructively, whereas signal 1 adds a certain amount of ISI.

The choice of the threshold value is a specific issue of this synchronisation strategy. It may be taken as the power corresponding to the minimum field strength or, more pragmatically, as a value, say 6 to 10 dB, below the strongest signal.

In a recent workshop (2003), EICTA have indicated that for DVB-T various manufacturers apply the “first signal above a threshold level”, or a strategy similar to it.

2.4.5. Centre of gravity

In this case the receiver looks at the impulse response, calculates the ‘centre of gravity’ of the impulse response spectrum and centres the FFT-window on that point in time:

$$t_c = \frac{\sum_i p_i t_i}{\sum_i p_i}$$

Where

t_c = centre of gravity

p_i = power of the i-th signal of the impulse response

t_i = time of the i-th signal of the impulse response

The impulse response of the chosen example with the corresponding centre of gravity indicated by a dashed line is given in Figure 2.21.

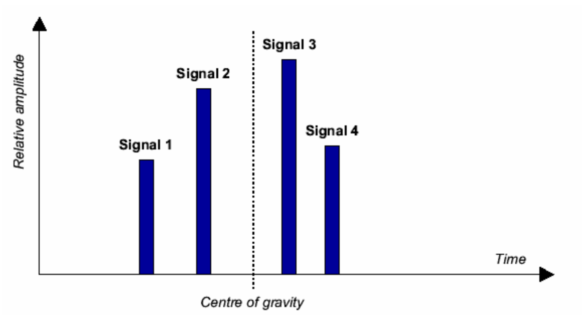


Figure 2.21: Synchronisation to the centre of gravity (between signal 2 and 3); impulse response

In this example, signals 2 and 3 fully contribute constructively. Signals 1 and 4 show a small amount of inter-symbol interference arising from an overlap of the FFT-window with symbol *n+1* of signal 1 and with symbol *n-1* of signal 4. This is depicted in Figure 2.22.

The centre of gravity approach responds well to pre-echoes and delayed signals of similar amplitude, since it does not fix the FFT-window to a particular signal but takes into account the average behaviour of the impulse response of the transmission channel. On the other hand, it can lead to ISI in cases where other strategies may not: for example, most two-echo cases, separated by virtually the whole guard interval, would cause this strategy difficulties unless the two echoes were of equal power.

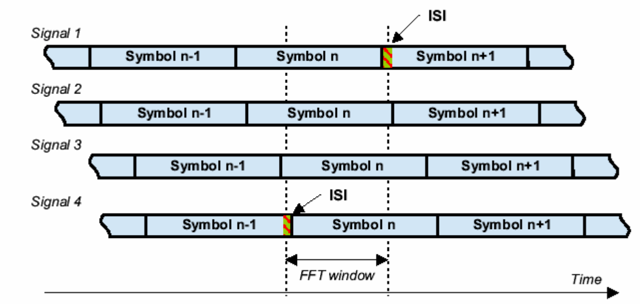


Figure 2.22: Synchronisation to the centre of gravity (between signal 2 and 3);
FFT-window position

2.4.6. Quasi-optimal

This strategy builds on that described in the chapter “first signal above a threshold” in an attempt to approach the "Maximum C/I" described below.

The first signal of the impulse response above a minimum threshold level is taken as a reference for the FFT-window. The process is described in the flowchart below, Figure 2.23.

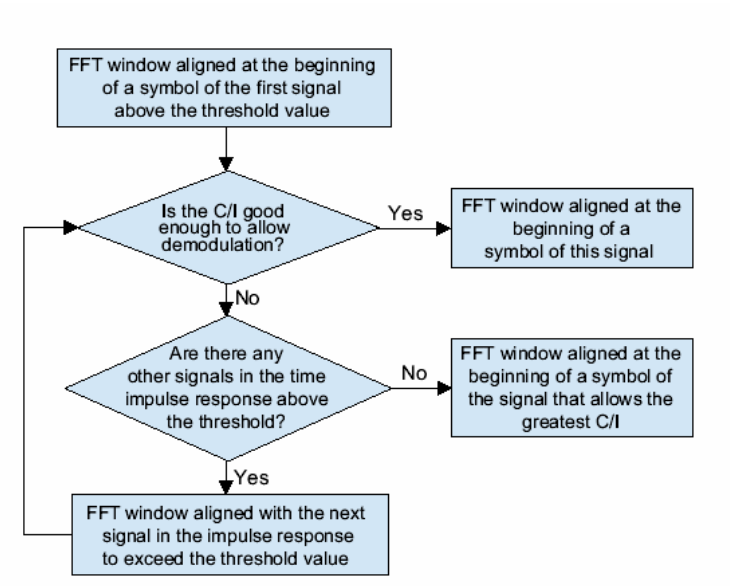


Figure 2.23: Flowchart describing the Quasi-Optimal Strategy

2.4.7. Maximum C/I

Whereas the previously discussed strategies all give means of quickly finding a good FFT-window position, an optimal choice would be a position where the effective C/I is maximised. This position, however, is not easily found and would in general take too much time to be calculated. Therefore, normally one of the above simpler strategies, or a combination of them, is applied. Such simpler approaches can be justified by the fact that the optimum C/I will often show a relatively flat maximum, i.e. errors introduced by sub-optimal synchronisation are small. But there are also difficult configurations possible, e.g. in a two-echo case, if the difference in delay is close to the guard interval, there is only one position that will result in no ISI, so the optimum here would be very sharp.

Note that the method in the previous chapter (the "Quasi-Optimal" strategy) does not attempt to find a position for the FFT-window that gives the best C/I. It merely seeks to find a position for the window at which the C/I is good enough to allow demodulation and decoding with an acceptable error rate.

Receiver manufacturers indicate that the evaluation of C/I is by no means trivial for a DVB-T receiver, and for a DVB-T mode with a large guard interval of $T_u/4$ there seem to exist theoretical limits for the evaluation of C/I which would prevent the application of a "maximum C/I" synchronisation strategy in this case.

With regard to receiver modelling in computer simulations, e.g. for coverage calculations, the detection of the maximum C/I position of the FFT-window is not a principle problem. A simple but time consuming approach would be to scan the time period of interest with an appropriate step size, calculate the C/I for each sampling point and to use the time position with the maximum C/I as the reference.

A more sophisticated strategy to find the maximum C/I position is based on the observation that the maximum C/I is always found at a position where the FFT-window is aligned with the start or the end of one of the incoming signals for the symbol under consideration. A check of all these possible positions, which amounts to 2N evaluations of C/I for N signals, then gives the maximum C/I position. Practical experience shows that the computational effort is about twice that of the basic strategies described in the previous chapters.

2.5. Inter-carrier interference

2.5.1. General

A further degradation mechanism may be present by loss of orthogonality of the carriers due to phase noise and Doppler shift in a time varying transmission channel. This mechanism is called inter-carrier interference (ICI). Phase noise and Doppler shift change the frequencies of the OFDM carriers in a non-unique way which destroys the orthogonality relation between the individual carriers. 2K systems are more robust against ICI than 8K systems since their carrier spacing is 4 times larger. The T-DAB system is more robust than the 2K DVB-T system.

2.5.2. Phase noise

Phase noise is usually created by all oscillators present in the transmission chain. The main source for phase noise in OFDM comes from the tuner of the receiver which has a PLL set up to tune RF channels over the entire UHF/VHF band with a relatively fine step (typically 166.5 kHz). This phase noise creates inter carrier interference, that is, each 1 kHz carrier leaks over the adjacent ones, thus suppressing the perfect orthogonality of the transmitted modulation scheme. Depending on the receiver, the phase noise tolerance may be very different, which affects the overall performance of the receiver.

Whilst it was predicted that phase noise would affect the performance of both T-DAB and DVB-T receivers this has not been the case in practice and so far no receiver problems have been identified.

2.5.3. Doppler degradation

Doppler degradation is encountered in mobile reception. Its origin is the Doppler shift of the carrier frequencies, in particular for those (reflected or SFN) signals arriving at the receiver from different directions.

Among all the parameters which characterize the service delivered to mobile receivers, the velocity of the mobile relative to the transmitter, corresponding to a given Doppler frequency value, f_d, as well as the required C/N for a certain f_d are the main variables.

The laboratory tests have demonstrated that, until a given Doppler limit (or inter-carrier interference level), the receivers are able to perform sufficient channel equalisation to demodulate the OFDM signal. Then, when the speed of the mobile (i.e.: the Doppler frequency) increases further, the signal recovery performance decreases drastically until a point where no demodulation remains possible.

In general the required C/N for a mobile channel is defined as the average C/N over a sufficiently long time as to obtain a stable value, and a sufficiently short time as to avoid any influence of shadow fading. This means that fast fading signal variations are included in the C/N values given but not the shadow (log-normal) fading. For a given DVB-T or T-DAB mode and a given channel profile, the required C/N for a certain quality level is therefore a function of Doppler frequency only, and a graph like the one presented in Figure 2.24 can be drawn.

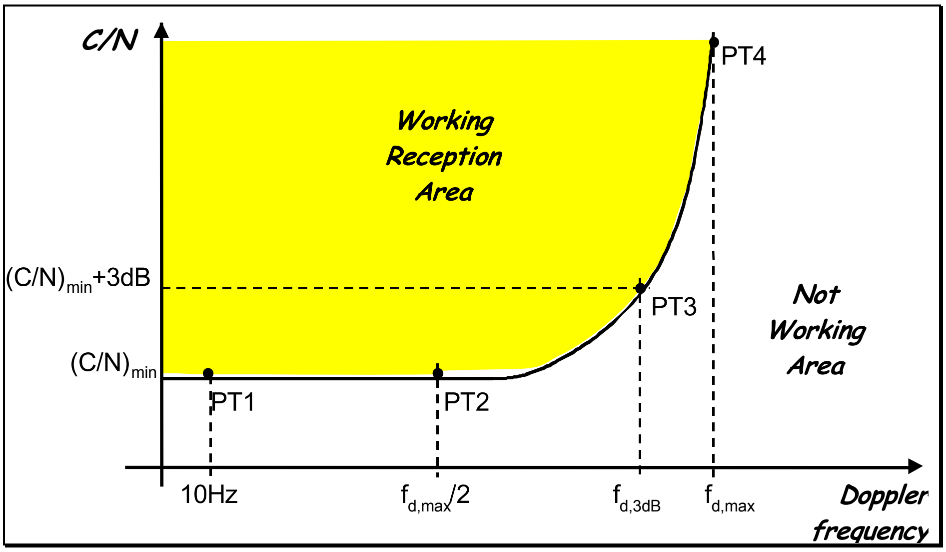


Figure 2.24: Receiver behaviour in a mobile propagation channel (from EBU BPN 047 [7])

This curve is characterised by a « C/N floor », $(C/N)_{min}$, which gives information about the minimum signal requirement for good reception when in motion. For low speeds, the required C/N value is relatively independent of the specific Doppler frequency. However the slope of the C/N curve at low Doppler (between PT1 and PT2 in Figure 2.24) varies with the DVB-T or T-DAB mode used and the QoS requirements. For higher velocities of the mobile relative to the transmitter (or higher Doppler frequencies) the required C/N value increases gradually until a maximum acceptable Doppler frequency is reached.

To characterize the “C/N versus Doppler” curve in a given mode, using a given channel profile, four measurement points are used:

PT1: the C/N at really low Doppler frequency (for example10 Hz)

PT2: the C/N_{min} which characterises the noise floor acceptable by the mobile receiver,

PT3: the C/N_{min} + 3 dB which gives indication on the speed limit,

PT4: the maximum Doppler limit which characterises the maximum speed when no noise is added. This corresponds to an infinite C/N loss.

Impairments occurring in the mobile environment are related to the Doppler characteristics of the propagation channel. “Doppler distortion” evolves proportionally both with the velocity of the vehicle and the signal centre-frequency. Hence, the RF channel used to deliver digital services to mobile receivers has a major impact on the service reception performance. Better performance is obtained when the lower frequencies are used, whilst worse performance will occur when higher frequencies are used. This implies that the C/N performances reported in this document will vary with the actual frequency used.

Recent investigations in Sweden and France have shown that Rayleigh fading and Doppler degradation in time varying broadcast channels can be overcome to a large extent by the application of antenna diversity in the receiver, see, e.g., [5] and chapter 2.8.

2.6. Network gain

In an SFN many receiving locations can be covered by more than one transmitter, thus introducing a certain level of redundancy in the signal sources and improving the service availability, especially when portable reception is required. Particularly in portable reception, the field strength from a single transmitter shows statistical variations due to the presence of obstacles on the propagation path. This field strength variation can be reduced by the presence of several transmitters, located in different directions, since when one source is shadowed, others may be easily receivable. This fact is known as "network gain".

As a result of network gain, SFN can be operated at lower power for the main transmitters and the field strength distribution is more homogeneous as compared to MFN. The impact of these features for fixed reception may not be very prominent but portable reception with its non-favourable receiving sites and less elaborate receiving antennas will benefit from these features to a large amount. The SFN approach seems to be the most reasonable way to provide satisfactory coverage for larger areas when portable reception is envisaged.

Network gain is dealt with in detail in chapter 4.4.

2.7. Minimum carrier-to-noise ratio and protection ratio

For frequency and network planning the most important parameters that characterize a broadcasting transmission system are the minimum carrier-to-noise ratio and the protection ratio. These two quantities describe the sensitivity of the system with regard to noise and interference. Since they are closely related to the description and evaluation of coverage they are discussed in detail in chapter 4.1.

2.8. Antenna diversity for DVB-T

Diversity receivers may be used for DVB-T to reduce the effect of the fast fading (Rayleigh) channel, which is always present in portable and mobile receiving environment. The general architecture of an antenna diversity receiver is described in Figure 2.25. Output signals obtained from several antennas are linearly combined using adjustable complex weight factors $\{w_i\}_i$ before being decoded using the standard DVB-T decoding algorithm. Implementations may differ:

- by the antenna system's characteristics: number of antennas, relative positions, orientation and characteristics of each antenna (polarisation, radiation pattern, etc).
- by the algorithm used to compute and eventually iteratively adapt $\{w_i\}_i$.

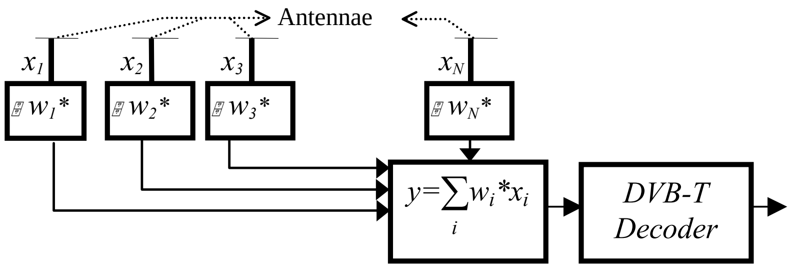


Figure 2.25: antenna diversity receiver

Antenna diversity is a key technique to overcome degradation effects in portable and mobile DVB-T reception:

- In mobile reception conditions, antenna diversity is expected to reduce the required transmitted power (by 6 to 8 dB at lower speeds and higher values at higher speeds) for the same coverage, but it should also allow an increase in the mobile's maximum speed for correct reception.
- The potential advantages of using antenna diversity for portable reception are considerable. This is especially important for the 8K modes in DVB-T, which are more sensitive to Doppler.
- As for low speed mobile reception, a 5 to 8 dB gain in robustness is expected. This should lead to an improved robustness against variations of reception quality due to people moving around the antenna or to channel changing.
- Additionally, since the signal is received on two antennas, and indoor reception conditions are know to vary very rapidly with location, it would be much easier to find an accurate position for good reception with a portable receiver featuring antenna diversity than with a single antenna receiver (the probability of having deep or flat fades on two antennas is much lower than on one single antenna). This gain is also increased if more than one multiplex is used and coverage is defined as reception of all available multiplexes.
-

3. Single Frequency Networks

3.1. Definition and characteristics of SFN

There are, in principle, two types of terrestrial digital broadcasting networks to be considered.

- Multi-Frequency Networks (MFN) which allow the same or different programmes to be carried by individual transmitters using different frequencies; and
- Single Frequency Networks (SFN) in which distributed emission is implemented whereby the required coverage is provided through the use of multiple transmitters operating on the same frequency and carrying the same programmes.

The type of network implemented will depend on the availability of frequencies, the type of coverage required, and the number of multiplexes to be provided and may depend on further national constraints or strategies.

The present report is dedicated to the SFN approach.

In an SFN, many receiving locations within the coverage area will be served by more than one transmitter. This introduces a certain level of redundancy to signal reception and improves the service availability. The field strength from a single transmitter shows statistical variations due to the presence of obstacles on the propagation path, particularly for portable and mobile reception. This field strength variation can be reduced by the presence of several transmitters, located at different bearings as seen from the receiver, since when one source is shadowed, others may be easily receivable. This aspect of an SFN gives rise to “network gain” which is explored in detail in the subsequent chapters. An SFN can be designed to provide a more homogeneous field strength distribution throughout its coverage area than a single transmitter covering the same area.

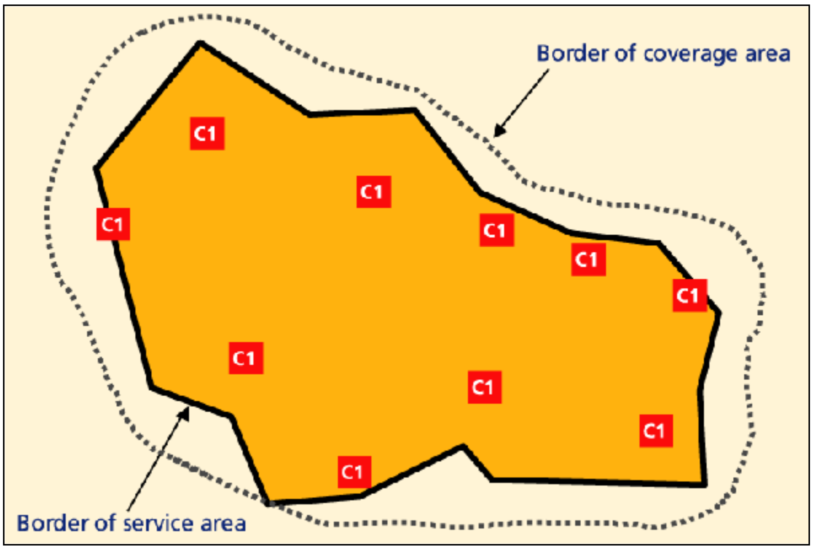


Figure 3.1: Single Frequency Network (SFN)

In a single frequency network all transmitters of a network use the same frequency. They possess a common coverage area and cannot be operated independently. This is sketched in Figure 3.1, where an SFN with 10 transmitters operating on channel C1 is described. The figure shows the service area as well as the common coverage area of the transmitters.

When operating in an SFN, the signals transmitted from individual transmitters should be:

- synchronous in time (or with a precisely controlled delay);
- nominally coherent in frequency (within a few Hz);
- must have identical multiplex content.

Usually, the SFN concept is based on the same network topology as that of the MFN approach, i.e. main transmitters with auxiliary gap fillers, if necessary.

The SFN approach allows for a more homogeneous field strength distribution than the MFN approach, which is particularly important for portable and mobile reception. In the case of mobile reception the SFN approach does not require a frequency hand over in the receiver when moving within the whole coverage area.

The use of SFN is facilitated by the multi-carrier OFDM modulation technique which enables the reception (and constructive summation) of more than one useful RF signal, as described in sections 2 and 4.

Compared with a conventional MFN, an SFN allows significant improvements in spectrum utilization. The network should be designed such as to avoid self-interference and to make use of the wanted echoes produced by the other transmitters. The echo delays depend on the difference of the propagation path lengths, and can be of the order of some tens to some hundreds of microseconds, depending on the transmitter distance.

3.2. Types of SFN

SFN can be classified according to various criteria:

Geometrical – this refers to the physical or geographical size of the coverage area. This could be defined as large, medium, small or, more quantitatively: more than 100 km, 25 to 100 km, less than 25 km radius.

Political – this defines coverage in a more generalised, imprecise manner as national, regional or local. This could be complicated to plan for, on a standard international basis, as the geographical size of nations and regions varies from country to country. For example the country of Luxembourg is smaller than many of the Länder in Germany

Structural – this relates to the coverage provided by a particular transmitter infrastructure. Countries may wish to continue using their analogue transmitter network for digital television, so for example, a main station and its relays may operate in a regional or local SFN. Alternatively, countries may wish to use a dense or distributed transmitter network for a large area SFN. Coverage is then defined by that provided by the particular transmitter network configuration

A further structural distinction of SFN is given by open and closed SFN.

In an **open network** no measures are taken to minimize the level of radiation towards areas outside of the coverage area. In the limiting case an open network can consist of only a single transmitter.

In a **closed network** the level of radiation towards areas outside of the coverage area is deliberately reduced without reduction of the coverage of the intended area. This can be done by using directional antennas on transmitting stations near the periphery of the coverage area.

3.3. Consideration of network structures for SFN

3.3.1. Open and closed configurations

In a real network, covering a large area there will be considerable distances between the transmitters. If such a network is designed as a closed network it will cause less interference at a given distance outside of its coverage area than if it had been designed as an open network. The reason for this is that the level of interference is mainly determined by the radiated power from the transmitters closest to the boundary of the coverage area in the direction considered.

However, in a closed network covering a small area the radiated power from transmitters on the side of the coverage area opposite to the direction under consideration contributes relatively more to the outgoing interference level than in a closed network covering a large area. Thus the use of directional transmitting antennas on transmitters near the boundary of the coverage area consequently brings less advantage than in the case of networks covering larger areas.

It follows from the above that for relatively large coverage areas, the separation distance between co-channel areas will generally be less for closed networks than for open ones. For smaller coverage areas the separation distance for closed networks approaches that for open networks.

3.3.2. Transmitting sites

Digital terrestrial broadcasting deployment can use existing sites, new sites, or alternative network architectures. These parameters thus affect the choice of the selected digital terrestrial broadcasting variant and the frequency requirements.

The number of transmitter sites deployed and the separation distances will vary a lot from country to country and will depend on the system variant, the reception mode (fixed, portable or mobile), the country size and boundary situations. For digital terrestrial broadcasting, the separation distance between transmitter sites may vary between 30 and 50 km in the most populated areas and between 75 and 125 km in the less populated areas.

In an SFN using appropriate digital terrestrial broadcasting standards, the separation distance between transmitters influences the choice of the guard interval, which in turn limits the size of the network. The separation distance and the effective height influence the effective radiated power e.r.p.

The use of “dense networks”, a network of closely situated, low to medium power stations, can offer some advantages over networks based on high power transmitters separated by large distances (sixty to some hundreds of kilometres).

Particularly in the case of regional SFN, but also for national SFN, it is possible to consider various forms of dense networks having significantly lower e.r.p. than that required by a single transmitter serving the same area. For digital terrestrial broadcasting, the concept of “distributed emission” can provide the needed field strength over the entire service area by a number of low power, synchronized SFN transmitters, located on a more-or-less regular lattice, or to use on-channel repeaters receiving their signal off-air from the main transmitter, to improve the coverage of the main transmitter. In the latter case, the re-transmitters need not be synchronized in time, and no parallel transmission infrastructure is needed to bring the signal to these on-channel repeaters.

Furthermore, local high density SFN could be used to supplement large SFN in areas where the coverage would otherwise be inadequate, due to the terrain topography. Finally, they offer a reduction of the impact of co-channel interference at the border of the service area, by introducing a sharper field strength roll-off. This can be further improved by a suitable exploitation of the transmitting antenna directivity.

For example, it is possible to envisage transmitter topologies in which the central part of the service area is covered by a large SFN (with high power transmitters separated by large distances), but near the border a dense transmitter network is installed (with low e.r.p., and with low-height and directive antennas). This allows the e.r.p. to be “tailored” according to the service area contour, reducing the interference to adjacent areas and keeping high the service availability inside the wanted area. This technique can be useful also on the borders of national SFN.

3.3.3. Transmitting antenna types and radiation patterns

Transmitting antennas will have either omni-directional or directional pattern. For stations located along or close to either country or sea borders directional antennas should preferably be used to reduce interference outside service areas, thus reducing the separation distance for the frequencies in question, and to protect coverage areas of existing services. This is especially true for high and medium power stations and will in general result in a more efficient use of the frequency spectrum.

Beam-tilt, applied for antennas with effective height more than 100 m, is an efficient tool to target the radiated power of high power stations to the outer part of the coverage area and, at the same time, to reduce the interference potential at large distances and to the aeronautical service.

3.3.4. Some factors influencing the transmitter distance

There are several factors that influence the transmitter distance, for example radiated power, antenna height, reception mode, system variant and propagation path. It must be noted that these may be different for different reference networks. In SFN networks, the distance between adjacent transmitters is limited by the length of the guard interval, see also chapter 3.3.2.

3.3.5. Some factors influencing the separation distance

The separation distance between two co-channel service areas is the minimum distance needed in order to avoid undue interference to either of the two service areas.

The separation distance has a significant influence on the number of frequency blocks or channels needed to establish coverage of a larger area containing several countries or regions, each having its own programmes transmitted in one frequency block or channel.

Coverage areas served by transmitters located along the periphery and using directive antennas pointing inwards (that is, in a closed network) will result in shorter separation distances compared to equivalent coverage achieved by the use of non-directional antennas (that is, in an open network). In the case of propagation paths with a significant amount of sea, separation distances will be larger than for the case of land-only paths.

3.3.6. Classification of transmitting stations

Transmitting stations for digital services can be classified according to their powers. For example section 1.6.17 of the Report from the First Session of the 2004/06 ITU Regional Radio Conference [8] classifies transmitting station powers as follows:

High power station:
A station with an e.r.p. greater than or equal to 10 kW.

Medium power station:
A station with an e.r.p. greater than or equal to 50 W and less than 10 kW in Band III, or greater than or equal to 250 W and less than 10 kW in Band IV/V.

Low power station:
A station with an e.r.p. less than 50 W in Band III, or less than 250 W in Band IV/V.

3.3.7. Mixed MFN - SFN

The SFN approach can also be mixed with the MFN concept. This may be encountered in the following cases:

Within an MFN using high power main stations, if one such station does not provide complete coverage, lower power relay stations (gap-fillers or repeaters) may complete the coverage using the same frequency as the associated main station. This configuration could also be called hybrid MFN - SFN.

Another case may consist of using an MFN structure for transmitting a national multiplex and an SFN structure for transmitting a regional multiplex.

In other cases, this type of mixed network scenario could arise from different approaches in adjacent countries (e.g. an MFN approach in one country and an SFN one in the other).

3.4. Impact of DVB-T parameters on SFN performance

3.4.1. Constellation

The DVB-T specification allows for three different phase/amplitude constellations, QPSK (4-QAM), 16-QAM and 64-QAM, in order to meet the different requirements in terms of spectral efficiency and the reliability of the broadcast service.

The choice of constellation determines the number of bits that are carried at a time on each sub-carrier; either 2 bits (QPSK), 4 bits (16-QAM) or 6 bits (64-QAM) may be carried. Moreover, the modulation has an important impact on the performance in a SFN as the choice of constellation also determines noise tolerance, with QPSK being around 4 to 5 times more tolerant than 64-QAM.

QPSK provides a low data capacity but it does provide a very rugged service. Networks using QPSK may be of particular value in urban areas for services to pedestrians and vehicles.

16-QAM provides a moderate capacity and, therefore, this variant may be of interest for providing reasonably rugged services to medium or densely populated areas.

64-QAM variant has a high data capacity but does not provide rugged services and is particularly sensitive to self-interference effects in large area SFN.

3.4.2. Code rate

Different code rates can be used to trade bit rate versus ruggedness, e.g. the signal strength required and interference protection required.

The code rate of 1/2 has the highest redundancy and in doing so the highest transmission safety albeit at the cost of data throughput. This mode should only be applied to channels that have a high degree of interference. The variants using code rates higher than 3/4 offer additional capacity but may be not worthwhile as the system becomes less rugged. For code rates 5/6 and 7/8 the implementation margins may also be higher than expected making those variants even less attractive. The code rate of 7/8 has the lowest redundancy but the highest throughput. As such, it should only be used for channels with low levels of interference.

In the case of mobile reception under SFN environment, since the speed of the mobile receiving terminal relative to different transmitters is often different, this will result in strong Doppler effects, which have to be dealt with by channel estimation and error correction system. A lower rate of convolutional coding like 1/2 is thus recommended for mobile implementation.

3.4.3. 2K/8K FFT

The DVB-T standard defines two FFT modes (2K and 8K) each using different numbers of sub-carriers (2048 and 8192) to constitute the OFDM signal. This means different symbol times T_u = 896 µs and T_u = 224 µs.

The 8K FFT systems provide a higher degree of protection against inter-symbol interference caused by multipath propagation. The use of a higher number of carriers within the same bandwidth increases the symbol period (in order to preserve orthogonality) and therefore the same proportion of guard interval gives a greater protection. In the 2K FFT systems, signal delays that exceed the guard interval are very much more conspicuous due to the considerably shorter usable symbol time of 224 µs. Thus, the 2K FFT systems are not meant for large area SFN.

However, the 8K FFT mode presents a higher complexity and a higher sensitivity to tuner phase noise and may be less suitable for mobile reception. The DVB-T 2K FFT systems can withstand moving echoes up to several hundreds Hz. Therefore, this mode is superior for mobile applications.

The working frequency of each SFN transmitter should be accurately managed and monitored. For COFDM SFN operation, the stability and the accuracy of the transmitter's working frequency shall ensure that each sub-carrier has the same absolute frequency position in the RF channel.

3.4.4. Guard interval

In an SFN each transmitter is required to radiate the same OFDM symbol at the same time. This comes from the fact that echoes (natural or artificially generated by co-channel transmitters) shall be confined in the guard interval period. The OFDM receiver has to setup a time-window during which it samples the on-air OFDM signal. The objective is to synchronize this time-window with the useful period of the OFDM symbol. Accordingly, it will ignore the signal during the guard interval period where the receiver signal is made of a mixture of two or more OFDM symbols. If the transmitters deliver the same OFDM symbol at the same instant, or with a sufficiently small time delay, the differential propagation path delay to the OFDM receiver will remain inside the guard interval period. Accordingly, the sum of the received signals will be constructive because they constitute the same OFDM symbol (no inter-symbol interference), see also section 2.

The DVB-T specification offers a selection of system guard intervals, i.e., 1/32, 1/16, 1/8 or 1/4 times the duration of the useful symbol duration. For 8K(2K) mode this represents a permitted guard interval duration of 28(7) µs, 56(14) µs, 112(28) µs and 224(56) µs, respectively.

The selection of the appropriate guard interval parameter for digital terrestrial television affords resilience against delayed, interference–causing signals in television reception. Moreover, the guard interval value chosen to operate an SFN has a major implication on the topology of the SFN network: as the guard interval duration governs the maximum echoes delay admissible by the system, it governs accordingly the maximum possible distance between co-channel transmitters (producing active echoes). Some modes allow setting up large SFN networks having a great distance between high and medium power transmitters sites. Some others allow smaller service areas with a greater density of low power transmitters.

The recommendation given in the Implementation Guidelines ETSI TR 101-190 [9] for DVB-T is that guard interval selection should be based on the distance between the transmitters. The spacing between adjacent transmitters in an SFN should not be significantly greater than the propagation time permitted in the guard interval:

In a 2K-FFT system the guard interval values are: 7 µs, 14 µs, 28 µs, 56 µs. These values translated into distance give respectively: 2.1 km, 4.2 km, 8.4 km, and 16.8 km.

In an 8K-FFT system the guard interval values are: 28 μs, 56 μs, 112 μs, 224 μs. These values translated into distance give: 8.4 km, 16.8 km, 33.6 km, and 67.2 km.

For an 8K-FFT system and guard interval of 1/4 it means that the permissible signal delay times are outside the signal delay between adjacent transmitters, when these transmitters are situated less than 67.2 km apart.

Studies on the maximum distance between transmitters in theoretical SFN for DVB-T and T-DAB systems have shown that together with the guard interval the maximum inter-transmitter distance is influenced by the system variant required and the effective radiated power of the transmitters in the network.

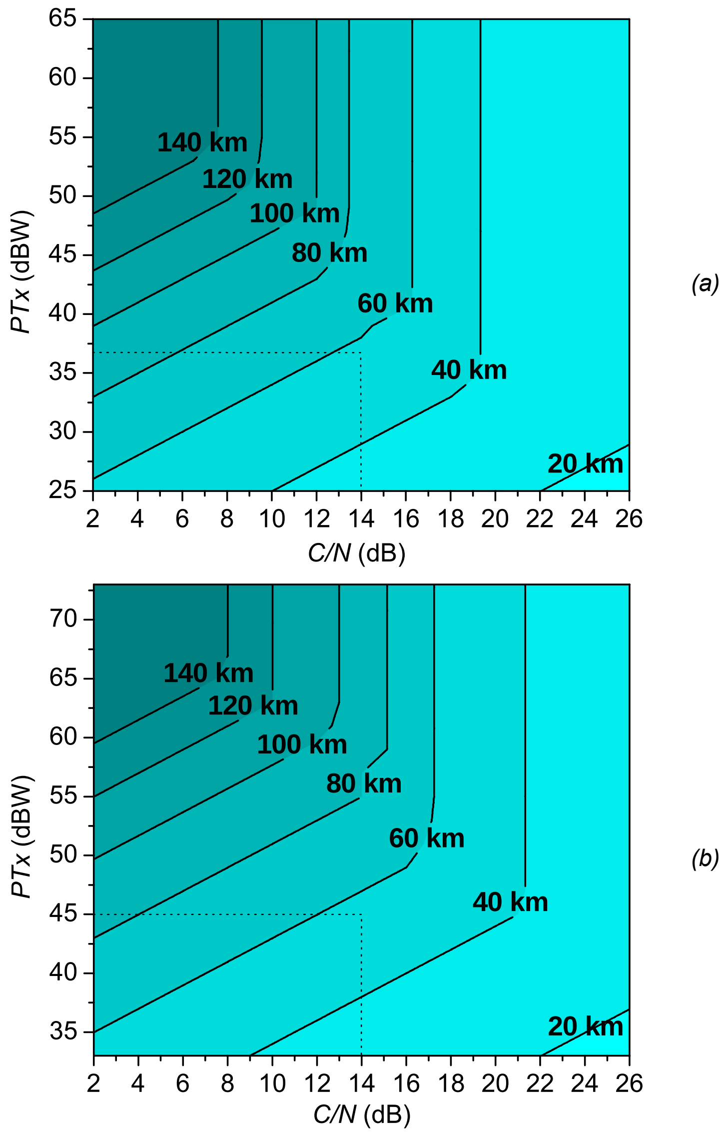


Figure 3.2. Dependence of the maximum distance between transmitters in a DVB-T SFN on the e.r.p. and minimum required *C/N* for coverage target of 100 %: (a) portable outdoor reception with 95 % of location probability in Band III; (b) portable outdoor reception with 95 % of location probability in Band IV.

For a given DVB-T system variant there exists an optimal SFN size with a proper radiated power of transmitters. The influence of *C/N* required by DVB-T system and the e.r.p. of the transmitters (P_{Tx}) on the maximum distance between transmitters D_{max} in the SFN to reach 100 % of the coverage is presented in Figure 3.2 for different frequency bands. With an increase of *C/N* and at fixed power levels, D_{max} should be decreased in order to maintain self-interference free SFN coverage. Increase of D_{max} could be obtained by augmenting the power radiated by transmitters in the SFN. However, this could be done up to a certain e.r.p. value only. After this limit the self-interference effects result in a degradation of the SFN coverage. This is reflected by vertical lines in Figure 3.2.

Because of the long guard interval (246 μs) and the relatively low required C/N (15 dB) in the case of T-DAB the size of the SFN is only limited by the e.r.p. of the transmitters but not by self-interference. This is demonstrated in Figure 3.3. The maximum distance increases as the power radiated by the SFN transmitters augments. It should be also mentioned that T-DAB is characterised by less rapid performance degradation versus the echo delay as DVB-T, see chapter 2.3.4.

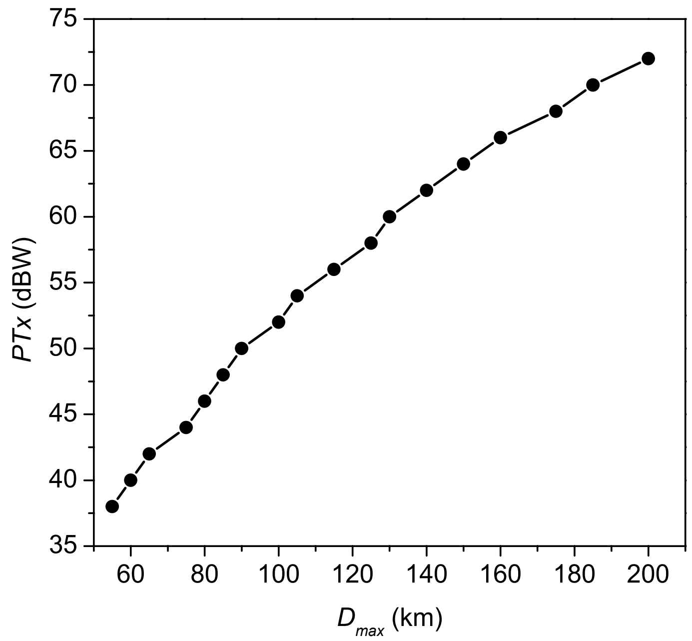


Figure 3.3. Dependence of the distance between transmitters in a T-DAB SFN on the e.r.p. for a coverage target of 100 % at portable indoor reception with 95 % of location probability in Band III.

Transmitter spacing can be increased beyond that defined by the guard interval by varying the radiated power, transmission polarisation and the relative transmitter timing. Effective planning of the required radiated power and transmission polarisation at the secondary site(s) will optimise SFN performance and provide effective management to eliminate most potential interference problems.

There is no limit on transmitter spacing providing the secondary site has a directional antenna transmitting away from the main site utilising an appropriate delay. However, where two transmit sites are radiating towards each other careful planning is required.

3.4.5. Data rate versus guard interval

Because the guard interval reduces the amount of time available for data transmission, its setting has an effect on the DVB-T net deliverable bit rate. Lengthening the guard interval decreases the bit rate. The guard interval 1/32, 1/16, 1/8, 1/4 produce respectively a loss of 3.1%, 6.2%, 12.5% and 25% in the transmitted bit rate. Table 3.1 indicates the net bit rate in Mbits/s for various modulations, combinations of guard interval settings and error protection code rates. The data are given for the bandwidth of 8 MHz and 7 MHz (in brackets).

Modulation	Code rate	Guard interval			
		1/4	1/8	1/16	1/32
QPSK	1/2	4.98 (4.35)	5.53 (4.84)	5.85 (5.12)	6.03 (5.28)
	2/3	6.64 (5.81)	7.37 (6.45)	7.81 (6.83)	8.04 (7.04)
	3/4	7.46 (6.53)	8.29 (7.26)	8.78 (7.68)	9.05 (7.92)
	5/6	8.29 (7.26)	9.22 (8.06)	9.76 (8.54)	10.05 (8.80)
	7/8	8.71 (7.62)	9.68 (8.47)	10.25 (8.97)	10.56 (8.80)
16 – QAM	1/2	9.95 (8.71)	11.06 (9.68)	11.71 (10.25)	12.06 (10.56)
	2/3	13.27 (11.61)	14.75 (12.90)	15.61 (13.66)	16.09 (14.08)
	3/4	14.93 (13.06)	16.59 (14.52)	17.56 (15.37)	18.10 (15.83)
	5/6	16.59 (14.52)	18.43 (16.13)	19.52 (17.08)	20.11 (17.59)
	7/8	17.42 (15.24)	19.35 (16.93)	20.49 (17.93)	21.11 (18.47)
64 – QAM	1/2	14.93 (13.06)	16.59 (14.52)	17.56 (15.37)	18.10 (15.83)
	2/3	19.91 (17.42)	22.12 (19.35)	23.42 (20.49)	24.13 (21.11)
	3/4	22.39 (19.60)	24.88 (21.77)	26.35 (23.05)	27.14 (23.75)
	5/6	24.88 (21.77)	27.65 (24.19)	29.35 (25.61)	30.16 (26.39)
	7/8	26.13 (22.86)	29.03 (25.40)	30.74 (26.90)	31.67 (27.71)

Table 3.1: DVB-T net bit rate in Mbits/s; 8 MHz bandwidth (in brackets for 7 MHz bandwidth)

To maximise the net bit rate, the guard interval is often chosen as small as possible, reducing accordingly the maximum echoes delay but also the maximum distance between transmitters, thus practically disallowing in many cases to operate 2K-SFN.

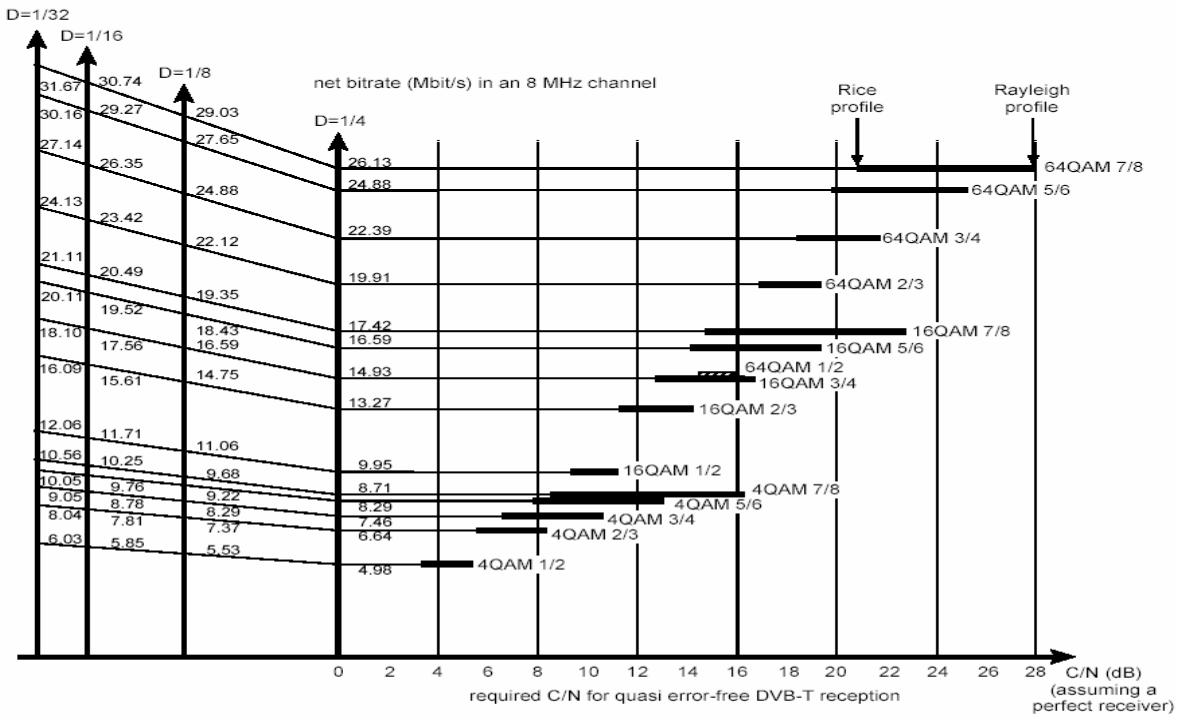


Figure 3.4: Relation between C/N, Profile, net bit rate and guard interval

Figure 3.4 gives an overview of the relation between C/N, profile, net bit rate and guard interval for the various DVB-T configurations.

3.5. Impact of T-DAB parameters on SFN performance

3.5.1. General

Several of the conclusions drawn in the previous chapter on the impact of DVB-T parameters on SFN performance are equally valid also for the T-DAB case. For reasons of a balanced presentation they are partly repeated in the present chapter on T-DAB properties.

3.5.2. Constellation

All T-DAB modes use QPSK (4-QAM) modulation. QPSK provides a low data capacity but it does provide a very rugged service for mobile reception.

3.5.3. Code rate

Different code rates can be used to trade bit rate versus ruggedness, e.g. the signal strength required and interference protection required.

Five protection levels are available for audio (forward error correction (code rate) ranges from 1/3 to 3/4) and eight protection levels are available for data services through using punctured convolutional coding.

In the case of an audio signal, greater protection is given to some source-encoded bits than others, following a pre-selected pattern known as the unequal error protection (UEP) profile. The average code rate, defined as the ratio of the number of source-encoded bits to the number of encoded bits after convolutional encoding, may take a value from 1/3 (the highest protection level, giving the lowest useful data capacity) to 3/4 (the lowest protection level which provides the highest data capacity). Different average code rates can be applied to different audio sources, subject to the protection level required and the bit rate of the source-encoded data.

Because different segments of the data stream for each programme service have different protection levels and therefore require different code rates, it is not possible to precisely specify the overall code rate for each programme service or for the overall multiplex of programme services and data. The code rate thus depends slightly on the data rate used for each programme service (or data service).

3.5.4. FFT

The DAB system has four alternative modes which allow for the use of a wide range of transmitting frequencies up to 3 GHz. These transmission modes have been designed to cope with Doppler spread and delay spread, for mobile reception in presence of multipath (passive) echoes and active echoes created by co-channel gap-fillers or transmitters in a single frequency network.

Mode I is most suitable for a terrestrial SFN in the VHF range, because it allows the largest distances between transmitters as it has the longest guard interval.

Mode II is most suitable for local radio applications requiring one terrestrial transmitter and hybrid satellite/terrestrial transmission up to 1.5 GHz. Mode II can also be used for a small-to-medium SFN at 1.5 GHz.

Mode III is most appropriate for satellite and complementary terrestrial transmission at all frequencies up to 3 GHz. Mode III is also the preferred mode for cable transmission up to 3 GHz.

Mode IV, a new mode, bridging the gap between Modes I and II, which is also optimized for operation at 1.5 GHz has been added with key values in a binary relationship to the previously developed modes. This mode provides for a longer constructive echo delay for easier SFN implementation, while keeping the effect of the Doppler spread at high vehicle speed within reasonable bounds.

		Mode I	Mode IV*	Mode II	Mode III
Typical use		Terrestrial VHF	Terrestrial Urban L-Band	Terrestrial L-Band	Satellite L-Band
Number of carriers	n	1536	768	384	192
Approximate Carrier spacing	Δf	1 kHz	2 kHz	4 kHz	8 kHz
Useful symbol duration	T_U	1 msec	500 μsec	250 μsec	125 μsec
Guard Interval	Δ	246 μsec	123 μsec	62 μsec	31 μsec
Total symbol duration	$T_S = T_U + \Delta$	1246 μsec	623 μsec	312 μsec	156 μsec
Max. speed (mobile) VHF	v_{max}	260 / 390 km/h	520 / 780 km/h	n.a.	n.a.
Max. speed (mobile) L-Band	v_{max}	40 / 60 km/h	80 / 120 km/h	160 / 240 km/h	320 / 480 km/h

* Mode 4 is an extension of the original ETSI standard specification [6] to improve multipath performance of L-Band SFN in urban areas, hence the table does not follow a natural sequence.

Table 3.2: Main characteristics for the four DAB transmission modes

3.5.5. Guard interval

In an SFN each transmitter is required to radiate the same OFDM symbol at the same time. This comes from the fact that echoes (natural or artificially generated by co-channel transmitters) shall be confined in the guard interval period. The OFDM receiver has to setup a time window during which it samples the on-air OFDM signal. The objective is to synchronize this time-window with the useful period of the OFDM symbol. Accordingly, it will ignore the signal during the guard interval period where the receiver signal is made of a mixture of two or more OFDM symbols. If the transmitters deliver the same OFDM symbol at the same instant, or with a sufficiently small time delay, the differential propagation path delay to the OFDM receiver will remain inside the guard interval period. Accordingly, the sum of the received signals will be constructive because they constitute the same OFDM symbol (no inter-symbol interference), see also section 2.

The T-DAB specification offers one system guard interval, i.e. 1/4 times the duration of the active symbol duration. This is shown in Table 3.2 above.

The selection of this guard interval parameter affords resilience against delayed, interference–causing signals for mobile reception. The guard interval value has a major implication on the topology of the SFN: as the guard interval duration governs the maximum echoes delay admissible by the system. It therefore governs the maximum possible distance between co-channel transmitters (producing active echoes). Mode I allows setting up large SFN networks having a great distance between transmitter sites.

For Mode I, when the transmitters are situated less than 75 km apart, the permissible signal delay times are greater that the actual signal delay between adjacent transmitters.

Transmitter spacing can be increased beyond that defined by the guard interval by varying the radiated power, transmission polarisation and the relative transmitter timing. Effective planning of the required radiated power and transmission polarisation at the secondary site(s) will optimise SFN performance and provide effective management to eliminate most potential interference problems.

There is no limit on transmitter spacing providing the secondary site has a directional antenna transmitting away from the main site utilising an appropriate delay. However, where two transmit sites are radiating towards each other careful planning is required.

3.5.6. Data rate versus guard interval

In each of the specified modes of T-DAB operation the guard interval is a set fraction, one fifth, of the overall symbol period. Whilst both the symbol period and the number of carriers transmitted vary between modes the total number of symbols over a given period is the same. As a result the transmitted data rate is only affected by a change in the error protection level used.

Table 3.3 indicates the net bitrate in Mbits/s for various error protection code rates.

Protection Level	Corresponding approximate Code Rate	Approximate Bit-Rate (Mbits/s)
1	0.34	0.78
2	0.43	0.99
3	**0.50**	**1.15**
4	0.60	1.38
5	0.75	1.73

Table 3.3: Net bit rate in Mbits/s for various error protection code rates

3.6. Spectrum utilization

Flexibility in use of spectrum

SFN configuration allows a very large flexibility in the use of spectrum. A network can be initially designed to provide coverage to fixed roof-level antennas, but can be developed later, without the need for additional frequencies, to provide mobile or portable services by the addition of supplementary frequency and time synchronised stations, all carrying the same data stream.

This can be a way of spreading the cost of introducing a new digital network over a period of time. For example: if the initial investment required to provide a network which delivers indoor coverage to the whole target area is too high, an administration could chose to implement a network with a variety of reception modes. For example coverage in general to fixed roof-level antennas with a priority given to portable reception in some towns inside the target area. The ‘fixed’ coverage network can then be developed to provide further indoor coverage over a period of time. However, this facility can be conceived only in a frame of a frequency planning studied in advance.

Another flexibility that the SFN brings is the freedom for a broadcasting operator to implement new stations to improve coverage within an existing network, without having to request additional spectrum.

4. Describing Coverage

4.1. Minimum carrier to noise ratio and protection ratio

4.1.1. General

Frequency planning for the introduction of a new broadcasting service is based on two main parameters of the transmission system: the minimum carrier-to-noise ratio C/N_{min} and the protection ratios PR needed to achieve a given quality target for the delivered service. C/N_{min} indicates the amount by which a wanted signal level C must exceed the noise level N in order to achieve reception at the intended quality. PR describes the amount by which a wanted signal level C must exceed an interfering signal I in order to achieve reception at the intended quality. C/N_{min} is also termed 'required C/N' or – in a short manner of speaking – only 'C/N'. In the latter case the exact meaning has to be concluded from the context.

The introduction of digital broadcasting television systems implies some reconsideration of the planning procedures, in order to take into account the different behaviour of these systems and requires some clarification in the interpretation of these two relevant parameters.

4.1.2. Dependence on the transmission channel

The characteristics of the terrestrial channel are random variables depending on the receiving location, on the receiving antenna and also on time. In fact the number of echoes, their amplitudes, delays and phases vary from place to place (and from time to time). Therefore at each location the frequency response of the channel is different. Even when the echo delays are within the guard interval, the input *C/N* required by the system[5] depends on the channel characteristics. The presence of echoes produces frequency selective attenuations (notches) within the signal bandwidth, whose depths depend on the echo amplitude. The reason for the system sensitivity to the channel characteristics is due to the fact that the spectrum notches heavily attenuate some OFDM carriers (while the noise level remains constant), increasing their un-coded BER. The use of powerful inner codes (e.g. coding rates 1/2, 2/3 or 3/4) allows good recovery of the information of the attenuated carriers by means of the information carried by the other carriers. Therefore the use of these coding rates reduces the system sensitivity to the channel characteristics. The noise margin loss between the Gaussian channel and the Rayleigh channel is of the order of 2 to 9 dB, depending on the echo characteristics and on the inner coding rate.

OFDM can exploit the power of multiple echoes in the sense that the available *C/N* at the receiver input increases, due to power summation of the *C* contributions, but at the same time the receiver performance can degrade (increase of the required *C/N*). As a result of these two effects, there can be a net performance gain or loss with multipath reception and SFN contributions. Apart from the low coding rate modes (e.g., coding rate 1/2), a single line-of-sight contribution (Gaussian channel) can give a better global performance than two 0-dB echoes (Rayleigh channel). Conversely, when the number of 0-dB echoes is larger than two, the required C/N does not increase further, and the global performance improves according to the growth of the available C/N.

Similar considerations apply to the interference from an unwanted signal, i.e. to the protection ratio PR.

4.1.3. EPT concept

Instead of a (static) required C/N ratio, the **"**Effective Protection Target**"** can be introduced, which represents the ratio between the power of the wanted signals (echoes within Δ and

[5] to achieve a final signal "quality" (e.g. BER<10^{-11} after Reed-Solomon decoding).

useful component of the echoes falling between Δ and T_p) and the sum of the powers of noise and effective interference (interfering component of the echoes falling between Δ and T_p echoes, and echoes outside T_p) at the system threshold. For the meaning of Δ and T_p see chapter 2.3.4.

The required *EPT* depends on the system parameters (modulation and code rate) and on the characteristics of the echoes inside T_p, which determine the *criticality* of the frequency selective channel.

For fixed reception, the channel is Ricean-type when a single transmitter dominates, while it becomes Rayleigh-type when a number of strong artificial echoes within the guard interval are present. In the case of portable reception, the channel is typically Rayleigh-type both with natural echoes and with artificial SFN echoes.

In SFN planning, it is assumed that the system can operate satisfactorily at a given location, in the presence of Gaussian noise, of echoes inside and outside the guard interval and of external noise-like interferers, when the available aggregate C/(N+I) is larger or equal to the required *Effective Protection Target* (*EPT*):

$$\left. C/_{N+I} \right|_{\text{Available}} \equiv \frac{1}{\left(C/_N\right)^{-1} + \left(C/_I\right)^{-1}} \geq \text{EPT}$$

EPT is given by the following empirical formula, where all the items are expressed in dB:

$$\text{EPT} = \begin{cases} \left.C/_N\right|_F + \left(\left.C/_N\right|_P - \left.C/_N\right|_F\right)\left(\dfrac{5}{\left(\left.C/_N\right|_P - \left.C/_N\right|_F\right)}\right)^{\frac{K_A}{10}} + \Delta_1 + \Delta_2 & \text{for fixed reception} \\ \left.C/_N\right|_P + \Delta_1 + \Delta_2 & \text{for portable reception} \end{cases}$$

where:

EPT is the required system effective protection target in a particular SFN echo environment

C/N(F) is the minimum carrier-to-noise ratio required by the system on the F1 channel as given in Annex A of the DVB-T specification ETSI Standard EN 300 744 [5]

C/N(P) is the minimum carrier-to-noise ratio required by the system on the P1 channel as given in Annex A of the DVB-T specification ETSI Standard EN 300 744 [5]

K_a "channel criticality due to artificial echoes" is the ratio between the power received from the main transmitter and the total power of the artificial echoes inside the guard interval (but K_a < 0 dB)

Δ_1 is the total system implementation loss. Often a value of 3 dB is chosen.

Δ_2 is an aggregate performance loss due to the echoes outside the guard interval which produce aliasing and noise increase on the channel estimation. Pending other results, Δ_2 should be set equal to 0 dB

(Implementation and performance loss Δ_1 and Δ_2 must not be mixed up with the guard interval Δ!)

Δ_1 and Δ_2 may be set to 0 when new and consolidated values for C/N(F) and C/N(P) based on a sufficiently large number of consumer receivers are available.

4.2. Definition of coverage

4.2.1. General

The main questions when building new digital terrestrial networks are the evaluation of the service area and the population covered. These evaluations are made through the estimation of the level of the wanted signal(s) and the level of the interfering signals. The relevant planning parameters in this context are the required carrier-to-noise ratio and the protection ratio which describe the sensitivity of the system under consideration against noise and against interference.

Concerning digital television, it is known that when the level of signal decreases and the carrier-to-noise ratio C/N or the carrier-to-interference ratio C/I falls below a given “minimum” value, the picture disappears completely with a further signal level reduction of less than about 1 dB. This behaviour is generally referred to as the “rapid failure characteristic of the digital system” and the limit value of the field strength is designated as the minimum field strength. If the same coverage definition as for analogue television were used for digital television, this would mean that 50% of the locations would not be served at or near the edge[6] of the service area or in any other areas of reduced signal caused by local obstructions. Therefore, a value of only 50% of locations receiving a picture is clearly unacceptable, higher values of the percentage of locations have to be selected in order to allow reception in a satisfactory number of locations, with a standard receiving installation. Values ranging from 70 to 99% are usually quoted for digital television transmissions.

The exact value chosen depends on the level of service quality which is aimed at, and that is why values can be different from one country to another or even from one company to another within a given country. Nevertheless, values of 70%, 95% and 99% of the percentage of locations have been chosen in the proposed coverage definitions.

Digital radio also experiences a rapid transition from perfect to no reception for a small reduction in signal level below the ‘minimum’ acceptable C/I. For T-DAB, which is designed for a mobile outdoor service, a percentage location value of 99% is used.

Under such considerations, some of the simpler tools used for analogue television coverage evaluations are not completely satisfactory and it is necessary to make more complex calculations.

In general, the reception of digital services is faced with a multi-signal environment, multiple interference as well as multiple wanted signals in the case of SFN. To assess the wanted and unwanted resultant field strengths the individual signals have to be combined. Since signal strengths are described by statistical quantities they have to be combined statistically.

Basically, this is true for both location and time statistics. However, it is usual to treat them in different ways. Time statistics are taken account of by using tabulated field strength propagation curves for the appropriate time percentages. Location statistics are dealt with by using field strength distributions.

4.2.2. Location statistics

4.2.2.1. Coverage of a single receiving location

For a receiving location to be covered by a digital broadcast service, we know that the level C of the wanted signal, expressed in dB, has to be higher than the level N of noise by a certain value which is the minimum C/N_{min} This can be expressed (in dB) by the condition :

$$C > C/N_{min} + N$$

In the same way, to overcome the effect of an interferer, the level C of the wanted signal must be higher than the level I of this interferer by a certain value referred to as the protection ratio PR for this particular type of interferer. It can also be expressed (in dB) by :

$$C > PR + I$$

[6] The term “edge” is taken to mean any transition between a covered area and a non-covered area. These “edges” may occur at the outer boundary of a coverage area or at the boundaries of any uncovered areas which may exist inside the overall area, usually as the result of local screening on the path of the wanted signal.

The sum PR + I (protection ratio + field strength of interferer) is often referred to as the nuisance field. In practice, the receiving antenna discrimination against the interfering signal may also need to be taken into account :

$$C > PR + I - A_d,$$

with A_d being the receiving antenna discrimination in the azimuth of the interferer.

In practice, the wanted signal has to fulfil both conditions which can be expressed as:

$$C > C/N_{min} + N + PR + I - A_d$$

For the case where more than one wanted and more than one unwanted signal is encountered, the condition for reception can be expressed as:

$$\Sigma P_C > P_{(N + C/Nmin)} + \Sigma P_{(PR+I-Ad)}$$

where:

ΣP_C	:	power of the wanted signals
$P_{(N + C/Nmin)}$	:	noise power equivalent + required C/N
$\Sigma P_{(PR+I-Ad)}$	:	power of the nuisance fields

4.2.2.2. Coverage of a small area

In practice, it is not possible to know the real values of the field strength for each receiving location in order to apply the previous formula and to determine precisely the coverage area. The only figures that can be evaluated are the mean values of the field strengths in small areas (typically, 100 m x 100 m). The variation over such a small area is often called long-term fading or shadow fading.

The problem is then to know if a given small area is inside or outside a coverage area and to calculate the probability of good reception in these areas. This probability represents the percentage of receiving locations which can receive a satisfactory signal (that is, whose power is greater than or equal to the sum of the noise and nuisance powers) within the small area. A small area is regarded as covered – and thus as belonging to the coverage area - if the probability is higher than a given threshold, e.g. 70%, 90% or 95%. This aspect is discussed more detailed in the next chapter 4.2.2.3.

The calculation of the probability is carried out - using the appropriate values for the noise level and the protection ratios of each type of interferer - for the field strengths which are random variables. The field strength prediction gives the mean level of the wanted field strengths and of the unwanted signals using the prediction method of, e.g., the ITU-R Rec. P.1546 [10] or prediction models using terrain data banks.

But, because the wanted and nuisance powers are random variables which are only known through their means and standard deviations, the formulas given in the previous chapter cannot be applied only to the means of the wanted and nuisance powers. It is necessary to refer to mathematical models for the distribution of field strength with locations and to use mathematical methods to obtain the result of the combination of several randomly distributed signals. This is dealt with in more detail in chapter 4.4.

A further aspect that is to be mentioned in this context is the fact that each propagation model is affected with a prediction error which adds a further statistical component. However, it will not be dealt with explicitly in this report, since the prediction error varies from one individual propagation model to the next. Often shadow fading and prediction error are dealt with together, and it is assumed that the applied standard deviation of the field strength covers both effects. It is this latter view that is taken in the present report.

4.2.2.3. Propagation prediction and its statistical background

Terrestrial broadcasting signals are 'propagated' through the atmosphere between the transmitter and the receiver. The characteristics of the propagation channel gives rise to a statistical time variation and a statistical location variation of the transmitted field. The time variation of a wanted field is in general very small compared to its location. These statistical variations are incorporated in well known propagation models such as ITU-R Rec. 1546 [10].

When discussing the statistics of received field strength, the variation of the wanted signal is determined over an area where the signal has an average value and a log-normal type of variation around this median value, with a known standard deviation. This value of the standard deviation normally varies between 3 and 6 dB. For planning of digital broadcasting services often a value of 5.5 dB is used. The areas over which this value has validity must have a suitable size. In other words, the area cannot be 'too large' or 'too small'. Typically, it has the size of 100 m x 100 m. A suitably sized area will be termed a '*Test Area*'.

As an illustrative counterexample, measurements of the field strength over an area stretching from the transmitter site outward to a concentric circle 100 km away will certainly have a standard deviation more than 5.5 dB. This would not be a test area. Likewise, if the area consists of only few closely located points, the location standard variation will be less than 5.5 dB. This would also not be a test area.

It must be remembered that field strength values provided by statistical propagation models do not give information about specific points, only about test areas. For example, a field strength level, X, may be achieved (or exceeded) at 50% of the locations at a given distance from a transmitter with a given effective antenna height and erp; another (lower) field strength level, Y, may be achieved (or exceeded) at, for example, 99% of those same locations for the same transmitting conditions. The difference, X-Y, is proportional to the standard deviation, and represents the (±) spread within which most field strength values will lie when measured at the points within the test area. No information is given as to which individual locations/points within the test area receive a field strength equal to a specified field strength level, or which individual locations/points receive a field strength that exceeds the specified field strength level.

If the transmitter power is now increased by a fixed amount (say, 3 dB), then the received field strength will be increased at each location/point by that amount (3 dB) and the field strength at more locations/points than before will equal or exceed the specified field strength level (X or Y). But there is still no knowledge of those specific locations/points where this happens. Nevertheless it makes sense to say that the field strength has been raised by 3 dB at all of the locations/points under consideration or, equivalently, that the specified field strength level (X or Y) is reached or exceeded at a higher percentage of locations/points (higher than 50% or 99%, respectively).

4.2.3. Time statistics

Time statistics for interfering fields are taken account of by basing calculations on 1% time propagation curves, whereas wanted field calculations are based on 50% (or 99%) time propagation curves. Normally, a more detailed treatment of time statistics is not performed in coverage calculations for digital broadcasting services. Actually, there are not even methods available to do so. To some extent this approach is justified – at least for wanted signals – by the fact that for shorter distances (less than 100 km) the time variation is much smaller than the location variation.

With respect to signal summation, self interference fields are treated as 'normal' unwanted signals. 1% time propagation curves are used, and they are added to the other source of possible interference from outside the SFN.

4.3. Minimum reception conditions

4.3.1. Single signal case

Location statistics of an individual (logarithmic) field strength originating from one transmitter is described by means of a normal distribution which is characterised by two parameters, mean value and standard deviation. Accordingly, the power of the signal is then distributed log-normally.

The key role of coverage probability targets as planning parameters for a digital system has been previously discussed. These target figures are related to the field strength distribution parameters. 50% coverage probability is determined by the mean value of the distribution, for the calculation of higher (and also lower) coverage probabilities both mean value and standard deviation of the signal distribution are needed.

In the case of a single signal, where the distribution parameters are known a priori from the propagation prediction, probability margins to cater for higher coverage probabilities are easily calculated and the minimum median field strengths for planning can be determined. The same applies to probability margins for protection ratios when one wanted and one unwanted field are involved. The exact definition of protection margin is given later in this chapter.

In chapter 4.2.2.1 the general formulation of the minimum reception conditions is given. In the case of a single wanted signal and a single unwanted signal this is (neglecting receiving antenna discrimination for simplicity):

$$C > C/N_{min} + N + PR + I.$$

In the absence of the interferer the formula gives the definition of the minimum field strength F_{min}:

$$F_{min} = C/N_{min} + N.$$

For proper reception, F_{min} must be exceeded by the wanted signal C, which – as a statistical variable with a normal distribution – is described by a mean value C_{mean} and a standard deviation σ_C:

$$C > F_{min},$$

or, to be more precise:

$$P(C > F_{min}) > p,$$

where P(A) denotes the probability of the event A and p the intended location coverage probability. With the given distribution parameters of C and the intended coverage probability p the minimum median equivalent field strength for planning F_{MME} can be evaluated:

$$F_{MME} = F_{min} + \mu_p{}^* \sigma_C.$$

F_{MME} is the planning parameter that must be exceeded by the mean value C_{mean} of the wanted signal C in order to guarantee proper reception with the intended coverage probability. The amount $\mu_p{}^* \sigma_C$ by which F_{MME} is larger than F_{min} is called the probability margin. It is a function of the standard deviation and of the percentile factor μ_p. Values of μ_p for typical coverage probabilities p are given in Table 4.1 below. Percentile factors are treated in detail in Annex A.4. Often the probability margin is also called propagation margin.

p = 0.50	μ_p = 0.00
p = 0.70	μ_p = 0.52
p = 0.95	μ_p = 1.64
p = 0.99	μ_p = 2.33

Table 4.1: Percentile factors for typical probabilities p

A similar consideration holds when the interference of the wanted signal (with level C) by an unwanted signal (with level I) is examined. For proper reception, the wanted signal has to fulfil the condition

$$C > PR + I,$$

or, again in statistical form:

$$P(C > PR + I) > p.$$

The evaluation of this expression renders the condition for the mean value C_{mean} of the wanted field:

$$C_{mean} > I_{mean} + PR + \mu_p^* \sqrt{(\sigma_C^2 + \sigma_I^2)}$$

The probability margin $\mu_p^* \sqrt{(\sigma_C^2 + \sigma_I^2)}$ now contains both standard deviations of the wanted as well as of the unwanted signal since both are statistical variables. The probability margin reduces to the well known form $\sqrt{2}*\mu_p*\sigma$, when the same standard deviations are assumed for the wanted and the unwanted signal: $\sigma_C = \sigma_I = \sigma$.

Since the standard deviations of the wanted and the unwanted field are known a priori (they are input parameters of the field strength prediction model), in the single signal case the probability margins can be calculated once and for all and be used as generally valid planning parameters.

The combined treatment of noise and interferer, as already indicated in chapter 4.2.2.1, contains elements of statistical summation and is therefore discussed in the next chapter.

4.3.2. Multiple signal case

In principle, the same minimum reception conditions as described in the previous chapter also apply in the case of a multiple signal environment. However, the fact that now statistical sums of the wanted signals and of the unwanted signals are involved introduces some interesting effects and makes the evaluation of coverage more complex. Multiple interfering signal configurations are well known in many broadcasting situations, whereas multiple wanted signals are a particular aspect of single frequency networks.

When a multi-signal situation is encountered, the parameters of the resulting signal distribution are no longer known a priori. Mean value and, especially, standard deviation strongly depend on the particular signal configuration having to be determined by means of statistical procedures. As a consequence, minimum field strengths and probability margins no longer have fixed values; they rather become variables depending on the number, strength and spread of the individual single fields. However, two general trends can be identified. Firstly, the mean value of the composite signal is larger than the arithmetic sum of the individual means and, secondly, the standard deviation of the composite signal is smaller than that of the individual signals, both facts creating the effect of network gain (in the case of wanted signals). Its physical background, location diversity, is discussed in chapter 4.4.2, its relation with the minimum median equivalent field strength in chapter 4.4.5.

The following example may give an impression of the significance of field strength summation effects. Maximum statistical network gain is achieved if the contributing fields are of equal strength at the receiving location. In the case of, e.g., three single signals it amounts to about 6 dB and lowers the minimum median field strength for planning at that location by this amount. If the three signals are not of equal strength network gain varies between 0 and 6 dB. In a similar way probability margins for protection ratios are reduced by signal summation effects. The example shows that signal summation effects in SFN may impact the coverage of a digital service to a significant amount.

It has already been stated that signal summation effects increase the mean value and lower the standard deviation of the resulting sum signal distribution as compared to the outcome of a non-statistical treatment. This is an important finding, since it gives the possibility to fix the results of the non-statistical treatment as an upper bound for initial planning estimates. Allowing for some additional implementation margin, they form an appropriate basis for planning when detailed information about the transmitter characteristics of a network is not available, e.g., when setting up an allotment plan.

On the other hand, detailed planning, e.g., for the implementation of a real transmitter network, has to take account of signal summation effects. Probability margins for minimum field strengths and protection ratios then no longer form suitable planning parameters. They have to be replaced by the more basic coverage probability targets.

Since network gain is a fundamental feature of single frequency networks this aspect is discussed in greater detail in the next chapter 4.4. Mathematical methods for the statistical signal summation and the calculation of coverage probabilities are described in chapter 4.5.

4.4. Network gain

4.4.1. General

When discussing network gain it is necessary to consider a test area where two (or more) signals are present and the necessary conditions (i.e., well-defined median value with appropriate standard deviation and a log-normal distribution) apply for both (or all) wanted signals individually. In different test areas, the specifics of these conditions may well differ, and this will give rise to differing values of the network gain. Just as the median value of field strength varies throughout the test areas of a coverage area, the network gain will also vary throughout the test areas of an SFN.

Sometimes the term ‘network gain’ is used to define a single number which is applicable to the entire SFN (or reference network) and this can lead to confusion[7]. To avoid this confusion the term ‘effective network gain’ will be introduced below to refer to network gain in such a large ‘non-test area’.

4.4.2. Definitions related to network gain

In order to clarify further the concept of network gain, the following set of definitions will be given. In each case the network gain involved is a function of the location probability concerned: in general the network gain for a given test area will increase as the location probability for which it is determined increases. This will be seen in numerical detail in Tables 4.2 and 4.3. Although not usually explicitly stated in the following, the dependence of network gain on location probability must always be kept in mind.

- The **total network gain** (**T**) refers to the total increase of received power, for a specific location probability in the reception test area as compared to the power received from one (the strongest) transmitter serving that test area for the same location probability. Actually care must be taken in using this definition. It must be recalled that, throughout the test area, the field strength due to the (strongest) transmitter itself varies. What is really meant is that over an extended, though small, test area the received power will be increased by at least the ‘total network gain’ at the specified location probability throughout the specified small test area.

  Several computer methods have been developed to calculate total network gain, see chapter 4.5 and Annex A.

The total network gain is sometimes considered to be composed of two contributions: a statistical part and an additive part.

[7] For example, in more familiar terms, we never talk about the average field strength over the entire coverage area, but rather about the average field strength at the edge of the coverage area.

- The **statistical network gain** (**S**) arises due to the purely statistical nature of the individual signals without taking into account their (potential) combination within the receiver. In determining the statistical network gain the location variation of the field strength is the dominant contributing factor: the time variation of the field strength is generally not taken into account because the time standard deviation is relatively small at the short distances involved in providing coverage[8].

  Statistical network gain can be understood in at least two equivalent ways:

  a) Area coverage: To overcome the statistical location variation in field strength, that is in order to ensure that with a single transmitter the minimum equivalent field strength value is achieved at a high percentage of a given area, it is necessary to transmit with more power. If, on the other hand, two (or more) transmitters can be used to cover the same area the percentage of coverage will also be increased without the need to increase the power. For example, if one signal covers an (overlapping) area with 60% probability and a second signal covers, independently, the same area with 55% probability, that area will be covered at {1 – (1 – 0.6) x (1 – 0.55) } = 0.82, that is 82% combined probability.

  The statistical network gain, in terms of coverage probability, would be: 82% – 60% = 22%. A third signal covering the same area with 45% probability would increase the combined probability to 90.1%, and this increase of coverage probability is achieved with no increase of power (of the individual transmitters).

  In situations where, in a given test area, one transmitter delivers the minimum field strength for a significantly higher percentage of locations than the other transmitters in the network (for example, sufficiently near any given transmitter) the statistical network gain will tend to zero.

  b) Mobile reception: In mobile reception the field strength from a single transmitter shows statistical variations due to the continual variation of obstacles on the propagation path. This field strength variation can be reduced by the presence of several transmitters (or echoes), located in different directions, since when one source is shadowed, others may be more easily receivable.

  Knowing the type of distribution (log normal) and the value of the standard deviation, it is relatively easy to calculate the amount of statistical network gain to be expected (see Annex A for examples).

- The **additive network gain** (**A**) is manifested as an effective increase in signal strength (or power) in a test area due to the incidence of two or more signals at the receiver antenna (i.e., the ‘additive point gain’) at each point in the test area. It is due to the ability of the receiver to add the signal powers delivered by the wanted signals (or echoes) arriving from the transmitters in the SFN and would arise even if there were no statistical variations in the propagation channel[9]. For example, two (three, four,…) signals with the same field strength level and no relative delay arriving at a receiving antenna (located at a point) from two (three, four,…) different transmitters in the SFN would result in a 3 dB (4.8 dB, 6 dB,…) increase of useful signal strength at that point (‘additive point gain’). However, because it is not possible (or practical) to determine field strength levels at individual points, it is necessary to define additive network gain over a test area, as was done above in the definitions for the total network gain and for the statistical network gain.

  But, taking into account the statistical variation of the fields, the levels of two or more fields are very rarely the same at any given point in a reception test area, even if the median values of the signals are the same in that test area. Thus it is not correct to

[8] A complete calculation of statistical gain would also take the time variation statistics into account.
[9] In a very simple case, two constant (i.e., non-varying) signals of the same level, if added, would result in a 3 dB increase of useful signal strength.

say that the additive network gain is 3 dB (4.8 dB, 6 dB,…)[10] if the two (three, four,…) median values of the contributing signals are equal. The 'additive point gain' at a particular location/point will depend on the relative field strengths received at the location/point which in turn are related to, but not explicitly determined by, the means and the location[11] variations of the contributing signals. And the final distribution of the 'additive point gains' throughout the test area will define the additive network gain.

Because the additive network gain is connected to the 'interaction' of signals at a point as well as the variation statistics of the signals at the points over a test area, it is not a simple matter to calculate it directly. The additive network gain can, however, be calculated indirectly by subtracting the statistical network gain from the total network gain: **A = T – S**.

- The **effective network gain** (**E**) is defined as follows for an SFN. An SFN coverage area consists of many test areas, each test area of which, A_i say, benefits from its own individual total network gain, T_i. Recall that this means that throughout each test area A_i the received power will be effectively increased by its individual total network gain T_i. In principle, it would be possible to reduce the powers of all the transmitters in the SFN by this amount and still maintain the same location probability in the test area as would be attained by the strongest received transmitter operating by itself (at its original power). As a result of network gain, the transmitters in an SFN can be operated at lower powers compared to those in an MFN. Moreover, the field strength distribution in the coverage area of the SFN will be more homogeneous. The temptation is to reduce the powers in an SFN by the maximum of the T_i for all the test areas in the SFN[12]. But this could lead to a reduction which is too large for certain test areas, see chapter 4.4.4 for an example. The effective network gain is that amount by which each transmitter power in an SFN may be reduced and still provide the required coverage probability throughout the SFN and, as just indicated, this may be less than the maximum T_i. Great care is needed to determine a suitable value for effective network gain.

4.4.3. Examples of network gain

Tables 4.2 and 4.3 below give the relevant values calculated for various numbers of contributing sources (2, 3 or 4) and for various percentages of location coverage (0.1% to 99.9%). It is assumed in each case that all sources are equal contributors (leading to the greatest resulting network gains), uncorrelated, with a log-normal distribution, a 5.5 dB standard deviation. The sum distributions for 2, 3, and 4 equal contributors is given pictorially in the Figures 4.1, 4.2 and 4.3[13] for the entire range of location percentages 0.1% to 99.9%, indicating total, statistical, and additive network gain components. Figure 4.4 shows a comparison between the total sum distributions for two, three, and four equal contributors. It can be seen that:

- the additive network gain is not constant[14] and is in fact an increasing function of the percentage location probability of interest;
- the amount of total network gain that can be achieved depends in the same way on the location percentage coverage that is being planned for;
- the overall standard deviation of the composite received signal is less than that of a single signal; hence the extra power margin needed to achieve, for example, a 95% or 99% location coverage can be reduced relative to the single transmitter case.

[10] Although it is a crude approximation.
[11] And also, in principle, the time variations.
[12] We are assuming that, in the design of the SFN, the minimum possible transmitter powers are used, while still ensuring that the minimum reference field strength is met or exceeded in all Areas of the SFN.
[13] The calculations were carried out using Monte Carlo simulation.
[14] In particular, the values are not generally 3.0, 4.8, 6.0 dB for 2, 3, 4 equal contributors.

# Tx	NETWORK GAIN (dB)														
	99.9%			99%			95%			90%			70%		
	Stat	Add	Tot	Stat	Add	Tot	Stat	Add	Tot	Stat	Add	Tot	Stat	Add	Tot
2	6.7	2.0	8.7	5.8	1.8	7.6	4.9	1.7	6.6	4.4	1.7	6.1	3.5	1.5	5.0
3	9.9	3.2	13.1	8.5	3.0	11.5	7.2	2.8	10.0	6.6	2.6	9.2	5.3	2.3	7.6
4	12.2	3.7	15.9	10.3	3.7	14.0	8.7	3.5	12.2	7.9	3.3	11.2	6.4	3.0	9.4

Table 4.2: Network Gain

# Tx	NETWORK GAIN (dB)														
	50%			30%			10%			1%			0.1%		
	Stat	Add	Tot	Stat	Add	Tot	Stat	Add	Tot	Stat	Add	Tot	Stat	Add	Tot
2	3.0	1.3	4.3	2.5	1.1	3.6	1.9	0.8	2.7	1.3	0.4	1.7	1.2	0.2	1.4
3	4.5	2.1	6.6	3.8	1.8	5.6	3.0	1.3	4.3	2.1	0.7	2.8	1.9	0.3	2.2
4	5.5	2.6	8.1	4.6	2.3	6.9	3.6	1.7	5.3	2.6	0.8	3.4	2.2	0.4	2.6

Table 4.3: Network Gain

In the more general case signal levels will differ at a specific location. Figure 4.5 shows how the total network gain varies as the relative levels of two contributing signals vary from 0 to 6 dB.

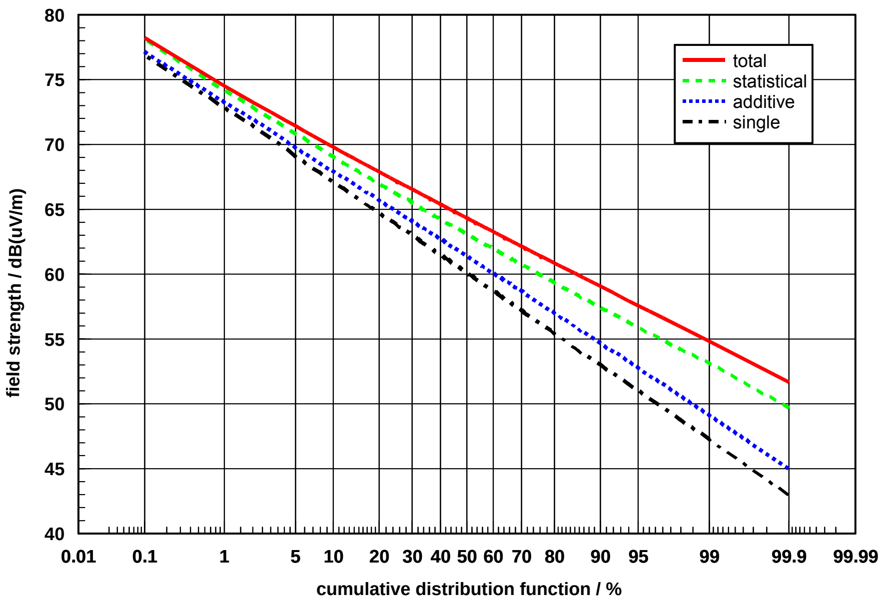


Figure 4.1: Sum distributions for 2 equal contributing signals

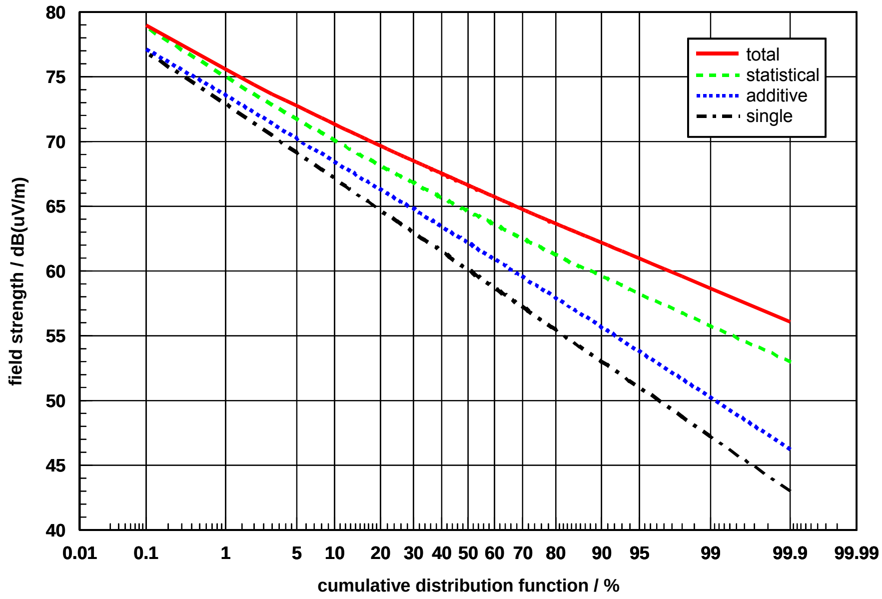


Figure 4.2: Sum distributions for 3 equal contributing signals

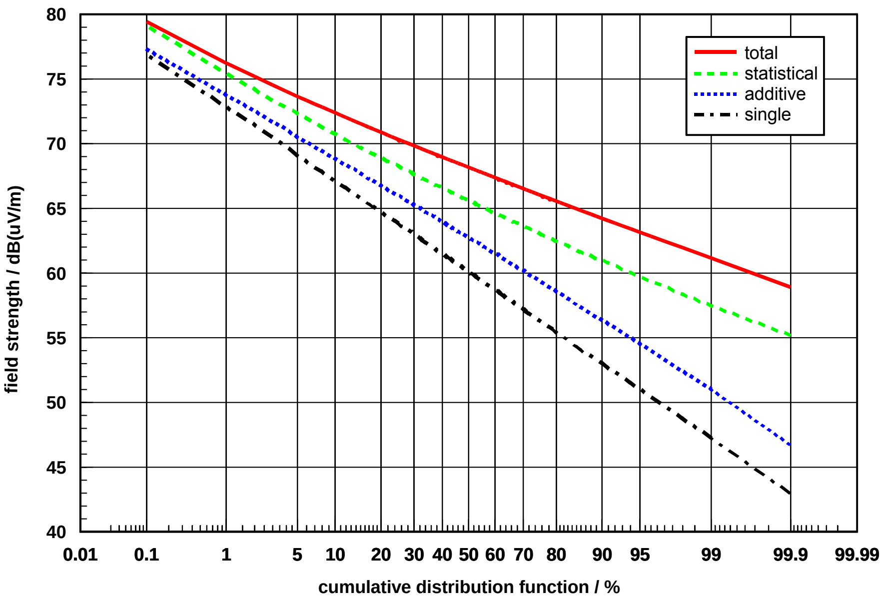


Figure 4.3: Sum distributions for 4 equal contributing signals

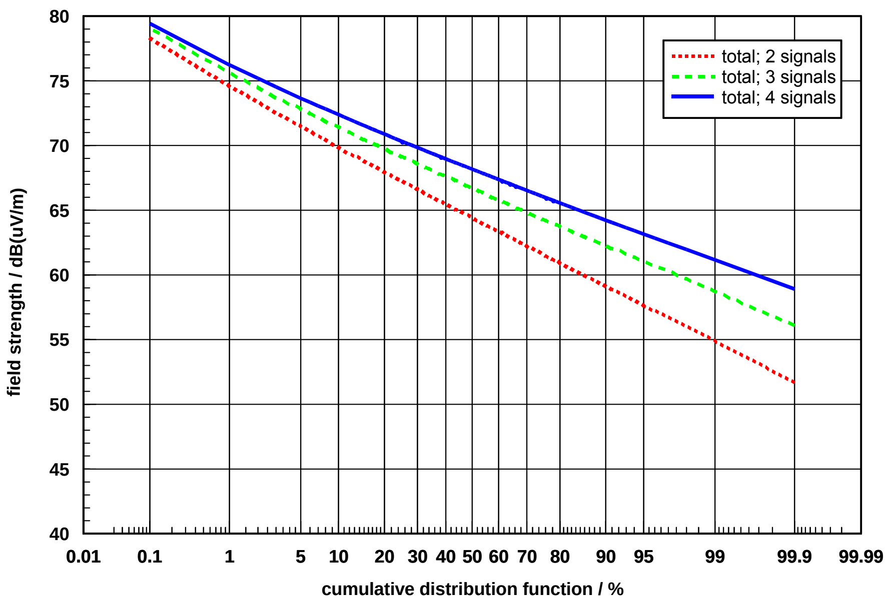


Figure 4.4: Comparison between the total sum distributions for 2, 3 and 4 equal contributing signals

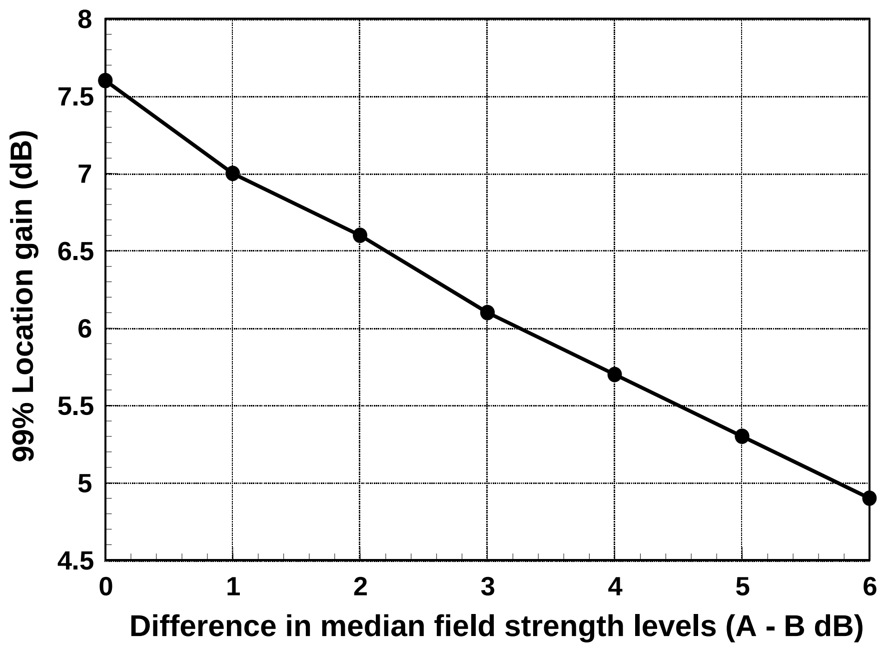


Figure 4.5: Theoretical total SFN Network Gain for two contributing sources A and B (Standard deviation σ = 5.5 dB)

4.4.4. Network gain and the design of an SFN

In the previous chapter 4.2 it was indicated that the total network gain of a particular test area cannot be generalized to be valid for the whole coverage area of the SFN. Further examples of typical network gain situations are presented in this chapter and it is shown that a careful assessment of the effective network gain is necessary in the design of an SFN.

In Figures 4.6 and 4.7, the two lowest curves sloping downward to the left and right, respectively, represent the individual field strength levels attained along a line separating two transmitters. In Figure 4.6, the two transmitters both have an effective antenna height equal to 37.5 m and are separated by 40 km. In Figure 4.7, the two transmitters have an effective antenna height equal to 37.5 m (at the left) and 1200 m (at the right), respectively, and are separated by 140 km. In both cases, Figure 4.6 and 4.7, the field strengths from the two transmitters are equal (giving the largest total network gain) at a distance 20 km from the transmitter on the left.

An example of a 'symmetric' case of network gain is shown in Figure 4.6. If the power is reduced by the total network gain the reference field strength level will still be reached elsewhere.

An example of an 'asymmetric' case of network gain is given in Figure 4.7. It can be seen[15] that the reference field strength level will not be achieved everywhere if the power is reduced by the maximum total power gain.

Thus it can be concluded that care must be taken with the simple 'recipe' which would allow the transmitters in a SFN to have their powers reduced by the maximum total network gain with the intent to maintain the desired minimum field strength achieved everywhere.

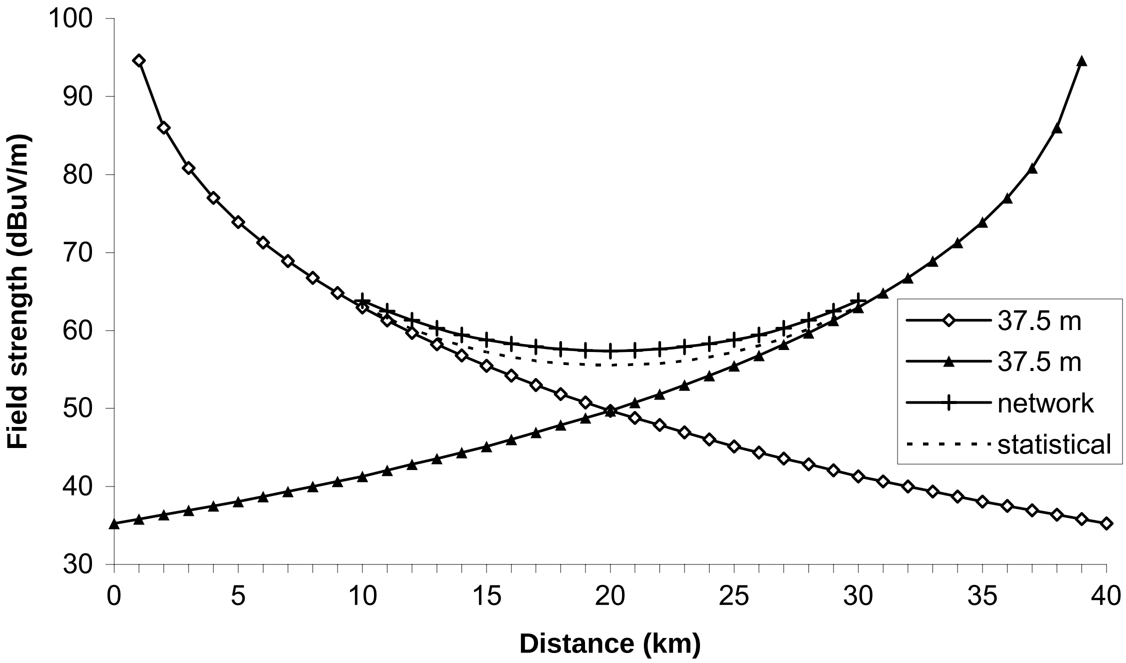


Figure 4.6: Symmetric situation

[15] See the horizontal line.

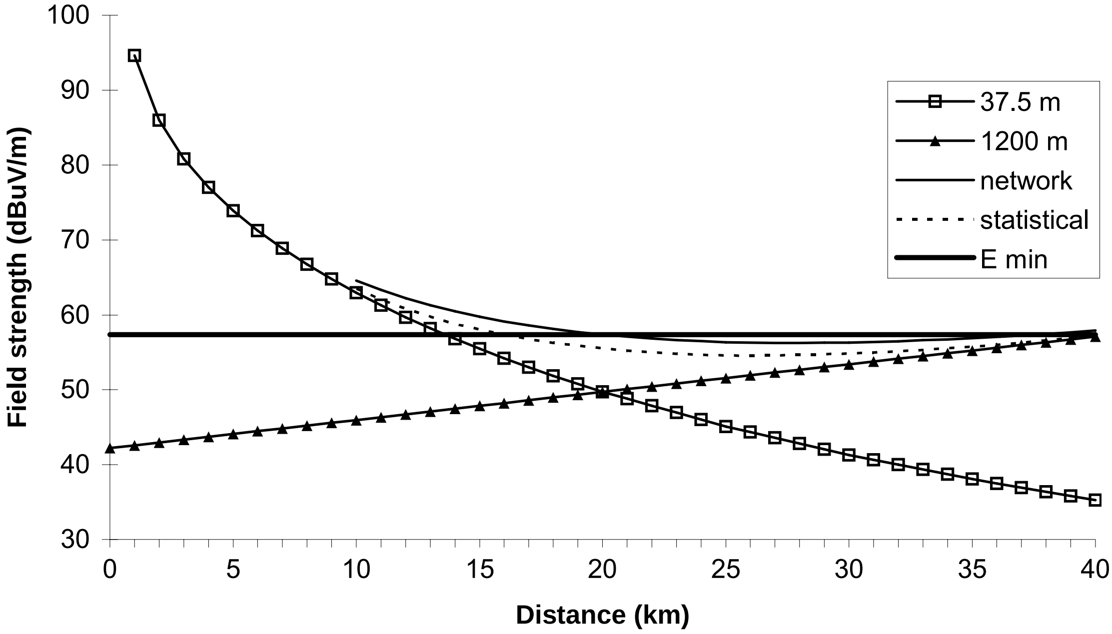


Figure 4.7: Asymmetric situation

4.4.5. Influence of network gain on the minimum median equivalent field strength

For the case of a single transmitter (MFN) the minimum median equivalent field strength to be used for planning is derived as described earlier in this section. For the case of SFN coverage the following must be observed.

Because of its higher complexity, a multiple signal configuration no longer allows the identification of a single, unique value of a field strength that must be exceeded in order to achieve proper reception (such as the “minimum median equivalent field strength for planning” in the single transmitter case). Since usually a large variety of signal configurations is encountered throughout the coverage area of an SFN a correspondingly large number of different minimum requirements for proper reception are found across the SFN area. The concept of the “minimum median equivalent field strength for planning” can therefore no longer be applied in a precise sense to SFN planning.

The alternative concept for SFN planning is based on the “minimum equivalent field strength at receiving place” and the envisaged location coverage probability as minimum requirements. The statistical treatment of a given signal configuration and a comparison with the new minimum requirements then provides the answer whether proper reception is possible at the location under consideration. For the case of a single transmitter this approach is identical with the “minimum median equivalent field strength for planning” concept. The appropriate statistical methods to deal with the alternative concept are described in detail in the subsequent chapters and in Annex A.

4.5. Signal summation and calculation of coverage probability

4.5.1. Summation of field strengths

In the course of planning a network, it is necessary to predict the level of interference field strength, both outgoing from and incoming to the network, i.e. to predict the interference field strength produced by one network in the service area of another.

For international co-ordination, in order to assess compatibility, it is necessary to quantify the sum of the outgoing field strengths from each transmitter in the wanted network into the service area of other networks using the same frequency.

In order to predict the coverage of a network, it is necessary to estimate the mean values and standard deviations of the wanted field strength and the unwanted field strength in a large number of test locations, and to calculate with these values the percentage of locations served within the area. The unwanted field strength will be a combination of self-interference from the network itself and interference from other networks.

4.5.2. Assessment of coverage probabilities

The calculation of the coverage probability is split into three parts:

- Calculation of the wanted sum field strength,
- Calculation of the interfering sum field strength, including self-interference
- Evaluation of the coverage probability.

One of the questions to be answered is how to combine interfering signals when there is more than one and how to take into account the effect of noise. Some of the calculation methods to deal with this question are presented below. They are all statistical methods which require computer processing and they use models of the real situation. In all the methods, except the power sum method which does not make use of statistics at all, it is assumed that field strengths have a log normal distribution with location.

It should be noted that though there may exist some correlation between the individual signals, wanted as well as unwanted signals, none of the methods described below include the treatment of correlation in their original form. However some of them can be extended to include correlation. The effect of correlation varies with the reception situation. It can produce either an increase or a decrease of coverage depending upon the particular correlation situation.

The proper treatment of field strength statistics automatically yields the pertinent values of C and N+I, including network gain. In particular, no extra effort for the calculation of network gain is necessary. However, the (100%) correlation between the wanted and self-interfering components of a given delayed wanted signal is not taken into account using this procedure and, depending on the overall configuration, can lead to an over-estimation of the interference potential.

4.5.3. Calculation methods

4.5.3.1. General

The basic principle when evaluating a service area is to estimate mean value and standard deviation of wanted field strength and unwanted field strength in a large number of test locations in the assumed service area and with these values, to calculate the percentage of locations served.

The determination of statistically summed field strengths and, further, the evaluation of coverage probabilities, can be performed using numerical methods, numerical integration, Monte Carlo simulation, or by means of approximations. Some of the methods commonly applied in network planning are described in the subsequent chapters The first method is a numerical approach which is capable of providing the required accuracy but at the expense of a large amount of computer time. The remaining methods are approximations which are presented in order of growing complexity and this increasing complexity corresponds to an increasing computer processing time. In Annex A detailed descriptions including formulas can be found.

4.5.3.2. The Monte-Carlo method

Apart from a deterministic (numerical integration) method, the Monte-Carlo approach is the most accurate method available to evaluate the coverage probability. With the mean value and the standard deviation of the distribution of each signal it is possible to simulate the situation for a large number of reception locations in a test area (say, 100 m x 100 m). This is done by generating one random value of each wanted field and one random value of each interferer. For each combination it is possible to check if the reception location is served or unserved by comparing the sum of the powers of the wanted signals with the sum of the powers of the noise and the nuisance fields. By repeating this simulation for a large number of combinations of wanted and unwanted signals, the coverage probability for a given test area may be derived. The higher the number of combinations, the more accurate the method becomes but this can lead to very lengthy computer processing times. In addition, the process must be repeated for a large number of test areas in order to represent the overall coverage area.

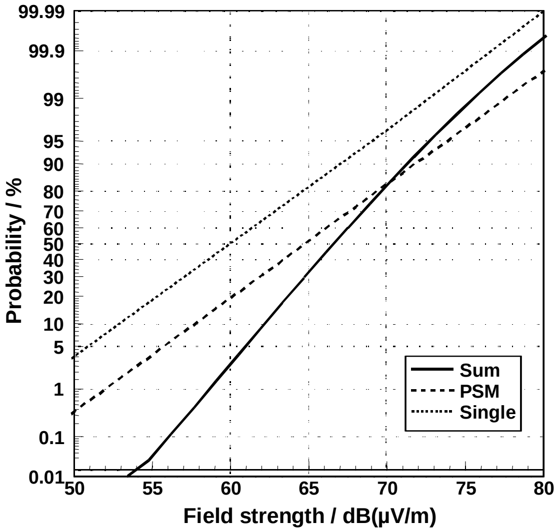
4.5.3.3. Power sum method

A description of the power sum method as applied to analogue television is given in EBU doc. Tech 3254 [11]. This method has been used for the assessment of multiple interference at several ITU conferences. The sum of the signal levels is calculated by a non statistical summation of the individual signal powers. For the unwanted signal, the powers of the mean values of the individual nuisance fields are added to the power of the minimum field strength (representing the noise contribution). For the wanted signal in an SFN, the powers of the individual useful fields are added. A 50% location coverage is obtained if the sum of the unwanted signal levels equals the sum of the wanted signal levels.

For digital services, a margin must be added to the resulting nuisance field in order to cover more than 50% of the locations. This margin is related to the target percentage of locations. Its value is not derived by the power sum method. Usually a value derived from the standard deviation of a single signal is used.

The method gives acceptable results for a 50% locations target but shows a poor behaviour for higher percentages due to its non-statistical character. Figure 4.8 gives an example of this in the case of three equal, non-correlated log-normal fields. The solid line represents the sum distribution (exact result). Its non-constant slope indicates the deviation from log-normal behaviour. For comparison, the dotted line represents the distribution of each one of the equal contributing fields. The third, dashed line, denoted by PSM, represents the result calculated by the power sum method; it is a good approximation between about 70 - 90% outage, corresponding with 10% - 30% coverage probability, which is generally of little interest for coverage purposes.

If the fields represent useful signals, Figure 4.8 gives the outage probability - which is the complement of the coverage probability - with regard to a threshold field strength, e.g. minimum field strength.



F_i = 60 dBµV/m, σ_i = 5.5 dB, i = 1, 2, 3

Figure 4.8: Sum distribution of 3 fields

4.5.3.4. Simplified multiplication method

The simplified multiplication method is a statistical computation procedure which has also been used for the assessment of multiple interference, for instance at the Regional VHF/FM Broadcasting Conference (Geneva, 1984) [12].

It gives the coverage probability in the presence of several interfering signals which are assumed to be log-normally distributed with known mean values and standard deviations. The coverage area can be determined by calculating the probability for different locations. The contour of the coverage area is made up of the set of locations where the coverage probability achieves the required value.

As the effect of noise is not taken into account in the statistical treatment, over-estimation of the coverage can be expected when the levels of the interferers are low. However, it is possible to add the effect of noise at the end of the calculation process.

This method is explained in detail in EBU doc. Tech 3254 [11], but it must be noted that it is not applicable to SFN since it cannot deal with multiple useful signals.

4.5.3.5. Log-normal method

The log-normal method is an approximation method for the statistical computation of the sum distribution of several log-normally distributed variables. In a coverage calculation it gives the coverage probability of the test area under consideration. The method is based on the assumption that the resulting sum distributions of the wanted and unwanted fields are also log-normal. It is composed of several steps. First the distributions of the composite wanted (C) and unwanted (I) fields are calculated. Then the corresponding distributions of C/I and C/N are evaluated. Finally, the combination of these distributions gives the coverage probability. To some extent, the LNM is able to cope with different standard deviations of the single field distributions.

To improve the accuracy of the LNM in the high probability region (that is, a high coverage value) a correction factor can be introduced. This version of the LNM is called k-LNM. Detailed formulas of standard LNM and k-LNM are given in Annex A.

4.5.3.6. The t-LNM method

The t-LNM method is a numerical approximation method for the statistical computation of the sum distribution of several log-normally distributed variables. Its structure is similar to that of the standard LNM and it is based on the same idea, i.e. that the sum distribution of two log-normal variables is also log-normal. However, the parameters of the sum distribution are calculated in a different way and, as a consequence, are different from those of the standard LNM.

This approach leads to a higher accuracy in the high probability region (that is, a high coverage value) compared to the standard and k-LNM approaches but this must be paid for with higher mathematical complexity. The t-LNM method is able to process different standard deviations of the single fields with few restrictions. The specific case of noise may be regarded as an interference signal with a standard deviation of 0 dB.

A description of the method is given in Annex A.

4.5.3.7. Schwartz and Yeh method

The Schwartz and Yeh method is an iterative method for calculation of the characteristics of the resultant of n fields. It make the assumption that the combination of two log normal variables also has a log normal distribution (this is a common approximation) and it gives the formulas to calculate the resultant of two variables. For more than two signals an iterative process is applied. Its general approach is very similar to that of t-LNM and the accuracy of both method is comparably high. Details can be found in [13].

4.6. Coverage requirements for SFN

4.6.1. General

Coverage is a term used to describe what portion of an area (for example, this could be a country or region) where a particular broadcasting service is predicted to be receivable. Coverage is usually expressed as the percentage of location or population covered in a given area. The prediction of coverage is normally carried out using a standardised set of requirements and assumptions (as agreed at an international level normally through the ITU or the CEPT for Europe). Coverage predictions are generated to ensure that a new service can operate at maximum power whilst minimising any interference to users receiving existing services.

Coverage requirements for SFN can be considered as follows:

- The length and breadth of the coverage area in terms of the physical size. The coverage area can also be approximated conveniently as circular, in which case a radius is usually quoted.
- The height at which the coverage is required. For fixed aerial reception, the standard height is 10 m. For portable reception, the height is usually set at 1.5 m above the floor level, which applies to the ground, the first or a higher floor depending on what is the requirement. For mobile reception, the height is usually set at 1.5 m above ground level.

As a country's coverage requirements may change as technology advances or consumer demand increases, a further dimension that may need to be considered is "time" (i.e. coverage requirements may change over time, so some element of "future-proofing" may need to be built in). The addition of transmitters at a later stage can enable the coverage to be completed if this is subsequently found to be necessary.

4.6.2. Type of service and quality of coverage

It is important for an administration to decide at an early stage of the planning process how much of the territory is to be covered, for a given type and number of services which may have different quality requirements.

The type of service means fixed, portable or mobile reception, which are not mutually exclusive, as a transmission intended for portable aerials will also be easily received using fixed aerials. Similarly, a transmission intended for fixed antenna reception could be received using a portable antenna, but only over a proportionally smaller area.

The quality of coverage, often also called “location probability”, is usually described as “good” or “acceptable”. “Good” is normally understood as a location probability of 95% while “acceptable” is taken to be 70% in a test area, i.e. where at least 95% or 70% of the locations are predicted to be served.

The service type and quality does not need to be homogeneous throughout a territory. Heterogeneous coverage can be planned so that portable reception is available in a densely populated urban centre with a location probability of 95%, which decreases to say 70% (fixed reception) as one moves outwards to more sparsely populated rural areas at the periphery.

4.6.3. Shape and size of coverage area

In an SFN, all transmitters in the network use the same channel. Thus they possess a common coverage area and cannot operate independently. They require a high degree of synchronisation; the emitted signal from different transmitters must be identical in content, signal emissions must take place at the same time (or with precisely controlled delays) and the RF carriers must comply with stringent frequency precision requirements.

Spectrum usage, network design and the shape and size of coverage are all inter-related. For example, a SFN using one frequency designed to achieve nationwide coverage will probably use a different network structure than a network chain that serves the same nationwide area by means of several SFN using several frequencies on a regional basis. SFN coverage, in general, could be considered in three different sizes:

- Firstly, a national SFN, where all the stations use the same channel. Complete implementation of such a network using the same frequency depends on the co-ordination of the frequency being agreed everywhere on the country borders, which may be difficult. A national SFN must broadcast the same programme everywhere. In a synchronised SFN, the coverage provided by each transmitter is limited in practice to 60 - 70 km radius, due to the guard interval limiting the distance between transmitters. Coverage areas may need to be decoupled, for example by sufficient distance separation or shielded from each other by mountains, to minimise self interference. Thus, national SFN providing complete coverage of a country may be generally difficult because of self-interference effects, depending on the chosen system variant.
- Secondly, a regional SFN, where all the stations in a region use the same channel, but neighbouring regional SFN use different channels. So, for example, four channels could be used in total to cover the country with a regional service, on a “map colouring” basis. Sites associated with different regions broadcast different programmes some of the time or all of time. Most of the European countries currently planning for SFN foresee regional SFN with areas of up to 200 km diameter (though the size of the regions is very different from one country to another, even for countries of comparable size).
- Thirdly, a sub-regional SFN configuration, where the main station and its relays use the same channel, but the neighbouring main station within the same region uses a different channel. For example four channels could be used to cover the country with sub-regional SFN on a “map colouring” basis. Sites associated with different sub-regions broadcast different programmes some of the time or all of time.

SFN based on the main transmitter infrastructure of existing analogue networks are likely to be best suited for fixed roof-level reception. For networks that are intended for portable or mobile reception a higher transmitter density is desirable in many cases.

One significant advantage of the SFN approach is the possibility to develop dense networks. These employ a different network topology, with a large number of low power stations (for instance < 100 W effective radiated power, < 75 m effective transmitting antenna height) distributed over the service area (potentially with a main transmitter at the centre) providing a more homogeneous field strength distribution. This type of network structure is chosen to provide a high level of field strength as is in particular necessary for portable and mobile reception. Careful consideration of site height, transmitter spacing and guard interval is essential to ensure that no self-interference effects are experienced.

4.7. Limitation on SFN performance

4.7.1. Self-interference

The power of all signals in an SFN received within the time width of the guard interval is treated as useful, and contributes to the total available signal power. Outside the guard interval, only a part of the echo power is associated with the same OFDM symbol as the primary signal, and therefore contributes positively to the total useful signal power.

The other part of the echo power is associated with the previous or subsequent OFDM symbol and produces inter-symbol interference. Therefore, as the signal delay is progressively increased beyond the guard interval, the useful contribution decreases and the inter-symbol interference increases, see also chapter 2.3.

4.7.2. Maximum transmitter separation distance and maximum allotment area size

This gives rise to two restrictions imposed on SFN. Firstly, for a given receiving location, the main contributing signals in an SFN come from the nearby transmitters. In order to keep these contributions constructive the time delay between them must not exceed the guard interval remarkably, which means that neighbouring transmitters have to keep a certain upper limit for the distance between them.

Secondly, even if the maximum separation distance for neighbouring transmitters is kept, more distant transmitters in the network may contribute destructively in such a way that a maximum extension of the SFN service area must not be exceeded in order to keep the number of relevant self-interfering transmitters small.

The significance of self-interference, the resulting maximum separation distance between neighbouring transmitters and whether there is an overall maximum extension of the SFN service area depends on the chosen guard interval, the sensitivity of the system with regard to self-interference, indicated by the relevant C/N value, and the density of the transmitters in the network.

In a large SFN, it may be difficult to plan the network so that signals from transmitters a long distance away from the receiver are always of an insignificant level compared to those from nearby transmitters. This difficulty is increased because

- the signal levels from distant transmitters have to be calculated for small percentages of the time (typically 1%) to ensure that reception is protected for high percentages of the time (typically 99%) and
- the receiving aerial for portable and mobile receivers is non-directional.

The issue of limitations on SFN performance is also dealt with in chapter 3.4.4, where the impact of the choice of the guard interval length is discussed.

5. Theoretical SFN Models

5.1. General considerations

The features and properties of SFN have been described in section 3. From there it is clear that an SFN is a more complex object than a single transmitter. Many aspects of the behaviour of a SFN can only be understood as a joint effect of the properties of all transmitters in the SFN. As a consequence, the degrees of freedom inherent to a SFN are higher than the degrees of freedom that can be found in an MFN. New concepts have to be developed in order to describe these collective properties.

The concept of ‘usable field strength’, often used in single transmitter considerations, may serve as an example. In the MFN context this term describes the condition for a wanted signal for acceptable reception in the presence of multiple interference. Strictly speaking, this concept is no longer viable for SFN since in a SFN these conditions depend on the structure of the multi-path environment of the wanted signals and cannot be formulated once and for all for the whole service area. These conditions have to be evaluated individually and can therefore no longer serve for a concept like the ‘usable field strength’. In proper SFN planning, coverage is therefore described by the more general – however, less specific - concept of ‘coverage probability’ which has been described in detail in section 4.

In order to understand the behaviour of SFN, theoretical network models have been designed. These models should help to exhibit in particular those properties which are different from the well understood multi-frequency networks and, on the other hand, should suppress the accidental influence of non-relevant factors which are always present in real networks. Such factors are irregular topology of transmitter sites, non-uniform transmitter characteristics or real world topography. Of course, when a real SFN implementation is intended to be planned, these factors have to be taken into account in each individual case. But for the understanding of the generic properties of SFN they should be excluded.

Such theoretical SFN models are frequently called regular SFN. In chapter 5.2 a number of these models and where and how they are used is described. Best known is their use in the definition of so-called ‘reference networks’, a basic concept of allotment planning, which is dealt with in more detail in chapter 5.3.

5.2. Regular SFN

5.2.1. Characteristics of regular SFN

Regular networks are a tool to investigate generic properties of SFN. For that purpose accidental factors of real networks are avoided. Therefore, regular networks exhibit a high degree of geometrical symmetry and the characteristics of the transmitters in the network are often chosen to be identical. Topography is assumed to be homogeneous in such investigations, i.e. path-general methods like ITU-R Rec. P.1546 [10] are employed.

As the standard type of regular networks a hexagonal shaped structure has been established for various reasons. Hexagons exhibit a compact geometry resembling circles. It is easy to extend hexagon structures to a large area without leaving holes and they show a very high degree of symmetry. Two typical hexagon regular networks are depicted in Figure 5.1.

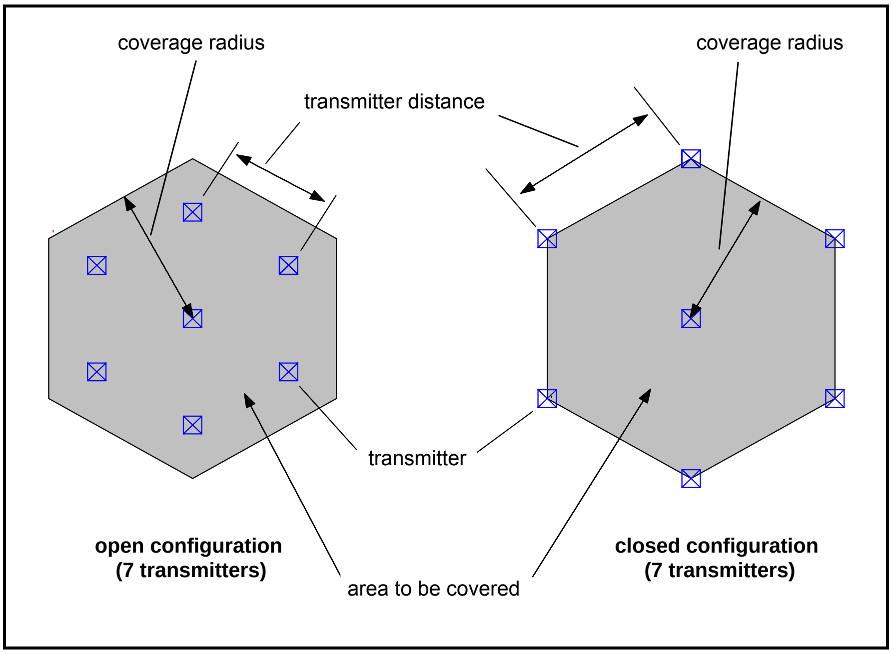


Figure 5.1: Hexagon models of regular single frequency networks

There is a further advantage of hexagon structures. Their high degree of symmetry makes computer calculations easier, since only a small part of the service area has to be calculated and the rest can be completed by repetition. This is in particular of interest when highly demanding mathematical methods are employed, as for example Monte-Carlo simulations, which need a lot of computing time.

The next three sections give examples of how regular networks have been used to investigate SFN properties.

5.2.2. Example: Self-interference in SFN

The phenomenon of self-interference is a novel aspect in SFN, not known before in broadcasting networks. Hence, the investigation of this particular aspect was one of the first and major tasks when the broadcasting sector started to deal with OFDM networks. In many of these investigations regular networks have been used in order to gain insight into the nature of self-interference.

Two examples are given here. The first example shows the impact of the inter-transmitter distance in a SFN on self-interference. A 7-transmitter hexagon network in the L-band has been chosen with a inter-transmitter distance of 15 km and T-DAB mode II has been employed. Figure 5.2 shows the coverage that is achieved with this configuration. It does by far not provide the quality that is demanded for mobile reception, i.e. 99% location probability over the whole service area. The reason is that the periphery of the service area is faced with severe self-interference problems.

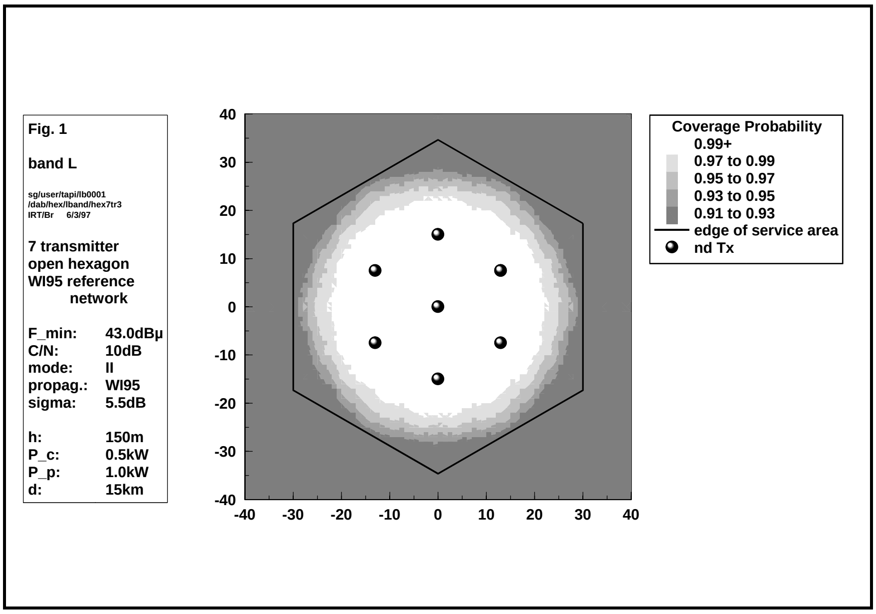


Figure 5.2: Coverage probability in a L-band T-DAB SFN

Figure 5.3 indicates that the coverage of the service area can be improved by using a different transmitter topology (moving the peripheral transmitter sites outwards). Normally, self-interference problems are overcome by increasing the transmitter density. However, the example shows that in some cases also the increase of the inter-transmitter distance may improve the situation.

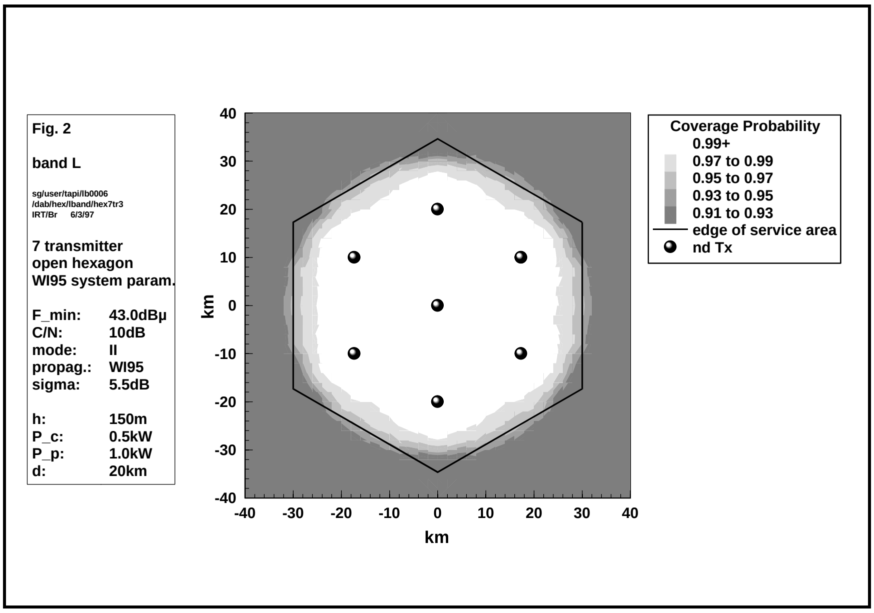


Figure 5.3: Coverage probability in a L-band T-DAB SFN. Different time delays employed

The second example shows the relation of self-interference and network size. A hexagonal SFN structure is assumed with a constant inter-transmitter distance and an increasing number of transmitters, see Figure 5.4. Firstly, only a network with 7 transmitters is investigated, secondly, a "ring" of transmitters is added resulting in a 19-transmitter network.

In the next step a further ring is added, and so on. In this way the size of the service area is increased and, as a consequence, self-interference in the network is increased, too.

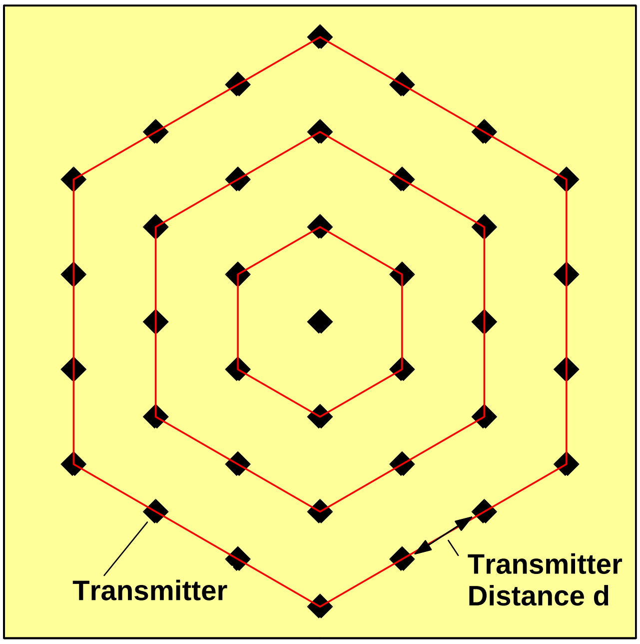


Figure 5.4: Model for the determination of the maximum size of a SFN

If the employed T-DAB or DVB-T variant is not rugged enough, then there exists an upper bound for the size of the network. Beyond that limit the self-interference degradation would be too large to guarantee for a sufficient coverage of, e.g., 95% location probability. In that way self-interference may limit the size of an SFN. Figure 5.5 gives an example for some DVB-T variants.

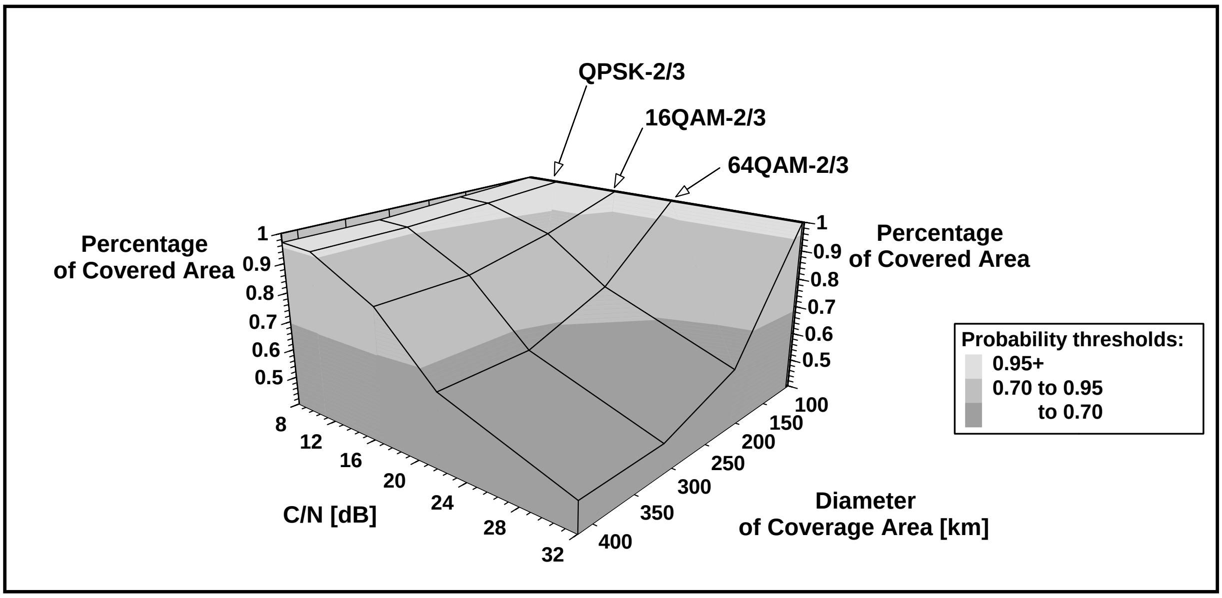


Figure 5.5: Maximum size of DVB-T SFN as a function of the employed system variant

The nature of self-interference and the restriction it imposes on the design of SFN is described in detail in sections 2 and 4.

5.2.3. Example: Synchronisation strategies of OFDM receivers

Regular networks are an appropriate means to investigate receiver behaviour by means of computer simulations. In the following example the impact of receiver window synchronisation on coverage is described.

The strategy for FFT-window synchronisation has an effect on the receiver performance in the presence of more than one signal (coming from either one transmitter or from transmitters in an SFN). In order to demonstrate how FFT-window synchronisation influences receiver performance, a regular 7-transmitter hexagonal network having characteristics similar to that of the Wiesbaden 95 Band III T-DAB reference network has been used. The network is open, and the central transmitter can be given a time offset. Specifically, T-DAB Mode I (Δ = 246 µs) is used in all the simulations shown in this example. With no time offset on the central transmitter, the area inside the hexagon is virtually free from inter-symbol interference. By applying a time offset of 300 µs to the central transmitter, a situation where ISI occurs has been deliberately created.

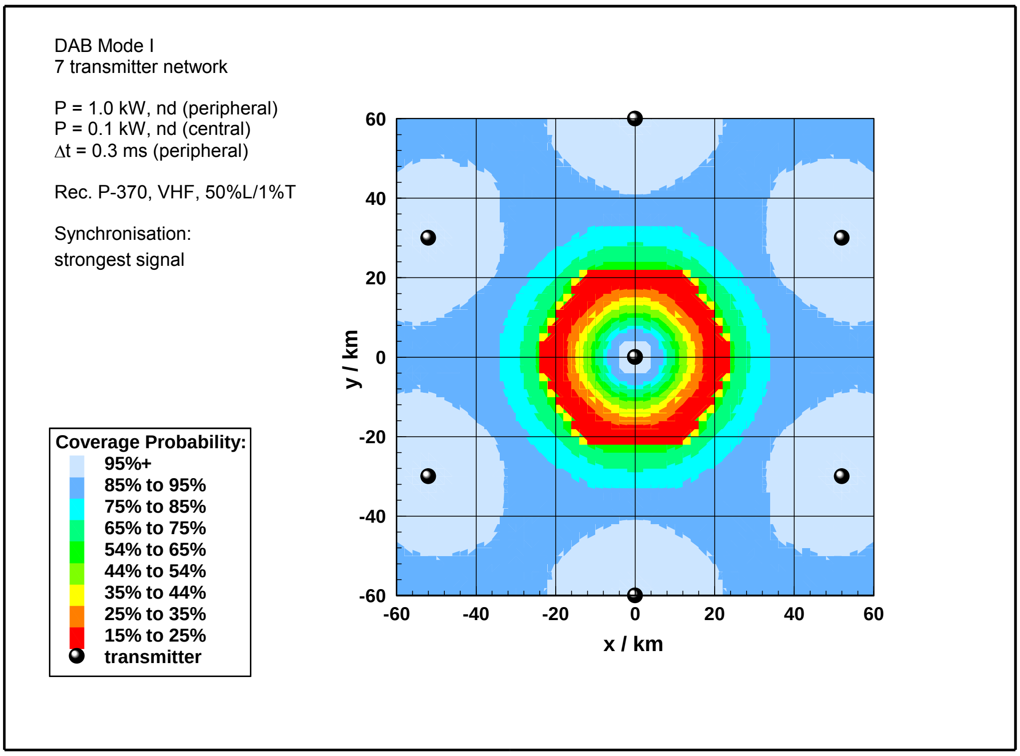


Figure 5.6: Synchronisation - Strongest Signal

Figures 5.6 and 5.7 show the results of coverage calculations for two different synchronisation strategies, "synchronisation to the strongest signal" and "synchronisation to the first signal". The differences between the two approaches can clearly be identified and the simulation may serve as a means to decide which strategy should be chosen. The matter of FFT-window synchronisation itself is dealt with in more detail in chapter 2.4.

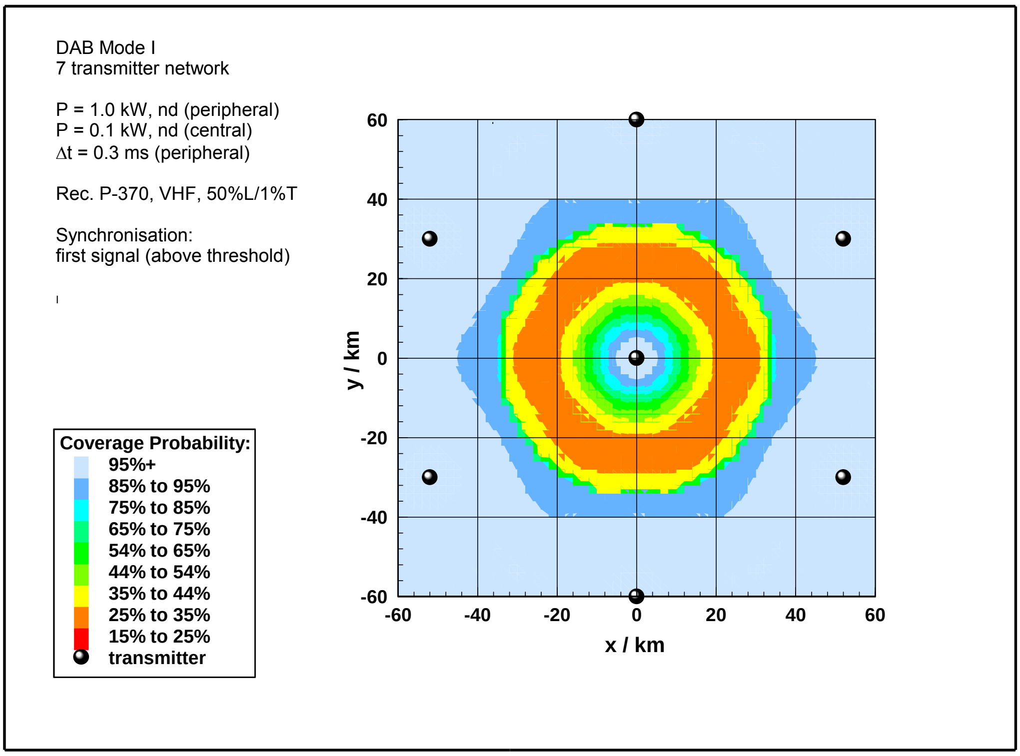


Figure 5.7: Synchronisation - "First Signal (above a threshold)"

5.2.4. Example: Separation distances for SFN and determination of spectrum requirement

The concept of separation distances, also called re-use distances, is an important tool in frequency planning for the assessment of the spectrum requirements of particular planning configurations of broadcasting systems. The separation distance describes the minimum distance that is to be kept between two co-channel service areas in order to keep the mutual interference at an acceptable level. Separation distances are generic properties of planning configurations describing average properties of real network implementations.

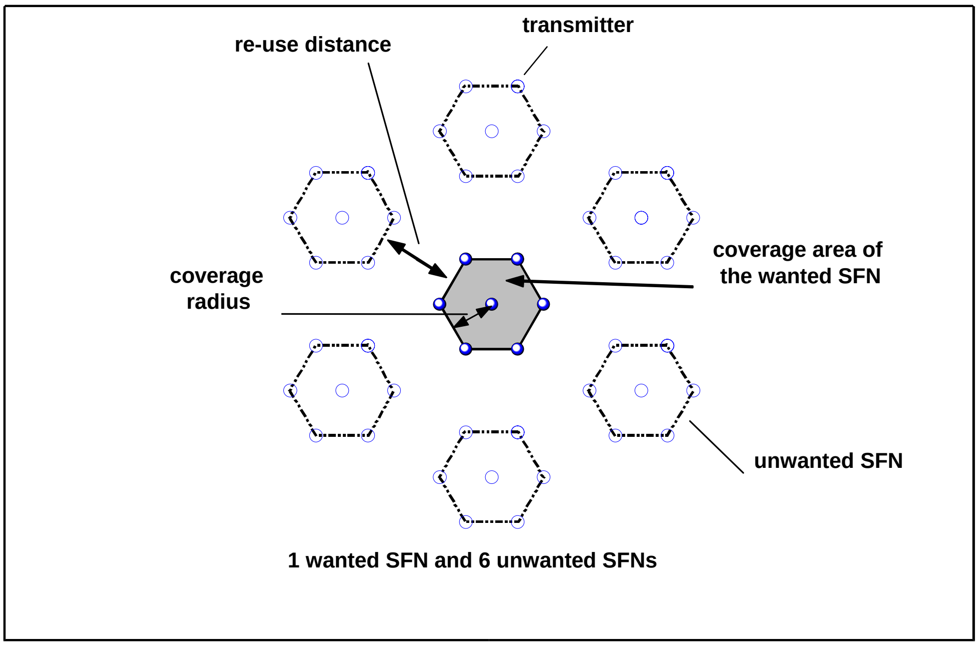
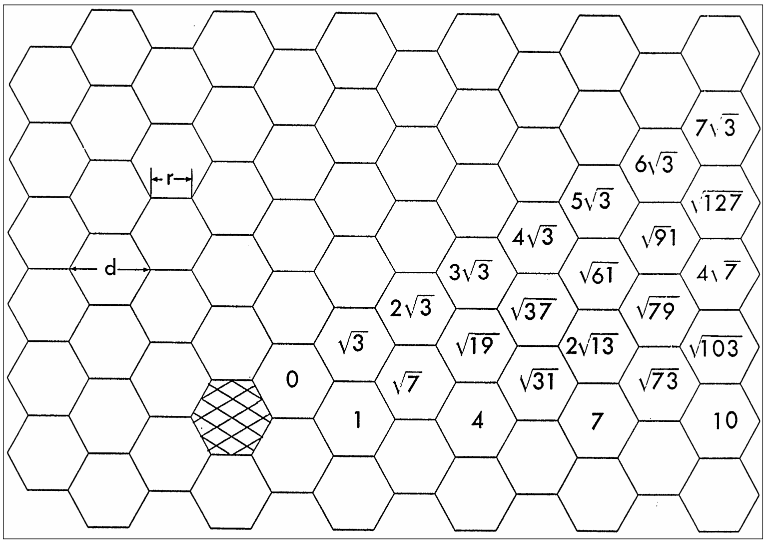


Figure 5.8: Network configuration to determine separation distances

Hence, for their evaluation typically regular networks are employed. An example is given in Figure 5.8. It consists of regular hexagonal lattices of transmitters, one wanted network and six unwanted networks. All networks – wanted as well as unwanted – are identical. They have the same effective heights, the inter-transmitter distance is the same and the networks are of the same type (closed or open). The separation distance is determined by moving the six interfering SFN towards the wanted network until the location probability in the wanted coverage area falls below the acceptable limit.

Based on the determination of separation distances, regular hexagonal network structures can be used to derive spectrum requirement figures. The relation between separation distance and network size can be used in a geometrical model, see Figure 5.9, to assess spectrum requirement figures as depicted, e.g., in Figure 5.10.



Uniform lattice of hexagonal networks. r = length of hexagon side; d (= 2r) is the ‚network size‘. The numerical values found within the hexagons indicate (as multiples of r) the shortest distance between the hexagon in question and the cross-hatched hexagon.

Figure 5.9: Model with hexagonal network structures to determine spectrum requirements

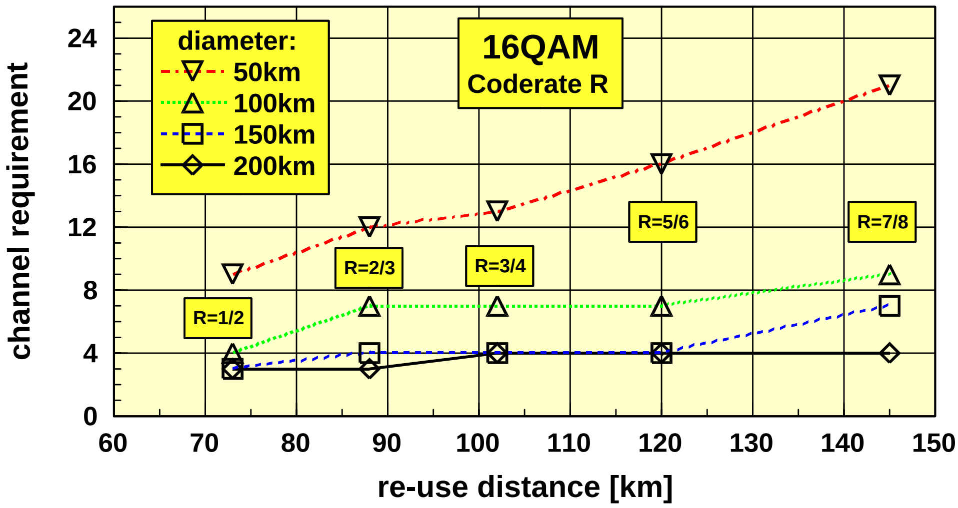


Figure 5.10: Spectrum requirement as a function of separation distance and network size

5.3. Reference networks

5.3.1. Reference networks in the frequency planning process

Theoretical SFN models as described in the previous chapters may serve in the context of a frequency planning process as reference networks. Reference networks are ideal representatives of real network implementations and are basic tools of allotment planning. They serve as planning objects in compatibility analyses, plan synthesis or coordination procedures where the real network characteristics are not (yet) known or where a detailed description of the networks is not needed. General aspects of this item are discussed in this chapter, properties of reference networks are dealt with in chapter 5.3.2, and chapter 5.3.3 describes as an example one of the reference networks that have been adopted by the RRC04. The context where reference networks are needed – allotment planning – is discussed in more detail in section 7.

A basic task when establishing a frequency plan is to perform compatibility analyses between transmitters and/or networks. For such a calculation the characteristics of the transmitters have to be known. However, there will be cases where the exact transmitter characteristics of a network will not yet be known at the time when a frequency plan is to be established. This will in particular be true for the case of SFN implementations where the service area may be already known but not yet the exact number, positions and powers of the SFN transmitters. Despite this lack of knowledge it is necessary to perform the compatibility calculations in order to establish the plan. For this purpose it is useful to define generic network structures which may act as representatives of the yet unknown real networks in a compatibility analysis. Such generic networks are called reference networks.

Reference networks are adapted to the frequency band and the intended specific reception mode of the real networks that they represent. Further aspects have to be considered with the design of reference networks: The size of the intended service has to be taken into account; the ground cover of the intended service area may have an important impact on the network implementation; a network for urban or dense urban areas will need significantly higher powers than a network for rural areas of the same size; finally, the case is to be considered when increased implementation efforts regarding transmitter locations and antenna patterns are undertaken in order to reduce the outgoing interference of the network, i.e. whether an open or a (semi-)closed network type is implemented.

Reference networks are regarded as ideal representatives of real network implementations. They exhibit a high degree of geometrical symmetry and homogeneity with regard to transmitter characteristics. They can be characterized by the following parameters:

- Transmitter number
- Transmitter distance
- Transmitter geometry
- Transmitter power
- Transmitter antenna height
- Transmitter antenna pattern
- Service area (area to be covered)

Generally, in the design of reference networks, transmitter characteristics are assumed to be the same for all SFN transmitters, i.e. all transmitters have the same power, antenna height and antenna pattern.

It has to be emphasized that real SFN implementations need by no means have the same properties as the reference networks, neither with regard to the location of the SFN transmitters nor with regard to the transmitter characteristics. Only very generic properties, as for example the interference potential, of a real network should resemble the reference network properties. This means that reference networks are never intended to be implemented in their ideal form in reality, and in particular the network structure needs not to be symmetrical as is the case with reference networks.

Reference networks are auxiliary means in order to facilitate the compatibility analysis and plan synthesis in frequency planning. Their main purpose is to determine interference potentials and interference susceptibilities of typical DVB-T and T-DAB implementations, which are the basic input for a compatibility calculation between service areas and by this fundamental for the production of a frequency plan.

The interference potential of a transmitter network is the outgoing interference that is produced by the transmitter network. If in the planning process the real interference potential of a network is not known, the interference potential of a reference network is taken as a representative of the real interference potential. For this purpose, the characteristics of the reference network and a procedure how to calculate the representative interference potential have to be defined.

Usually, the interference potential of a reference network is represented by a field strength curve which is calculated by summing the interfering field strengths of the transmitters of the reference network along a line directing outwards of the reference network and starting at the border of the service area of the reference network. An example is given in chapter 5.3.3. The summation can be performed by means of the power sum method or a statistical summation method.

In a compatibility analysis the interference potential curve is used to calculate the hypothetical interference at a certain location by assuming that the test points on the border of the service area of the network under consideration are – one by one - the source of interference. The highest interfering field strength value is then taken as the representative of the interference at that location. Of course, also a direct evaluation of the interference produced by the reference network transmitters at that location is possible in a compatibility analysis, after having defined the exact position of the reference network with regard to the boundary test point.

5.3.2. Properties of a reference network

A reference network is a basic tool used in allotment planning to assess the outgoing interference from a given allotment while achieving full coverage of the allotment area. It is a theoretical construct which usually consists of a set of reference transmitters geometrically arranged in a regular polygon, for example a square or a hexagon, etc. The dimensions of the reference polygon can be large (e.g., 100 km side length or more) or small (e.g., 20 km side length or less) or anywhere in between.

At the vertices (and also perhaps at the centre) of the reference polygon, reference transmitter characteristics are specified which will ensure adequate coverage over the entire reference network area: that is, the minimum field strength will be achieved (or exceeded) everywhere within the reference network using the characteristics of the reference transmitters. These characteristics include effective antenna height, erp, antenna pattern, and perhaps other parameters, see the example in chapter 5.3.3.

The intended coverage area of the reference network is either defined by the transmitter polygon or slightly extended beyond this polygon, typically by 10 to 20% of the polygon area diameter.

Once the coverage within the service area of the reference network is ensured, the outgoing interference produced by the reference network can be calculated. This is usually done on a power sum basis using the individual field strength contributions from the reference transmitters situated at the vertices (and centre) of the reference network. A point called the reference point is defined (on the boundary of the service area of the reference network) from which outgoing interference from the reference network is calculated (see Figure 5.15).

In order to optimise the reference network, combinations of relevant parameters are chosen which minimise the ratio of separation distance to coverage radius as much as possible, while at the same time ensuring that other network design requirements are met. One or more different reference networks can be used simultaneously in the allotment planning, while only one reference network is specified for each allotment. The size of the reference network chosen will depend to a large extent on the type of service desired.

It is often convenient to develop interference curves of reference networks based on the total combined interference issuing from the reference network itself. These derived curves, though based upon, will not be the same as the propagation curves defining the agreed propagation model, e.g., Rec. ITU-R P.1546 [10]. There will be, however, a superficial resemblance between the two. A graph showing the interference potential of a reference networks is given in chapter 5.3.3.

5.3.3. Example: A large service area reference network

As an example, the large service area DVB-T reference network adopted by the RRC04 is presented in more detail. For further explanation on this example, see ECC Report 49 [14] and the RRC04 report [8].

The reference network represents a class of networks consisting of six individual network implementations: for fixed, outdoor/mobile and indoor reception (these reception conditions being termed ‘reference planning configurations’), each for Band III and for Band IV/V. This reference network is intended for large service area SFN coverage. It is assumed that main transmitter sites with a reasonable effective antenna height are used as a backbone for this type of network. At least for portable and mobile reception the size of the real service areas for this type of SFN coverage will be restricted to 150 to 200 km in diameter because of self-interference degradation, unless very rugged DVB-T system variants are used.

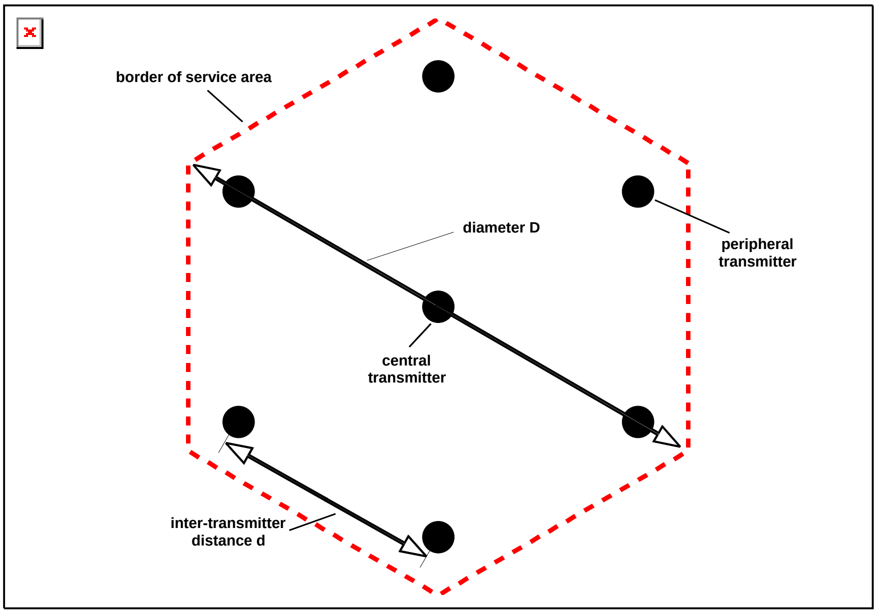


Figure 5.11: Reference network for a large service area DVB-T SFN

The network consists of seven transmitters situated at the vertices of a hexagonal lattice. An open network type has been chosen, i.e. the transmitters have non-directional antenna patterns and the service area is assumed to exceed the transmitter hexagon by about 15%. The geometry of the network is given in Figure 5.11.

Reference planning configuration (RPC)		RPC 1	RPC 2	RPC 3
Type of network		Open	Open	open
Geometry of service area		Hexagon	Hexagon	hexagon
Number of transmitters		7	7	7
geometry of transmitter lattice		Hexagon	Hexagon	hexagon
Inter-transmitter distance d/km		70	50	40
Service area diameter D/km		161	115	92
Tx antenna height/m		150	150	150
Tx antenna pattern		non-directional	non-directional	non-directional
ERP / dBW	Band III	31.1 + Δ	33.2 + Δ	37.0 + Δ
	Band IV/V	39.8 + Δ	46.7 + Δ	49.4 + Δ

The interference margin Δ is chosen to be 3 dB

Table 5.1: Parameters of the large service area DVB-T SFN

As the guard interval length the maximum value 1/4 T_u of the 8K FFT mode has been chosen. The inter-transmitter distance in an SFN should not exceed by too much the distance equivalent to the guard interval length. In this case the guard interval length amounts to 224 μs which corresponds to 67 km. The inter-transmitter distance for a fixed roof-level reception has been chosen to be 70 km. For portable and mobile reception, 70 km seems to be too large a distance from a power budget point of view. The powers of the transmitters would have to be up to several hundred kW in the case of portable indoor reception which seems not to be reasonable. Therefore, smaller values for the inter-transmitter distance have been selected, 50 km for mobile reception and 40 km for portable indoor reception. Table 5.1 gives the parameters and the power budgets of this class of reference networks.

The power budgets have been calculated on a noise-limited basis. In order to allow for interference-limited planning, a interference margin of 3 dB is adopted.

As an example, Figure 5.12 gives the coverage probability of the least covered pixel in the service area as a function of the radiated power in the network for the portable outdoor reception case in Band IV/V. The indicated power is that of one transmitter. The curves serve as a means of determining the necessary power budget in order to achieve everywhere across the service area the intended coverage probability.

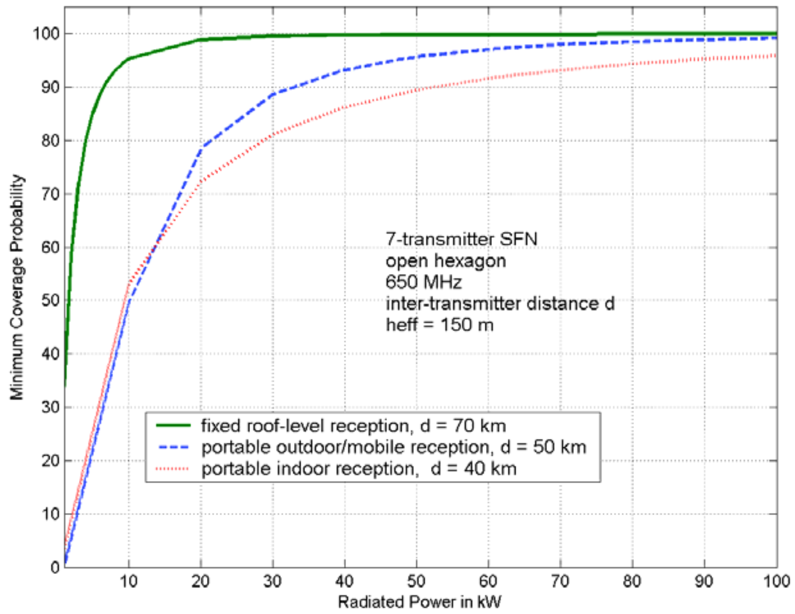


Figure 5.12: Determination of the power budget

Figure 5.13 shows a coverage plot of the reference network. The position of the 7 transmitters can clearly be identified. The pattern of the coverage probability exhibits the hexagonal symmetry of the network. The coverage probability does not fall below 95% across the whole service area.

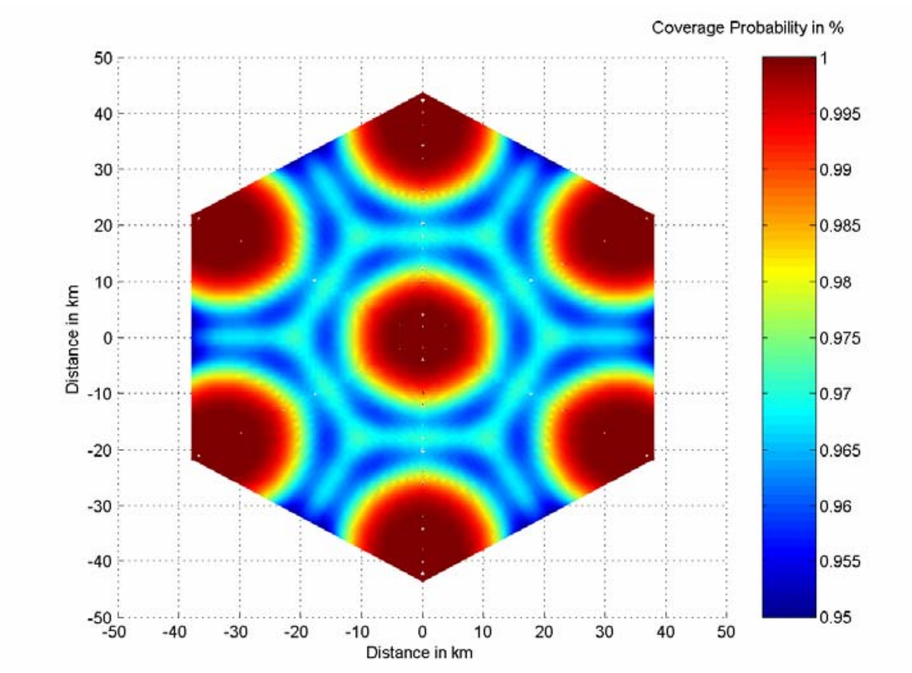


Figure 5.13: Coverage probability plot for RN 1, portable indoor reception, Band IV/V

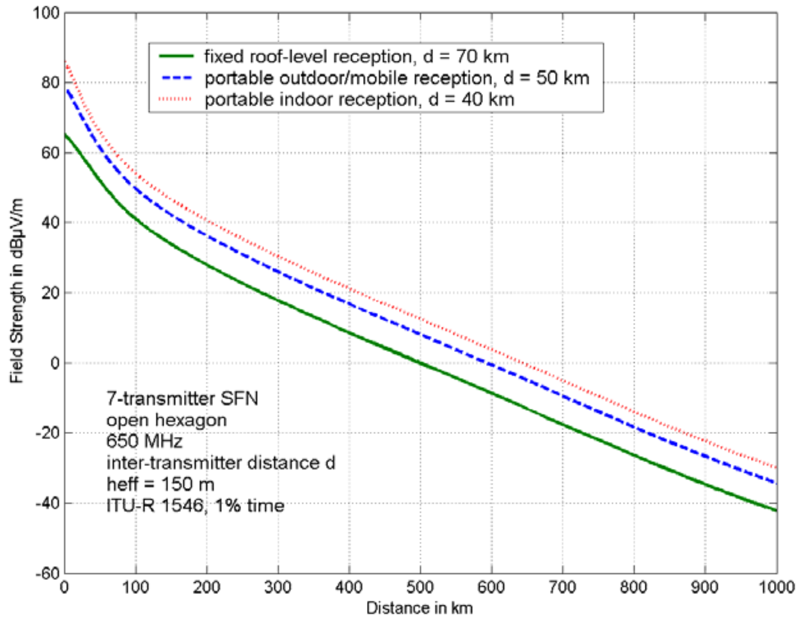


Figure 5.14: Interference Potential, Band IV/V, land path

Figure 5.14 gives as an example the corresponding interference potential of the reference network. Figure 5.15 below explains how the interference potential may be calculated, see also chapter 5.3.2.

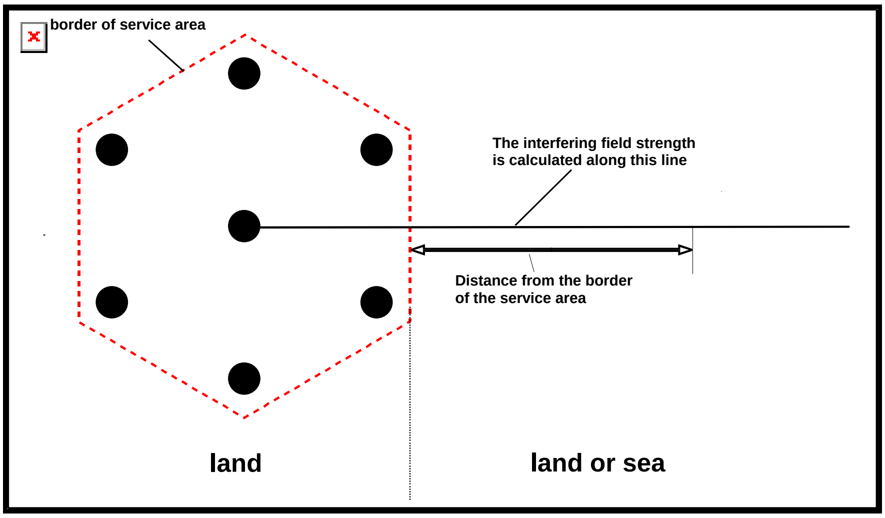


Figure 5.15: Calculation of the interference potential

6. Implementation

6.1. General

The implementation of any particular single frequency network is unlikely to be identical to any other. Factors such as terrain, population distribution and coverage requirements will vary and have a significant impact on network design and implementation. The text which follows is intended to provide some guidelines and practical advice on the design and development of a network. This section can not be entirely comprehensive and planners should use their own knowledge and judgement on which parts are appropriate to their needs.

In the DVB-T case, before planning commences the question of where in the analogue to digital transition period the work is being carried out should be considered. The transition period may lead to the need for a step-wise implementation of the network as analogue services migrate to digital.

6.2. Service requirement definition

To begin the planning process a precise definition of the service to be designed is required. It is quite possible that a long time period will have elapsed between the agreement of the SFN allotment, say at RRC06, and its implementation many years later. A change to the service requirements could easily have an effect on the usability of the original allotment. For instance:

- Is the reception mode still the same? – Is a change from fixed to portable, or vice-versa, required?
- Is the allotment size still appropriate for the need? – An increase in size is likely to be problematic, whereas a reduction should lead to easier implementation.
- Does any change mean that the proposed system variant or SFN size is no longer appropriate?

As well as having a frequency and an area attributed to them, all coordinated allotments have a right of implementation defining their in-coming interference environment and the allowable level of out-going interference they can cause. Provided that the overall out-going interference is not increased a different implementation could be used. However, if there has been a significant change how can it be accommodated? It may be possible to resolve the situation by one or more of the following:

- Re-coordinating the allotment with some or all of those neighbouring administrations which might be affected.
- The size or reception mode of the wanted service may be changed to enable the required coverage, whilst remaining compliant with international constraints
- The transmitter network may be made denser, thereby providing higher wanted field strengths whilst maintaining the level of out-going interference
- The planner may also need to achieve a coverage target for the proposed service, for example:
- Is the service to cover a specific geographic area, a certain level of population or both? If so on what basis will this be defined and measured?
- What type of service is to be delivered? – Mobile, portable, fixed or possibly even a mixture, such as portable in urban areas and fixed in rural ones.
- Might the requirement change over time?
- If a number of multiplexes are being planned are they all expected to have similar coverage areas?

6.3. Site selection and management

Once the planner has a definition of the service requirements the next stage is to consider what resources are available and what sort of transmission network will be required to deliver it. Chapter 3.3 gives guidance regarding some of the different types of network structures which could be implemented.

The first requirement of any terrestrial broadcast network is the sites at which it is to be implemented. Are the existing broadcast sites sufficient to facilitate the service or are others likely to be required? In some cases more sites will be needed for a digital service than for an analogue one due to the requirement to deliver services to a higher percentage of locations and the use of more difficult reception modes. When considering sites the following criteria should be considered:

- What sites are presently available?
- Existing broadcast sites used at high powers for analogue services may not be appropriate for implementing some types of SFN coverage, due to their distance from population centres and the large distances over which they can cause out-going interference.
- Are rooftop sites within towns and cities more appropriate for delivering the required coverage? Although there may be concerns over high field strengths in populated areas.
- There may be economic advantages using particular sites, for example those already used for broadcasting.
- Is aperture available at the site? If not it may be possible to combine some services, for instance VHF FM and DAB services may be able to share aerial aperture.
- Is there an existing antenna at the site and if so can this be shared? This may not be the case if allotments using the site have different constraints, service areas or implementation rights.
- Consideration might also be required when trying to serve population centres at the edge of an allotment, for example in coastal areas.
- It is becoming more difficult to achieve approval for the use of new sites due to the perceived EMC hazards.

Where multiple services are present in the same area some further considerations may need to be taken into account:

- Whilst adjacent channel digital services can operate in the same area, care should be taken to avoid interference between them. Interference may occur to other services around a transmitter site from which only one of the services is transmitted. In most cases this problem can be resolved by site sharing, even if the services have very different radiated powers and aerial patterns.
- Different types of network, both in terms of size of coverage (local, national etc.) and reception mode may require significantly different transmitter network configurations. This difference may in turn lead to adjacent channel interference problems.
- If a number of different multiplexes are expected to have similar coverage areas, but have very different frequencies allocated to them, use of the same transmission parameters for each will not necessarily deliver this. To facilitate similar coverage differing radiated powers, and possibly, aerial systems may be required.
- It is likely that the interference environment of different frequencies will vary.

6.4. Coverage and interference management

6.4.1. General

In an ideal situation the planner can design a network which delivers the required coverage whilst keeping outgoing interference within the levels allowed for the coordinated allotment. However, in reality achieving an acceptable final result will often require a number of compromises, these may not all be of a technical nature.

Whilst the allotment will have been planned to have an acceptable level of in-coming interference it would be advisable to calculate what the actual level is. This will give the minimum usable field strength for the wanted service over the coverage area. This calculation may be difficult to quantify exactly especially where interference comes from unimplemented allotments.

The coverage and interference planning process normally involves a number of steps which may form an iterative loop. The main steps being the calculation of wanted coverage and out-going interference.

6.4.2. Wanted coverage prediction

In order to start the process a calculation of the wanted coverage should be made. Initially this should only be the coverage provided from the primary sites selected for the service, on the basis that they are likely to be the main sources of out-going interference. Account should be taken of the following factors during the prediction process:

- transmitter powers
- aerial directionality, both in azimuth and the vertical plane
- aerial height
- polarisation
- network gain; see chapter 4.4 of this report.
- the level of background interference
- the reception mode
- initial signal launch delay

When a good level of coverage is achieved from these sites proceed to the stage described in chapter 6.4.3 below.

6.4.3. Out-going interference management

6.4.3.1. General

Having achieved a good level of coverage from the primary sites the next step is to make your own calculation of the level of out-going interference. There is little point spending a significant period of time producing a final network design at this stage. This is because if the out-going interference is unacceptably high the proposed network will need to be modified significantly. There are different methods of calculating the out-going interference from T-DAB and DVB-T allotments; these are considered in the two following sub-sections below.

If the out-going interference exceeds the required limit some steps will need to be taken to resolve the problem. Whilst the options are similar to those available for analogue systems they are detailed below.

- Reduce the radiated power at the worst sites.
- Increase directional restrictions – either in azimuth or VRP.

- Change one or more of the primary sites.
- Can other sites with more terrain shielding be used?
- Can international co-ordination be carried out to increase the allowable levels of out-going interference?

Most of these options will have an impact on the wanted coverage. As a result some amount of re-planning will be required before re-calculating the outgoing interference.

Once the levels of out-going interference and the coverage are acceptable the final network plan should be completed. Since it is expected that the rest of transmitters will be of a lower power or cause less out-going interference they should not cause any significant co-ordination problems. However, it would be advisable to re-calculate the level of the overall network before proceeding further.

6.4.3.2. Calculation of out-going T-DAB interference

For T-DAB out-going interference is calculated to a set of test points generated specifically for the purpose. Details of the test points and their use are given in chapter 7.4.2 of this report. In the T-DAB case it may be possible to relax interference levels at some test points, for instance where they lie either in the sea or within your own country boundary.

6.4.3.3. Calculation of out-going DVB-T interference

In the DVB-T case there is no agreed method of calculating out-going interference yet. The allowable levels of out-going interference caused by an allotment are agreed through bilateral and multilateral agreements between the administrations concerned. This means that there may be different methods of calculating the levels of interference and different field strength limits imposed.

6.5. Co-ordination phase

Once the network plan is finalised it will need to be formally communicated to relevant neighbouring countries for either coordination or notification. This aspect is covered in section 7 of this report.

6.6. Implementation of the transmitter network

6.6.1. General

Once co-ordination is successfully completed the transmitter network can be implemented. At this point some additional transmitter characteristics specific to SFN will need to be considered. These are the self-interference caused within the network and transmitter synchronisation.

6.6.2. Self-interference

In a large SFN it is possible for signals to arrive from distant transmitters outside the guard interval of more local ones. This is described as the self-interference of the network. Chapter 4.7 and chapter 6.6.3 gives more details about this issue. Although it may only occur for short percentages of time it does need to be considered. Self-interference can be reduced by either advancing or delaying the launch of the service from some transmitters in relation to some fixed reference.

6.6.3. Transmitter synchronisation

6.6.3.1. General

In order for an SFN to operate correctly all of the transmitters in the network need to be synchronised with on another. This requirement is true in both the frequency and time domains.

6.6.3.2. Frequency synchronisation

The frequency accuracy of the digital transmitter will normally be very stable. However in order to minimise any drift all transmitters should be locked to a reference source, for instance the time signal of GPS.

6.6.3.3. Timing synchronisation

6.6.3.3.1. General

In order to reduce intra-network interference it is possible to adjust the time at which a specific signal frame is launched from each transmitter of the network, the relative transmitter timing. Optimising this delay allows the signals from both near and distant transmitters to arrive at the receiver within the guard interval, thus being constructive rather than destructive. The relative transmitter timing can be adjusted to be either in advance of or after the reference point.

However, in all cases the time of signal transmission at each transmitter of the network needs to be referenced to a time reference. Distribution of the service content also needs to be considered so that the same data frame is transmitted during the same time period, either with or without any required delay. Over a large, e.g. national, network the arrival of the content information to transmitters may vary significantly. One option is to feed the content signal directly to the network sites using satellite distribution.

In a small SFN, i.e. one that is not larger in diameter than the signal can travel in the guard interval, it should not be necessary to consider this element of network planning.

When initially designing the network configuration the planner needs to predict both the wanted coverage and the interference potential of each transmitter. These predictions should be carried out at 50% time for the wanted service and 1% time for the interferer. With the relative timing delay set to zero the coverage of the whole network can be derived. At which point the overall interference caused by each transmitter into the SFN can then be calculated.

In general it will be the highest power assignments which will cause the most interference and it is reasonable to focus on them initially. However, adjusting the timing of sites with lower erps can lead to significant coverage gains around the periphery of their service areas.

Once the destructive transmitters have been identified the network timings can be adjusted and the interference recalculated. It should be noted that the transmitter causing the greatest interference may not be the one to adjust since a change may simply cause a problem in a different part of the network. It may be a better strategy to retard the smaller site(s) so that their signals are received within the guard interval of the distant high power site.

Consideration should also be given to how receiver FFT implementation affects prediction models. However, since manufacturers are reluctant to disclose details of how their receivers operate it is difficult to give guidance on the matter.

Chapter 3.4.4 gives more information on guard intervals and this aspect of SFN planning, and chapter 2.4 gives further information on FFT aspects.

6.6.3.3.2. DVB-T

There are numerous variants of DVB-T each with a specified guard interval. Choice of the correct system variant at the planning stage is critical so that one appropriate to for SFN usage can be agreed.

6.6.3.3.3. T-DAB

In the case of T-DAB operating in mode I the guard interval is 246 µS, which equates to a distance of around 75 km. In reality this long distance means that intra-network interference is unlikely to occur over all land paths. Interference problems will generally only occur over long sea paths where higher field strengths will be present than for a similar length land path.

6.6.3.4. Effect of synchronisation loss

If a transmitter is allowed to drift out of synchronisation with the rest of the network it will become a source of interference to the coverage of the rest of the network. This will be noticeable as an area of lost coverage toward the periphery of the un-synchronised transmitter's service area, a "mush" zone. As the transmitter drifts further out of synchronisation with the rest of the network the mush zone will become progressively larger. It should be noted that reception close to the drifting transmitter, where received field strengths are high, are unlikely to be affected.

6.7. Post implementation of the network

6.7.1. Network coverage and improvement

Once the network is in operation some consideration of the following might be appropriate:

- The coverage delivered by the network could be measured in order to confirm that any planned target has been achieved.
- Measurements to confirm that network self-interference is managed correctly.
- Shortfalls in predicted coverage may be filled by the addition of additional gap filling transmitters.
- Gap filling transmitters can also be built to compensate for environmental changes, such as the construction of new buildings.

6.7.2. Network problems

As mentioned in chapter 6.6.3 the transmitters of an SFN need to be synchronised in order to prevent self-interference. If a fault occurs it is possible for a transmitter to loose this synchronisation. The effect is that the transmitter will slowly move out of phase with the ones which surround it and become a source of destructive interference. This will result in a narrow ring of lost coverage developing around, but kilometres away from, the faulty transmitter, although users near to it are unlikely to notice a problem. In the T-DAB case some mobile listeners may only notice a small zone of lost coverage as they pass through it. A fault like this may take a significant time before it manifests itself, and before being identified could have an impact over a significant area.

Changes to coverage may occur due to seasonal variations, such as snow causing reflection points. Problems of this type are extremely difficult to resolve.

The implementation of a new transmitter for service operating on an adjacent channel may cause a problem to an existing service. In such cases users may lose a service for no apparent reason and receivers may still display information for services which are no longer available. This problem can be resolved through the use of a transmitter co-sited with the interferer or avoided through agreements between operators to use common sites.

7. Frequency Planning and Coordination Aspects

7.1. General

In a general sense, coordination of DVB-T-SFN and of DVB-T-SFN transmitters follows the same lines and rules as are well known from the procedures of coordination for analogue broadcasting services. However, some of the new features of DVB-T and T-DAB have also an impact on the way the new digital services are to be coordinated.

The allotment approach is often felt as the more appropriate way to describe SFN service areas in coordination procedures, since for an SFN the coverage area is a unique and undividable object which corresponds in the allotment approach with the envisaged service area.

7.2. Planning approaches

7.2.1. Assignment planning

In the past, terrestrial television planning (and most other broadcasting) in Europe has been implemented by way of assignment conferences. In assignment planning, a significant amount of individual station planning is needed to prepare for a planning conference.

In assignment planning, a specific channel is assigned to an individual transmitter site location with defined transmission characteristics (for example, radiated power, antenna height, etc.). At the completion of the assignment plan, the locations and characteristics of all transmitters are known and the transmitters can be brought into service without further coordination.

Assignment planning, based on a lattice structure, for terrestrial digital television is appropriate where all the transmitter sites can be assumed to have the same characteristics. This is not to say that station characteristics are fixed for all times. For example, the ST61 Agreement [1] allows for some flexibility and indeed there have subsequently been many modifications and additions to the Plan.

The assignment plan provides a frequency for each station and at the completion of the assignment planning process the locations and characteristics of the transmitters in the planning area are known. The transmitters can be brought into service without further coordination.

For practical reasons a lower limit for the radiated power is normally defined for stations to be dealt with in the planning process. Stations with a radiated power below the limit are then included in the plan subsequently. For example in 1961 the lower limit was set to 1 kW for VHF stations and to 10 kW for UHF stations.

7.2.2. Allotment planning

The possibility of obtaining allotments at a terrestrial broadcasting conference has received attention in recent years, particularly because of the opportunities offered by SFN. Allotments may also be applicable for MFN planning where a country has no plans to use specific transmitter sites and wishes to retain some flexibility for the future.

In allotment planning a specific channel is “given” to an administration to provide coverage over a defined area, called the allotment area. The parameters required for planning are the allotment area, the channel and the interference potential of the allotment. Transmitter sites and their characteristics are unknown during planning and should be defined at the time of the conversion of the allotment into one or more assignments.

Thus in order to carry out planning it is necessary to define some reasonably realistic reference transmission conditions, which represent the potential interference which could be caused, so that any necessary compatibility calculations can be made. These are called reference networks and chapter 5.3 provides more detailed consideration of them.

The resulting allotment plan shows the frequencies to be used in particular areas without specifying the stations to which the frequencies are assigned.

7.2.3. The link between allotment and assignment planning

An assignment plan contains the detailed transmitter data from the day it is established and therefore allows for implementation immediately when the plan comes into force. However, subsequent changes to the network are likely to require coordination with relevant neighbours.

The coverage area of an assignment can be mapped to an allotment by approximating its coverage area as appropriate. However, the assignment planning approach implicitly defines some form of coverage.

In order to implement an allotment, it is necessary to convert the allotment into individual transmitter assignments. The detailed technical characteristics of the transmitters are normally planned subsequent to a planning conference, but can also be established during a conference, if required. Each allotment may then contain several transmitters forming an SFN or, in the simplest case, a single transmitter. Due to the definition of an allotment the transmitters, or transmitter, may subsequently be modified without coordination providing that the outgoing interference does not exceed that which is permitted to the allotment by the plan.

It is likely that the RRC06 planning conference will have to deal with both allotments and assignments in an appropriate manner. This is essential if allotments are to be included, as it is reasonably certain that the conference will have to allow for continued operation of analogue assignments following the conference. In both cases, the network structure could be SFN, MFN or a mixture of the two.

It is important to stress that an allotment should not be seen to be inevitably associated with “national coverage” nor with SFN as the only possible network structure. Recent planning for T-DAB has demonstrated that allotments can be an appropriate method for planning small, or even very small, areas.

7.3. Allotment plans

7.3.1. Characteristics of an allotment

In allotment planning a specific channel is allocated to an administration to provide coverage over a defined area, called the allotment area. The parameters required for planning are the allotment area, the channel and the interference potential of the allotment. Transmitter sites and their characteristics are unknown during planning and should be defined at the time of the conversion of the allotment into one or more assignments. Conversion here denotes the regulatory action to be undertaken by an administration when a real SFN is implemented in an allotment.

Thus, in order to undertake planning it is necessary to define some reasonably realistic reference transmission conditions, which represent the potential interference which could be caused, so that any necessary compatibility calculations can be made. The resulting allotment plan shows the frequencies to be used in particular areas without specifying the stations to which the frequencies are assigned.

Thus an allotment is characterized by:

- A service area, normally defined by a polygon whose vertices are given by geographical coordinates.

- The service type, reception mode and network type (all together often called 'reference planning configuration') that are intended to be implemented in the allotment area.
- A channel, that is assigned to the service area and which can be used within the service area
- A prescription that restricts the interference potential of the network operating in that service area to a certain level.

7.3.2. An Example: The Maastricht 2002 T-DAB Allotment Plan

Following an agreement of the CEPT administrations to plan for additional L-band frequencies for T-DAB, supplementary to those available at the Wiesbaden 1995 conference, a planning conference took place at Maastricht in June 2002 [15].

The purpose of the conference was to allocate a single L-band frequency block to each allotment area (input requirement) defined by the participating administrations. This allocation was to be in addition to those given at Wiesbaden, although the Wiesbaden frequencies could also be used where available. This would give three layers of T-DAB coverage over every country, in addition to any allotments co-ordinated post Wiesbaden.

At Maastricht there were three different reference networks available, including the one defined for the Wiesbaden conference, upon which input requirements were based. The reference networks were designed to serve areas of different sizes and had different levels of allowable incoming and outgoing interference. Administrations were required to choose the reference network which were most appropriate for their required service area.

Initial planning calculations indicated that very few requirements could be accommodated. In order to resolve this a number of steps were required:

- The compatibility analysis software used at the conference specified the level of restriction needed to allow requirements to operate co-block. Where the incompatibility was in the order of a few dBs agreements could be made between the allotments of the administrations concerned. In many cases this meant agreements were needed between two requirements of a single administration.
- In some cases higher levels of predicted incompatibility could be agreed upon, for instance where significant terrain shielding was available.
- The type of reference network proposed for a requirement could be changed to reduce the levels of out-going interference.
- Requirements could be merged to reduce the overall number of frequencies required in an area.

After a number of planning runs, each followed by further negotiations and adjustment to the input requirements, a final Plan was arrived at. A snapshot of which is shown in Figure 7.1. It shows only a small part of the whole plan and each colour represents a specific frequency block.

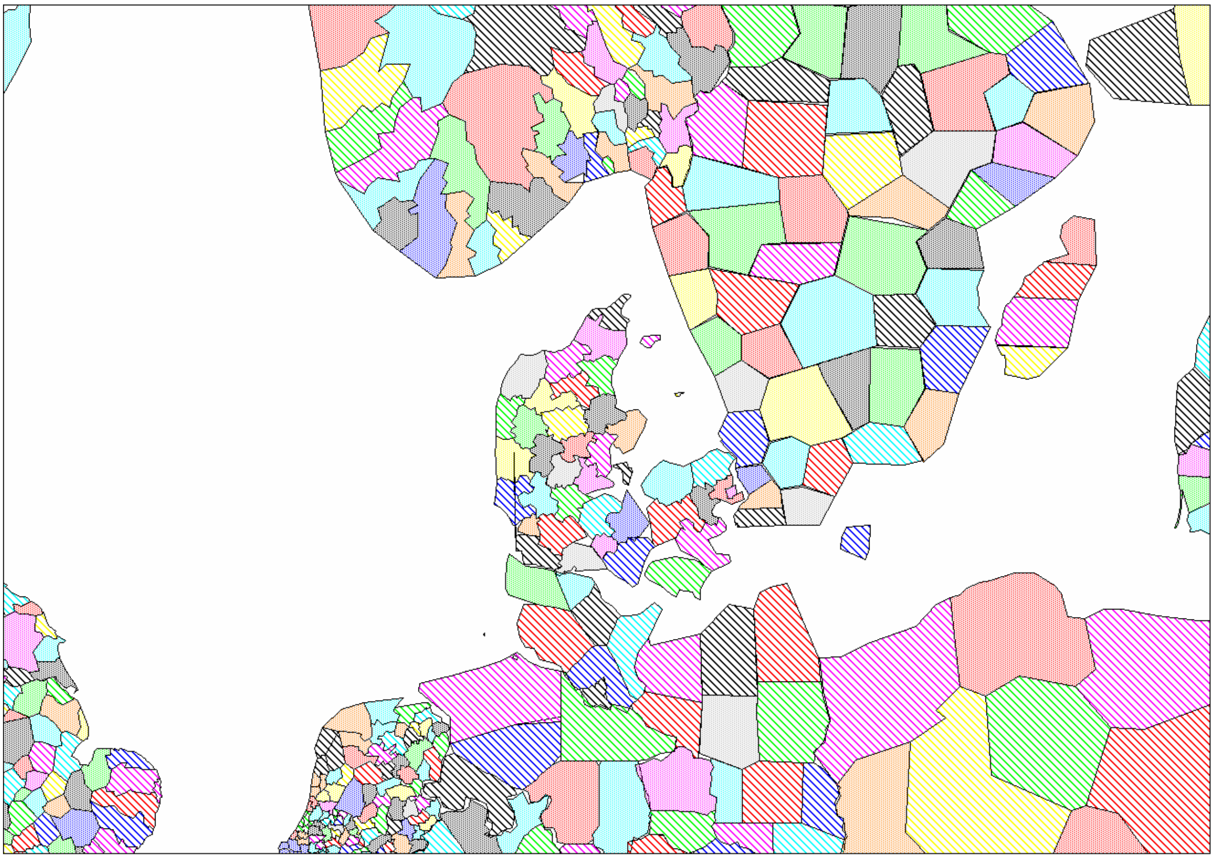


Figure 7.1: Part of the allotment Plan agreed at the 2002 Maastricht conference

7.4. Co-ordination of allotments

7.4.1. Co-ordination of a DVB-T allotment

Prior to the RRC06 there are no DVB-T allotments and no agreed method of co-ordinating them. In order to implement a DVB-T SFN the Chester Annex 6 conversion procedure [16] described in chapter 7.5.1 needs to be applied.

7.4.2. Co-ordination of a T-DAB allotment under the Wiesbaden 1995 and Maastricht 2002 Agreements

As with all broadcast services there are two methods of seeking international approval for an assignment. The first being through a planning conference to agree an overall plan and the second for individual transmitters on an ad-hoc basis through a formally agreed procedure. The same is true for T-DAB, although in the T-DAB case it is an allotment which is initially agreed. A co-ordinated allotment defines an area, a frequency and a right of implementation in terms of the allowable levels of both out-going and in-coming interference. However, with an allotment there is also the requirement to achieve additional agreement for the conversion from an allotment to a set of assignments.

In order to start the co-ordination process an available frequency and a set test points which define the T-DAB requirement are needed. The requirements were defined by up to 36 locations given as a latitude and longitude pair which form a polygon around the proposed service area. If a national service is required the country boundary could be requested, although in reality it is unlikely that a frequency would be available for a large country in a mature plan.

The requirement details are forwarded to the plan management body (PMB), in the T-DAB case this is the ERO, for publication. A set of calculation test points will also be derived for the requirement. For consistency the calculation test points are generated by the PMB and distributed to all administrations. These test points can also be generated from the alloment data using the freely available ERO DAB Computer Analysis (or DACAN) software [17]. At the calculation test points the field strength of the reference network will have decayed to 27 dBμV/m. However, in the case of T-DAB to T-DAB the interference from the real transmitter network may be allowed to sum to 33 dBμV/m. Article 4 of the Maastricht Agreement [18] describes how receiving administrations should deal with allotment co-ordination requests.

After publication the affected administrations have 12 weeks to consider the request and respond to the requesting administration accordingly. If agreement is reached the allotment enters the plan. However, before implementation the allotment will need to be converted into a set of assignments which may need further co-ordination before implementation, this aspect is discussed in chapters 6.3.1, 6.3.2 and 7.5.2.

7.5. Co-ordination of SFN

7.5.1. Co-ordination of a DVB-T SFN

At present there are no allotments for DVB-T and any SFN needs to be co-ordinated under the rules defined at the CEPT conference held at Chester in 1997 [16]. More accurately, they form a conversion from an existing analogue assignment to a digital SFN. The following sections summarize the Chester 1997 coordination procedures for new and converted SFN.

New SFN

When an administration proposes to put into operation a new SFN i.e. not appearing in the Stockholm 1961 plan as an analogue assignment, the following action is taken:

If the distances from one of the stations forming the SFN under consideration to the nearest points of the boundaries of other countries are less than limits agreed in Chester 1997 (corresponding to the proposed power and effective antenna height of the station), the administrations of those countries shall be consulted regarding all the stations of the SFN which have not already been coordinated.

Converted SFN

When an Administration proposes to convert an analogue television broadcasting station, shown in the Stockholm 1961 plan, into a DVB-T SFN, the following action is taken:

If the distances from one of the stations forming the SFN under consideration to the nearest points of the boundaries of other countries are less than limits agreed in Chester 1997 (corresponding to the proposed power and effective antenna height of the station), the administrations of those countries shall be consulted regarding all the stations of the SFN which have not already been coordinated.

Rules for SFN Conversions

Chester 1997 also contains rules for the conversion of an analogue station into an SFN. Administrations are meant to undertake a conversion analysis based on:

the nuisance field strength of the original analogue assignment not being exceeded by the power sum of the nuisance field strengths of the converted digital assignments forming the SFN, and

the power sum of the field strengths of the converted digital assignments forming the SFN being at least 7 dB below the field strength of the original analogue assignment.

If these conditions are not met then the proposal should be treated as a new SFN proposal and not a conversion.

Bilateral Agreement of SFN
Ultimately, coordination of SFN (and any new or modified television transmitter) can only be agreed bilaterally between administrations. The practical experience of some CEPT administrations in implementing the Chester 1997 agreement, with regards to bilateral coordination of SFN, can be outlined as shown in the steps below.

1. Agree test points and calculate the reference usable field strength at each test point using agreed methods.

2. Sum the characteristics of each transmitter in the SFN using a signal summation method (some of which are described in chapter 4.5.)

3. Calculate the interfering (nuisance) field strength at the same test points due to the SFN, using a bilaterally agreed method such as ITU-R Rec. P.1546 [10] with or without terrain.

4. If the increase in the resulting usable field strength is less than 0.3 dB, the request should normally be accepted.

5. If the increase in the resulting usable field strength is more than 0.3 dB, discuss the situation bilaterally, and maybe adjust the characteristics of individual transmitters in the SFN to accommodate agreed restrictions or to minimize interference to particularly sensitive test points or areas.

Repeat steps 1 to 5 as many times as necessary in order to obtain coordination agreement (or not as the case may be in which case the administration in question will need to revise its plans).

7.5.2. Coordination of a T-DAB SFN

In order to convert an allotment to an SFN a set of transmitter characteristics are required. Section 6 gives guidance on how to plan such a network. Once the initial transmitter network is designed it is useful to use the agreed Bonn summation method, which is part of the Wiesbaden 1995 Agreement [18], to derive the field strengths at the calculation test points of the allotment. The example below gives details of how to do this.

Explanation of the Bonn Summation Method
The individual field strength produced by each transmitter of the real network should be determined using the field strength prediction method specified in the Appendix of the Final Acts of the CEPT T-DAB Planning Meeting Maastricht, 2002, [18], at each of the allotment's calculation test points. The value of the determined individual field strength should be modified, where relevant, by taking account of any receiving antenna discrimination. The cumulative interfering field strength of the entire transmitter network is calculated by the power sum method, with the result rounded to one decimal place as explained below. Only the interference from the allotment being converted into assignments will be taken into account.

The individual field strengths obtained at any test points from all transmitting stations of the T-DAB allotment are processed in decreasing order. The power sum is obtained as follows:

1. starting from the highest, the power values equivalent to the interfering field strengths are added, one after the other;
2. at each summation, the result is compared to the previous one;
3. if the increase in power is greater than or equal to 0.5 dB, the summation process continues;
4. if the increase in power would be less than 0.5 dB, the summation process is stopped and 0.5 dB is added, giving the result of the power sum;
5. repeat for all calculation test points.

If all resulting power sums at every location do not exceed 33 dBµV/m the requesting administration can notify the PMB of it's intention to convert the allotment. If any test point exceeds 33 dBµV/m full co-ordination is required. The primary difference between notification and co-ordination is that the former should take six weeks less to complete. However, a receiving administration may carry out its own calculations and consider that co-ordination is required and hence trigger the requirement for full co-ordination.

If a calculated field strength at a test point is significantly greater than the 33 dBµV/m it may be worth considering adjusting the characteristics of one or more transmitters in the network to reduce this. However, the co-ordination procedure does specify that when considering requests for co-ordination, administrations should note that it is difficult, when planning real networks, to avoid exceeding the field strength from a reference network by small amounts (1 to 2 dB), at a small number of test points. It also says that such cases should be considered in a spirit of co-operation during the co-ordination process.

The following example of a Bonn Summation is taken from the UK case study in Annex B.7.

Example:
For a single calculation test point, with a T-DAB allotment converted into a network of 5 assignments, transmitters 1 to 5, the power summation process would be as detailed below:

Note: The first stage of the summation process is to sort the transmitters in order of decreasing equivalent field strength.

The corresponding power factor, power summation and conversion back to the resulting equivalent field strength are calculated according to the formulae below:

Formulae used:

Corresponding Power Factor	$P_f = 10 \wedge^{(E_n\ /\ 10)}$
Power Summation	$\sum_p = P_{fn} + P_{fn+1}$
Corresponding Equivalent Field Strength	$E_{ps} = 10 \log (\sum_p)$

Transmitter	Equivalent Field strength E_n (dBµV/m)	Corresponding Power Factor P_f	Progressive Power Sum $\sum_p$	Corresponding Equivalent Field Strength E_{ps} (dBµV/m)	Increase (dB)	Comment	Resulting Equivalent Field Strength (dBµV/m)
Tx 3	13.55	22.65	22.65	13.55		Continue summation	13.55
Tx 4	12.73	18.75	41.40	16.17	2.62	Increase due to this Tx will be more than 0.5 dB, so continue.	16.17
Tx 2	11.88	15.42	56.81	17.54	1.37	Increase due to this Tx will be more than 0.5 dB, so continue.	17.54
Tx 5	11.21	13.21	70.03	18.45	0.91	Increase due to this Tx will be more than 0.5 dB, so continue.	18.95
Tx 1	8.31	6.78	76.80	18.85	0.40	Increase due to this Tx will be less than 0.5 dB, so add 0.5 dB and stop summation.	19.45

Table 7.1: Example of the Bonn summation method

8. Case studies on SFN implementation

8.1. General

A relevant part of this report contains case studies of SFN simulations which have been performed in different countries. The studies highlight the different aspects that are important for practical DVB-T and T-DAB SFN implementations. Chapters 8.2 to 8.8 summarize the main issues that are addressed in the studies. The complete documentation of these studies is given in Annex B.

8.2. Netherlands : Solving some problems in DVB-T single frequency networks (2001)

The studies describes solutions for improving DVB-T coverage in cities by planning more dense SFNs and solutions for reducing internal network interference by a combination of artificial delays and additional fill-in stations.

8.3. Switzerland: Coverage in digital single-frequency network: Theoretical case study (2003)

The study investigates the coverage potential of a DVB-T SFN based on the transmitter infrastructure of three existing analogue transmitters. A number of DVB-T variants are examined with regard to their usability for fixed roof-level and portable indoor reception. FFT-window synchronisation techniques as well as the improvement of the coverage by use of transmitter time delays are discussed.

8.4. Finland: SFN-coverage in Lapua and Vaasa (2003)

A mini-SFN consisting of two transmitters with a distance of 77 km is examined in this study. The network is operated with the DVB-T variant 64QAM-2/3 with a guard interval of 1/8. In this situation self-interference is not negligible and the study investigates its impact on the coverage. The results of the computer simulation are compared with measurements.

8.5. Germany: DVB-T – Network structures and costs for full coverage (2001)

The study investigates the possibilities to implement a regional SFN for portable indoor DVB-T reception. The region was chosen in the north of Germany where the topography is flat. Major issues of the study are the question to what extent the existing analogue network infrastructure can be re-used and the cost aspect. The network comprises up to 10 transmitters. MFN as well as SFN approaches are investigated. The study concludes that on the basis of the existing infrastructure a portable indoor coverage of the whole region can be achieved for a target location probability of 70%. The cost reduction for the provision of one programme could be up to a factor of 4 as compared to the current analogue programme provision.

8.6. Sweden: SFN experience in Sweden (2003)

The study shortly summarizes main aspects and problems that are encountered in the DVB-T SFN implementation in Sweden. In particular it deals with network structure aspects and echo delay handling.

8.7. Singapore: A commercial DVB-T mobile network in Singapore (2004)

A short introduction is given to the implementation of a commercial DVB-T mobile network that has been built in Singapore in the year 2000.

8.8. United Kingdom: Planning T-DAB networks in the United Kingdom (2004)

A report is given to the planning methodology of both public and commercial Band III T-DAB networks which have been implemented in the United Kingdom. These range in size from local networks a few tens of kilometres in diameter using two or three transmitters to the BBC national network service which has been planned to serve the whole of the UK, a north-south distance of some 900 km.

9. Sources / References

[1] ITU-R: Regional Agreement for the European Broadcasting Area Concerning the use of Frequencies by Broadcasting Service in the VHF and UHF Bands, Stockholm, 1961

[2] ITU-R: Final Acts of the Regional Administrative Conference for the Planning of VHF/UHF Television Broadcasting Area and Neighbouring Countries, Geneva, 1989

[3] W.C.Y.Lee: Mobile Communications Engineering. McGraw Hill, New York, 1982

[4] T.S.Rappaport: Wireless Communications. Prentice Hall, New York, 1996

[5] ETSI: Standard EN 300 744 - Digital Video Broadcasting DVB; Framing structure, channel coding and modulation for digital terrestrial, 2001

[6] ETSI: Standard EN 300 401 - Radio Broadcasting Systems; Digital Audio Broadcasting (DAB) to mobile, portable and fixed receivers, 2001

[7] EBU: BPN047 - Planning Criteria for Mobile DVB-T, Geneva, 2002

[8] Resolutions of the First Session of the Regional Radiocommunication Conference for planning of the digital terrestrial broadcasting services in parts of Regions 1 and 3 in the frequency bands 170 – 230 MHz and 470 – 862 MHz Geneva, 10 – 28 May 2004

[9] ETSI: Tech. Rep. TR 101 190 - Digital Video Broadcasting DVB; Implementation guidelines for DVB terrestrial services; transmission aspects, 1997

[10] ITU-R: Rec. P.1546 - Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz, Geneva, 2003

[11] EBU: Doc. Tech. 3254 - Planning parameters and methods for terrestrial television broadcasting in the VHF/UHF bands , Geneva, 1988

[12] ITU-R: Final Acts of the Regional Administrative Conference for the Planning of VHF Sound Broadcasting (Region 1 and Part of Region 3), Geneva, 1984

[13] S.C. Schwartz and Y.S. Yeh: On the distribution function and moments of power sums with lognormal components. The Bell System Technical Journal, 61(7), 1982.

[14] CEPT: ECC-Report 49 - Report on technical criteria of digital video broadcasting – terrestrial (DVB-T) and terrestrial- digital audio broadcasting (T-DAB) allotment planning, Copenhagen, 2004

[15] CEPT: Final Acts of the CEPT T-DAB Planning Meeting (4) Maastricht, 2002.

[16] CEPT: The Chester 1997 Multilateral Coordination Agreement relating to Technical Criteria, Coordination Principles and Procedures for the introduction of Terrestrial Digital Video Broadcasting (DVB-T) Chester, 25 July 1997

[17] CEPT: DACAN No 7 – DAB Computer Analysis, CEPT T-DAB Frequency Plan, EROSoft, Copenhagen, 1998

[18] CEPT: Final Acts of the CEPT T-DAB Planning Meeting (3) Maastricht, 2002. The Wiesbaden 1995 Special Arrangement, as revised in Maastricht 2002

[19] NAG: - Numerical Algorithm Group: http://www.nag.co.uk/numeric/numerical_libraries IMSL Numerical Libraries: http://www.vni.com/products/imsl

[20] M. Abramowitz, I. Stegun: Handbook of Mathematical Functions. http://jove.prohosting.com/~skripty/

Further information on the issues dealt with in this report can be found in:

R. Beutler: Frequency assignment and network planning for digital terrestrial broadcasting systems, Boston, Kluwer, 2004

A. Ligeti: Single Frequency Network Planning. Thesis, KTH, 1999, Stockholm

U. Reimers: DVB - The Family of International Standards for Digital Video Broadcasting, 2nd edition, Berlin, Springer, 2004

EBU: BPN003: Technical Bases for T-DAB Services Network Planning and Compatibility with Existing Broadcasting Services, 3rd edition, Geneva, 2003

EBU: BPN005: Terrestrial Digital Television. Planning and Implementation Considerations, 3rd edition, Geneva, 2001

EBU: BPN020: Implementing T-DAB Networks. Problems and Solutions, Geneva, 1999

EBU: BPN028: Regional and Local Sound Broadcasting Services in the Digital Era, Geneva, 2000

EBU: BPN033: Ideas on Migration from Analogue to Digital Television in the European Broadcasting Area, Geneva, 2001

EBU: BPN038: Report from Ad-hoc group B/CAI-FM24 to B/MDT and FM PT24 on Spectrum Requirements for DVB-T Implementation, Geneva, 2001

EBU: BPN043: Issues concerning DVB-T and T-DAB in Band III, Geneva, 2001

EBU: BPN053: Planning Methods for Use at a Conference, Geneva, 2003

EBU: BPN059: Impact on Coverage of Inter-Symbol Interference and FFT-window positioning in OFDM receivers, Geneva, 2003

ITU-R: Rec. BT.1368-4 - Planning criteria for digital terrestrial television services in the VHF/UHF bands, Geneva, 2004

ITU-R: Report to the first session of the regional radiocommunication conference for planning of the digital terrestrial broadcasting service in parts of Region 1 and 3, in the frequency bands 174-230 MHz and 470-862 MHz, Geneva, 2003

The EBU Technical Review has published many articles on T-DAB and DVB-T dealing with system, network planning and frequency planning aspects: http://www.ebu.ch/en/technical/trev/trev_home

Annex A:

A. Summation methods

A.1. Numerical methods

A.1.1. General

In chapter 4.5 calculation methods for signal summation and the evaluation of coverage probabilities are described comprising numerical as well as analytical approaches. Annex A gives details of these approaches.

Numerical methods in general provide a better accuracy than analytical methods, however they take more time. On the other hand, reference situations could preferably be done by numerical methods such as the Monte Carlo simulation without leading to a time problem, because they are carried out only once.

A.1.2. Numerical Integration

Numerical integration can be performed with the help of standard quadrature routines which are contained in commonly available mathematical libraries, for instance, the NAG or IMSL libraries [19].

A.1.3. Monte Carlo Simulation

An alternative approach is the treatment by means of a Monte Carlo (MC) simulation, which will be described in more detail. A sample of some 10,000 to 50,000 reception situations, for each small area calculation within the coverage area, yields reliable statistics.

Suppose there are given:

> n wanted logarithmic fields F_i^w with Gaussian distribution
(parameters $\overline{F}_i^w, \sigma_i^w, i = 1 \ldots n$),

> m logarithmic interfering fields F_k^{int} with Gaussian distribution
(parameters $\overline{F}_k^{int}, \sigma_k^{int}, k = 1 \ldots m$),

> a protection ratio PR and noise N;

all quantities are given in dBs and represent system values, i.e. do not include probability margins.

The task is then to find the corresponding protection margin or coverage probability:

1. Using a random number generator, produce n sets:

$$\{F_{ij}^w, j = 1 \ldots s\}, i = 1 \ldots n,$$

   with Gaussian distribution (parameters $\overline{F}_i^w, \sigma_i^w$) for the n wanted fields,

   where s is the number of field strength values contained in each set.

2. Using a random number generator, produce m sets:

$$\{F_{kj}^{int}, j = 1 \ldots s\}, k = 1 \ldots m,$$

   with Gaussian distribution (parameters $\overline{F}_k^{int}, \sigma_k^{int}$) for the m interfering fields.

3. Transform the field strengths F_{ij}^w and F_{kj}^{int} to powers P_{ij}^w and P_{kj}^{int}:

$$P_{ij}^{w} = 10^{F_{ij}^{w}/10}, \quad P_{kj}^{int} = 10^{F_{kj}^{int}/10}.$$

4. Calculate the power sum of the wanted signals:

$$P_{j}^{w} = \sum_{i=1}^{n} P_{ij}^{w}, \ j = 1 \ldots s.$$

5. Calculate the power sum of the interfering signals and add noise, where noise, N (absolute value), is derived from the difference between the minimum field strength, F_{min} (logarithmic value) and the required carrier to noise ratio, R (logarithmic value):

$$P_{j}^{int} = N + \sum_{k=1}^{m} P_{kj}^{int}, \ j = 1 \ldots s,$$

where $N = 10^{\frac{(F_{min}-R)}{10}}$

6. Evaluate the signal-to-(noise + interference) ratio:

$$\frac{P_{j}^{w}}{P_{j}^{int}}, \ j = 1 \ldots s.$$

7. Transform the signal/(noise + interference) ratio to logarithmic scale:

$$\left(\frac{C}{I+N}\right)_{j} = 10 \log_{10}\left\{\frac{P_{j}^{w}}{P_{j}^{int}}\right\}, \ j = 1 \ldots s.$$

8. Sort the set $\left\{\left(\frac{C}{I+N}\right)_{j}, \ j = 1 \ldots s\right\}$ and extract the distribution density $g\left(\frac{C}{I+N}\right)$ by normalisation.

9. Derive from $g\left(\frac{C}{I+N}\right)$ the probability distribution $P\left(\frac{C}{I+N}\right)$.

10. The value of P at $\frac{C}{I+N} = PR$ gives the coverage probability CP at the location under consideration.

If only the margin for a given percentage of locations is wanted, then it is not necessary to carry out the last three steps (8, 9 and 10). Instead, after step No 6 above, perform the following:

6.1 Sort the set $\left\{\frac{P_{j}^{w}}{P_{j}^{int}}, \ j = 1 \ldots s\right\}$ and extract the value for the wanted location probability.

6.2 Transform the signal/(noise + interference) ratio to logarithmic scale:

$$\text{Margin}\,\textit{(\%location)}\,(\text{dB}) = 10 \log_{10}\left\{\frac{P^{w}}{P^{int}}\right\}\textit{(\%location)}.$$

A.1.4. Computation aspects

Both approaches, numerical integration as well as the Monte Carlo simulation, need a considerable computational effort which is inconvenient for practical coverage calculation purposes. Therefore, it is desirable to have approximations allowing for an analytical or at least a fast numerical treatment.

A.2. Analytic approximations

A.2.1 General

Many analytic approximations to the solution of the summation of statistical field strengths have been developed. Details of some of these are given below.

It should be noted that in the case of fields having greatly different standard deviations, it may lead to incorrect results if ‘low’ fields are omitted from the calculations if they have a ‘high’ standard deviation. This situation could give rise to the largest field values at small % of locations. This does not apply to the power sum method.

A.2.2. Power sum method

The power sum method is a procedure for the approximate calculation of the mean value of a sum field. If the mean value of the (logarithmic) field strength of a single signal is denoted by $\overline{F}$ and is expressed in dBµV/m, its power P (in absolute units) is given by

$$P = 10^{\frac{\overline{F}}{10}}.$$

For n individual fields, the respective powers are added:

$$P_\Sigma = \sum_{i=1}^{n} P_i .$$

and the mean value $\overline{F}_\Sigma$ of the (logarithmic) sum field strength is calculated as:

$$\overline{F}_\Sigma = 10 \times \log_{10}(P_\Sigma)$$

For the unwanted signal, the powers of the mean values of the individual nuisance fields are added to the power of the minimum field strength (representing the noise contribution). For the wanted signal in an SFN, the powers of the individual useful fields are added. A 50%-location coverage is obtained if the sum of the unwanted-signal levels equals the sum of the wanted-signal levels.

For T-DAB and DVB-T, a margin must be added to the resulting nuisance field in order to cover more than 50% of the locations. This margin is related to the target percentage of locations. Its value is not derived by the power sum method. Usually a value derived from the standard deviation of a single signal is used.

A.2.3. Simplified multiplication method

The simplified multiplication method gives the coverage probability in the presence of several interfering signals which are assumed to be log-normally distributed with known mean values and standard deviations. The coverage area can be determined by calculating the probability for different locations. The contour of the coverage area is made up of the set of locations where the coverage probability achieves the required value.

As the effect of noise is not taken into account in the statistical treatment, over-estimation of the coverage can be expected when the levels of the interferers are low. However, it is possible to add the effect of noise at the end of the calculation process.

The method is explained in detail in EBU doc. Tech 3254 [11], but it must be noted that it is not applicable to SFN since it cannot deal with (the power addition of) multiple useful signals.

A.2.4. The LNM method

The log-normal method is an approximation method for the statistical computation of the sum distribution of several log-normally distributed variables. The method is based on the assumption that the resulting sum distributions of the wanted and unwanted fields are also log-normal. To some extent, the LNM is able to cope with different standard deviations of the single field distributions.

To improve the accuracy of the LNM, a correction factor can be introduced. This version of the LNM is called k-LNM. As can be seen from step 4 in chapter A.2.6 below, k-LNM is identical to the standard LNM if the factor k is equal to 1.

A.2.5. LNM related methods

In the following sections, two approximations, k-LNM and t-LNM, are described. k-LNM differs only slightly from the standard LNM approach by the additional use of a correction factor k, enabling more accurate results to be obtained for the distributions of the summed fields in the probability range of interest for coverage calculations (e.g. 95% or 99% location probability). The t-LNM method offers greater accuracy, at the expense of increased calculation time and complexity.

A.2.6. k-LNM

The approach assumes that the distribution of the sum of log-normally distributed statistical variables can be described by a new log-normal distribution, the mean value and standard deviation of which are taken to be identical with those of the true sum distribution:

$$M^{approx.}_{power} = M^{true}_{power}\,,\; S^{approx.}_{power} = S^{true}_{power}\quad ,$$

where M and S denote mean value and standard deviation of the respective log-normal power distribution. The approximation is based on the fact that for all kind of distributions mean value and standard deviation of the distribution of the sum of individual statistical vairiables are given by the sums of the mean values and standard deviations of the individual statistical variables.

Since the resulting approximate sum distribution is log-normal, it can be combined again with a third log-normal distribution, and so on, thus enabling the construction of an approximate distribution of n log-normally distributed statistical variables. This procedure can be performed analytically.

k-LNM suffers from the drawback that the appropriate correction factor k depends on the number, the powers and the variances of the fields being summed, as well as the location percentage for which the calculation is being done. To obtain optimal results, an interpolation table for the derivation of the value of k would be necessary, which is not suitable for a heuristic approach like k-LNM. Therefore, to keep the simple and analytic character of the approximation, an average value of k is chosen, derived from a sample of representative field configurations. This simplification still results in an inaccuracy for a few, none the less typical, configurations which amount to some dBs for 99% locations. For the summation of fields with standard deviations between 6 and 10 dB the value k = 0.5 seems to represent a fair compromise. For smaller values of standard deviations a higher value for k should be used, e.g. k = 0.7.

If k is set to 1.0, k-LNM is identical to the standard LNM approach. This choice should be taken for the summation of interfering fields, since for these the low probability domain is of interest.

Following, the method is described in detail:

Suppose there are given:

> n logarithmic fields F_i with Gaussian distribution (parameters $\overline{F}_i, \sigma_i$, $i = 1 \dots n$), i.e., the corresponding powers are log-normally distributed.

The task is to determine the approximate log-normal distribution of the power sum, or, equivalently, to find the parameters of the Gaussian distribution of the corresponding logarithmic sum field:

1. Transform $\overline{F}_i, \sigma_i$, $i = 1 \dots n$, from dB scale to Neper scale (this avoids nasty constants in the calculation):

$$X_{Neper} = \frac{1}{10 \times \log_{10}(e)} * X_{dB} \ .$$

2. Evaluate the mean values M_i and the variances S_i^2 of the n power distributions:

$$M_i = e^{\overline{F}_i + \frac{\sigma_i^2}{2}}, \quad S_i^2 = e^{2\overline{F}_i + \sigma_i^2} \times \left(e^{\sigma_i^2} - 1\right), \quad i = 1 \dots n, \qquad \text{(Neper scale)}$$

3. Determine mean value M and variance S^2 of the sum power distribution:

$$M = \sum_{i=1}^{n} M_i, \quad S^2 = \sum_{i=1}^{n} S_i^2, \qquad \text{(Neper Scale)}$$

4. Determine the distribution parameters $\overline{F}_\Sigma$ and σ_Σ of the approximate log-normal sum distribution:

$$\sigma_\Sigma^2 = \log_e\left(k\frac{S^2}{M^2} + 1\right), \quad \overline{F}_\Sigma = \log_e(M) - \frac{\sigma_\Sigma^2}{2}, \qquad \text{(Neper Scale)}$$

5. Transform $\overline{F}_\Sigma$ and σ_Σ from Neper scale to dB scale:

$$X_{dB} = 10 \times \log_{10}(e) * X_{Neper} \ .$$

$\overline{F}_\Sigma$ and σ_Σ are the mean value and the standard deviation, respectively, of the Gaussian distribution of the logarithmic sum field.

EXAMPLE

In the following example the evaluation of the parameters of the sum distribution of three identical fields is demonstrated and the numerical values of the intermediate results of steps 1 to 5 are given. The parameters are chosen to be 60 dBμV/m for the mean values of the distributions of the logarithmic fields and 5.5 dB for the standard deviations. The k-factor is set to k = 0.7.

1.1	$\overline{F}_i^{(dB)} = 60.000, \quad \sigma_i^{(dB)} = 5.500,$	i = 1,2,3	(dB scale)
1.2	$\overline{F}_i^{(Neper)} = 13.816, \quad \sigma_i^{(Neper)} = 1.266,$	i = 1,2,3	(Neper scale)
2.	$M_i = 2.230 \times 10^6, \quad S_i^2 = 1.975 \times 10^{13},$	i = 1,2,3	(Neper scale)

3. $M = 6.689 \times 10^{6}$, $S^{2} = 5.925 \times 10^{13}$, (Neper scale)

4.1 $\overline{F}_{\Sigma}^{(Neper)} = 15.388$, $\sigma_{\Sigma}^{2(Neper)} = 0.656$, $\sigma_{\Sigma}^{(Neper)} = 0.810$, (Neper scale)

4.2 $\overline{F}_{\Sigma}^{(dB)} = 66.830$, $\sigma_{\Sigma}^{(dB)} = 3.517$, (dB scale)

A.2.7. t-LNM

More accuracy within the framework of the LNM can be obtained with the t-LNM approach. It approximates the distribution of the logarithmic sum field strength by a Gaussian distribution which possesses the same mean value and the same variance as the true distribution:

$$M^{approx.}_{fieldsstrength} = M^{true}_{field\,strength}, \quad S^{approx.}_{field\,strength} = S^{true}_{field\,strength} \quad .$$

This approach gives a better description of the true sum distribution, in particular, of its lower tail as compared to the k-LNM approach, where the equality of the mean values and the variances of the powers is assumed.

Since the resulting approximate distribution is Gaussian, as are the distributions of the individual fields, the method allows for the successive construction of the distribution of the logarithmic sum field strength built from n single fields.

A difficulty for the approach arises from the fact that M and S cannot be calculated analytically. As a consequence, an extensive interpolation table (some 1000 values) has to be prepared by means of numerical integration or Monte Carlo simulation for a reasonable range of possible field strength values and standard deviation values. The basic evaluation for two fields can then be performed by trilinear interpolation (t-LNM Version V1). By replacing the two trilinear interpolations by three bilinear interpolations further computational improvement can be obtained (t-LNM Version V2).

Once the interpolation table has been set up, the method is easily applied with a computational effort similar to that of the analytical standard LNM. The benefits of the approach are given by its high accuracy (1 - 2 dB for the 1%-fractile) and its applicability to a large variety of field configurations.

A.2.8. t-LNM (V2)

This method of computing the sum field from component field parameters (mean, variance) which provides a reduction of computational load compared to earlier versions of t-LNM. The principal structure of computing the sum field by combining the n-th component field with the sum of the fields 1 to n-1 by means of interpolation tables has been retained. By exploiting the properties of a suitably chosen analytical approximation of the expression for the sum of two fields it has become possible to compute the interpolation tables at run time and to replace the two trilinear interpolation steps by three bilinear interpolations, which cuts down the number of necessary operations to almost ½ of the double trilinear version t-LNM (V1).

A.2.9. The t-LNM (V2) Algorithm

Let f_1 and f_2 be the (uncorrelated and normally distributed) intensity levels of the two fields to be combined. The corresponding sum field level is given by:

$$f = \log_e (e^{f_1} + e^{f_2}), \qquad (1)$$

which can be written in the form

$$f = \frac{1}{2}(f_1 + f_2) + \log_e\left(e^{x/2} + e^{-x/2}\right), \qquad (2)$$

where

$$x = f_1 - f_2 \ . \tag{3}$$

From (2) it follows that the mean value <f> of the sum field level f has the form

$$\langle f \rangle = \frac{1}{2}\big(\langle f_1 \rangle + \langle f_2 \rangle\big) + U\big(\bar{x}, \sigma_x\big), \tag{4}$$

where $<f_1>$ and $<f_2>$ are the mean values of f_1 and f_2, respectively and

$$U(\bar{x}, \sigma_x) := \langle \log_e(e^{x/2} + e^{-x/2}) \rangle . \tag{5}$$

For convenience, $\bar{f}$ is used in place of <f> in some of the following equations.

Clearly $U(\bar{x}, \sigma_x)$ depends on the parameters of the distribution of x only; by proposition, x is normally distributed with mean $\bar{x} = \bar{f}_1 - \bar{f}_2$ and variance $\sigma_x^2 = \sigma_1^2 + \sigma_2^2$. The variance of f can be written in the form

$$\langle f^2 \rangle - \langle f \rangle^2 = \frac{1}{4}\sigma_x^2 + V(\bar{x}, \sigma_x) - \left[U(\bar{x}, \sigma_x)\right]^2 + \tilde{W}(\bar{x}, \sigma_1, \sigma_2), \tag{6}$$

where

$$V(\bar{x}, \sigma_x) = \langle \left[\log_e(e^{x/2} + e^{-x/2})\right]^2 \rangle \tag{7}$$

and

$$\tilde{W}\big(\sigma_1, \sigma_2\big) = \langle \, (f_1 - \bar{f}_1 + f_2 - \bar{f}_2) \times \log_e(e^{x/2} + e^{-x/2}) \, \rangle . \tag{8}$$

The term $\log_e(e^{x/2} + e^{-x/2})$ can be approximated by:

$$\log_e(e^{x/2} + e^{-x/2}) = \frac{1}{2}|x| + Ce^{-A|x| - Bx^2} . \tag{9}$$

Using the coefficients

A = 0.685437037

B = 0.08198801

C = 0.686850632

The maximum error in equation (9) is less than 7×10^{-3}, occurring for x in the interval [-4, 4].

When the approximation (9) is inserted into the expressions (5), (7) and (8) the mean values can be evaluated. It turns out that

$$U(\bar{x}, \sigma_x) = \bar{x}\left[\Phi\left(\frac{\bar{x}}{\sigma_x}\right) - \frac{1}{2}\right] + \frac{\sigma_x}{\sqrt{2\pi}} e^{-\frac{\bar{x}^2}{2\sigma_x^2}} + \frac{Ce^{-\frac{\bar{x}^2}{2\sigma_x^2}}}{\sqrt{1 + 2B\sigma_x^2}}\left[e^{\frac{K_+^2}{2}}\Phi(-K_+) + e^{\frac{K_-^2}{2}}\Phi(K_-)\right], \tag{10}$$

where

$$K_{\pm} = \frac{\bar{x}/\sigma_x \pm A\sigma_x}{\sqrt{1 + 2B\sigma_x^2}} \tag{11}$$

and where $\Phi(y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y} e^{-\frac{m^2}{2}} dm$ is the cumulative normalized normal distribution.

V is given by

$$V(\overline{x},\sigma_x) = \frac{1}{4}(\overline{x}^2 + \sigma_x^2) + \frac{C\sigma_x}{1+2B\sigma_x^2} e^{-\frac{\overline{x}^2}{2\sigma_x^2}} \bullet \left[\sqrt{\frac{2}{\pi}} - K_+ e^{\frac{K_+^2}{2}} \Phi(-K_+) + K_- e^{\frac{K_-^2}{2}} \Phi(K_-) \right]$$

$$+ \frac{C^2}{\sqrt{1+4B\sigma_x^2}} e^{\frac{-2B\overline{x}^2 + 2A^2\sigma_x^2}{1+4B\sigma_x^2}} \bullet \left[e^{\frac{2A\overline{x}}{1+4B\sigma_x^2}} \bullet \Phi\left(-\frac{\overline{x}/\sigma_x + 2A\sigma_x}{\sqrt{1+4B\sigma_x^2}} \right) + e^{\frac{-2A\overline{x}}{1+4B\sigma_x^2}} \bullet \Phi\left(\frac{\overline{x}/\sigma_x - 2A\sigma_x}{\sqrt{1+4B\sigma_x^2}} \right) \right] . \quad (12)$$

$\tilde{W}$ finally can be written as

$$\tilde{W} = (\sigma_1^2 - \sigma_2^2) \bullet W(\overline{x},\sigma_x) \; , \quad (13)$$

where

$$W(\overline{x},\sigma_x) = \Phi\left(\frac{\overline{x}}{\sigma_x}\right) - \frac{1}{2} + C e^{-\frac{\overline{x}^2}{2\sigma_x^2}} \bullet$$

$$\left\{ \frac{1}{\sigma_x(1+2B\sigma_x^2)} \left[K_+ e^{\frac{k_+^2}{2}} \Phi(-K_+) + K_- e^{\frac{k_-^2}{2}} \Phi(K_-) \right] - \right.$$

$$\left. \frac{\overline{x}}{\sigma_x^2 \sqrt{1+2B\sigma_x^2}} \left[e^{\frac{k_+^2}{2}} \Phi(-K_+) + e^{\frac{k_-^2}{2}} \Phi(K_-) \right] \right\} . \quad (14)$$

Once the functions U, V and W have been tabulated (which due to the many similarities of the terms appearing in (10), (12) and (14) consumes only a moderate amount of computing time) the combination of two fields can very simply be accomplished by first computing $\overline{x}$ and σ_x, then finding the corresponding values of the functions U, V and W by bilinear interpolation in the respective tables, and finally computing the mean sum field level by formula (4) and the variance as:

$$\langle f^2 \rangle - \langle f \rangle^2 = \frac{1}{4}\sigma_x^2 + V(\overline{x},\sigma_x) - [U(\overline{x},\sigma_x)]^2 + (\sigma_1^2 - \sigma_2^2) W(\overline{x},\sigma_x) . \quad (15)$$

The error involved in this approximation depends on the detail of the tables constructed for U, V and W.

A.3. Applications for the LNM methods

A.3.1. Evaluation of protection margin

The protection margin for a given reception situation is defined as the difference between the sum of the wanted fields and the sum of the unwanted nuisance fields, including noise, i.e. the minimum field strength, and including the appropriate probability margins. In the following example a reception situation with three wanted signals and no interfering signal, but including noise, is described.

In order to determine the protection margin, the following procedure can be carried out using the formula for determining the field strength exceeded for p% of locations in terms of the median field strength and the standard deviation:

$$F(p\%) = F_{med} + f(p\%) \cdot \sigma ,$$

where

F(p%) is the field strength exceeded for p% of locations

F_{med} is the median field strength

f(p%) is the probability correction factor for p% of locations

σ is the standard deviation.

Then, using the parameters in the example of chapter A.2.6:

1.	F^1_{med}	=	60.000 , σ = 5.500 dB , f(99%) = -2.33
2.	$F^1(99\%)$	=	47.185 dB,

and for the sum of 3 identical fields:

3.	F^3_{med}	=	66.830 , σ = 3.517 dB , f(99%) = -2.33
4.	$F^3(99\%)$	=	58.635 dB,
5.	Protection Margin	=	$F^3(99\%) - F_{min}$ = 58.635 - 58 = 0.635 dB

A.3.2. Evaluation of network gain

6.	Network Gain	=	$F^3(99\%) - F^1(99\%)$
	Network Gain	=	58.635 - 47.185 = 11.450 dB

A.3.3. Evaluation of coverage probability

The calculation of the coverage probability is split into three parts:

- Calculation of the sum of the wanted field strengths,
- Calculation of the sum B_Σ of the nuisance fields, which are composed of the interfering field strengths F_i^{int} plus the corresponding protection ratios PR_i

$$B_\Sigma = \sum_i \left(F_i^{\text{int}} + PR_i\right) + F_{\min} ,$$

- Evaluation of the coverage probability.

For the first two steps the LNM approximations may be applied to sum the fields. A standard deviation of 0 dB is attributed here to the minimum field strength F_{min}.

In the third step the coverage probability CP can be calculated by simple error function evaluations as shown in the following equations, where $\overline{F}^w_\Sigma, \sigma^w_\Sigma$ and $\overline{B}_\Sigma, \sigma^B_\Sigma$ denote the distribution parameters of the relevant fields and P(A) the probability of the event A.

$$CP = P(F^w_\Sigma - B_\Sigma > 0) = J\left(\overline{F}^w_\Sigma - \overline{B}_\Sigma, \sqrt{(\sigma^w_\Sigma)^2 + (\sigma^B_\Sigma)^2}\right)$$

where the function J is given by

$$J(F,\ \sigma) = \frac{1}{2}\left(1 + erf\left(\frac{-F}{\sqrt{2}\sigma}\right)\right)$$

The error function erf is evaluated with the help of tables or parametrisations. These can be found in mathematical handbooks, e.g. [20]. A short overview is given in section A.4.

If F_{min} cannot be included in B_{Σ}, as is the case for example for k-LNM because of the particular structure of this approach, the following approximation may be applied (where the corresponding nuisance field is now denoted by B'_{Σ}):

$$B'_{\Sigma} = \sum_i \left(F_i^{\text{int}} + PR_i\right),$$

$$CP = P(F_{\Sigma}^{w} - B'_{\Sigma}\ >\ 0) * P(F_{\Sigma}^{w} - F_{\min}\ >\ 0)$$

$$CP = J\left(\overline{F}_{\Sigma}^{w} - \overline{B}'_{\Sigma},\ \sqrt{(\sigma_{\Sigma}^{w})^2 + (\sigma_{\Sigma}^{B})^2}\right) * J\left(\overline{F}_{\Sigma}^{w} - F_{\min}, \sigma_{\Sigma}^{w}\right)$$

A.4. Distribution function p

The cumulative distribution function p:

$$p(x) = \frac{1}{2}\left(1 + erf(x)\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{\frac{-t^2}{2}}\, dt$$

gives the total (cumulative) probability, p, that the value x of a continuous random variable, with a Gaussian distribution*, is not exceeded in a trial with a large number or random events.

The inverse cumulative distribution function

$$x(p) = I(p)$$

gives the value x of the random variable which will not be exceeded, with probability p, in a trial with a large number of random events. The expression for *I(p)* cannot be expressed in a closed form. It can be approximated with the following equations:

1) if $0 < p \leq 0.5$, then

$$I(p) = -\left[t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}\right]$$

with $t = \left[\ln\left(\frac{1}{p^2}\right)\right]^{\frac{1}{2}}$

and c_0 = 2.515517 $\quad$ d_1 = 1.432788

c_1 = 0.802 853 $\quad$ d_2 = 0.189269

c_2 = 0.010328 $\quad$ d_3 = 0.001308

2) if $0.5 < p \leq 1$, then

* The Gaussian distribution in question is normalised to have a standard deviation equal to 1.

$$I(p) = S - \frac{c_0 + c_1 S + c_2 S^2}{1 + d_1 S + d_2 S^2 + d_3 S^3}$$

with $S = \left[\ln\left(\frac{1}{1-p}\right)^2 \right]^{\frac{1}{2}}$

and c_0, c_1, c_2, d_1, d_2, d_3 as in case 1).

Using the formulas one can establish the following table of conversion:

p	x
0.00	- ∞
0.01	-2.32692
0.05	-1.64476
0.10	-1.18147
0.15	-1.04637
0.20	-0.84161
0.25	-0.67453
0.30	-0.52443
0.35	-0.38527
0.40	-0.25338
0.45	-0.12570
0.50	0.0
0.55	0.12570
0.60	0.25338
0.65	0.38527
0.70	0.52443
0.75	0.67453
0.80	0.84161
0.85	1.04637
0.90	1.18147
0.95	1.64476
0.99	2.32692
1.00	+ ∞

Table A.1: Distribution function p

Annex B:

B Case Studies on SFN Planning

B.1 Netherlands (2001)

Solving some problems in DVB-T single frequency network in the Netherlands

In the Netherlands DVB-T SFNs have been introduced in the central and western part of the country, the so-called Randstad area. This is a very densely populated area.

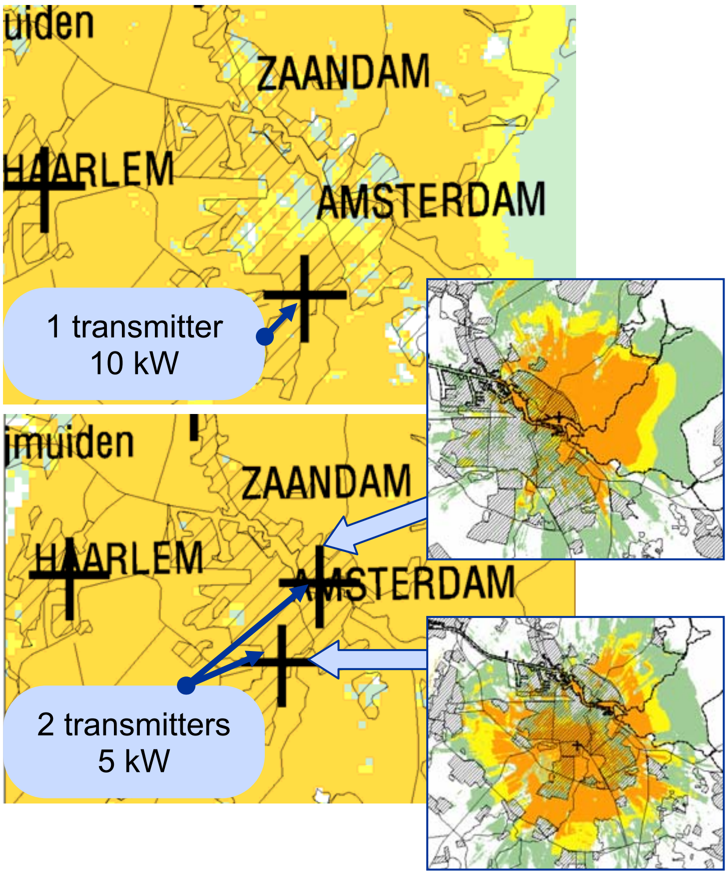


Figure 1 Improving coverage by planning more dense network

One of the aims of the DVB-T services is to provide indoor portable coverage in the whole area and in particular in the cities. For that reason a relative dense network has been built with sites near the main cities. Figure 1 gives an example that shows that (as part of a larger SFN) two 5 kW transmitters give a better coverage than one 10 kW transmitter in the city of Amsterdam.

Details shows the coverage of each of the two 5 kW transmitters when these are not working in SFN mode.

Large SFNs may give internal network interference. Figure 2 shows coverage calculated for 1 % of time of an SFN using channel 34 without measures for reducing internal network interference.

In order to reduce the internal network interference the following measures have been taken:

- Artificial delays
- Additional fill-in transmitters

Because of the artificial delays internal network interference in the south-west part increases. That area will be covered by another SFN.
Figure 3 shows the results (coverage calculated for 1% of time).

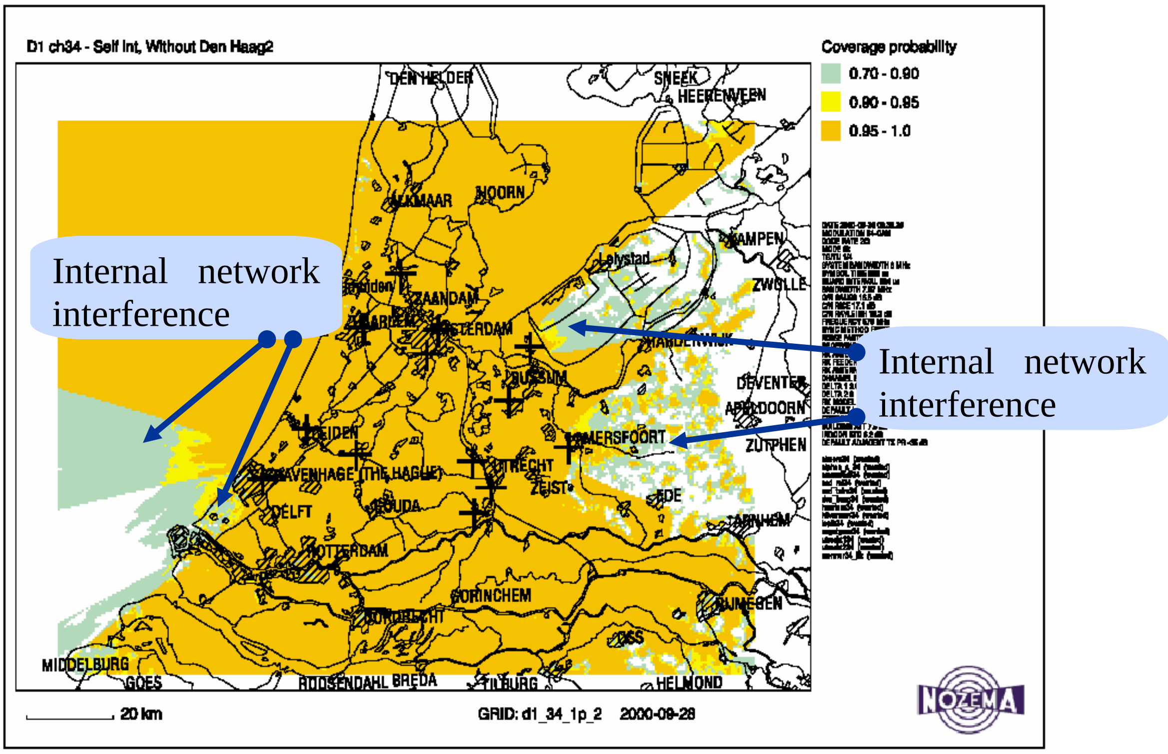


Figure 2 Coverage of SFN (1% time) without measures for reducing internal network interference

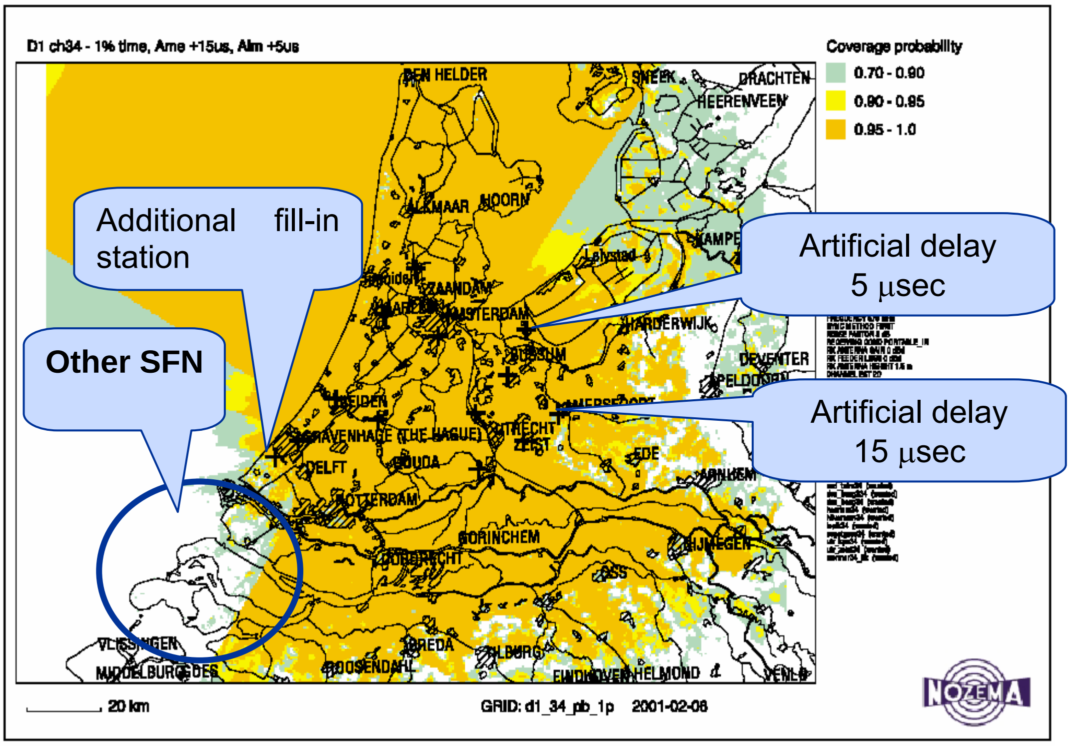


Figure 3 Coverage of SFN (1% time) with several measures for reducing internal network interference

B.2 Switzerland (2003)

Coverage In Digital Single-Frequency Network: Theoretical Case Study

1. Introduction

The transition of television from analogue to digital transmission will inevitably take place in the years to come. DVB-T technology has been standardised for digital terrestrial television in Europe [1]. Immunity of DVB-T against echoes or ghosting allows the possibility of single frequency network (SFN) [2]. An SFN is built up out of broadcast stations which simultaneously broadcast identical data streams on the same carrier frequency. Neighbouring broadcast stations support each other in their function.

Recently, a case study has been carried out [3] in order to compare service coverage for analogue and digital multi-frequency networks (MFN). The so-called "conventional MFN planning" has been used. The digital transmitters have been assumed to re-use the same sites as existing analogue stations with all the relevant characteristics (RF channel, polarisation, antenna height and diagram). The effective radiated power (e.r.p) of the transmitters has been lowered by 7 dB with respect to its value used for analogue broadcasting. The system variant 16-QAM with code rate 3/4 has been identified as most suitable that provides the coverage close to the analogue one, if a fixed outdoor reception is used. Portable indoor reception seems to be achievable for 74 % of population.

However, a final state of digital coverage is supposed to be realised by transmitters operating in SFNs [4]. Therefore, it is of interest to use SFN to cover the area considered for the case study of Zurich in [3]. It has been thus attempted to characterise the impact of the SFN parameters on the service availability in the area. The results are presented and discussed in this paper.

2. Methodology and calculations

The region around Zurich, which is the most populated one in Switzerland, has been chosen for this case study. The area of interest is outlined by administrative borders of four cantons (Zurich, Zug, Schwyz and Schaffhausen).

The transition to digital terrestrial television is connected with the wish to reuse as much as possible the current analogue transmitter cites. Therefore, an irregular SFN has been modeled using three main transmitters of the existing analogue network infrastructure, namely Uetliberg, Schaffhausen and Rigi Kulm. The distance between Schaffhausen and Uetliberg is 38.5 km, 32.8 km between Uetliberg and Rigi Kulm, and 70.5 km between Schaffhausen and Rigi Kulm. The digital transmitters are assumed to use the same antenna height and diagram as those for analogue stations. Planning examples have been made for Band III (196.25 MHz) and Band IV (519.25 MHz). The e.r.p. of the transmitters has been scaled between 0 and 50 dBW. Two different types of SFN have been considered. In the first one all three transmitters in the network are allotted identical e.r.p. values. The second implementation supposes Uetliberg to be a main station with two additional transmitters serving as gap fillers. For the simplicity these SFN types are referred bellow in the text as symmetrical and asymmetrical SFNs.

Different system variants have been tested (Table 1). 8K FFT size has been used. Fixed outdoor reception using roof-top antennas and portable indoor reception at ground floor have been considered at 95 % and 70 % of locations, respectively. The corresponding values of minimum usable field strength and protection ratio have been calculated according to Chester'97 agreement [5].

Table 1. Systems variants considered in the study with corresponding values of minimum usable field strength (FS_{min}), protection ratio (C/I). Values of FS_{min} and C/I are given for fixed outdoor (portable indoor) reception at 95 % (70 %) of locations in Band III. For Band IV frequencies, 5.0 dB (6.8 dB) is to be added to FS_{min} values.

Modulation	Code Rate	Guard Interval	Bit Rate (Mbit/s)	FS_{min} (dBμV/m)	C/I (dB)
16-QAM	2/3	1/8	14.75	42.5 (64.3)	14.6 (17.2)
16-QAM	3/4	1/8	16.59	43.9 (66.8)	16.0 (19.7)
16-QAM	5/6	1/8	18.43	45.3 (69.4)	17.4 (22.3)
16-QAM	7/8	1/8	19.35	45.9 (72.9)	18.0 (25.8)
64-QAM	1/2	1/8	16.59	45.6 (66.1)	17.7 (19.0)
64-QAM	2/3	1/8	22.12	48.0 (69.4)	20.1 (22.3)

In hilly and mountainous areas the terrain irregularity is an important factor in the path loss mechanism. Switzerland is particularly affected by this situation. Therefore, the deterministic model CRC-Predict developed at the Communications Research Centre Canada has been used for calculation of coverage areas of single transmitters [6]. Network coverage is further proceeded by CovCAD, which is a planning software developed in Switzerland. It allows dealing with large number of transmitters in the network .

It should be noticed that only artificial SFN echoes, e.g. those produced by transmitters in the network, have been considered within simulations presented, while the natural multipath echoes generated by the obstacles (mountains, hills, buildings) are neglected. The latter may appear at the receiver input as either constructive or destructive signals depending on the terrain and network topology. More sophisticated and as a rule more time consuming 3D algorithms are needed to take into account these effects.

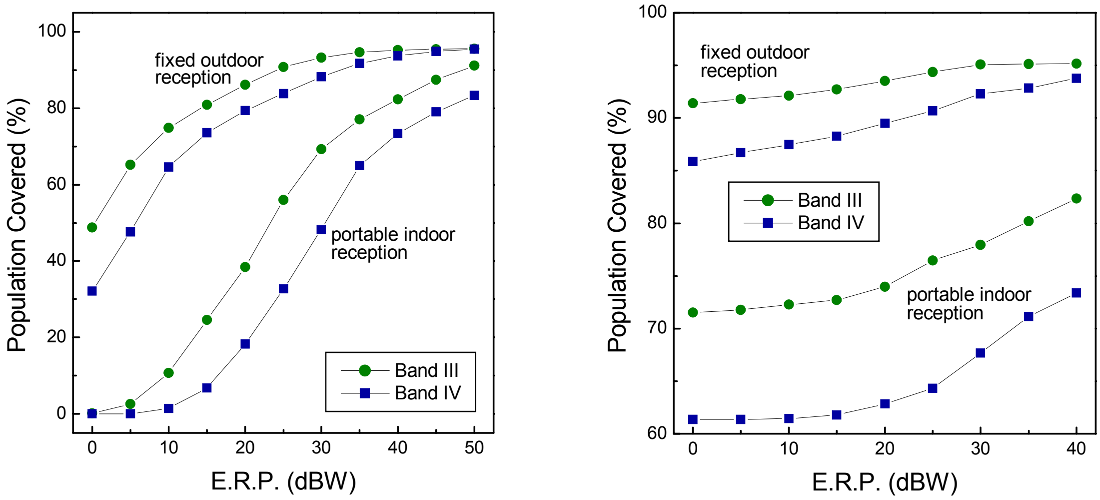
The results of the coverage calculations have been evaluated in terms of the population covered.

3. Results and discussions

3.1. Power dependence

Effect of transmitter e.r.p. on the service availability has been investigated for two SFN implementations. When all transmitters in the network operate with the same values of e.r.p. the percentage of population covered increases rapidly for low and medium power. The results are presented in Fig. 1*a*. When the e.r.p. of transmitters becomes rather high a steady increase in the coverage takes place. For the fixed outdoor reception a saturation is observed. The rest of population not served by the SFN lives in regions, where the reception of direct signal is prevented by mountains. However, additional transmitters might not be necessary as reflected signals, often present in the mountainous and hilly environment may be constructive in DVB-T. The observed saturation in the population coverage for outdoor reception can also be partly explained by self-interference effects appearing in some locations.

Further, an example of asymmetrical SFN (one main station and two gap-fillers) is considered. The e.r.p. of the main station (Uetliberg) has been fixed to 40 dBW. The e.r.p. of gap-fillers has been varied from 0 to 40 dBW. However, in the latter case the transmitters in Schaffhausen and Rigi Kulm can not be considered as gap-fillers with respect to Uetliberg. The population coverage calculated for different reception modes is characterised by a monotonous increase as a function of the e.r.p. of gap-fillers. It is illustrated in Fig. 1*b*. From the results presented in Fig. 1*a* and *b* one may conclude that a symmetrical configuration of SFN would be preferable for coverage in portable indoor reception. However, implementation of asymmetrical SFN may provide a suitable coverage in outdoor reception.

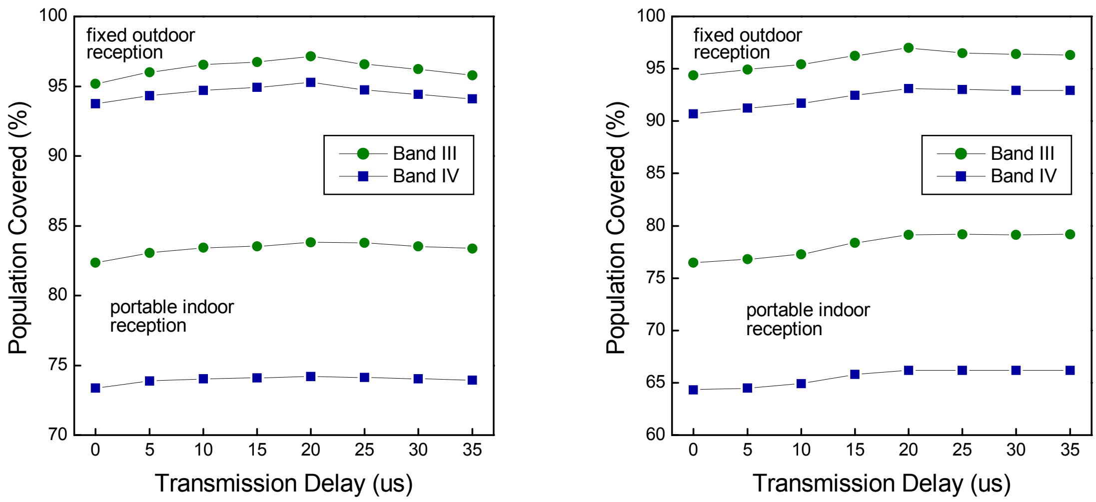


(a) *(b)*

Fig. 1. Simulated population coverage in the Zurich region by SFN (16-QAM 3/4 GI = 1/8) as a function of transmitter e.r.p.: *(a)* symmetrical network consisted of three transmitters with the same power; *(b)* asymmetrical SFN with Uetliberg as a main station (with fixed e.r.p. of 40 dBW) and two gap fillers.

3.2. Transmission delay effect

In considering SFN it should be recognised that not all the transmitters in a network will contribute to the wanted signal. Some signals may become interferers. The effect of self-interference of the SFN becomes even more pronounced if the distance between transmitters exceeds the one defined by DVB-T parameters used. This is the present case as the distance between Uetliberg and Schaffhausen is higher than the maximum allowed (33.6 km) for the guard interval chosen (112 μs). Therefore, further insight into the problem of optimisation of the network in view of maximising the population coverage can be obtained from the study of influence of the transmission delay. The signal from the transmitter Schaffhausen has been delayed with respect to the one from the station Uetliberg. The results of simulations are presented in Fig. 2*a* and *b* for symmetrical and asymmetrical SFN implementations, respectively. It is found that significant improvement in the population coverage occurs when the delay increases from 0 to 20 μs. Then a kind of saturation in the coverage for indoor reception is observed, while outdoor reception characterised by a maximum with a following decrease. This is due to appearance of self-interference effects in some other locations.

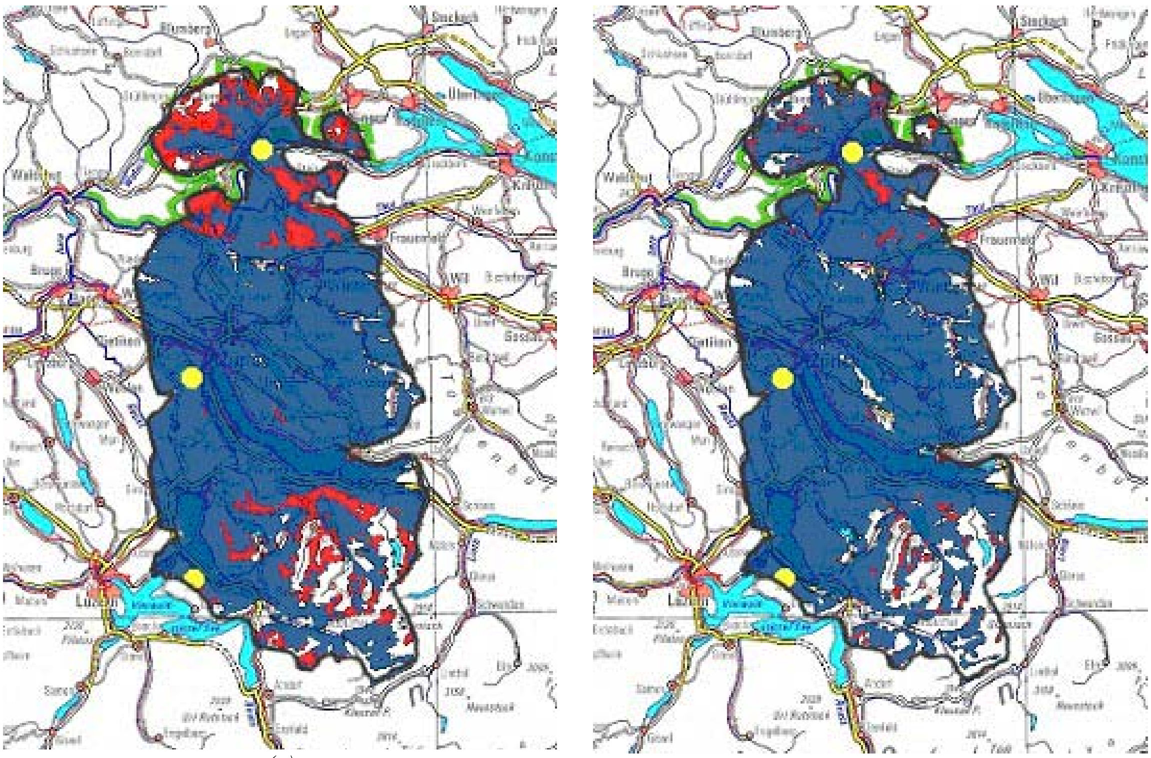


(a) *(b)*

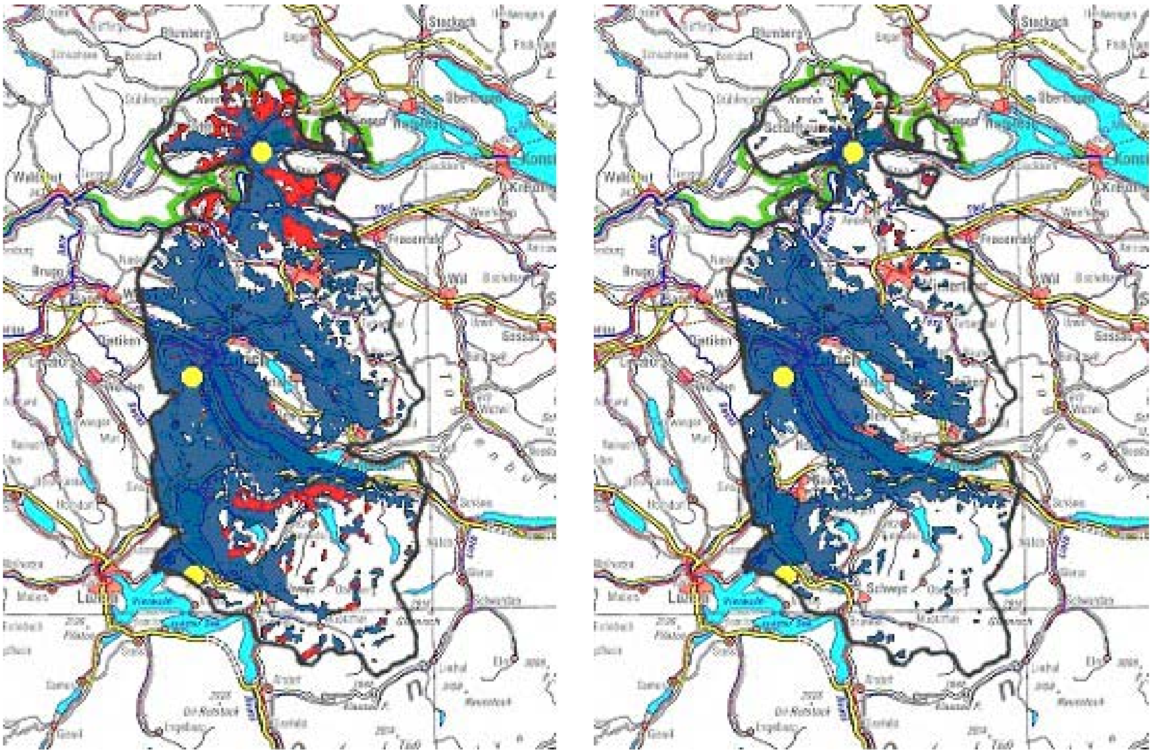
Fig. 2. Simulated population coverage in the Zurich region by SFN (16-QAM 3/4 GI = 1/8) as a function of the transmission delay for the transmitter Shaffhausen: (a) symmetrical network (e.r.p. of all transmitters is 40 dBW); (b) asymmetrical SFN configuration (e.r.p. of Uetliberg is 40 dBW, e.r.p. of Schaffhausen and Rigi Kulm is 25 dBW).

3.3. Coverage maps

The predicted digital coverage map in Band IV using the DVB-T variant 16-QAM with code rate 3/4 is represented in Fig. 3 for fixed outdoor and portable indoor reception modes, respectively. Both symmetrical and asymmetrical SFN implementations are shown.



(a) *(b)*



(c) *(d)*

Fig. 3. Simulated digital SFN (16-QAM 3/4 GI = 1/8) coverage in the Zurich region for fixed outdoor *(a,b)* and portable indoor *(c,d)* reception in Band IV: *(a,c)* symmetrical network (e.r.p. of all transmitters is 40 dBW); *(b,d)* asymmetrical SFN configuration (e.r.p. of Uetliberg is 40 dBW, e.r.p. of Schaffhausen and Rigi Kulm is 25 dBW). Zones of self-interference are marked with red. The region of interest is contoured by black line. The transmitter sites are marked by yellow solid circles and named from up to down as Schaffhausen, Uetliberg, and Rigi Kulm. Signal from Schaffhausen is delayed by 20 s.

Due to large differences in the values for minimum usable field strength significant differences in coverage between outdoor and indoor reception are clearly seen. However, urban regions seem to be provided with portable indoor reception. Only the area around Winterthur would require an additional transmitter to improve the indoor reception. There is no large difference in coverage for symmetrical and asymmetrical SFN implementations when outdoor reception is considered. The percentage of population covered is around 95 % and 93 % for the symmetrical and asymmetrical SFNs, respectively. However, portable indoor reception is evidently better for the symmetrical network configuration than under the asymmetrical SFN implementation. The population coverage amounts to 74 % and 66 % for symmetrical and asymmetrical SFNs, respectively. Moreover, the dense network is characterised by appearance of zones with self-interference marked in Fig. 3 by red colour. These effects are less pronounced for the mini SFN.

3.4. Dependence on system variant

The population coverages as a percentage of the total population in the area of interest for six system variants considered are given in Table 2. Symmetrical SFN implementation is modelled with e.r.p. of the transmitters equal to 40 dBW and the transmission delay of 20 μs between Shauffhausen and Uetliberg. It appears that the population coverage for fixed outdoor reception is more or less the same in Band III and Band IV despite of different usable field strength limits. This is because population is not uniformly distributed over the territory but rather concentrated in certain regions. This is clearly seen when considering the coverage for portable indoor reception. In this case the border of coverage map is often passing across densely populated regions. Therefore, the difference in usable field strength limits for Band III and Band IV results in a significant difference in coverage.

The results presented in Table 2 allow for the same conclusion made in [3] that in the trade-off between the data capacity, service raggedness and coverage the system variant 16-QAM with code rate 3/4 seems to be the most appropriate in the present case. However, the data do not differ much from one variant to another. It can be also noticed that the values of population coverage in Band IV are comparable with those obtained within MFN studies [3]. Meanwhile, building up an SFN in Band III allows for better results.

Table 2. Simulated percentage of the population covered by digital SFN in the Zurich region for different system variants. E.r.p. of all transmitters is 40 dBW. Signal from Schaffhausen is delayed by 20 s.

Modulation	Code Rate	Bit Rate (Mbit/s)	Outdoor Reception		Indoor Reception	
			Band III	Band IV	Band III	Band IV
16-QAM	2/3	14.75	97.4 %	95.8 %	86.9 %	77.7 %
16-QAM	3/4	16.59	97.1 %	95.3 %	83.8 %	74.2 %
16-QAM	5/6	18.43	96.9 %	94.6 %	80.4 %	69.9 %
16-QAM	7/8	19.35	96.7 %	94.3 %	75.8 %	61.9 %
64-QAM	1/2	16.59	96.8 %	94.4 %	84.7 %	75.2 %
64-QAM	2/3	22.12	96.1 %	93.1 %	80.4 %	69.9 %

3.5. Receiver synchronisation effect

The delay spread of the echoes is one of the most important parameters in the design of a digital television system. The problem arises with the treatment of the interfering and the contributing signal parts [7]. The synchronisation algorithm used to open the guard interval window may significantly affect the DVB-T coverage probability in the SFN configuration. To study this eight possible echo combinations within the symbol have been considered. For each algorithm the population coverage has been calculated using the system variant 16 – QAM 3/4. Only signals inside the guard interval are regarded as wanted, whereas signals outside the guard interval are treated as interference (cliff-edge transition). The results are compared in Table 3. From the study it appears that aligning of the starting edge of the guard interval window either with the first signal or with the first signal above a certain threshold (in the present study it is fixed to 20 dB above noise floor) are the optimum algorithms. However, this may be not the case if another network infrastructure is used.

Table 3. Simulated percentage of the population covered by digital SFN (16-QAM 3/4 GI = 1/8) in the Zurich region for different synchronisation algorithms at the receiver. E.r.p. of all transmitters is 40 dBW. Signal from Schaffhausen is delayed by 20 s.

Guard Interval Window	Outdoor Reception		Indoor Reception	
	Band III	Band IV	Band III	Band IV
Start = the first signal	97.1 %	95.3 %	83.8 %	74.2 %
Start = the strongest signal	85.8 %	86.1 %	78.0 %	70.7 %
Start = the first signal over threshold	97.1 %	95.3 %	83.8 %	74.2 %
Start = the barycentre of all signals	1.4 %	2.0 %	0.8 %	0.7 %
Centre = the first signal	74.2 %	74.6 %	61.7 %	58.2 %
Centre = the strongest signal	74.5 %	74.9 %	61.7 %	58.2 %
Centre = the first signal over threshold	74.2 %	74.6 %	61.7 %	58.2 %
Centre = the barycentre of all signals	77.8 %	77.7 %	63.7 %	59.9 %

4. Conclusion

Calculations of population coverage, which could be achieved by an SFN of digital television transmitters, have been carried out. Four cantons in Switzerland have been chosen to form an SFN allotment. Three existing analogue main stations have been used to simulate SFN topology. This results in the network, where the distance between some transmitters exceeds the value defined by the guard interval chosen (112 μs). Antenna height and diagram of the digital transmitters have been left as they are in analogue use.

For a symmetric SFN configuration, when all three transmitters possess the same e.r.p. (from 0 to 50 dBW), the population coverage is found to increase rapidly with increase of the transmitter power approaching saturation for relatively high values of e.r.p. While for asymmetrical SFN implementation, when one deals with one main station (40 dBW) at the centre and two gap-fillers (from 0 to 40 dBW), the population coverage is characterised by a relatively moderate increase as a function of the e.r.p. of gap-fillers. It is also found that significant improvement in the population coverage can be achieved when the signal from the transmitter Schaffhausen is delayed 20 μs with the respect to the transmission from Uetliberg.

The system variant 16-QAM with code rate 3/4 and guard interval 1/8 has been identified as the optimum providing population coverage of 97 % (95 %) for outdoor reception and 84 % (74 %) for indoor reception in Band III (Band IV). These values are comparable with date from previous studies on possible MFN coverage in the area of interest. Further improvement in the indoor reception is seen possible by the introduction of an additional transmitter near Winterthur. Some increase in the coverage can also be expected by proper optimisation of antenna diagrams of digital transmitters.

Different algorithms of synchronisation of the receiver on the incoming signals have been compared. The methods, when the start of guard interval window is aligned either with the first signal or with the first signal above a certain threshold, are shown to be the most preferable for the case considered.

Acknowledgement

The authors would like to thank H. Vogel for valuable discussions. This work has been carried out within the project "Migration to Digital Television" between the Federal Office of Communications and the Biel School of Engineering and Architecture.

References

[1] Ronald de Bruin, Jan Smits, Digital Video Broadcasting: Technology, Standards, and Regulations (Artech House, Inc., 1999).

[2] Terrestrial Digital Television: Planning and implementation considerations, European Broadcasting Union, BPN 005.

[3] A. Kholod, S. Ménard, R. Tschannen, and M. Liniger, Comparison of Analogue and Digital Multi-Frequency Networks: Theoretical Case Study, European Broadcasting Union, B/MDT Doc. 154, MDT-M1 Doc. 026 (2001).

[4] J. Frank and G. Petke, DVB-T – network structure and costs for full coverage, EBU Technical Review (June 2001).

[5] The Chester 1997 Multilateral Coordination Agreement relating to Technical Criteria, Coordination Principles and Procedures for the introduction of Terrestrial Digital Video Broadcasting.

[6] R. Voyer, D. Camiré and A. Rime, Relevance of Empirical Propagation Models for Interference Coordination in Mountainous Areas, IBC 2000 Conference Publication, 262 – 267 (2000).

[7] A. Morello, B. Sacco, A. Bertella, M. Tabone, Laboratory Tests on Professional and Consumer DVB-T receivers – Strategy for OFDM Window Synchronisation, EACEM, March 2000.

B.3 Finland (2003)

SFN-coverage in Lapua and Vaasa

Introduction

The digitalisation process will proceed in accordance with the timetable in Finland and at this moment three DVB-T multiplexes are covering over 70 % of the population. These three DVB-T networks are based on MFN planning but in two places mini-SFN's were planned because no MFN-frequencies couldn't have been coordinated. In autumn 2001 the first mini-SFN network started in Finland including the stations of Lapua and Vaasa on channel E38 (610 MHz). Lapua has a maximum ERP of 50 kW and Vaasa 10 kW. The UHF transmitting antennas are located at 313 meters above ground level in Lapua and at 117 meters in Vaasa. The distance between the stations is 77 kilometers. Because of the used DVB-parameters (8K, 64-QAM, CR=2/3, GI=1/8) it is very likely that the self interference will be the limitation factor near Vaasa when the guard interval (112 μs) is exceeded.

Coverage area calculations

In figure 1 it can be seen the predicted coverage area of Lapua and Vaasa in fixed reception using the above mentioned DVB-parameters. Yellow means at least 95 % of receiving locations within it are predicted to be covered and correspondingly red means the location probability of 70 %. The field strengths are predicted by the CRC method where values for 50 % of the time are appropriate for wanted signals and values for 1 % of the time are appropriate for unwanted signals (a block of 500 meters × 500 meters is used). The coverage probabilities are calculated for the noise limited case (only the self interference is considered). The statistical summation of field strengths is performed by means of the Monte Carlo technique. It is supposed that when the echo is within the guard interval T_g its power adds to the useful signal, and when the echo is outside T_g it is to be considered as pure interference (the exponential degradation is not used outside T_g). According to the figure the self interference seems to affect very strongly when GI = 1/8.

To improve the situation it was studied to delay Vaasa in proportion to Lapua. Many simulations were done and in figure 2 it is presented the effect on coverage population when Vaasa is delayed. The calculations show that the best improvement in coverage population would be achieved when the delay is 70 μs. In figure 3 it can be seen the predicted coverage area using this delay.

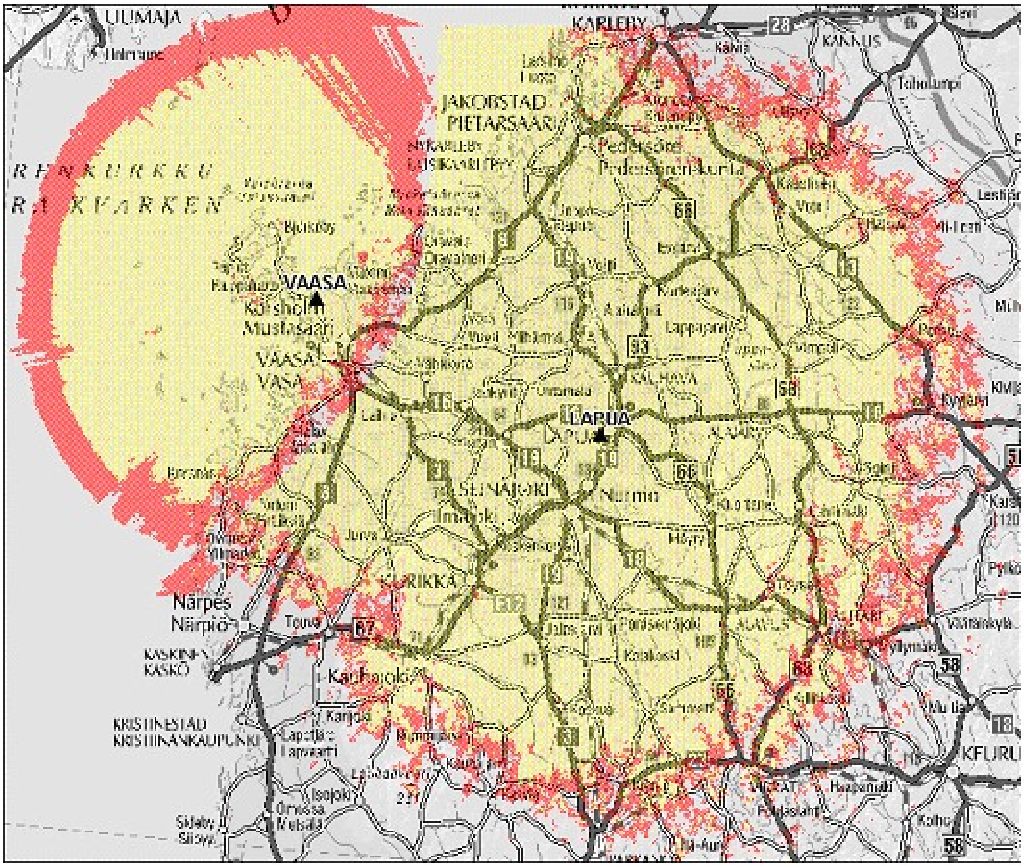


Figure1. SFN, Fixed reception, 64QAM2/3, t_g = 1/8.

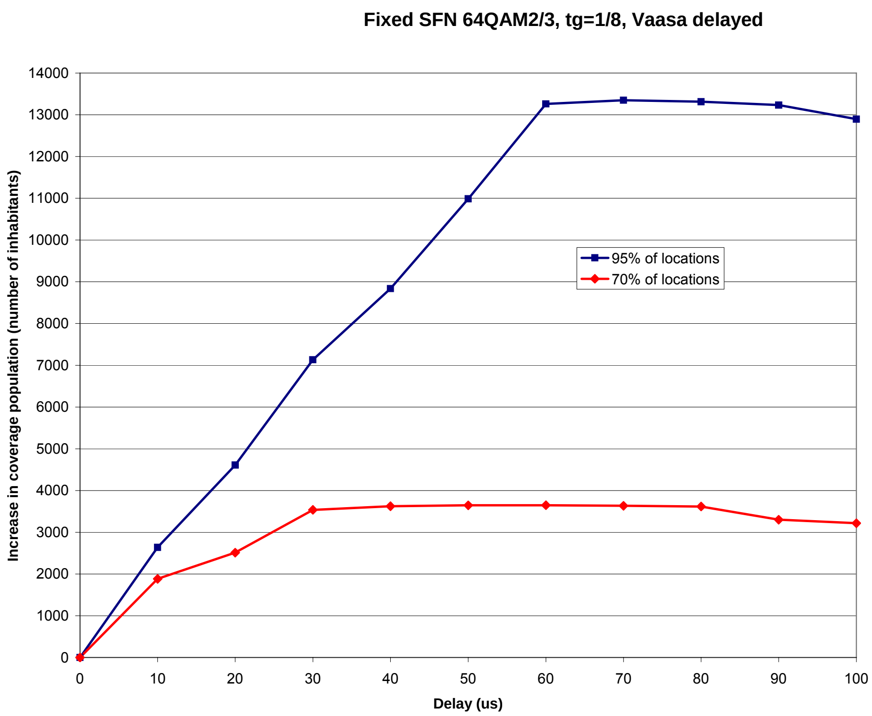


Figure 2. Increase in coverage population when Vaasa delayed.

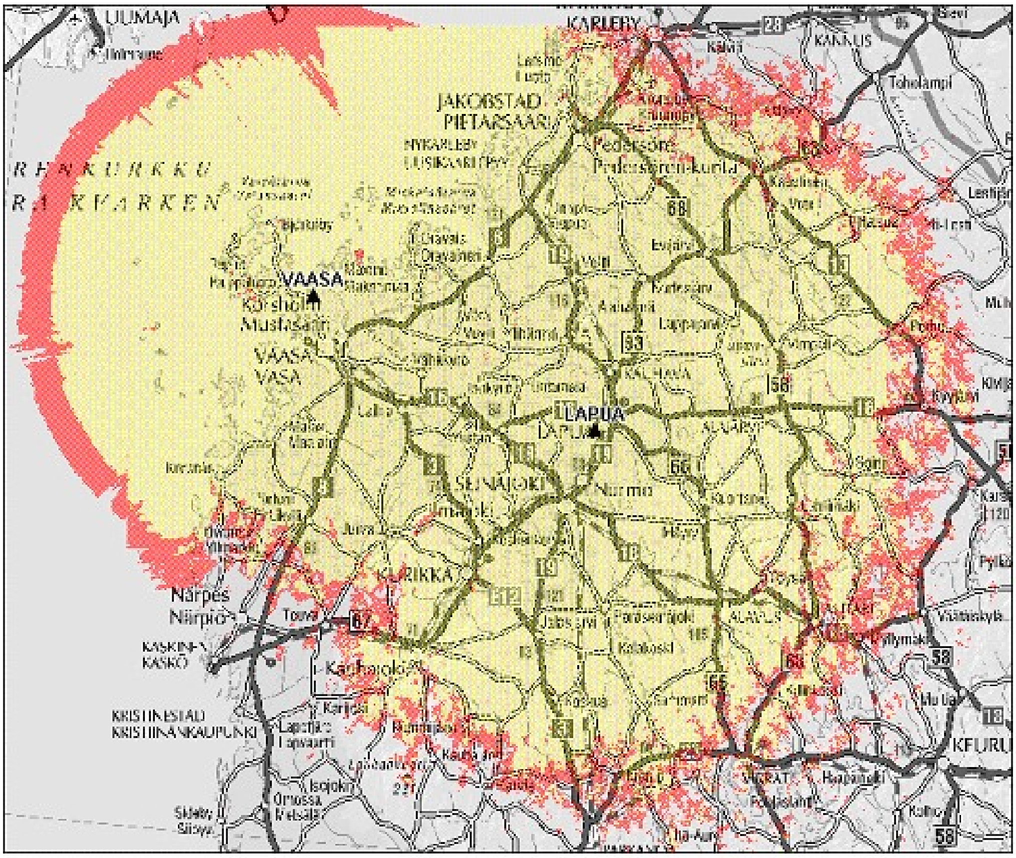


Figure 3. SFN, Fixed reception, 64QAM2/3, t_g = 1/8, Vaasa delayed 70 μs.

3. Field measurements

To verify the situation in the field a little measurement campaign was carried out with measurement van. In some predicted problem places the channel power from both stations was recorded. At the same time the visibility of the picture on TV-monitor was checked using one commercial Set Top Box. The measurements were done in the same places with the delay of 70 μs and without it. The receiving antenna was situated at 10 meters above ground level and it was a 10-element yagi antenna directed towards the measured station. The measurement results can be seen in table 1 and correspondingly the measurement places are located on the map in figure 4.

No.	MEASUREMENT PLACE	distance/km VAASA	distance/km LAPUA	difference km	Power/dBm VAASA	Power/dBm LAPUA	RECEPTION SUCCESSFUL			
							delay 70µs		no delay	
							Vaasa	Lapua	Vaasa	Lapua
1	VÄHÄKYRÖ,HOLTTILA	24,9	53,4	28,5	-52	-57	X	X	X	X
2	MAXMO,MARTOINEN	22,7	56,5	33,8	-70	-60	X	X	X	X
3	VAASA,HÖSTVESI	19,4	61,3	41,9	-63	-63	X	X	X	X
4	VANHA VAASA TEOLL.TH	18,3	62,9	44,6	-55	-60	X	X	X	
5	SEPÄNKYLÄ,NESTE	13,2	65,5	52,3	-57	-68	X	X	X	
6	KOIVULAHTI,K-KAUPPA	16,3	60,8	44,5	-53	-61	X	X	X	
7	MAXMO,ÖSTERHANKMO	20,1	61,1	41	-61	-59	X	X		X
8	MAXMO,SPARBANK	26,4	53,5	27,1	-68	-63	X	X		X
9	MAXMO,PIRKLOT	28,5	64,8	36,3	-50	-54	X	X	X	
10	VAASA,TÖLBY,ESSO	21,8	61,9	40,1	-58	-52	X	X		X
11	MALAX,KESKUSTA TH	29,2	71,4	42,2	-66	-66	X	X	X	X
12	KORSNÄS,MOIKIPÄÄ	44,4	85,1	40,7	-66	-72	X	X	X	X

Table 1. The measurement results.

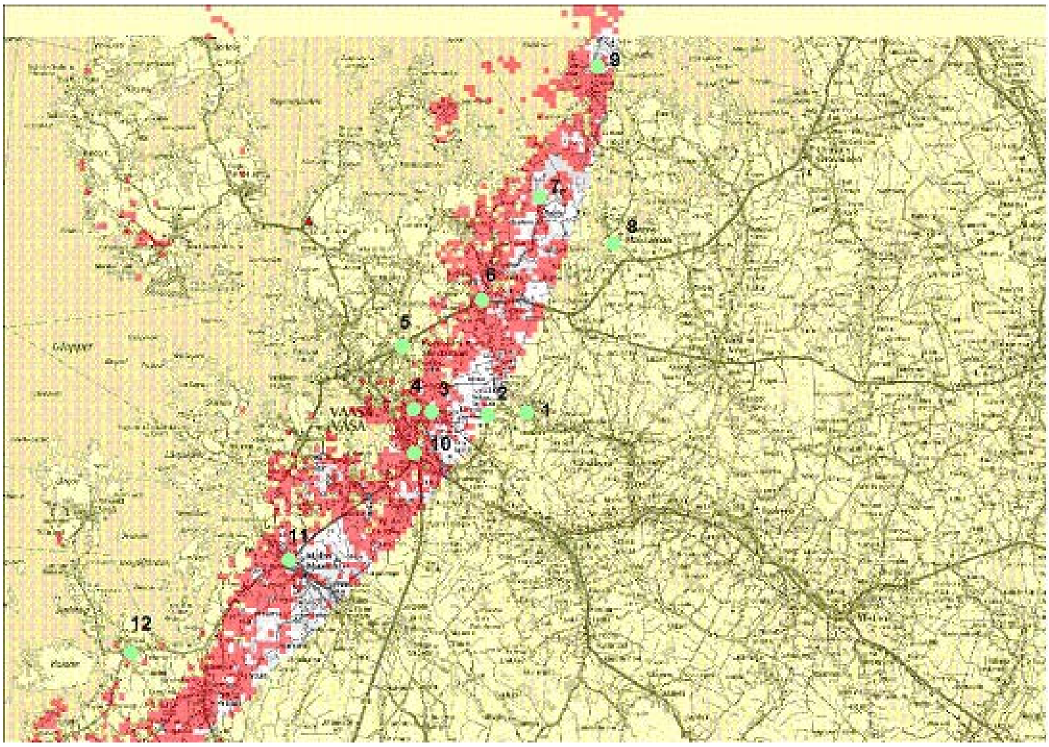


Figure 4. The measurement places.

Conclusion

According to the theoretical calculations and field measurements the effect of the self interference seems to disappear near Vaasa when Vaasa is delayed 70 µs in proportion to Lapua compared with the situation without any delay. However it must be keep in mind that the self interference is not entirely vanished but it is still present in some other locations. In the case of Lapua-Vaasa-SFN the main target is to improve DVB-T reception in severely interfered areas near Vaasa and this comes true very well.

B.4 Germany (2001)

This SFN study (EBU Tech. Rev. June 2001) is only available in a pdf version of an article in EBU Technical Review 2/2001. Therefore it is included here in this form. (Pages are counted as 116-1 to 116-10)

B/MDT 124

DVB-T — network structures and costs for full coverage

J. Frank and G. Petke
IRT

Due to the high penetration of cable and satellite TV services in Germany, the take-up of terrestrial TV is currently less than 10% (at least for the main receiver in each home), and with a slowing tendency. Therefore, in order to reverse this trend, viewers of future DVB-T services will have to be offered new incentives such as portable indoor reception, without the need for a classical roof-top antenna.

In the present study, the extent to which full area coverage could be achieved – for portable indoor reception – was investigated in the Schleswig-Holstein region. During the transition period, the level of the effective radiated transmitter power will have to be reduced in accordance with the Chester agreement. It is shown that, after conversion of the existing transmitter network in Schleswig-Holstein, a DVB-T coverage probability of 70% could be reached.

Higher coverage probabilities, for portable indoor reception, can only be realized in a cost-effective way by the use of single-frequency networks. However, this implies a revision of the Stockholm Agreement 1961.

Introduction

The existing analogue transmitter networks – for both sound broadcasting and television – were largely designed for full area coverage. The transmitter density required to achieve this has represented a considerable factor in the cost of programme distribution. In Germany, for example, 320 main transmitters and more than 8,000 fill-in stations (relays) are required to provide national coverage of the three public-service TV programmes (ARD, ZDF and the third programme). The transition to digital terrestrial television is of course connected with the wish to save on the cost of programme distribution. In the German IDR (Initiative Digital Radio), the consensus is that typically 50% of the programme distribution costs could be saved, provided that no – or few – additional transmitters were needed to provide national DAB coverage using the existing network of FM transmitter sites.

Cost analyses for specific transmitter network structures have recently been carried out in order to estimate the total costs involved in the introduction of DVB-T services in Germany. In 1999, the "Landesanstalt für Kommunikation" (LfK) in Baden-Wuerttemberg published the results of an investigation, containing the costs for DVB-T coverage of the Stuttgart region. Because of the difficult topography in this area, it was not possible to extrapolate the results to estimate the network structure required to provide national coverage of Germany. Instead, the costs for national programme distribution were derived after carrying out a further investigation in the federal state of Schleswig-Holstein, where the terrain is – to a large extent – rather flat. Thus the application of simpler field-strength prediction methods (e.g. ITU-R Rec. P.370 [1]) could be applied here.

The degree of coverage achievable, with a chosen transmitter network structure, largely depends on the chosen DVB-T variant. The variant 16-QAM with code rate 2/3 was chosen for the investigation in Schleswig-Holstein. This variant is based on a C/N value of 17 dB and offers a net bit-rate of 13.27 Mbit/s. It is expected that this bit-rate will allow four digital programmes to be carried within an 8 MHz TV channel.

Analogue coverage in Schleswig-Holstein

The starting point for our considerations was the present analogue coverage of the Second Programme (ZDF) in Schleswig-Holstein. It was shown that full area DVB-T coverage could be achieved with the nine analogue TV transmitters which are in operation in this federal state. The coverage boundary is based on the so-called *minimum usable field strength contour* (noise-limited), which determines the coverage area in the absence of interference. Since no interference is considered, this value is in general too optimistic.

Table 1
Analogue and digital transmitter powers.

Transmitter site	Channel (analogue and digital MFN)	Analogue transmitter power (kW)	Digital transmitter power, MFN (kW)	Digital transmitter power, SFN (kW)
Cuxhaven	24	330	66	50
Eiderstedt	31	500	100	100
Eutin	21	500	100	100
Flensburg	39	250	50	50
Hamburg	30	500	100	100
Kiel	35	250	50	50
Lübeck	23	250	50	50
Niebüll	34	200	40	50
Schleswig	26	100	20	50
Itzehoe	26	-	-	50

The description of the coverage boundaries by the so-called *interference contour*, taking into account all potential sources of interference, in general approaches the actual situation better. *Fig. 1* [1] shows the analogue coverage in the Schleswig-Holstein region, taking interference into account. It shows clearly that, based on the transmitter powers given in *Table 1*, the theoretical determination of the interference contours leads to coverage deficits in the area north-west of Hamburg (Neumünster-Heide-Itzehoe).

The reasons for this are due to the assumed topography. The field-strength prediction method that was used – based on ITU-R Recommendation P.370 [1] – assumes, among other things, a predetermined ground roughness that is described by the so-called Δh value. This value is taken as 50 m. The majority of the terrain in Schleswig-

1. The eight figures (i.e. maps) accompanying this article are displayed in *Appendix A*, with a reasonable image quality that is consistent with keeping the overall PDF file size small. By clicking on the caption to each figure, a higher-quality JPEG image of each map can be downloaded: the largest of these JPEG images is around 500KB.

Holstein, however, has a Δh value of 10 m. This results in a considerable error margin when calculating the wanted field strengths and, in practice, these coverage deficits do not exist.

Digital coverage

Considering the digital coverage, one must distinguish between the different phases: the introduction phase, the transition period and the final state.

During the introduction phase and the transition period, transmitters are generally converted from analogue to digital according to the Chester Agreement (CH97). In this case, a single analogue transmitter can be converted into one or several digital transmitters, operating in a small-cell SFN. Also, additional frequencies (e.g. channels above ch. 60) can be used. The conversion of analogue transmitters into digital transmitters, according to the Chester Agreement, requires at least a 7 dB reduction in the transmitted power *(Table 1)*. After the conversion of all transmitters, this reduction is no longer required, provided all the digital transmitters increase their ERP by this amount.

In the final state, the full area coverage will mainly be realized by large-area SFNs. This aim can only be achieved by a revision of the Stockholm 1961 Agreement since, as mentioned above, the current network structure only allows for small-cell SFNs, and further frequency resources in general are not available. It is most unlikely that a revised Stockholm Agreement will come into force before the year 2010. Therefore, a higher number of programmes (the foreseen target is currently 20 - 24 programmes in total) cannot be realized until then. During the transition period, it will not be possible to radiate more than 12 programmes from each transmitter, unless higher modulation schemes are used. Full area coverage at that stage can only be achieved with a moderate coverage probability (cp ≈ 70%).

Transition period

The transition period which was taken as a basis in the LfK study should first be considered. With the coverage aim of providing “portable indoor reception" and using the DVB-T variant 16-QAM, R=2/3, the values for the minimum median usable field strength (at 10m agl) are quite high *(see Table 2)* and clearly above those for analogue television. *Fig. 2* shows the DVB-T coverage of Schleswig-Holstein using nine transmitters, on the basis of the ITU-R propagation curves for 70% coverage probability. Both the minimum usable field strength and the interference contours are represented. Significant differences between both contours are hardly noticeable. For a coverage probability of 70%, the theoretical coverage gaps are larger than those of analogue TV. In *Fig. 3*, the coverage for 95% coverage probability is additionally shown (inner contours).

Table 2
Minimum usable field-strength values for DVB-T (16-QAM, R = 2/3) in UHF bands IV and V *(values for band V are in brackets)***.**

	Minimum median usable field strength (dBμV/m)	
	Fixed reception	Portable indoor reception
	Antenna height = 10m	Reference antenna height = 10m (ITU-R Rec. P.370)
Coverage probability 70%	44 (48)	71 (75)
Coverage probability 95%	50 (54)	81 (85)

If the coverage calculation is performed in conjunction with a topographical database which considers the more favourable propagation conditions that are applicable in Schleswig-Holstein, then more realistic statements can be made. *Fig. 4* shows that for a coverage probability of 70%, only small coverage deficits may be expected. On the other hand, the available transmitter network structure is not sufficient to provide for a DVB-T coverage probability of 95% *(Fig. 5)*. The DVB-T coverage assuming the use of roof-top antennas (i.e. stationary reception with a coverage probability of 95%) is represented in *Fig. 6*. In spite of the transmitter power being reduced by around 7 dB during this phase, the entire area is well covered.

Final state

After the transition period, i.e. when the results of the revised ST61 conference come into force, the transmitters should become operational in an SFN. Due to the network gain which is normal within SFNs, a clear improvement in the coverage situation can be expected. The coverage map shown in *Fig. 7*, which assumes portable indoor reception, is based on the situation where all transmitters are operated as an SFN. The transmitter powers are between 50 and 100 kW *(Table 1)*. On account of the dimensions of Schleswig-Holstein, self interference is already noticeable in some areas. It can be expected that a subdivision of the area will improve the situation to a great extent.

A further (tenth) transmitter was introduced at Itzehoe (north west of Hamburg). This transmitter provides clear improvements in the area as shown in *Fig. 8*. Time-delay optimization may improve the results even further.

Costs

The costs to be expected will largely be influenced by the degree of coverage and the network structure envisaged. Due to the linearity requirements of the COFDM signal, a so called "back-off" in the order of 6 dB is deemed to be necessary for the transmitter final stage, i.e. the nominal output power of the final transmitter stage should be 6 dB above the operational transmitter power. According to the Chester Agreement the digital transmitter power should be at least 7 dB below the analogue transmitter power, i.e. the nominal transmitter output power for analogue and digital operation is nearly the same. Under this condition and neglecting the cost of the multiplexer, in a first approximation the costs at the transmitter site will remain constant. However, the extension of the infrastructure (power supply, antennas, buildings) which may be necessary at certain transmitter sites, would lead to a corresponding increase in the costs.

For a coverage probability of 70%, the cost factor for one digital programme would be 25% of that of an analogue one. For higher degrees of coverage, in the case of MFN structures this value will increase proportionally with the number of transmitters. Compared to MFNs, the possible transition to SFNs – after the Revision of ST 61 – would lead to greater improvements at the higher degrees of coverage. However, an investigation of more difficult topographical areas is required to ascertain what the relevant cost factors would be.

Abbreviations

16-QAM 16-state quadrature amplitude modulation
agl Above ground level
C/N Carrier-to-noise ratio
COFDM Coded orthogonal frequency division multiplex
DAB Digital Audio Broadcasting
DVB-T Digital Video Broadcasting - Terrestrial
ERP Effective radiated power
ITU International Telecommunication Union
ITU-R ITU - Radiocommunication Sector
JPEG Joint Photographic Experts Group
MFN Multi-frequency network
NW North-west
PDF (Adobe) portable document format
SFN Single-frequency network

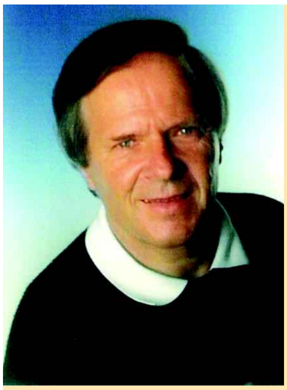
Conclusions

On the basis of the assumed planning parameters and the use of an MFN to cover the federal state of Schleswig-Holstein, it can be expected that satisfactory full area coverage for portable indoor reception of DVB-T may be achieved with probabilities of 70%. With the existing transmitter network, full area coverage with higher probabilities (95%) can only be achieved for stationary reception using roof-top antennas.

With the MFN concept, during the transition period the realization of higher coverage probabilities can only be envisaged in a financially justifiable frame. This could possibly lead to transmitter network structures which may not be required in the final state, i.e. the realization of SFNs. Operating the present transmitter network as an SFN, a division of Schleswig-Holstein into sub-regions may be advisable, to reduce the system-dependent self interference.

On the basis of the results obtained, for the transition period some statements concerning costs can be made. In the case of an MFN, these costs widely depend on the degree of coverage envisaged. With the reception mode "portable indoor" and coverage probabilities up to 70%, the lower limit of the expected costs would be in the order of 25% per programme, when compared with one existing analogue programme.

On account of the different topographical terrain within Germany, the results cannot simply be extrapolated to other federal states.



Gerd Petke is Head of the Frequency Planning and Management section of the Institut für Rundfunktechnik (IRT). After having studied RF-transmission techniques and telecommunications at the University of Hannover, he joined the IRT in 1971, where he was involved in all aspects of broadcasting transmission systems (radio and television). In 1984 he was appointed Head of the Frequency Planning and Management Section.

In connection with his continuous frequency planning activities, Mr Petke is involved in all planning aspects for future transmission systems, such as T-DAB and DVB-T, and in establishing sharing criteria between broadcasting and other services. He is an active participant in several international working groups of the EBU and the CEPT, dealing with aspects of terrestrial broadcasting.

Jürgen Frank, born in 1964, studied electrical engineering at the University of Stuttgart with an emphasis on telecommunications. After completing his studies in 1992, he joined the Institut für Rundfunktechnik (IRT) as a scientific employee in the specialist field of antenna systems and wave propagation. His special area there was the planning and implementation of measurements and system tests in the DAB radio channel.

Since 1996, Mr Frank has been a member of the IRT's Frequency Planning and Management Section, working on planning matters of digital terrestrial transmission systems such as T-DAB and DVB-T.

Bibliography

[1] ITU-R Recommendation P.370: **VHF and UHF propagation curves for the frequency range from 30 MHz to 1 000 MHz. Broadcasting services**
http://www.itu.int/itudoc/itu-r/rec/p/index.html

Appendix A:
Coverage maps

The following maps have been produced at medium resolution (150dpi) and by using high JPEG compression — to keep the overall PDF file size of this article within manageable limits.

By clicking on any of these maps, you can download a higher-quality JPEG version of the map.

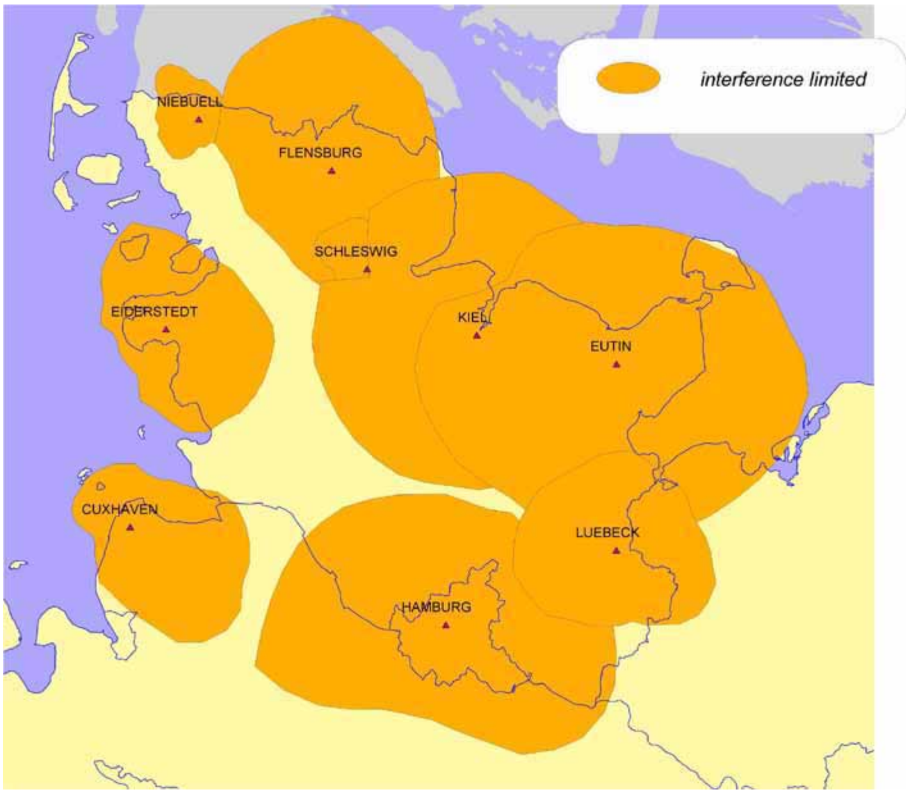


Figure 1
Analogue coverage in the Schleswig-Holstein region, taking interference into account.

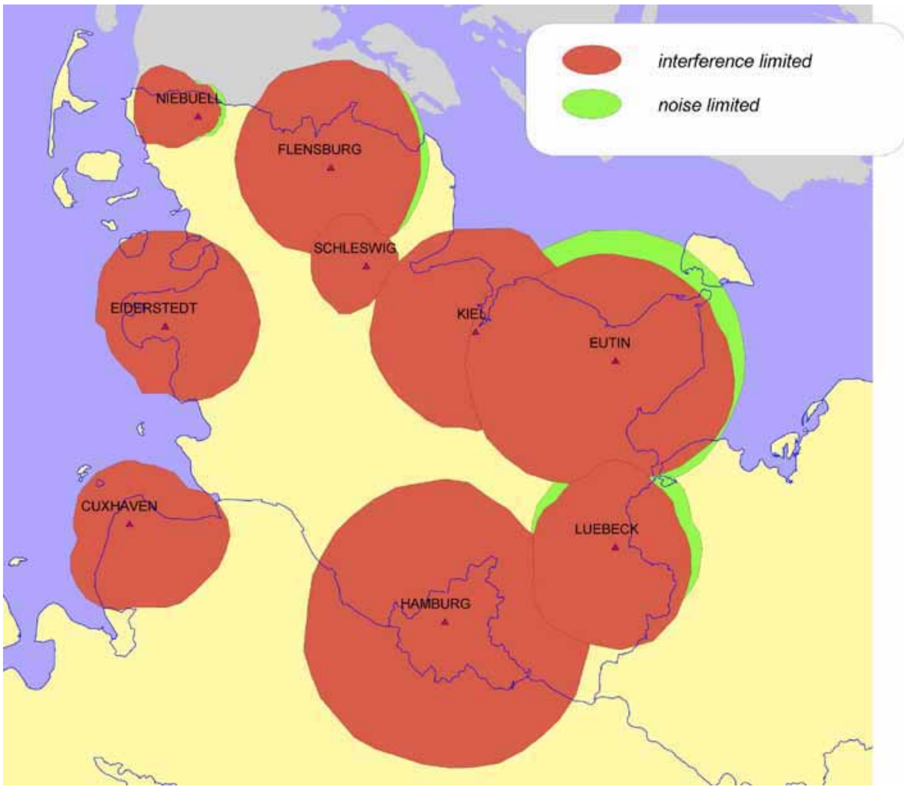


Figure 2
DVB-T coverage (for portable indoor reception) in the Schleswig-Holstein region using the DVB variant 16-QAM, R = 2/3, and showing the 70% probability contours.

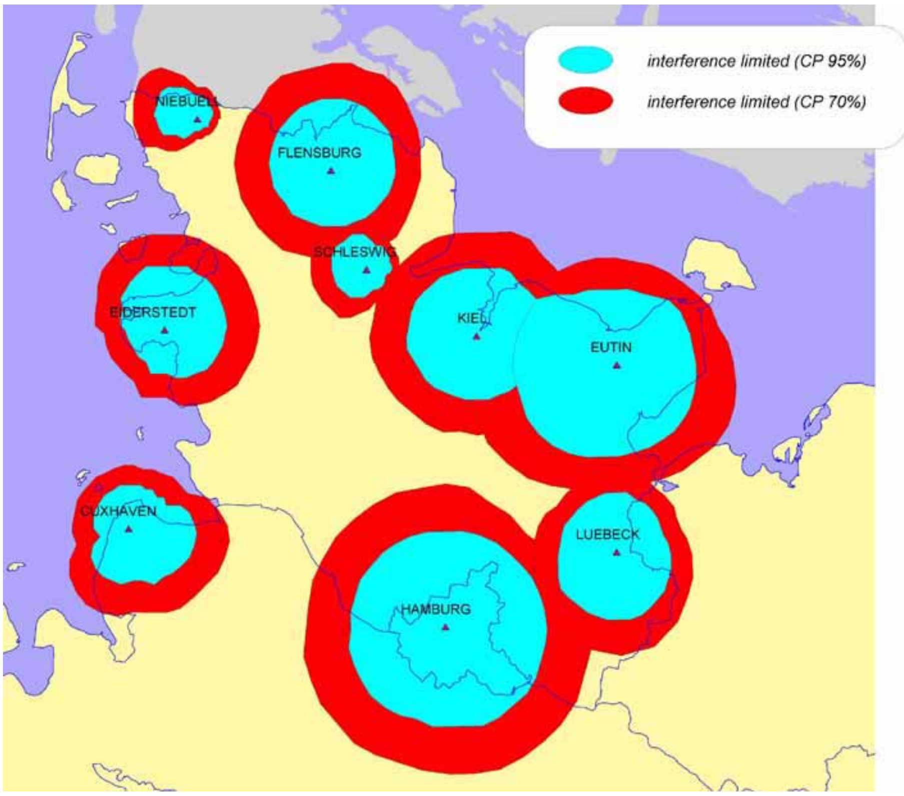


Figure 3
As Figure 2 but additionally showing the 95% probability contours.

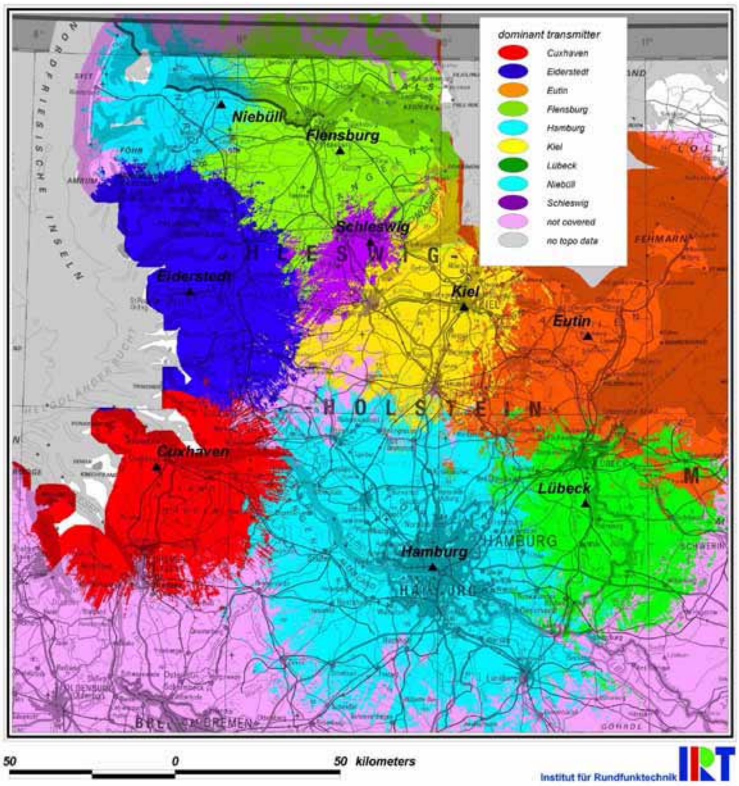


Figure 4 – Calculated DVB-T coverage for portable indoor reception (70% probability) In this case, only small coverage deficits would be expected.

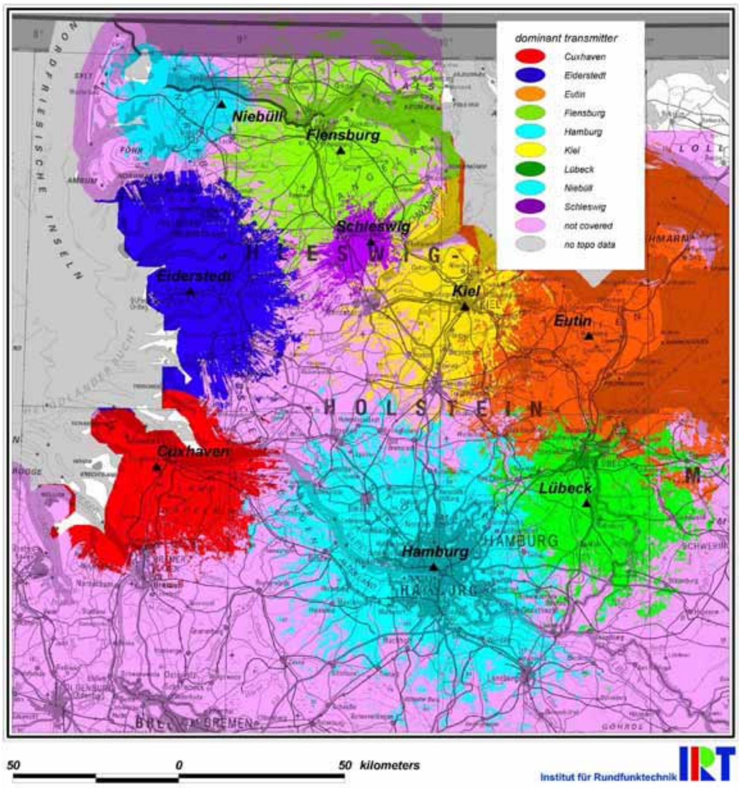


Figure 5 – Calculated DVB-T coverage for portable indoor reception (95% probability) In this case, the existing infrastructure (with nine transmitters) would not be adequate.

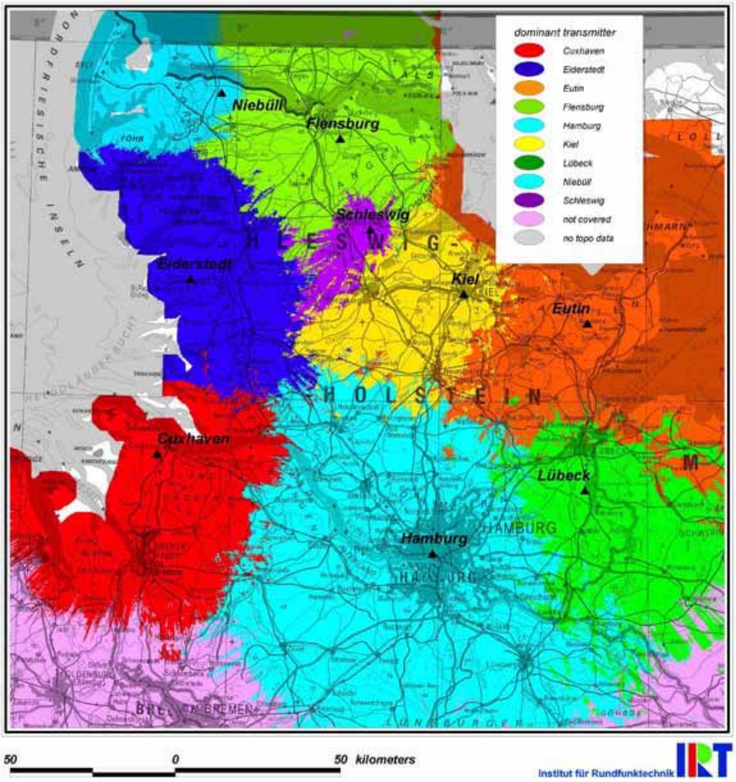


Figure 6 – Calculated DVB-T coverage for fixed-antenna reception (95% probability) Despite a 7dB reduction in transmitter power, the entire area is well covered.

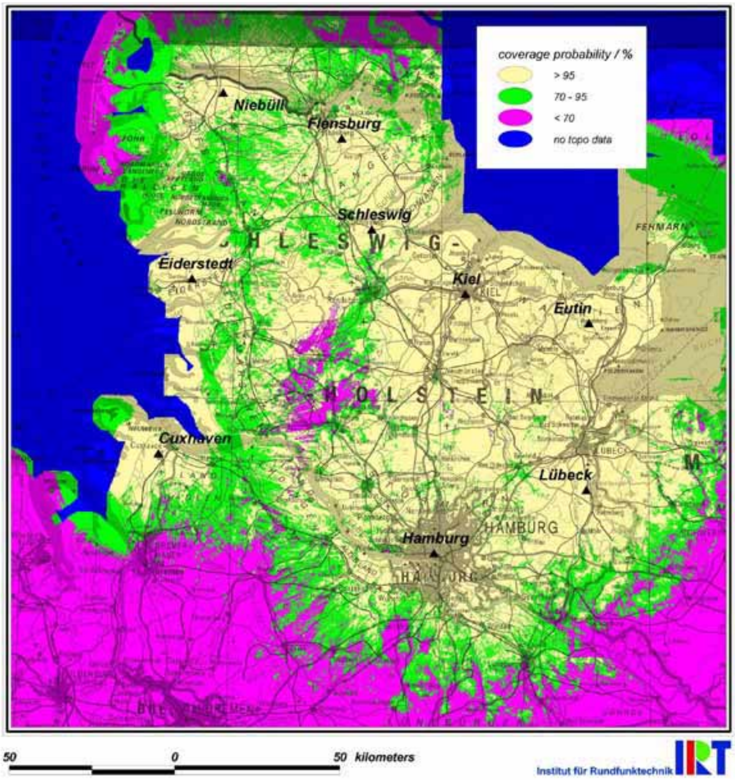


Figure 7 – Calculated DVB-T coverage for portable indoor reception (95% probability)
In this case, an SFN has been used, yielding significant coverage gains.

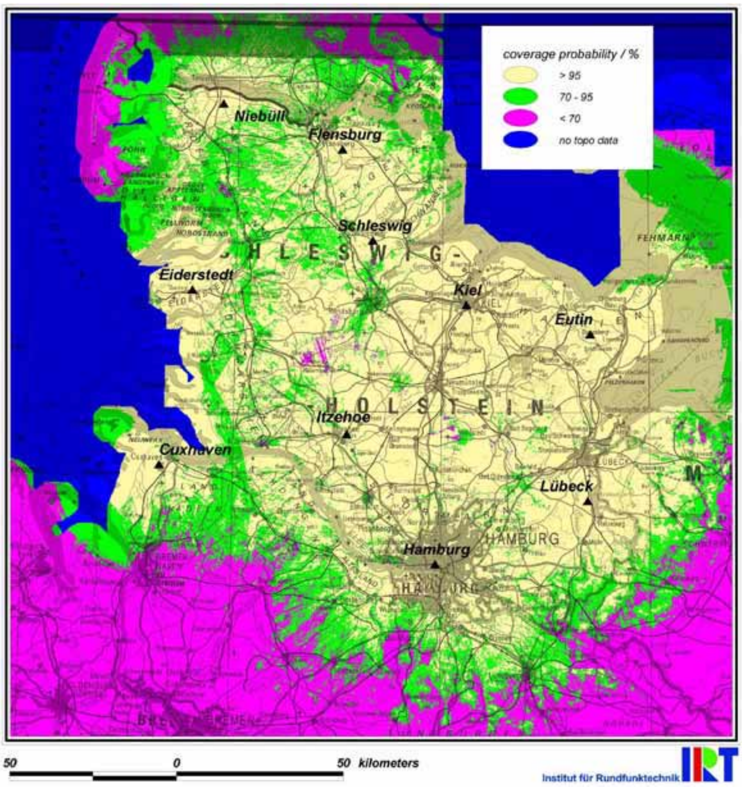


Figure 8 – Calculated DVB-T coverage for portable indoor reception (95% probability)
As Figure 7 but with an extra SFN transmitter to cover the Itzehoe area (NW of Hamburg).

B.5 Sweden (2004)

SFN experience in Sweden

Ever since the launch of DVB-T in Sweden in 1999 regional SFNs have formed part of the network. Sweden has chosen to use SFNs for the following reasons:
To ease coordination and facilitate frequency planning
To improve and extend coverage

There are in principal two types of SFNs in Sweden
- SFN between two or more high-power transmitters, covering comparatively large geographical areas.
- SFN between a high-power transmitter and one or more low-power transmitters to improve and extend the coverage from the high-power transmitter.

SFN between high-power transmitters

Typically the transmitters have ERPs in the range 10 to 50 kW. The distance between high-power transmitters is often longer than the shortest guard interval, 1/8.

Depending on the ERP levels for the transmitters forming the SFN two different DVB-T modes are used. In the case they have the same ERP level, the mode 64-QAM with code rate 3/4 and guard interval 1/4 is used. If the difference in ERP is 7 dB or more the mode 64-QAM with code rate 2/3 and guard interval 1/8 is used. In the latter case time delay is introduced in order to overcome self-interference.

SFN between high- and low-power transmitters

Typically, the high-power transmitter has an ERP of 10 to 50 kW while the low-power transmitters have ERPs not higher than 5 kW.

For this type of SFN the DVB-T mode 64-QAM with code rate 2/3 and guard interval 1/8 is used. If the distance between the transmitters is longer than the shortest guard interval, 1/8, time delay is introduced in order to overcome self-interference.

Difficulties related to echo handling

Many of the receivers available on the market today have deficient echo handling. The reason for this is often the chip implementation. This is especially true for the weaker code rates in combination with a long guard interval. The defective echo handling is most obvious for 0 dB or near 0 dB echoes. One may argue that these kinds of echoes are very unusual in a real network. However, because of the time variance of the individual signal components it is very likely to sometimes have these kinds of echoes, even though this does not seem to be the case when planning the SFN network. This is at least true for portable reception where no antenna discrimination is present.

The EPT model given in section 4.1.3 of this document does not fully take into account these difficulties resulting in an insufficient increase of the required C/N. Measurements performed by Teracom have shown that up to 3 dB higher C/N is needed for 64-QAM with code rate 2/3 and up to 7 dB higher C/N for 64-QAM with code rate 3/4, compared to the above mentioned model. Teracom has therefore chosen to implement an alternative EPT model in the network planning system GiraPlan, to better take into account these difficulties for the two DVB-T modes mentioned.

B.6 Singapore (2004)

A commercial DVB-T mobile network in Singapore

A commercial DVB-T mobile network has been built in Singapore in the year 2000. This network was to provide coverage to non-diversity receivers that were available at the time. The network was designed with a 2K system variant of 16QAM ½ rate with a full ¼ guard interval.

The network consists of one high power station which is horizontally polarised with an ERP of ~40 kW, nine lower power gapfillers vertically polarised of ERP ~1 kW and two very low power 'On-Channel' repeaters of ERP~250 W.

The distribution was provided by a low power UHF channel from the main station radiating an ERP of 2 kW. The gapfillers required modulators so the network could be adequately 'timed' to avoid inter SFN interference. Network timing is extremely critical for this network as the guard interval 'distance' is only approximately 15-16 km (approximately 1/3 distance of the East-West distance of the island of Singapore).

The market for this network was for the Singapore Bus Service, who installed receivers and screens on all its buses on the major bus routes. This was approximately 1000 buses. The coverage of this network was designed to give 99% location probability and coverage across the main island. The network does provide "near complete" coverage across the island to this service level. There do still remain some very small areas of which are not served to required level of service.

B.7 United Kingdom (2004)

Planning DAB Networks in the UK

1. Introduction

In planning DAB networks there are two levels to be considered. The first is at an administrative level – where general limits, international and national, are set on DAB allotments. The second is at a more practical level – how to best design a network within the administrative constraints, while meeting performance, infrastructure and cost constraints imposed by transmission providers and broadcasters.

This note briefly summarises the various stages involved in planning at the second level – designing real networks, i.e. populating an allotment with assignments.

2. Regulatory Constraints

In the UK, a primary constraint on all DAB networks is the requirement to limit interference to other countries. Rules governing interaction between DAB networks were agreed at the CEPT conferences at Wiesbaden, Bonn and Maastricht.

In addition to international requirements – local regulations impose further national constraints, in terms of limits placed on co-block interference, adjacent channel interference and site selection, coverage requirements and editorial overlap.

2.1. International Test Points

2.1.1. Bonn Summation method

In the rules for DAB co-ordination agreed at the Bonn conference, the field at a particular test point is determined by the sum of the contributions from all the stations that increase the field by 0.5 dB or more. Stations that contribute less than 0.5 dB are not included in the summation.
The Bonn Summation is described as follows:

- starting from the highest, the power values equivalent to the interfering field strengths are added, one after the other;
- at each summation, the result is compared to the previous one;
- if the increase in power is greater than or equal to 0.5 dB, the summation process continues;
- if the increase in power is less than 0.5 dB, the summation process is stopped and 0.5 dB is added, giving the result of the power sum.

Example:

For a single calculation test point, with a T-DAB allotment converted into a network of 5 assignments, Transmitters 1 to 5, the power summation process would be as detailed below:

Note: The first stage of the summation process is to sort the transmitters in order of decreasing equivalent field strength

The corresponding power factor, power summation and conversion back to the resulting equivalent field strength are calculated according to the formulae below:

Formulae used:

Corresponding Power Factor	$P_f = 10 \wedge^{(En\ /\ 10)}$
Power Summation	$\sum_p = P_{fn} + P_{fn+1}$
Corresponding Equivalent Field Strength	$E_{ps} = 10 \log (\sum_p)$

Transmitter	Equivalent Field strength E_n (dBµV/m)	Corresponding Power Factor P_f	Progressive Power Sum $\sum_p$	Corresponding Equivalent Field Strength E_{ps} (dBµV/m)	Increase (dB)	Comment	Resulting Equivalent Field Strength (dBµV/m)
Tx 3	13.55	22.65	22.65	13.55		Continue summation	13.55
Tx 4	12.73	18.75	41.40	16.17	2.62	Increase due to this Tx will be more than 0.5 dB, so continue.	16.17
Tx 2	11.88	15.42	56.81	17.54	1.37	Increase due to this Tx will be more than 0.5 dB, so continue.	17.54
Tx 5	11.21	13.21	70.03	18.45	0.91	Increase due to this Tx will be more than 0.5 dB, so continue.	18.95
Tx 1	8.31	6.78	76.80	18.85	0.40	Increase due to this Tx will be less than 0.5 dB, so add 0.5 dB and stop summation.	19.45

2.2. Internal restrictions

2.2.1. Adjacent channel interference

When DAB was first launched in the UK, there were two national networks. The BBC National Network on 12B across the whole UK, and the Digital One network across Great Britain (i.e. excluding Northern Ireland), using 11C in England and Wales, and 12C in Scotland.

When a new station is brought on air on a block which is adjacent to an existing service, from a new site which is not being used by the existing service, there may be an area around the new site where the field strength of the new service is likely to exceed the field strength of the existing service by more than the relevant adjacent channel protection ratio (30dB). This can be seen as ring of interference around the new site, where the existing service may no longer be received (also called the halo effect). This can be prevented by either ensuring the new service is of sufficiently low level not to exceed the adjacent channel margin, or by ensuring the new site is co-located.

It was therefore recognised that to reduce the effect of adjacent channel interference in Scotland between the BBC network and Digital One's network, it was preferable to co-locate the services wherever possible.

When the local and regional services in blocks 11B, 11C, 11D, 12A, 12C and 12D were planned in different parts of the country, often by different transmission service providers, it became important to co-ordinate the choice of sites at a national level.

Since this time, additional work has been undertaken on typical receivers, and it has been found that in many cases the receiver response on the 2nd or 3rd adjacent channel is only 5 to 6 dB better than the adjacent channel response, and it is therefore important to ensure even non-adjacent block transmitters are co-located where possible.

2.2.2. Self-Interference

Self-Interference is not generally an issue for the smaller regional or local Band III DAB networks, as the guard interval is normally comparable to or greater than the target service area. However, for national networks self-interference can be an issue, particularly where sea paths are involved. The UK national DAB networks have transmitters over 70km apart, Figure 1. Careful design of antenna patterns and optimisation of the relative timing between stations can be used to limit any self-interference and to optimise coverage. It should be noted that the receiver synchronisation model used within the coverage prediction software tool may have a significant effect on predicted coverage, some being more susceptible to pre or post-echo interference.

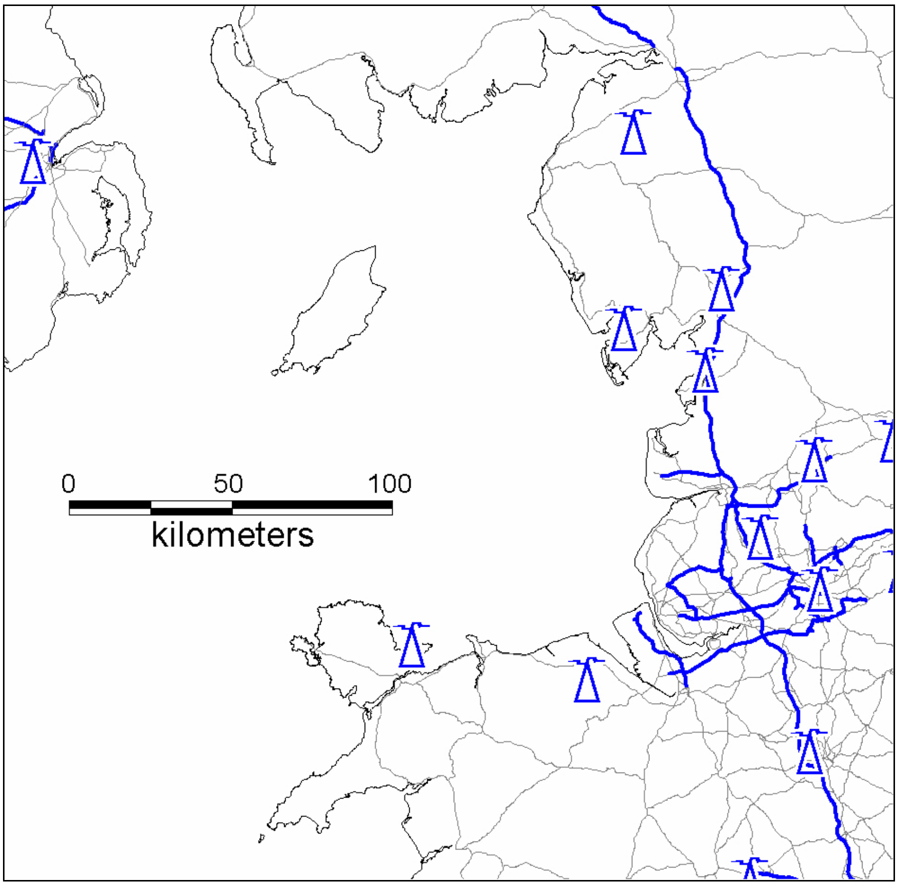


Figure 1: UK National DAB transmitters located around the Irish Sea

2.2.3. Interference to co-block allotments

Within national boundaries a DAB block may be reused several times. In planning interference between allotments within the UK, the UK regulator normally specifies interference in terms of damage not exceeding that which would occur if a particular representative station within the allotment were to operate at a given ERP and antenna height. To this example transmitter an additional allowance of 2 dBs is allocated to represent the other transmitters of the network being planned.

2.2.4. Editorial Overlap

An additional constraint placed upon the coverage of commercial DAB multiplexes is a limit on the spill over in to adjacent editorial areas. Commercial multiplexes are licensed to serve particular areas, to limit coverage in adjacent areas restrictions are imposed by the regulators.

3. Practical Constraints

When planning a network the planner not only needs to think about meeting the regulatory requirements, i.e. the international and national restrictions, but also how best to implement the network within constraints imposed by available infrastructure.

3.1. Site Selection

The costs involved, as well as general opposition by the public to the proliferation of radio masts, pretty much exclude the option of building new transmitting stations with their associated infrastructure, masts/towers and buildings. Consequently the planner is restricted in the choice of transmitting station with regard to the location of the station and the infrastructure available. However, in choosing a site the planner need not be constrained to broadcast sites – in many cases broadcast sites are distant from population and are exposed making control of out going interference difficult. Subject to meeting RF planning requirements, obtaining access to a site, meeting any RF Hazard obligations and being able to provide a programme feed to a site, there need not be any restriction on the type of site considered for a DAB network, broadcast, telecommunications, cellular or roof top.

3.2. Existing Infrastructure

With space on radio masts being at a premium the use of existing sites is likely to place limits on the type of antenna that can be deployed. The planner needs to be aware of these limitations and explore all options for deploying his preferred solution within in the constraints imposed by mast loading.

At sites with existing VHF/FM or DAB services, prior to considering new antennas, the planner should assess the suitability of either sharing aperture with the VHF antenna or sharing the existing DAB antenna.

3.2.1. Shared aperture

At sites where VHF/FM antennas are deployed and the VHF/FM antenna consist of an array of panels a DAB antenna could be built in the same aperture as the VHF/FM antenna.

3.2.2. Shared antennas

At a site where there is an existing DAB service consideration should be given to using existing antennas. Issues that need to be considered are

- Antenna pattern
    - Does this match that required with respect to out going interference to test points, national and international, at the proposed ERP.

  - o Does it allow the ERP to be optimised – an antenna designed to meet one set of test point restrictions may not be best suited to another. An example of this being the difference between the BBC (12B) and D1 (11D) multiplexes in the UK.
  - o Can the antenna be configured to give different radiation patterns for different frequencies.
  - o Power handling.
- Cost of sharing
  - o The cost of sharing an antenna needs to be considered as part of a design. Sharing an antenna, whilst it may avoid the cost of a new antenna does require a combiner. The cost of the combiner, the cost of sharing an existing antenna, the power handling of an existing antenna – it may need upgrading all need to be considered.
  - o Though adjacent channel interference is an issue, the planning rules do allow the use of alternative sites located close to an existing DAB site. Occasionally it may be more cost effective not to share a site.

3.3. Optimising the network

If the type of network adopted is traditional broadcast, a main station(s) and relays, rather than cellular, the discontinuity in the Bonn summation method can be exploited to make planning of networks easier.

Using the traditional broadcast approach, it is important that the main stations are designed first and are used to ‘saturate’ the test points. The smaller relay stations can then use the fact that provided it contributes less than 0.5 dB to the test point it doesn’t appear in the summation. Thus, subject to the propagation path from the relay to the test point, the relays can operate at levels 9 dB below that of the dominant main station. i.e. if the main stations are 10 kW, any number of relays at ~ 1kW can be added to a network without affecting the summation.

Derivation of the 9dB limit is as follows.

$$10\log\left(\frac{\sum_{i=1}^{n} P_i + P_{i+1}}{\sum_{i=1}^{n} P_i}\right) < 0.5\,\text{dB}$$

From this the ratio of P_{i+1} to $\sum_{i=1}^{n} P_i$ can be determined,

$$\frac{\sum_{i=1}^{n} P_i + P_{i+1}}{\sum_{i=1}^{n} P_i} < 1.122018$$

$$P_{i+1} < 1.122018\sum_{i=1}^{n} P_i - \sum_{i=1}^{n} P_i$$

$$P_{i+1} < 0.122018\sum_{i=1}^{n} P_i$$

$$10\log\left(\frac{P_{i+1}}{\sum_{i=1}^{n} P_i}\right) < 10\log(0.122018) = -9.1\,\text{dB}$$

Given the international and national restrictions imposed on regional and local multiplexes the best coverage is usually achieved by closed networks.

4. Conclusion

Using seven frequencies in Band III and the methodologies described in this paper the United Kingdom has successfully rolled out the T-DAB services below:

One national network to serve most of the United Kingdom (England, Northern Ireland, Scotland and Wales) on block 12B a north-south distance of some 900 km.
One network to serve most of England and Wales on block 11D.
One Network to serve most of Scotland on block 12A.
48 local or regional services varying from 30 to 100 km in diameter.