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GUIDELINES FOR DAB NETWORK PLANNING

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Guidelines for DAB network planning

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Introduction

Over the last few years, digital radio has increasingly been adopted, with the DAB system being the most widespread standard.

Many, especially European, countries are extending and updating their existing DAB networks to enhance their radio offerings, to meet the higher quality expectations of listeners and to reduce energy consumption. Norway is a clear example of this trend; it has just successfully completed its national analogue radio switch off.

The EBU's previous report on DAB planning issues, TR 021 [EBU_1], was prepared in 2003 and it still remains a useful guide. Since then, however, the widespread availability of new receivers, the experience gained by network planners and the revision by ETSI of the DAB standard in January 2017, has highlighted the need for an updated planning document on DAB.

This report provides guidance on key elements that are necessary to plan and design a DAB network. No information on the overall transmitter network planning process has been included as this is specific to country situations and constraints and it can be found in other documents, e.g. TR 021 [EBU_1]. The latest release of the DAB standard only covers the VHF band, which includes Bands I, II and III. In this report only Band III is considered.

This report has eight sections in its main body and eleven annexes (Annex A - K).

The annexes are detailed studies of subjects already considered in the main body of the report and which are not publicly available elsewhere.

The use of the term 'DAB' in this report applies to both DAB and DAB+ systems (see §1.2). Where there is a difference in the impact on network planning between the two systems, this is explained.

1. The DAB standards

1.1 Short review of DAB standards

The DAB digital broadcasting system originated from a European funded project known as Eureka 147. The members of the project team decided to standardize the system at ETSI and the system standard was first published in 1995 as ETS 300 401 [ETSI_1]. The DAB standard has been supported and developed for many years by the WorldDAB Forum, a not-for profit membership organization, and is actively supported by the European Broadcasting Union (EBU). The latest version of the DAB standard was published by ETSI in January 2017 as EN 300 401 V2.1.1 [ETSI_2].

The core DAB standard describes the coding, modulation and transmission system parameters. Two basic data mechanisms are provided: stream mode and packet mode. Also defined is the signalling channel that allows a receiver to make sense of the content of the multiplex[1]. Compared with analogue broadcast radio systems, a DAB transmission is relatively wideband, this extra bandwidth allowing several services to be carried on the transmission. Such a transmission carrying more than one service is known as an ensemble. Originally, the DAB audio coding mechanism, using MPEG Layer II coding, was included in the core specification, ETS 300 401 [ETSI_1]. Later developments in audio coding efficiency led to the introduction of DAB+ audio coding, based on MPEG-4 AAC coding, which is described in a separate specification, TS 102 563 [ETSI_3]. With the release of EN 300 401 V2.1.1 [ETSI_2] the DAB audio coding definition was also transferred into a separate specification, TS 103 466 [ETSI_4].

DAB is most widely used as a digital radio transmission system for audio services using DAB+ audio coding, with text messages carried as dynamic labels. Additional data can accompany the audio services, visuals via the SlideShow application and logos and programme information via the Service and Programme (SPI) application. The SPI application also allows carriage of other non-audio services such as mobile video services, traffic data and a host of other applications.

Additional standards documents have been created to facilitate additional features, interoperable equipment interfaces, additional transport modes, data applications, etc. A useful guide to the DAB standards is available as ETSI TR 101 495 V2.1.1 [ETSI_5].

1.2 DAB and DAB+; what is the difference?

Some ambiguity surrounds the terms DAB and DAB+, owing to the way that the DAB system has developed over time. Often, DAB+ is used to describe the whole transmission system, although this would more correctly be described as a DAB ensemble with exclusively DAB+ audio services. The coding, modulation and transmission systems are identical whether the ensemble carries DAB audio services, DAB+ audio services, DMB[2] video services, data, or any combination of these[3].

Today, the majority of DAB ensembles used for digital radio services carry those services using DAB+ audio coding. This is because DAB+ audio is more bandwidth efficient, using around half of the bitrate needed by DAB audio for the same subjective quality, and it is slightly more robust than DAB audio at the same protection level (see § 2.4.1).

DAB audio coding was designed at the same time as the coding, modulation and transmission system. Five levels of Unequal Error Protection (UEP) were specified which provide additional protection to the more sensitive parts of the audio frame. DAB+ audio coding was designed to fit into the existing DAB system, the AAC audio frames are collected into audio super-frames of constant duration and are further protected by a Reed-Solomon (RS) coding. DAB+ audio sub-channels are protected using one of four levels of Equal Error Protection (EEP).

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[1] Multiplexing is a technical process of sharing the capacity and includes multiplexing of Fast Information Channel (FIC) and Main Service Channel (MSC), whereas an ensemble is a logical container for services.

2 DMB is a video and multimedia enabled version of DAB designed mainly for handheld reception. Planning parameters and network aspects for DMB are addressed in [EBU_2] and [EBU_3].

[3] The applications carried by the core DAB standard have particular encodings, but all applications are carried in sub-channels and the coding and modulation refers to the system, which is OFDM, DQPSK with time and frequency interleaving and convolutional error correcting coding. DAB audio is a streaming application carrying MPEG-1 and MPEG-2 Layer II audio coding, DAB+ is a streaming application carrying MPEG-4 HE-AACv2 audio coding and DMB is a streaming application carrying MPEG-4 SL with MPEG-2 TS and MPEG-2 video and audio coding. All the applications can be mixed on the core DAB system layer.

2. System properties of DAB

2.1 Modulation Scheme and guard interval

2.1.1 General

DAB uses 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 planning[4].

2.1.2 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.

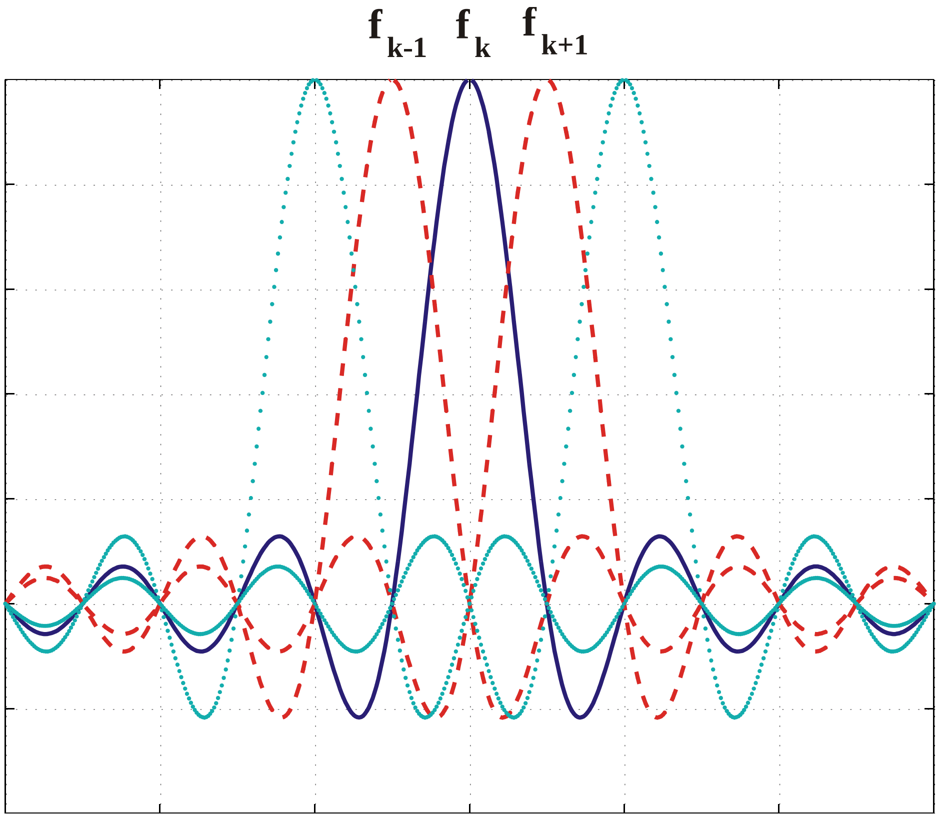


Figure 1: Schematic presentation of carrier orthogonality in an OFDM signal (after windowing)

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 1). The multiplex of carriers may be conveniently generated digitally using the inverse Fast Fourier Transform (FFT) process.

All carriers added together give a noise-like power density over the bandwidth of the OFDM signal. Figure 2 shows the sum of the power spectral density of all carriers for the DAB system.

[4] Further information on OFDM can be found in many texts - for example 'Orthogonal Frequency Division Multiplexing for Wireless Communications', Y. G. Li and G. L. Stuber, Springer - 'OFDM Concepts for Future Communication Systems', H. Rohling, Springer.

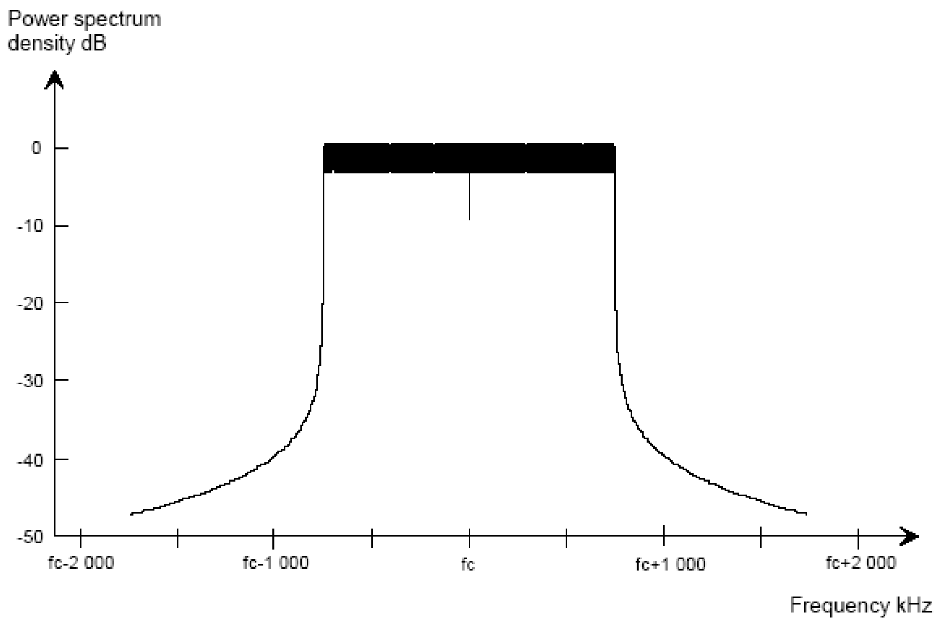


Figure 2: DAB transmission signal spectrum (1.536 MHz channel)
(from ETSI Standard EN 300 401 [ETSI_2])

2.1.3 Carrier structure DAB

DAB uses a convolutionally coded D-QPSK OFDM signal. The system is based on the use of 1536 active carriers with a frequency spacing of 1 kHz. All carriers are transmitted at the same power level. Four DAB frequency 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.

2.1.4 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, DAB uses 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 frequency selective fading and significantly improves the performance of the decoder.

2.1.5 Time interleaving

An important property of a broadcast system targeting mobile reception is the use of time interleaving. In a mobile radio propagation channel, errors often appear in bursts. This may happen, for example, when field strength is too low at some reception points on the route along which a mobile receiver is moving.

In this case, use of time interleaving ensures that the errors resulting from these outage points are distributed over several transmission frames allowing the error protection/correction to rectify any errors that may occur. In DAB the interleaving depth is 16 logical frames which is equivalent to 384 ms.

Time interleaving is, however, most effective above a certain speed. In the case of DAB the time interleaving is less effective at speeds below roughly 15 km/h. This means that the portable indoor reception case may be a worst case scenario.

2.1.6 Single frequency networks

OFDM signals allow for single frequency network (SFN) operation. This is due to OFDM's multi-path immunity (see § 2.1.7). SFN operation is possible when exactly the same signal, in terms of bits/content, 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 § 2.1.7 and in § 3.11.

2.1.7 Multipath capability of DAB

OFDM, when coupled with appropriate channel coding (error correction coding), can achieve a high level of immunity against multipath propagation and co-channel interference.

In OFDM, 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. At the end of the time period the modulation is changed and the next symbol carries the next portion of information.

A DAB receiver has to cope with the adverse conditions of the broadcast transmission channel. Unless measures are taken, signals arriving at a receiver by different paths will have different time delays which will result in inter-symbol interference (ISI) and 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 period in which useful information can be extracted from symbol's that are delayed. The FFT-window, i.e. the time period for the OFDM demodulation is then positioned to minimise the inter-symbol interference. The insertion of the guard interval, whilst helping avoid ISI reduces the data capacity because less of the symbol duration is used for "useful" data - the guard interval is a period where the received signal is not used to make received data decisions; it is only used to avoid ISI from the previous symbol due to multipath delays.

In a multipath or SFN environment, where many potentially useful signals are available to the receiver, the choice of the FFT-window position may be a complex task. A number of different synchronization strategies that could be applied are briefly discussed in § 2.3; more detail can be found in EBU TR 029 [EBU_4]).

All signals with time delays that cannot be absorbed by the guard interval in the way described above introduce a degradation of reception.

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.

2.2 Transmission modes

In the first edition of the DAB standard published in 1995, ETSI ETS 300 401 [ETSI_1], three transmission modes were defined to allow the DAB system to be used in both terrestrial and satellite network configurations and over a wide range of operating frequencies. A fourth transmission mode was later added (see Annex A). With the latest version of the standard, ETSI EN 300 401 V2.1.1 [ETSI_2], only Mode I, corresponding to use in the VHF Band (30 to 300 MHz) has been retained.

Transmission Mode I is intended to be used for terrestrial Single Frequency Networks (SFN) and local-area broadcasting in Bands I, II and III. It may also be used for cable distribution and for Multiple Frequency Networks (MFN) as well.

Table 1: Mode I features

Typical Use	Mode I Terrestrial VHF
Number of carriers	1536
Carrier spacing [kHz]	1
Useful Symbol duration [μs]	1000
Guard interval [μs]	246
Total Symbol Duration [μs]	1246
Max Speed VHF [km/h]	260/390[5]

2.3 Receiver time synchronization

The synchronization of an OFDM receiver is performed in two stages:

- the initial synchronization in which the receiver is aligned with the symbol rate,
- the secondary synchronization in which the receiver positions the FFT-window to demodulate the signal.

To facilitate receiver synchronization, the transmitted signal is built up with a frame structure having a fixed sequence of symbols. Each transmission frame begins with a null symbol of duration T_{NULL} for coarse synchronization (when no carrier is transmitted), followed by a phase reference symbol for differential demodulation. The null symbol duration T_{NULL} is of 1297 μs.

The receiver should carefully position its symbol window (equivalent to the FFT analysis period) so that any Inter-Symbol Interference due to multi-path reception (or, in an SFN, multiple transmitter reception) is kept within the guard-interval. From the FFT resultant, only the N middle carriers contain useful data, where N=1536 sub-carriers, as there is only Mode 1.

Repositioning of the symbol window, from frame to frame, will only result in a phase shift of each carrier. This does not affect differential demodulation between adjacent symbols.

The null symbol provides coarse receiver synchronization but can also carry Transmitter Identification Information (TII). The receiver could also use the null symbol to analyse the transmission channel and take account of the level of interference and noise which may be present.

The phase reference symbol provides fine synchronization information allowing the receiver to extract frequency information and a phase reference for differential demodulation. The receiver does not need to extract a carrier reference for signal demodulation.

In a real multipath environment, the receiver encounters a multitude of echoes that make the second-stage synchronization process, finding the “best” position for the FFT-window, a complex task. Various strategies can be applied optimize the receiver performance.

For coverage calculations, a model is needed to describe the synchronization 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 DAB system specifications. This means that manufacturers have their own solutions and, moreover, regard these various solutions as confidential, making a single description of receiver FFT-window positioning difficult.

[5] For the maximum speed two values are given: the first figure applies to urban / suburban areas, and the second applies to rural areas. See ITU-R, DSB Handbook, “Terrestrial and satellite sound broadcasting to vehicular, portable and fixed receivers in the VHF/UHF bands”, 2002. https://www.itu.int/pub/R-HDB-20.

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 could get 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 that only take into account 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 synchronization modelling is no longer unique since there may be 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 synchronization instants and the time variation of shadow fading in a transmission channel. It means however that a real receiver will not show exactly the same synchronization behaviour as that described in the simple model cases below.

Synchronization strategies

FFT-window synchronization is of particular importance for mobile and portable reception, when the receiver will need to be able to synchronize 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 for synchronization, and where the receiver sets the FFT-window relative to this peak.

Five different strategies are commonly used in receiver modelling. When two or more signals are involved various approaches are possible. Four of them are relatively simple, straightforward strategies, while the fifth is an idealised, optimal strategy:

- Strongest signal
- First signal above a threshold level
- Centre of gravity
- Quasi-optimal
- Maximum C/I

Further information about the various synchronization strategies can be found in EBU TR 024 [EBU_5].

2.4 Protection levels, coding and net bit rates

Convolutional encoding is applied to each of the data sources feeding the multiplex to ensure reliable reception (see [ETSI_2] § 11 “Convolutional coding”). The encoding process involves adding deliberate redundancy to the source data. In the ETSI standard specification for the DAB system [ETSI_2], five Unequal Error Protection (UEP) levels are available (used for DAB audio) and eight Equal Error Protection (EEP) levels are available (used for DAB+ audio and data) that use punctured convolutional coding.

The total capacity of the Main Service Channel (MSC) can be partitioned into several sub-channels. Depending on the number of sub-channels the net bit rate is calculable. Some net bit rates, using the example of 6, 12 and 18 sub-channels carrying DAB audio services, are given in Table 2 for the UEP protection levels.

Table 2: Net bit rates per sub-channel for DAB audio services*

Protection Level UEP	Net bit rate in kbit/s		
	6 sub-channels	12 sub-channels	18 sub-channels
1	128	64	32
2	128	64	48
3	192	96	64
4	192	112	64
5	256	128	80

*The bit rates shown are those allowed being the closest to but less than the bit rate for the strongest UEP code rate in the protection level, e.g. UEP-1 results in 2304 kbit/s x 0.34 = 783.36 kbit/s for the MSC payload, which when divided by 6 channels is 130.56 kbit/s, the closest allowed bit rate being 128 kbit/s.

In the case of the Equal Error Protection (EEP) levels, there are two options, each consisting of four different Protection Levels. For each option, Level 1 represents the strongest and Level 4 the lowest error protection. Option A has sub-channels in multiples of 8 kbit/s and offers the maximum flexibility for segmentation for service providers and is the option generally chosen for DAB+ audio services. In contrast, Option B has sub-channels in multiples of 32 kbit/s and is designed primarily for DMB video services where the greater bit-rate granularity is less important.

Table 3 shows the corresponding code rates for EEP Options A and B:

Table 3: Code rates for EEP Options A and B

Protection Level	EEP-1A	EEP-2A	EEP-3A	EEP-4A
Code rate	1/4 (0.25)	3/8 (0.375)	1/2 (0.5)	3/4 (0.75)
Protection Level	**EEP-1B**	**EEP-2B**	**EEP-3B**	**EEP-4B**
Code rate	4/9 (0.444)	4/7 (0.571)	4/6 (0.667	4/5 (0.8)

Table 4 is a table of net bit rates, similar to Table 2, but for an ensemble carrying DAB+ audio protected using EEP Option A profiles.

Table 4: Net bit rates per sub-channel for DAB+

Protection Level EEP	Net bit rate in kbit/s		
	12 sub-channels	18 sub-channels	24-sub-channels
1A	48	32	24
2A	72	48	32
3A	96	64	48
4A	144	96	72

The values shown in Tables 2 and 4 are for the case when all sub-channels have the same bit rate; a situation which will usually result in reduced efficiency. The allocation of different bit rates to each sub-channel (for example, higher bit rates for music and lower for news) enables more efficient use of the spectrum.

2.4.1 Coding advantage of DAB+

DAB+ uses MPEG-4 (HE-AACv2) whereas DAB uses MPEG-1 Layer II (MP2) therefore DAB+ audio requires lower bit rates than DAB audio to achieve comparable audio quality, although opinions vary as to what bitrates correspond to an equivalent audio quality [OS_1]. Without entering into detail, it may be summarized that for an equivalent audio quality it would be possible to operate around 1.5 to twice as many DAB+ audio programmes as DAB audio programmes in a given bit rate capacity. For example, to achieve a quality better than FM stereo would require about 160 kbit/s for DAB and about 80 kbit/s for DAB+. See also “ITU-R BS.1534-2 (MUSHRA), codec and bitrate test - Performed for Danmarks Radio” [OS_2].

2.5 C/N values for DAB

2.5.1 General and background

The C/N value is a fundamental planning parameter for DAB networks. Generally, the C/N should ensure acceptable audio quality at a Bit Error Ratio (BER) of 1 x 10^{-4} after Viterbi.

Previously DAB planning has been based on the WI95 [EU_1] and GE06 [ITU_1] agreements. The planning values in these two agreements are mainly based on the EBU planning guideline BPN 003 (issues 1 and 2) [EBU_6]. The coverage criteria used has been mobile reception assuming DAB audio coding in a Rayleigh channel, in a rural environment (RA) at a speed of 130 km/h with an associated C/N of 15 dB (values for a typical urban environment (TU) at a speed of 15 km/h are also given).

Measurements quoted in an early ITU-R Recommendation [ITU_2] suggested a Gaussian C/N value for Mode I at UEP-3 of 7.1 dB. This was simplified to 7 dB for the Wiesbaden planning process. A revision of Recommendation ITU-R BS.1114 [ITU_3], gave a value of 7.6 dB for Mode I and 7.4 dB for Modes II and III. The value of 7 dB was adopted in EBU planning guideline BPN 003 [EBU_6] for all modes in a Gaussian channel.

The EBU guideline TR 021 [EBU_1] considered that for UEP-3 protected sub-channels a C/N value of 7.4 dB is required to achieve a Bit Error Rate (BER) of 1 x 10^{-4} after Viterbi decoding in a Gaussian channel. For Rayleigh channels a figure of between 13 and 13.5 dB is quoted, this being based on operational DAB networks. Corresponding DVB-T planning values are then used to extrapolate / interpolate for all code rates, followed by variable implementation margins for different channel types to derive the results reproduced in Table 5.

Table 5: C/N values for UEP protection (EBU TR 021[EBU_1])

Protection Level	C/N (dB) for BER of 1 x 10^{-4} after Viterbi	
	Gaussian channel	Rayleigh channel - TU 6
UEP-1	5.9	12.1
UEP-2	6.7	12.6
UEP-3	**7.4**	**13.3**
UEP-4	8.4	14.9
UEP-5	10.2	18.6

Planning values optimised for ensembles carrying DAB+ audio services are given in TR 025 [EBU_7]; these values being based on measurements carried out by the IRT[6]. In these measurements, a Gaussian type channel was assumed for fixed reception, whereas for mobile and portable reception a Rayleigh channel (profile TU 12 at 25 km/h and 178 MHz) was assumed. The measurements resulted in the following proposal for C/N values:

Table 6: C/N values for EEP protection (IRT measurements, TR 025 [EBU_7])

Protection Level	Fixed Reception (C/N, dB) - Gaussian channel	Mobile and Portable Reception (C/N, dB) - TU 12 at 25 km/h
EEP-1A	3.8	7.0
EEP-2A	4.4	9.3
EEP-3A	**5.7**	**11.8**
EEP-4A	8.6	17.3

The measurements were based on two arbitrarily chosen DAB+ receivers. The measured receiver noise figures were 4.7 dB and 6.7 dB. At that time, it was concluded that measurements with more receivers would be required to achieve higher accuracy regarding C/N values and receiver noise figures, see §2.5.2.

Table 7 shows a summary of C/N values discussed above for the case of mobile reception using different channel models for UEP-3 and EEP-3A protection levels.

Table 7: C/N values from different sources

	Source	Channel model	Mobile Reception (C/N, dB)
DAB audio, UEP-3	GE06 and WI95 and EBU BNP 003 issues 1 and 2	Rayleigh, RA 6 (at 130 km/h)	15.0
	IRT Measurements	Rayleigh, TU 6 (at 50 km/h)	13.3
	EBU TR 021 (BPN 003 issue 3)	Rayleigh, TU 6	
DAB+ audio, EEP-3A	IRT measurements and EBU TR 025	Rayleigh, TU 12 (at 25 km/h)	11.8

The first row gives the C/N value for DAB from the GE06 [ITU_1] and WI95 [EU_1] agreements. In the second and third rows the C/N value is the result of DAB measurements in a mobile TU 6 channel (50 km/h and 226 MHz) [OS_3] and an estimation of the C/N in a Rayleigh TU 6 channel;

6 Institut Für Rundfunktechnik - an EBU member.

these being based on the most commonly used DAB Mode I with UEP Protection Level 3 (code rate 1/2). The fourth row corresponds to the C/N value for DAB+ with EEP-3A protection level from TR 025 [EBU_7].

2.5.2 C/N values from new measurements

C/N values for DAB ensembles intended to carry EEP protected sub-channels have been determined by a set of measurements carried out by the IRT and Rai Way. These measurements are based on nineteen arbitrarily chosen DAB+ receivers and three different profiles, one for fixed reception and two for mobile and portable reception. The two Rayleigh profiles are Typical Urban 12, TU 12 (speed 25 km/h twelve taps), and Rural Area 6, RA 6 (speed 120 km/h six taps). The results, shown in Table 8, are the averages of the minimum values of the proper operation of the receivers.

Table 8: C/N values for EEP-A protection

Protection Level	Corresponding code rate	Gaussian channel dB	TU 12 dB	RA 6 dB	Approximate bit-rate (Mbit/s)
EEP-1A	0.25	3.7	7.8	7.8	0.58
EEP-2A	0.375	4.4	9.7	9.9	0.86
EEP-3A	**0.5**	**5.6**	**11.9**	**12.6**	**1.15**
EEP-4A	0.75	8.6	18.1	20.7	1.73

For both UEP and EEP, the differences between the C/N values of the various protection levels are not constant and the measurements show that the higher code rate, which results in lower protection, requires significantly more C/N to achieve reliable reception. Moreover, in EBU TR 021 [EBU_1] it is stated that the Protection Level 5 does not work for the mobile high-speed worst-case reception situation. This was confirmed by the tests made with DAB+ audio which proved that some receivers are not able to lock the signal when using the RA 6 profile with EEP-4A.

The C/N values for EEP-3A, highlighted in bold in Table 8 have been used in the link budget calculations in § 4.2 and § 5.1 of the report.

3. Planning criteria and parameters

3.1 Reception modes

Traditionally, radio networks have been planned on the basis of fixed roof top reception with the receive antenna mounted 10 m above the ground. However, this is generally not considered a reception scenario for the planning of DAB networks. DAB networks in most cases are planned for portable or mobile reception and within the service area of the portable or mobile service fixed roof-top reception is guaranteed. Therefore, in this report, parameters for fixed roof-top reception are provided mainly for information purposes only.

Six reception modes are considered within this report. Table 9 lists these, covering portable and mobile reception scenarios to handheld, kitchen radio and vehicle installed devices. All assume reception at no less than 1.5 m above ground level.

Table 9: Summary of reception modes considered in this report

	Reception mode	Channel model		Receiver type	Antenna Type*	High speed 120 km/h
1	Mobile reception (MO)	Rural	RA 6	Mounted inside the car and connected to the car antenna	Mounted outside the vehicle	Yes
2	Portable outdoor reception (PO)	Urban/ Suburban	TU 12	Stand-alone (table top or kitchen type)	Built-in (folded or telescopic)	No
3	Portable indoor reception (PI)	Urban/ Suburban	TU 12	Stand-alone (table top or kitchen type)	Built-in (folded or telescopic)	No
4	Handheld portable outdoor reception (PO-H/Ext)	Urban/ Suburban	TU 12	Handheld (e.g. smartphone type)	External (e.g. wired headset or telescopic)	No
5	Handheld portable indoor reception (PI-H/Ext)	Urban/ Suburban	TU 12	Handheld (e.g. smartphone type)	External (e.g. wired headset or telescopic)	No
6	Handheld mobile reception (MO-H/Ext)	Rural	RA 6	Handheld (e.g. smartphone type)	External (e.g. wired headset or telescopic)	Yes

*For more details of the different receiver and antenna types considered in this report, see Annex B and § 3.3, respectively.

3.1.1 Fixed roof-top reception

Fixed reception (FX) is defined as reception where a directional receiving antenna mounted at roof level is used. It is assumed that near-optimal reception conditions (within a relatively small volume on the roof) are found when the antenna is installed. In calculating the field-strength levels for fixed antenna reception, a receiving antenna height of 10 m above ground level is used.

3.1.2 Mobile reception (vehicle mounted receiver) (MO)

Mobile reception (MO) is defined as reception by a receiver installed in a vehicle with an antenna mounted outside the vehicle situated at no less than 1.5 m above ground level or floor level.

In this report, it has been assumed that networks to be planned for mobile reception are to be based in a Rayleigh channel with man-made noise, in rural environment at a vehicle speed of 120 km/h (corresponding to the channel model RA 6).

3.1.3 Portable reception (stand-alone receiver) (PO/PI)

In general, portable reception means reception by a portable stand-alone (table-top or kitchen type) receiver with an omnidirectional built-in (folded or telescopic) VHF antenna pattern used, outdoors or indoors, at no less than 1.5 m above ground level. It is to be expected that ‘portable coverage’ will be mainly aimed at urban and suburban areas.

In this report, portable receiving locations are:

- **Indoor reception (PI)** is defined by a portable stand-alone receiver with stationary power supply used indoors at no less than 1.5 m above floor level in rooms on the ground floor and with a window in an external wall. It is assumed that optimal receiving conditions will be found by moving the antenna up to 0.5 m in any direction and the portable receiver is not moved during reception and large objects near the receiver are also not moved.

- **Outdoor reception (PO)** is defined as reception by a portable stand-alone receiver with battery supply used outdoors at no less than 1.5 m above ground level. It is assumed that the receiver is at rest (stationary reception) or at very low speed (walking speed).

In this report, it has been assumed that networks to be planned for portable reception are to be based in a Rayleigh channel with man-made noise, in urban/suburban environment at a speed of 25 km/h (corresponding to the channel model TU 12).

3.1.4 Handheld reception (stand-alone handheld receiver)

The definition of handheld receivers is given in EBU BPN 067 [EBU_8].

"*Handheld devices ('handhelds' for short) are personal wireless devices, normally of a very small size, similar to that of a mobile phone or PDA (Personal Digital Assistant), with the capability of receiving audiovisual streams and data services, often with facilities for bidirectional voice/data communication*."

The receiving conditions will be distinguished due to the variability of handheld reception situations with different receiver antenna-types and also different reception conditions.

3.1.4.1 Portable outdoor handheld reception (PO-H/Ext) and portable indoor handheld reception (PI-H/Ext)

- This situation models the reception scenario with a handheld receiver with an external antenna (for example, telescopic antennas or the cable of wired headsets) at no less than 1.5 m above ground level. It is assumed that the portable handheld receiver is not moved during reception.

In this report, it has been assumed that networks to be planned for portable handheld reception are to be based in a Rayleigh channel with man-made noise, in urban/suburban environment at a speed of 25 km/h (corresponding to the channel model TU 12).

3.1.4.2 Mobile handheld reception (MO-H/Ext)

- This situation corresponds to the reception scenario inside a moving vehicle at no less than 1.5 m above ground level at high speed with a handheld receiver without connexion to the external antenna of the vehicle but with its own external antenna (for example, telescopic antennas or the cable of wired headsets).

In this report, it has been assumed that networks to be planned for mobile handheld reception are to be based in a Rayleigh channel with man-made noise, in rural environment at a vehicle speed of 120 km/h (corresponding to the channel model RA 6).

3.2 Coverage definitions

Generally, the coverage area is the area within which the field strength of the wanted transmitter is equal to or greater than the usable field strength for the class of reception required, e.g. mobile, portable-indoor as defined in § 3.1.

It is necessary to have definitions for the coverage of a digital terrestrial transmitting station or a group of such stations. Digital service coverage is characterized by a very rapid transition from near perfect reception to no reception at all and it thus becomes critical to be able to define which areas are going to be covered and which are not. However, because of this very rapid transition, there is a cost penalty if the coverage target within a small area (say, 100 m x 100 m) is set too high. This occurs because it is necessary either to increase the transmitter powers or to provide a larger number of transmitters to guarantee coverage to the last few percent of the worst-served small areas.

For this reason, the coverage definition of “good” and “acceptable” have been developed. The definitions do not aim to describe the area where coverage is achieved under worst case conditions. They provide a description of the area where "good" or "acceptable" coverage should be achieved under representative practical conditions. They may be regarded as describing the “quality” of the coverage achieved.

In defining the coverage area for each reception condition, a three-level approach is taken:

Receiving location

The smallest unit is a receiving location with dimensions of about 0.5 m × 0.5 m. In the case of portable antenna reception, it is assumed that optimal receiving conditions will be found by moving the antenna or by moving the portable or handheld terminal up to 0.5 m in any direction.

Such a location is regarded as covered if the required carrier-to-noise and carrier-to-interference values are achieved for 99% of the time.

Small area coverage

The second level is a "small area" (typically 100 m x 100 m) with coverage being defined by the percentage of locations served for 50% of time referred to the useful signal and typically for 1% of time referred to the unwanted signals.

The coverage of a small area is classified as:

- ‘Good’, if at least 95% of receiving locations within the area are covered for portable reception and 99% of receiving locations within it are covered for mobile reception.
- ‘Acceptable’, if at least 70% of receiving locations within the area are covered for portable reception and 90% of receiving locations within it are covered for mobile reception.

Note: Since mid 1990’s, the “small area”, or pixel, has been defined as 100 m x 100 m. This size was typically determined by resolution of Digital Terrain Map (DTM) available at the time and the fact that it was computationally acceptable to use this pixel size with empirical propagation models such as Recommendation ITU-R P.1546 [ITU_4]. In recent times, deterministic propagation models have been further developed and high resolution DTM data has become available. This has allowed broadcast coverage to be modelled in smaller pixels typically around 20 m x 20 m. This smaller size allows more accurate prediction and comparison with measurement data. While in general higher resolution, or smaller pixel, modelling provides improved coverage accuracy it also requires similarly high resolution clutter information and suitable processing capacity.

Coverage area

The third level is the coverage area.

The coverage area of a transmitter, or a group of transmitters, is made up of the sum of the individual small areas in which a given class of coverage is achieved.

The coverage area should not be confused with the service area which is defined as “*The area within which the administration has the right to demand that the agreed protection conditions be provided*" (Geneva 2006 Agreement [ITU_1]).

3.3 Antenna gain

Table 10 summarises the antenna gains for DAB receivers in Band III calculated in the sections hereafter. These are given for the following reception modes and antenna types:

- Mobile (car) reception using a built-in antenna mounted on the outside of the car
- Portable reception using a stand-alone type of receiver (table top or kitchen radio) with a

built-in (folded or telescopic) antenna
- Handheld reception using an external antenna (e.g. wired headset or telescopic)
- Handheld reception in a moving vehicle with an external antenna (e.g. telescopic or wired headset)

Table 10: Antenna gains G_D

200 MHz		
Reception mode	**Antenna type**	**Antenna gain G_D**
Mobile (car) reception (MO)	Adapted antenna	-5 dBd to -10 dBd
Portable reception (PO, PI)	Built-in	-8 dBd to -10 dBd
Portable and mobile handheld reception (PO-H, PI-H, MO-H)	External*	-13 dBd

(*) Telescopic or wired headsets

3.3.1 Antenna gain for car installations

At a time of increasing use of digital radio in cars, it is vital to assess and understand parameters which are keys for the best user experience.

3.3.1.1 ETSI standard for DAB car antenna installation

ETSI has published TS 103 461 V1.1.1 (2017-08) [ETSI_6] the technical specification for DAB+ car reception in August 2017.

This technical specification defines an antenna gain of minimum -5.3 dBd for cars and for solutions when receiver and antenna are sold together, Table 11.

Table 11: Antenna gain estimated from measurements of cars in Gaussian channel (C/N 6 dB) assuming car receiver to meet ETSI reference receiver

Reception Sensitivity [dBuV/m]					
12C			7D		
mean	**min**	**max**	**mean**	**min**	**max**
29.5	29.5	29.5	28.2	28.2	28.2
Antenna Factor [dB/m]					
12C			7D		
mean	**min**	**max**	**mean**	**min**	**max**
20	20	20.2	18.9	18.9	18.9
Antenna Gain [dBd]					
12C			7D		
mean	**max**	**min**	**mean**	**max**	**min**
-5.1	**-5.1**	**-5.1**	**-5.3**	**-5.3**	**-5.3**

3.3.1.2 Estimate of installed DAB car antenna gain

In [OS_4] the Swiss public broadcaster (SRG/SSR) presents measurements of required field strength for cars with built in DAB receivers. In total 11, 9 and 10 cars with different DAB receivers were measured in 2014, 2015 and 2016 respectively. Based on these measurements the approximate antenna gain for the full receiver installation, assuming a Gaussian channel and a minimum signal needed for the receiver of -97.7 dBm @ 50 Ω according to ETSI TS 103 461 V1.1.1 [ETSI_6], has been calculated. The measurements, which show that only a few car radios fulfil the above-mentioned specification, were made in Band III on channel 7 (190 MHz) and channel 12 (226 MHz).

The SRG/SSR results can be summarised as follows:

- There are large variations of antenna gain values from vehicle to vehicle
- Estimated mean antenna gain values are between -9 dBd and -11 dBd
- Feeder loss is included in the presented values
- Antenna gains vary considerably between different receiver installations
- Antennas are generally not omnidirectional
- Previously assumed antenna gains for mobile receivers installed in cars are optimistic
- Antenna gain is slightly lower at lower frequencies in Band III (Channel 7)

Vehicle antenna tests were also undertaken by Commercial Radio Australia[7] (CRA) using a range of external roof mounted antennas including sharks fin, reference monopole, slant monopole and mini monopole antennas, see details of antenna patterns in Annex C. The results of these measurements taken in channel 9B show average receive gain values of between 0 and -11.3 dBd, with maximum gain peaking at 5.3 dBd and minima of -20.0 dBd. In particular the positioning of the roof mounted antennas was shown to be critical to avoid very deep nulls in the horizontal pattern. Generally the antennas should be placed at least 300 mm from the roof edge to avoid poor performance.

There is an increasing trend in vehicle antenna placement for 'in-window' solutions. Many such installations are on side windows causing significant nulls in the horizontal pattern. Some vehicle manufacturers have recognised this and are, in some cases, opting to use dual antenna diversity receive systems to help reduce the impact of nulls.

3.3.1.3 Defining the planning value

This planning report will follow the ETSI TS 103 461 [ETSI_6] specification with the following definitions.

- The minimum field strength (see Table 11) shall be deemed to be applicable for new cars with DAB reception as well as for aftermarket solutions.
- The specified antenna gain shall be understood as the maximum antenna gain in direction the antenna has the best performance.

The SRG/SSR and CRA results as well as the ETSI technical specification strongly suggest adjusting the vehicle antenna gain used for planning to a value between -5 dBd and -10 dBd.

3.3.2 Stand-alone type of receiver

In frequency planning, e.g. the CEPT WI95 plan [EU_1], [EU_2] and [ITU_5], the antenna gain G_D (dBd) for portable reception refers to a half-wave dipole.

In practice, portable stand-alone antennas tend to be monopole whip antennas with a limited ground plane/counterpoise. Consequently, their performance is substantial less than a half-wave dipole. The gain of such antennas is typical -8 to -10 dBd.

3.3.3 Handheld receivers

An antenna integrated into a handheld terminal would, because of the dimensions of the device, be very small when compared to the relevant wavelength. This would lead to a very inefficient (in terms of gain) antenna. For this reason, handheld devices need to have an external antenna, for example a telescopic antenna or an antenna as part of a wired headsets.

[7] Vehicle DAB+ Antenna characteristics, BTC Australia and CRA, 2011.

Another issue is the influence of the user on the radiation characteristic of the antenna. Depending on the relative position of the user to the hand-held terminal, the human body can act as an absorber or as a reflector.

With respect to integrated antennas, external antennas improve reception and dramatically reduce the network complexity/cost requirements. The improved reception will also provide the customer a better experience through higher service quality. In this report only handheld receivers with an external antenna have been considered.

3.4 Feeder loss

Feeder loss is usually small for reception cases of interest for DAB. It is suggested that a feeder loss of 0 dB should be used for the portable, handheld and mobile reception cases.

3.5 Allowance for man-made-noise (MMN)

The effect on system performance of man-made noise, MMN, received via the antenna needs to be considered as it impacts the coverage field strength target calculations, see § 5.1.

Recommendation ITU-R P.372-13 § 5 [ITU_6] provides information on how to calculate the man-made noise effective noise figure F_{am} for different environmental categories and frequencies, along with the definitions of antenna noise figure, and the values of decile variations (10% and 90%) as measured in different regions.

In link budgets used for coverage calculations, the receiver self generated noise is taken into account by its noise figure F_r (in dB). The effect of the man-made noise received by the antenna is equivalent to an increase of the receiver noise figure F_r by an amount P_{mmn} (in dB), called man-made noise allowance.

The value of F_{am} and F_r are used to calculate P_{mmn} which for the case of a receiver noise figure of 6 dB, operating at 200 MHz with a 0 dBi antenna gain are shown in the first three lines of Table 12. For the antenna gains shown in Table 10, please refer to Table 13.

Table 12: P_{mmn} values in dB for 0 dBi antenna gain

Values for 200 MHz	F_{am} (dB)	P_{mmn} (dB)
ITU Rural	3.5	1.6
ITU Residential/suburban	8.8	4.0
ITU City (Business)/urban	13.1	7.0
IRT Urban indoor [EBU_9] 2005[8]	16.5	10.0
SRG Urban indoor 2017 @ 3 m[9]	21.1	14.3
SRG Urban indoor 2017 @ 1 m[10]	30.6	23.6

The IRT carried out indoor-measurements of man-made noise in 2005 [EBU_9]. SRG carried out indoor measurements of man-made noise in 2017. From these measurements, the extrapolated value of F_{am} for 200 MHz is shown in the last three lines of Table 12. The values of IRT and SRG are considerably higher than the values given in Recommendation ITU-R P.372-13 [ITU_6]. The ITU values were measured many years ago outside buildings when there were few PCs, no

[8] Measurements procedure is comparable to ITU-R SM.2093 [ITU_7].

[9] Measurements have been performed for real environments and for specific reception cases rather than according ITU-R SM.2093. [ITU_7]. Median value was built over 11 measurements with a distance of 3 metres between main interferer to receiver.

[10] If a lower separation between receiver and interferer shall be allowed as encountered during these measurements, significant higher P_{mmn} must be forseen in the link budget. It is up to the DAB network operator to decide the P_{mmn} to be included.

DSL-connections and no widespread mobile and WLAN telecommunication systems as found nowadays and which contribute significantly to man-made noise level. Today, especially in buildings, and in proximity to many noise sources, the antenna external noise figure F_{am} can have higher values than the values measured many years ago outside buildings.

Antenna gain values for in-home and in-car receivers are generally much less than 0 dBi (-2.2 dBd) [ITU_5] as discussed in § 3.3. The negative antenna gains can be traced back to a lack of efficiency caused by mismatches between antenna and receiver, and between antenna and the received signal, often due to antenna size relative to the wanted signal wavelength. Therefore, the man-made noise received by the antenna is attenuated as is the wanted signal. Consequently, a negative antenna gain induces a modification of the man-made noise allowance value. Based upon the values in Table 12 the value of P_{mmn} for planning can be calculated for different antenna gains. Calculations are based upon [OS_5][11].

The results are presented in Table 13. The calculations are based on the F_{am} values in Table 12 and related mainly to the antenna gains in Table 10.

Table 13: P_{mmn} in dB as function of antenna gain (F_r = 6 dB, f = 200 MHz)

Antenna gain [dBd]	-2.2	-5	-8	-10	-13	-17
ITU Rural	1.6	0.9	**0.5**	0.3	0.2	0.1
ITU Residential/suburban	4.0	2.5	**1.5**	1.0	0.5	0.2
ITU City (Business)/urban	7.0	5.0	**3.2**	2.2	1.3	0.5
IRT Urban indoor [EBU_9] 2005[12]	10.0	7.6	**5.3**	4.0	2.4	1.1
SRG urban indoor 2017 @3 m to interferer[13]	14.3	11.6	**8.9**	7.2	5.0	2.7
SRG Urban Indoor 2017 @1 m to interferer[14]	23.6	20.9	**17.9**	15.9	13.0	9.4

Field strength targets are usually focused on vehicles in rural areas and table top radios for in-building reception in suburban and urban grade areas. Observing the values in § 3.3 leads us to a typical antenna gain value for planning of G_a =-8 dBd. The resulting MMN adjustment value P_{mmn} to be used in coverage field strength planning is highlighted in Table 13.

Whilst we have witnessed an increase in man-made noise, further increases can be expected as new electronic devices, in particular LED lights, are introduced. As a consequence of these ongoing changes, levels of MMN need to be monitored; studies and measurements of MMN should continue.

3.6 Coverage prediction height

Two main mechanisms give rise to variations in field strength with height.

The first is simply that diffraction losses will tend to fall as an antenna is raised above the level of surrounding clutter.

The second effect leading to variation of field strength with height is one due to interference between direct and reflected waves, this effect is dependent on polarisation and overall path geometry such as possible ground reflected wave in open/rural environments, however reflected waves are not normally taken into account in prediction models.

11 The calculation presented in [OS_5] is an updated version of the derivation in [EBU_10].

12 Please refer to footnote 8 of Table 12.

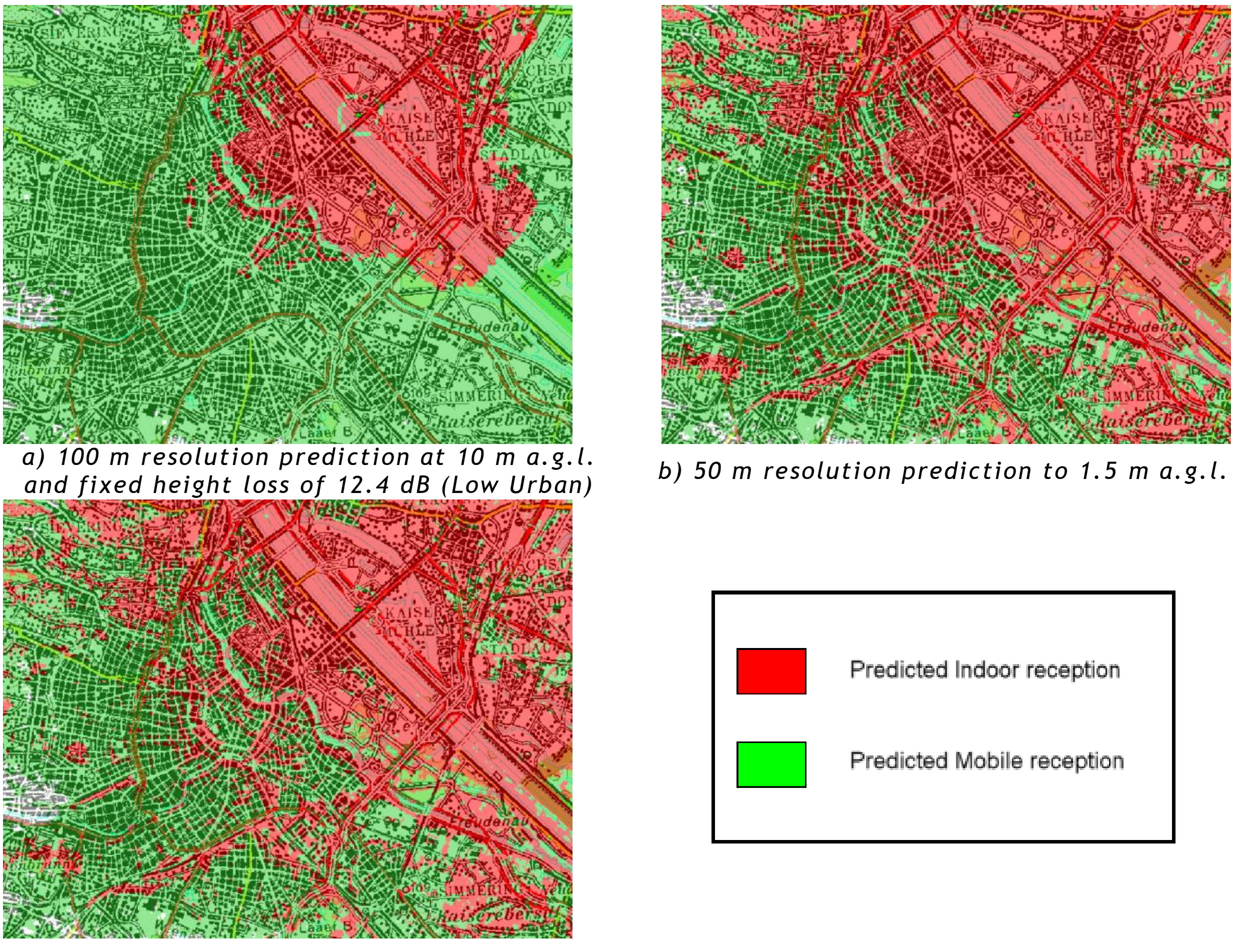
13 Please refer to footnote 9 of Table 12.

14 Please refer to footnote 10 of Table 12.

Historically radio services were received at rooftop level (clear of the clutter), typically 10 m above ground level (a.g.l.) and hence propagation prediction methods provided field-strength values at 10 metres. This was necessary since receiver performance was relatively poor compared to today's standards. However, using modern receivers, listening is now predominantly carried out on mobile and indoor portable receivers and a representative height of typically 1.5 m is assumed. An adjustment to 1.5 m would therefore have to be applied.

The alternative prediction approach is to construct the propagation geometry from the transmitter to the receiver on the basis of the required receiver height, i.e. direct to 1.5 m a.g.l.

Advances in computing power and storage and the availability of affordable fine resolution clutter data (density and heights of buildings, trees etc.) for large areas, allows for predictions to be made directly to the intended receiver height. This method is recommended when developing or updating deterministic prediction tools.



a) 100 m resolution prediction at 10 m a.g.l. and fixed height loss of 12.4 dB (Low Urban)

b) 50 m resolution prediction to 1.5 m a.g.l.

c) 25 m resolution prediction to 1.5 m a.g.l.

Key to maps

Figure 3: Examples of clutter resolution when comparing predictions at 1.5m a.g.l. with a prediction at 10 m a.g.l. with fixed height loss. The terrain data resolution is matched to the clutter resolution. These maps have been produced with a low transmit power to demonstrate the differences

As the resolution of clutter data becomes finer, the difference in 10 m predictions using a height loss factor compared to a prediction directly to 1.5 m becomes more apparent. Figure 3 compares a 10 m fixed height loss prediction with predictions to 1.5 m at different clutter data resolutions. It demonstrates that the finer resolutions can show more detail in the coverage which otherwise may have been overlooked. The terrain data resolution should be matched to the clutter data resolution and defines the minimum pixel size used in the predictions. The finer the detail of the predictions the more computational power and storage is required. By predicting direct to the receiver height, the need to set height loss values, either a fixed value or by receiving environment, is avoided.

If clutter data of a suitable resolution is not available or computational power or storage is limited then predictions to 10 m a.g.l. with a height loss correction factor, L_h (dB), being applied are suggested. This height loss correction factor is the method used in the ITU-R published empirical based propagation models. The height loss relative to 10 m above ground level (a.g.l.) or the 'representative clutter height' can be calculated.

For long distance interference analysis, the deterministic models used for coverage planning may not provide accurate results due to the extended range that interference travels and the impact of tropospheric conditions such as ducting. In this case the interfering field strength calculations can still be based on empirical models, typically Recommendation ITU-R P.1546 [ITU_4].

The height loss correction factor from 10 m to 1.5 m can be taken directly from the Final Acts of GE06, § 3.2.2.1 of chapter 3 of Annex 2 (Considerations on height loss) [ITU_1]. This factor depends on the frequency and receiving environment.

Some example calculated values at 200 MHz [ITU_4] have been populated in Table 14, based on UK and Austrian clutter samples. The Austrian examples represent the clutter categories seen in the map in Figure 3.

For planning purposes height loss values can be calculated using relevant clutter heights for the country or area in question and based on ITU method [ITU_4], some example calculations have been reproduced in Annex D.

Table 14 a and b: Calculated Height loss examples for some different environment classes in the UK and Austria

Band III at 200 MHz	Typical UK Clutter height	Rec. 1546 Calculated Height Loss
Urban	18 m	17.6 dB
Suburban	9 m	11.4 dB
Low Suburban	6 m	7.9 dB
Rural	6 m	7.9 dB

Band III at 200 MHz	Typical Austrian Clutter height	Rec. 1546 Calculated Height Loss
Dense Urban	30 m	21.7 dB
Low Urban	10 m	12.4 dB
Suburban	10 m	12.4 dB
Rural	0 m	Not applicable

Table 14a shows some example calculated height loss values for the UK and Table 14b shows some for Austria which have been used in the map of Figure 3a. These examples show that height loss decreases with lower clutter heights.

In Australia a measurement campaign has been carried out to obtain a better understanding of height loss. Commercial Radio Australia in conjunction with the Australian Broadcast Corporation undertook measurements in a range of different environments from line-of-sight to various shadowed environments from high to low field strengths. All measurements were taken in Canberra where there is a single medium power (3.1 kW ERP) high tower transmission, and hence there is no influence from SFN transmissions which tend to reduce the height loss due to multiple sources of received signal. The results are shown in Figure 4.

The measurement results at 25 out of the 28 measurement sites, i.e. 90%, had height loss values of less than 10.5 dB, and the average height loss value was between 7 and 8 dB.

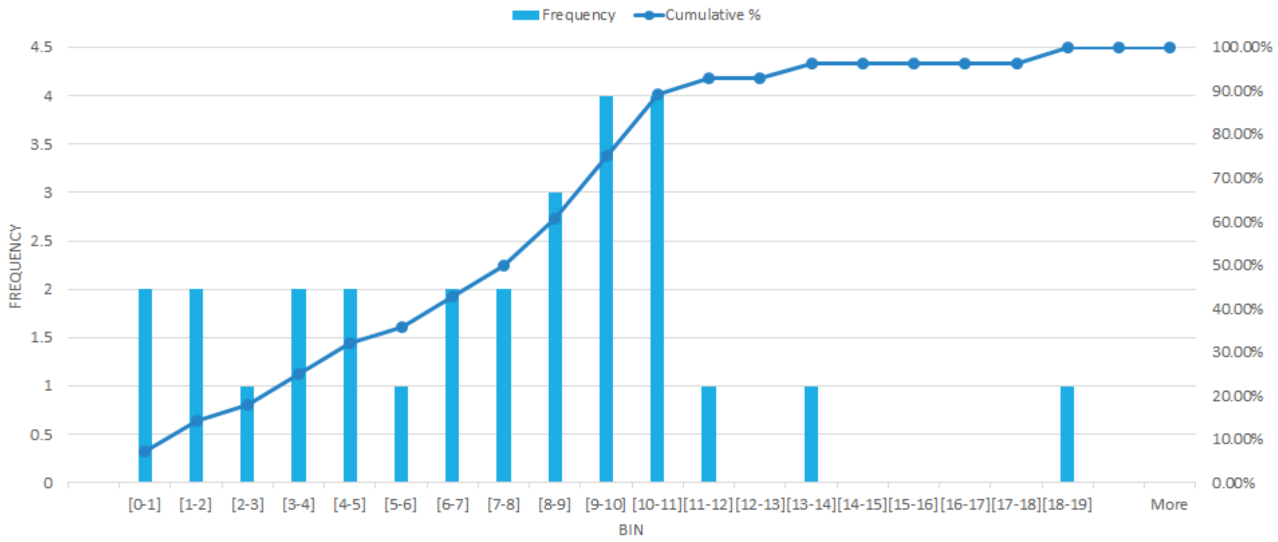


Figure 4: Height loss measurement results

The measurement results provide a basis for the height loss value used in 10 m to 1.5 m prediction methods, where 90% of values will be less than 10.5 dB, hence Australia has opted for a value of 10 dB as being appropriate, the same value is used in the UK where similar results were found during early Band III DAB survey measurements.

Due to the differences in building types, spacing and construction methods between countries or even areas, it is pragmatic to carry out survey and analysis work when calibrating a prediction model for 1.5 m reception. For predictions based on 10 m a.g.l. and including a height loss factor it is recommended to classify typical environments (such as urban, suburban) with a height loss value for each category. To calibrate and validate a prediction model measurements should be considered in areas where co-channel interference is at a minimum and there is a single wanted signal, they should be carried out at 10 m a.g.l. (or clear of local clutter) and also at the target receiver height of 1.5 m. Once below the clutter height and diffraction path an omnidirectional receive antenna should be used for measuring due to the much greater importance of reflections. As mobile measurements using a nominally omnidirectional receive antenna are fairly quick and easy to make compared to 10 m measurements, the validation of predictions direct to 1.5 m receiver height can be made much quicker.

Typically, when planning for indoor reception, the urban and dense urban areas which may represent a small percentage of the overall area whilst exhibiting higher building entry loss, will be targeted first and served with high field strengths from one or more transmitters and any increase in height loss becomes less noticeable in the predictions. For these reasons and evidence from survey measurements, the examples of Australia and the UK use a single value representing the Suburban environment. It should be stipulated that these values are examples provided as guidance for the inclusion of height loss in the development of coverage predictions.

3.7 Building and vehicle entry loss

Traditionally the loss associated with the RF signal entering a building or vehicle was referred to as the ‘penetration’ loss [ITU_5]. In the latest ITU Recommendation [ITU_8] from Working Party 3K on this subject the term ‘entry’ has replaced ‘penetration’. For consistency with the latest ITU Recommendation this report will refer to entry loss.

3.7.1 Building entry loss

Portable reception can take place at both outdoor and indoor locations. For indoor locations, depending on the materials, the construction and orientation of the building, the field strength can be significantly attenuated. The ratio between the mean field strength inside a building at a given height above ground level and the mean field strength outside the same building at the same height above ground level expressed in (dB) is the mean building entry loss.

In many planning documents, such as [ITU_1], [ITU_5], [EBU_2], [EBU_1], the mean building entry loss L_b and standard deviation σ_b for Band III are assumed as given in Table 15.

Table 15: Building entry loss L_b and standard deviation σ_b

Frequency (MHz)	200
Mean building entry loss L_b (dB)	9
Standard deviation of the building entry loss σ_b (dB)	3

Recently, the issue of building entry loss has been revisited.

ITU-R WP 3K has compiled measurement data on building entry loss [ITU_9] - as building entry loss is termed in WP 3K - and has prepared Recommendation ITU-R P.2109 "Prediction of building entry loss" [ITU_8].

Teracom have made additional measurements and have developed a more sophisticated model for building entry loss (see Annex E).

A major finding of recent investigations is the observation that a principal distinction is to be made between buildings equipped with metalized windows and other measures to provide thermal efficiency and those which are not.

For example, [ITU_8] proposes for 200 MHz a median building entry loss of 10.5 dB for traditional buildings and 34.4 dB for thermally efficient buildings, as calculated in Table 16 below.

Table 16: Example of calculation of median building entry loss -
The value of the coefficients u and v are given in Table 1 of [ITU_8]

	Traditional building	Thermally-efficient building
Frequency f	0.2 GHz	0.2 GHz
Model coefficient r	12.64	28.19
Model coefficient s	3.72	- 3.00
Model coefficient t	0.96	8.48
Median loss for horizontal paths $L_h = r + s \log(f) + t [\log(f)]^2$	10.5	34.4
Correction for elevation angle of the path at the building façade $L_e = 0.212 \lvert\theta\rvert$ where θ is the elevation angle	~ 0	~ 0
Median building entry loss $L_h + L_e$	10.5 dB	34.4 dB
$\sigma_1 = u + v \log(f)$	8.2 dB	10.8 dB

In addition, for both cases the standard deviation σ_1, is much higher than the standard deviation given in Table 15. Detailed values may be calculated by the formula given in [ITU_8].

This large difference between traditional buildings and thermally efficient buildings and the much higher spread of the building entry loss values is confirmed by the Teracom measurements.

The values in Table 15 represent a reference from which DAB networks have been planned for indoor reception. However, with building regulations changing to provide more thermally efficient buildings which in turn leads to extremely high median value for the building entry loss (Table 16), achieving reliable indoor RF coverage may, in future, be challenging. Network designers may need to consider alternative means for providing a service indoors within thermally efficient buildings.

3.7.2 Vehicle (car) entry loss

A study presented in [OS_6] shows in-car entry losses of 8 dB with an associated standard deviation of 2 dB, based on measurements at 800 MHz. Due to the lack of investigations concerning the car entry loss and its variation with the frequency, the same value is taken for Band III. Furthermore, it is expected that the value of 8 dB will not be sufficient for estimating entry loss into trains.

3.8 Location percentages

3.8.1 Signal level variation

Field strength variations can be divided into macro-scale and micro-scale variations. The macro-scale variations relate to areas with linear dimensions of between 10 m and 100 m or more and are mainly caused by shadowing, reflection and scattering. The micro-scale variations relate to areas with dimensions in the order of a wavelength and are mainly caused by multi-path reflections from nearby objects. The effect of micro-scale fading is normally taken into account by use of an appropriate C/N value for the transmission channel under consideration. Moreover, as it may be assumed that for portable reception the position of the antenna can be optimized within the order of a wavelength, micro-scale variations will not be too significant for planning purposes.

Macro-scale variations of the field strength are very important for coverage assessment. In general, a high target percentage for coverage would be required to compensate for the cliff edge failure effect of DAB digital radio reception. Therefore, as field strength predictions are based on signal level calculated for 50% of locations, an extra correction is required to the value to ensure the necessary quality of service is met.

The Location Variation Standard Deviation σ is used when determining the field strength required for specific coverage classes. For each class there are different factors that need to be taken into account, see § 3.2, with σ_{LV} being one of them. Historically the value of σ_{LV} has been set to 5.5 dB. This was the result of empirical measurements in pixel sizes of 500 x 500 m and is considered to be a 'worst case' value. Recent measurements and studies have shown a value of 5.5 dB may be too high for predictions based on 100 m or smaller pixels and may artificially lead to higher field strengths being required than necessary. This in turn complicates network planning due to the implied need for higher power transmissions or a higher density of transmission sites.

3.8.2 Location statistics within a pixel and prediction error

Slow fading effects are due to ground cover variations, which are important for pixel sizes substantially greater than the relevant morphography. Since the local distribution of morphographic influences within the pixel will usually be homogenous and their effects occur in a multiplicative way along the path, the loss due to slow fading fits a log-normal distribution, independent of the signal's bandwidth, and consequently slow fading is often called "Log-normal Fading". Measurements validate this assumption.

Due to the log-normal distribution of the slow fading, the logarithm of the field strength (including slow fading only) fits a normal distribution. The field strength is characterized by a median value and its standard deviation within the area of one pixel.

More information on the location variation of field strength and its implementation for coverage prediction is given in Annex F.

In many frequency planning documents, e.g. [ITU_1], a standard deviation for wideband signals of 5.5 dB is used.

Recent studies [OS_7], [OS_8], [OS_9] [OS_10], where a large number of measurements have been taken, show that the standard deviation of the field strength distribution within a pixel of between 20 x 20 m to 100 x 100 m in size is, depending on the clutter and also the size of the pixel, between about 2 and 4 dB. The larger the pixel size, the higher the standard deviation of the field strength distribution.

The minimum median field strength values calculated in § 5.1.1 use a standard deviation value of 4.0 dB as being a representative value.

3.8.3 Location correction factor

To obtain signal levels for planning, i.e. the minimum field strength needed to provide reception at a higher percentage of locations, a location correction factor C_l has to be applied. In calculating the location correction factor, a log-normal distribution of the received signal with location is assumed.

The location correction factor C_l can be calculated by the formula:

$$C_l = \mu \times \sigma \qquad (3.1)$$

σ is the standard deviation of the field strength distribution,
μ is the normal distribution factor.

Values for some often used cases are given below:

Table 17: Normal distribution factor values for commonly used % of locations values

Normal distribution factor μ	% of locations
0.00	50
0.52	70
1.28	90
1.64	95
2.33	99

Values of μ for other percentages of locations[15] can be found from the normal distribution table in [ITU_4].

Depending on the reception mode, different values for μ and for σ have to be applied.

3.8.4 Location correction factors for different reception modes

In § 3.1 different reception modes are defined:

MO: Standard mobile reception
PO: Standard portable outdoor reception
PI: Standard portable indoor reception
PO-H/Ext: Handheld portable outdoor reception with external antenna
PI-H/Ext: Handheld portable indoor reception with external antenna
MO-H/Ext: Handheld mobile reception with external antenna.

[15] The Excel function =normsinv(x) where x = a value >0 and <1 will provide values for μ.

In many cases the location correction factor is influenced not only by the location variation but also by the standard deviation of additional losses such as building entry loss or vehicle entry loss. When this is the case the resulting standard deviation can be calculated using:

$$\sigma_{res} = \sqrt{(\sigma_{LV}^2 + \sigma_{OL}^2\,)} \qquad (3.2)$$

The values used for various reception modes are shown in Table 18. For indoor reception in a building, the values are on the basis of entry loss measured in traditional buildings (see § 3.7).

Table 18: Location Correction value calculations for various reception modes

Reception mode	**Service quality**	Location variation σ_{LV} (dB)	Variation of other losses σ_{OL} (dB)	Composite location variation SD σ_{res} (dB)	**Location probability** **%**	**Distribution factor value** **μ**	**Location correction factor** **C_l (dB)**[16]	**Comments**
1. MO (rural)	Good	4.0	0	4.0	99	2.33	9.32	
	Acceptable	4.0	0	4.0	90	1.28	5.12	
2. PO (suburban)	Good	4.0	0	4.0	95	1.64	6.56	
	Acceptable	4.0	0	4.0	70	0.52	2.08	
3. PI (urban)	Good	4.0	8.2	9.12	95	1.64	14.96	BEL
	Acceptable	4.0	8.2	9.12	70	0.52	4.74	BEL
4. PO-H/Ext (suburban)	Good	4.0	0	4.0	95	1.64	6.56	
	Acceptable	4.0	0	4.0	70	0.52	2.08	
5. PI-H/Ext (urban)	Good	4.0	8.2	9.12	95	1.64	14.96	BEL
	Acceptable	4.0	8.2	9.12	70	0.52	4.74	BEL
6. MO-H/Ext (rural)	Good	4.0	2	4.47	99	2.33	10.42	VEL
	Acceptable	4.0	2	4.47	90	1.28	5.72	VEL

BEL = Building Entry Loss VEL = Vehicle Entry Loss

3.9 Location correction margin

When determining the maximum permissible field strength of an interfering signal both the location variation of the wanted signal and the interfering signal should be taken into account. The amount of protection achieved for a given wanted signal with respect to a given interfering signal is related to the difference of the wanted and interfering field strengths. This difference is a statistical variable that depends on:

- the median values of the two fields, and on
- their location standard deviations,

and which has a standard deviation that can be calculated as follows:

$$\sigma_{res} = \sqrt{(\sigma_{wanted})^2 - 2\rho \times \sigma_{wanted} \times \sigma_{interferer} + (\sigma_{interferer})^2} \qquad (3.3)$$

It is assumed that the wanted and interfering signals are both log-normally distributed and are un-correlated, i.e. correlation factor $\rho = 0$. If they have identical standard deviations, then;

Since $\sigma_{wanted} = \sigma_{interferer}$ and $\rho = 0$,

$$\sigma_{res} = (\sigma_{wanted}) \times \sqrt{2} \qquad (3.4)$$

[16] The values in the Location correction factor column do not have any rounding as may be found by using the base numbers in this table which are shown as having only 2 decimal places.

The resulting combined location variation standard deviation is used to determine the Location Correction Margin (*LCM*).

The value of *LCM* is obtained from the % availability for the wanted field strength, μ, and the combined location variation standard deviation as

$$LCM = \mu \times \sigma_{res} \tag{3.5}$$

The median maximum interfering field strength can be derived from

$$E_I^{Max} = E_W^{Min} - PR - LCM \tag{3.6}$$

where E_I^{Max} is the maximum permissible interfering field strength, E_W^{Min} is the minimum median wanted field strength and *PR* is the Protection Ratio.

Typically, interference situations are calculated for the minimum field strength that is protected; usually the mobile outdoor (MO) reception mode. The availability (percentage locations served) for that reception mode is 99% with the resulting value of μ being 2.33, and hence the value of *LCM*=2.33σ_{res}. If we use a value of 4.0 dB for the value of $\sigma_{wanted} = \sigma_{interferer}$ then the resulting value of σ_{res}=5.66 dB and the value of *LCM*=13.19 dB.

3.10 DAB transmitter spectrum masks

Outside the 1.5 MHz wide COFDM spectrum, the signal contains natural sidebands, attenuated relative to the main signal by some 40 - 50 dB. Although a high degree of linearity is employed, commonly used power amplifiers produce intermodulation products that increase the level of the sidebands, in some cases to only 30 dB below the main signal. These sidebands are unwanted, are considered spurious signals and should as far as possible be suppressed to allow optimum usage of the frequency spectrum. This attenuation (also called shoulder attenuation) is of importance because it allows adjacent DAB frequency blocks to be used in adjacent service areas.

The DAB signal spectrum is measured in a 4 kHz bandwidth. Inside the 1.5 MHz block the power level therefore reduces by (10 x $\log_{10}$(4 / 1536)) dB = -26 dB (see [ETSI_7]) relative to the total power of the signal. The (shoulder) attenuation of the sidebands (out-of-band signals) is expressed in dB relative to this value.

The out-of-band radiated signal spectrum in any 4 kHz band shall be constrained by one of the masks defined in Figure 5 and Table 19. The solid line mask shall apply to DAB transmitters in critical areas for adjacent channel interference. The dotted line mask shall apply to DAB transmitters in other circumstances for suppression of adjacent channel interference.

Note: with increasing frequency difference, the attenuation will further increase. However, it is difficult to measure such high values of attenuation. To assist with measurements, it may be necessary to use special notch filters (e.g. at the distress frequency 243 MHz).

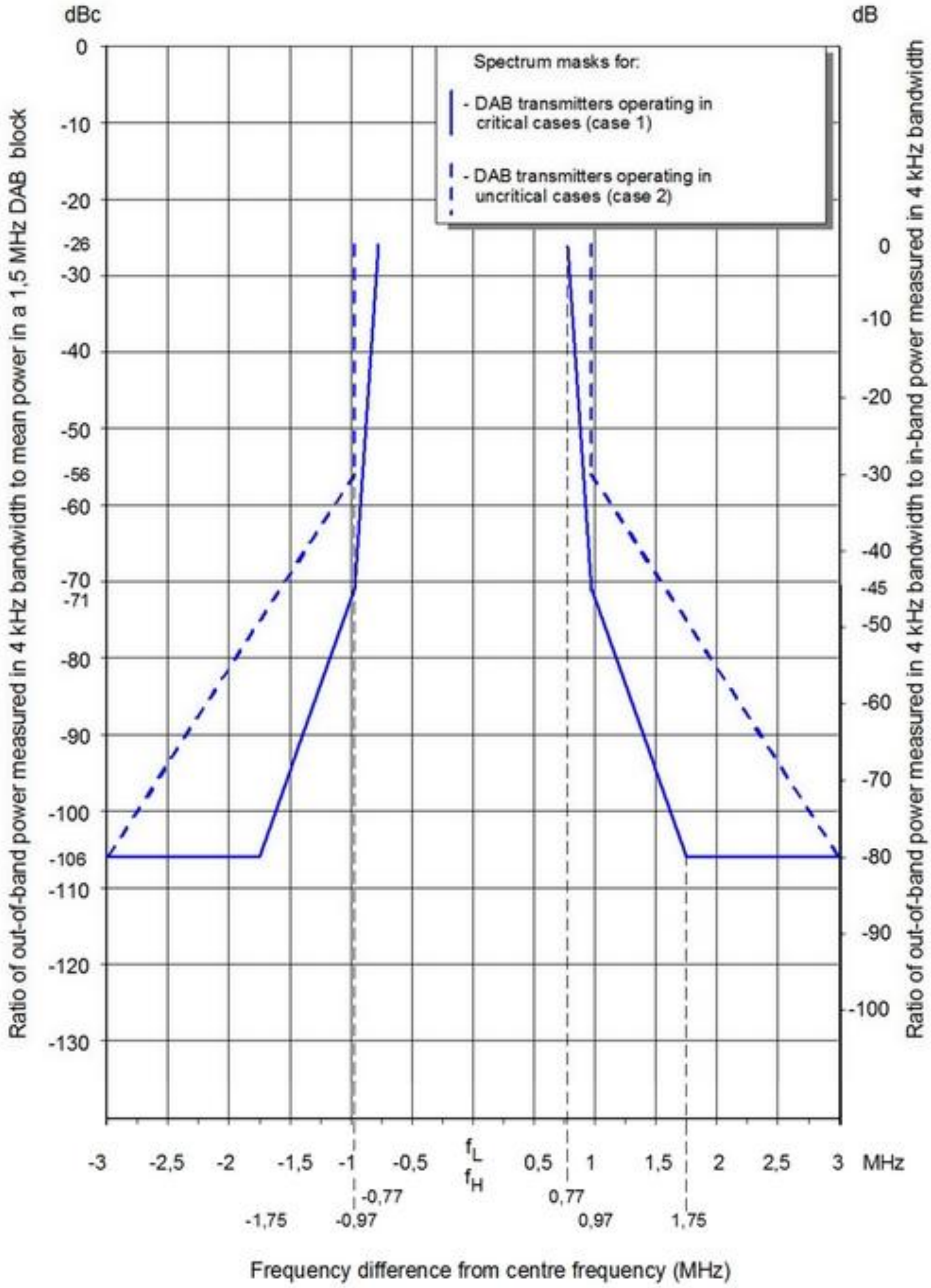


Figure 5: Spectrum masks for DAB out of band radiation

Table 19: Break points for spectrum masks in Figure 5

Frequency relative to the block centre frequency [MHz]	Case 1 (critical cases) relative level [dB]	Case 2 (uncritical cases) relative level [dB]
±0.77	-26	-26
±0.97	-71	-56
±1.75	-106	n.a.
±3.00	-106	-106

3.11 SFN performance for DAB

3.11.1 Theoretical evaluation of SFN performance

In Single Frequency Networks (SFNs) transmitters are required to radiate the same OFDM symbol at the same time. This comes from the fact that "echoes" generated by co-channel transmitters shall be confined within the guard interval period: 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; differently another part of the echo power is associated with the previous or subsequent OFDM symbol and produces inter-symbol interference (ISI), which has a similar effect to uncorrelated Gaussian noise interference. In Figure 6 the splitting of a generic signal power into useful and interfering components is shown, where Δ is the guard interval length and T_u is the useful symbol length [EBU_5].

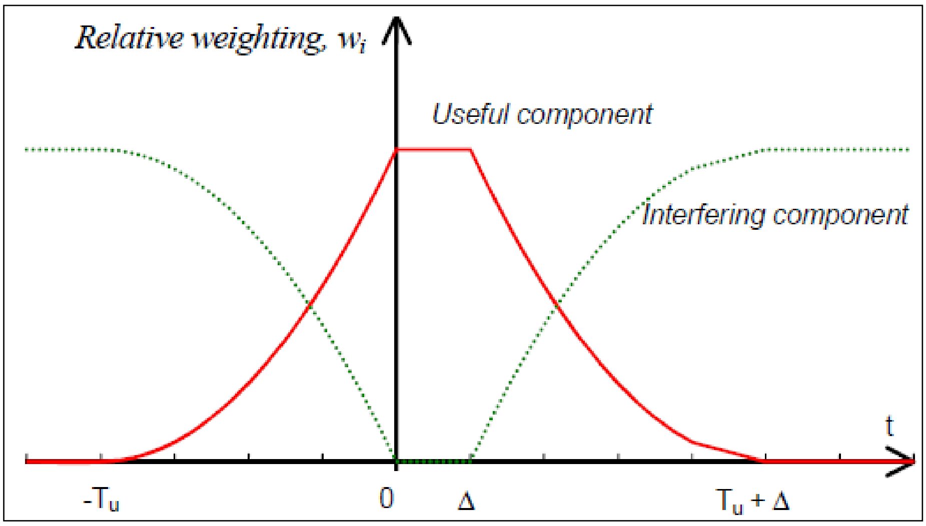


Figure 6: DAB model - splitting of a generic signal power into useful and interfering components

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

$$w_i = \begin{cases} 0 & if \quad t \le -T_u \\ \left(\frac{T_u + t}{T_u}\right)^2 & if \quad -T_u < t \le 0 \\ 1 & if \quad 0 < t \le \Delta \\ \left(\frac{(T_u + \Delta) - t}{T_u}\right)^2 & if \quad \Delta < t \le T_u + \Delta \\ 0 & if \quad t > T_u + \Delta \end{cases} \tag{3.7}$$

$$C = \sum_i w_i \times C_i \tag{3.8}$$

$$I = \sum_i (1 - w_i) \times C_i \tag{3.9}$$

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, the total effective interfering power, is weighted by the established DAB-to-DAB protection ratio when being regarded as a source of interference in a coverage calculation.

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. 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 (with no ISI).

In the design of SFNs the inter-transmitter distance is proportional to the maximum echo delay acceptable by the transmission system, which depends on the guard interval. Actual transmitter spacing can be increased beyond that defined by the guard interval with network optimization in terms of static delays, antenna patterns and power of transmitters.

As an example, let's consider a 2-path scenario with power $P_1 = P$ for signal 1 and power $P_2 = aP$ for signal 2; the requirement for an allowed delay of signal 2 is given by:

$$\frac{P_1 + w \times P_2}{(1-w) \times P_2} = \frac{P + w \times aP}{(1-w) \times aP} = \gamma \qquad (3.10)$$

Where γ is the required protection ratio for the considered service, w the weighting function and a is the allowed power of signal 2, expressed as a percentage of the power of signal 1. w is a function of t, the relative delay of signal 2. All quantities are expressed in linear scale.

The value of the parameter a is sought as a function of the delay t. It is independent of the particular value of P; it can therefore be written as:

$$a(t) = \frac{1}{\gamma - (1+\gamma) \times w(t)} \qquad (3.11)$$

Table 20 gives the results for a protection ratio γ = 13.5 dB and a guard interval Δ = 246 μs.

Table 20: Theoretical values of the required difference in power for a delayed signal

Relative delay [μs]	*w*	*a*	Required difference between P_1 and P_2 → 10 log(*a*) [dB]
0 ≤ t ≤ 246 (i.e. inside the guard interval)	1	1	0 (i.e. not required)
300	0.8949	0.6859	1.64
335	0.8299	0.3358	4.74
365	0.7762	0.2362	6.27
400	0.7157	0.1770	7.52
t > 1246	0	1/γ = 0.0447	13.5

It has been found that practical SFN performance (§ 3.11.2) aligns quite well with the theoretical considerations based on the formulae 3.7 to 3.9 and shown in Figure 6 (see also § 2.6 of EBU TR 021 [EBU_1]).

The effective planning of the required radiated power and the optimization of static delays at the secondary site(s) will improve SFN performance as well and provide the effective management to eliminate most potential interference problems.

3.11.2 Practical SFN performance

In some countries, large area SFNs will need to be considered due to frequency constraints. For this reason an experimental verification of the behaviour of DAB receivers in presence of signals beyond the guard interval is required, in order to optimize the setup of this kind of network.

Rai Way performed several tests on this issue in the laboratory and in a sample service area.

In both cases a number of models of commercial receivers sold in Italy (Continental, Blaupunkt and Pure) were tested. The transmission Mode I was considered as a reference as it is used in real DAB+ networks deployment in the VHF Band in Italy. The theoretical value of the guard interval, Δ, used was 246 µs.

Tests were specifically focused on the identification of the “minimal condition” which allows the commercial receivers to correctly demodulate the content when one or more echoes are beyond the guard interval, taking into account the power levels of the signals and their relative delays. These tests showed that far beyond the guard interval the difference in the signal levels of transmitters at the receiving point represents the discriminating factor which guarantees (or not) a good reception quality, in line with the theoretical analysis of § 3.11.1. Therefore, this difference has been named as the required *protection ratio* ζ to make the reception feasible in presence of signals beyond the guard interval. It is important to notice that the parameter γ (introduced in the previous section) and ζ have a different meaning: ζ expresses the difference in the signal levels of transmitters at the receiving point (only in SFN mode) which might guarantee a good reception quality. Therefore, it does not have a fixed value, but rather a value which varies and depends on the relative delay among the SFN echoes. For this reason, ζ cannot be considered in the same way as γ, although if a specific condition arises in the considered SFN network (see Table 21) the value of the two parameters corresponds.

The behaviour shown by commercial receivers in the service area was very similar to that seen in the laboratory tests. From the results of these studies, Rai Way derived the values in Table 21; the conditions required in a DAB+ SFN in order that commercial receivers may correctly demodulate the audio content with good quality.

Table 21: Conditions to be respected by DAB signals in SFN configuration (transmission Mode I) to make audio reception feasible with good quality on commercial receivers

Required protection ratio ζ	Relative delay
0 (i.e. not required)	$0 \le t \le 246$ µs (i.e. inside the guard interval)
5 dB	$246 < t \le 350$ µs
13.5 dB	$t > 350$ µs

It is important to notice that for the range 0 µs to ~350 µs the values of Table 20 fit quite well with the figures of Table 21. In the range beyond 400 µs the degradation as reflected in Table 21 is faster than the one derived from the theoretical formula presented in § 3.11.1. On the other hand, the conditions shown in Table 21 are quite conservative and might be slightly adjusted after further tests are performed on commercial receivers. Also, a more complex mathematical function that better describes the real behaviour of receivers in presence of echoes beyond the guard interval could be derived.

Additional tests should be performed for case of pre-echoes those “in advance” of the time window, i.e. for $t < 0$. Unless otherwise demonstrated, planning analysis should not rely on the symmetry of the theoretical DAB model with respect to the time axis, as shown in Figure 6 (for $t < 0$ a *protection ratio* ζ of about 13.5 dB should be considered).

In Annex H, all the details and the results of the tests performed by Rai Way on SFN performance, both in the laboratory and in a sample service area, are reported.

Laboratory and field testing by CRA has shown situations where SFN performance could be degraded under certain conditions even though the reception of two SFN signals is within the guard band, i.e. less than 246 µs apart. This particular situation occurs when the signals from both transmitters are very close in power, e.g. less than 1 dB difference - the ‘zero dB’ echo case. The two signals are combined at the input to the antenna non-coherently and consequently the relative phase of each sub-carrier in the OFDM symbol will determine the resulting power. This is shown in Figure 7 where the delay between the two equal power signals is 10 µs. The result is that there are several sub-carriers in the symbol which are significantly reduced in power, in this case by over 20 dB relative to the peak sub-carrier power. The impact of this ‘scalloping’ is a reduction in receiver performance when the received signal power is less than approximately 20 dB above the minimum received signal power threshold. This reduction is due to the poor C/N for the specific sub-carriers in the symbol which effectively propagate through the receiver signal processing as errors and can result in an effective increase in the noise floor. The result can be to raise the minimum receive signal power by typically between 3 and 6 dB for FEC code rate EEP-3A, dependent on the second path delay and the receiver implementation.

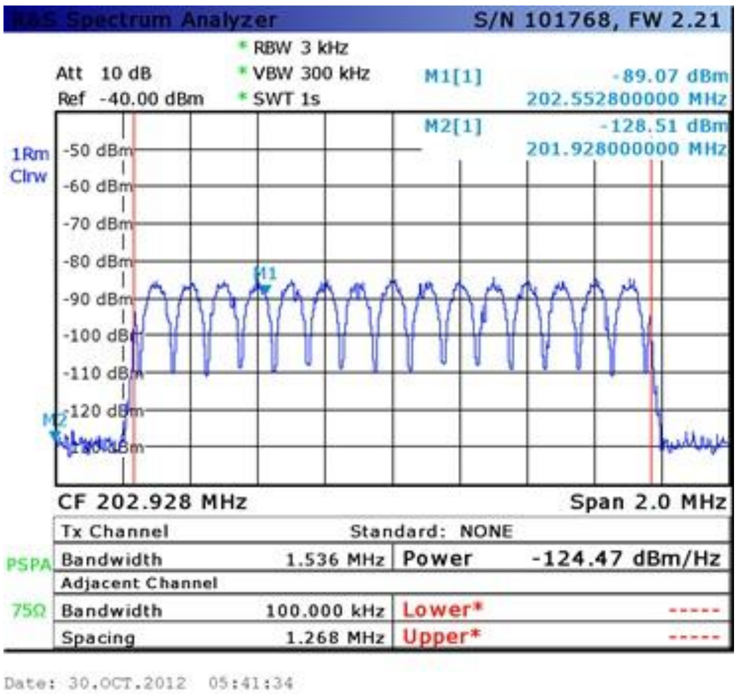


Figure 7: the spectrum of two equal power DAB signals combined with 10 µS delay

This situation typically will only occur when the receiver is in a situation where the signal received from both transmitters is not only equal power but also ‘clean’, that is there are no significant multipath signal components present. As the power difference between the two received signals increases the performance is dominated by the stronger signal. Also, the presence of multipath components helps ‘dilute’ the effect by adding further non-coherent signal components that can reduce the depth of some notches.

4. Receiver properties

4.1 Receiver noise figure

A noise factor of 7 dB has been used since the early days of DAB. This value is also suggested by the EBU in their DAB planning guideline document [EBU_6]. However, some receivers, in particular mobile DAB receivers, are likely to perform better, i.e. having a noise figure of about 5 dB or better.

IRT has made measurements of the receiver noise figure [OS_11] and found that values lay in the range 4.7 dB to 6.4 dB. On the basis of these tests and experience with modern receivers, a noise figure of 6 dB is regarded as a reasonable compromise to cover different receiver types.

It is suggested that a noise figure of 6 dB should be used for planning.

4.2 Minimum receiver signal input levels

To illustrate how the C/N ratio influences the minimum signal input level to the receiver, the latter has been calculated for representative C/N ratios, including the implementation margin. For other values simple linear interpolation can be applied.

The receiver noise figure has been chosen as 6 dB (see § 4.1). The noise figure is given for all the frequencies within Band III and thus the minimum receiver input signal level is independent of the transmitter frequency. If other noise figures are used in practice, the minimum receiver input signal level will change correspondingly by the same amount.

The minimum receiver input signal levels calculated here are used in § 5.1 to derive the minimum power flux densities and corresponding minimum median equivalent field strength values for various reception modes.

Definitions:

B	: Receiver noise bandwidth [Hz]
C/N	: RF signal to noise ratio required by the system [dB]
F_r	: *Receiver noise figure [dB]*
P_n	: *Receiver noise input power [dBW]*
$P_{s\,min}$	: *Minimum receiver signal input power [dBW]*
$U_{s\,min}$	: *Minimum equivalent receiver input voltage into Z_i [dBμV]*
Z_i	: *Receiver input impedance (75Ω)*

Constants:

k	: Boltzmann's Constant = 1.38×10^{-23} Ws/K
T_0	: Absolute temperature = 290 K

Formulas used:

$$P_n \text{ (in dBW)} = F_r + 10 \log (k \times T_0 \times B)$$

$$P_{s\,min} \text{ (in dBW)} = P_n + C/N$$

$$U_{s\,min} \text{ (in dB}\mu\text{V)} = P_{s\,min} + 120 + 10 \log (Z_i)$$

Table 22: Minimum required input signal levels for different C/N values

Band III - 7 MHz channels			
Channel model		**TU 12**	**RA 6**
Equivalent noise bandwidth	B [Hz]	1.536×10^6	1.536×10^6
Receiver noise figure	F_r [dB]	6	6
Corresponding receiver noise input power	P_n [dBW]	-136.10	-136.10
RF signal/noise ratio	C/N [dB]	11.9	12.6
Min. receiver signal input power	$P_{s\ min}$ [dBW]	-124.20	-123.50
Min. equivalent receiver input voltage, 75 ohm	$U_{s\ min}$ [dBµV]	14.55	15.25

5. Calculation of signal levels and protection ratio

5.1 Signal levels for planning

In § 4.2 the minimum signal levels to overcome noise are given as the minimum receiver input power and the corresponding minimum equivalent receiver input voltage. No account is taken of any propagation effect. However, it is necessary to consider propagation effects when considering reception in a practical environment.

In defining coverage, it is indicated that due to the very rapid transition from near perfect to no reception at all, it is necessary that the minimum required signal level is achieved at a high percentage of locations. These percentages have been set at 95% for "good" and 70% for "acceptable" portable reception. For mobile reception the percentages defined were 99% and 90%, respectively, see § 3.2.

In § 5.1.1 minimum median power flux densities and equivalent field strengths are presented which are needed for practical planning considerations. Six different reception modes are described which are listed in Table 23. The C/N values are those described in Table 8 for protection level EEP-3A associated with the reception modes defined in Table 9.

Table 23: Reception modes, C/N values

	Reception mode	C/N (dB)	Channel model
1	Mobile reception / rural (MO)	12.6	RA 6
2	Portable outdoor reception / suburban (PO)	11.9	TU 12
3	Portable indoor reception / urban (PI)	11.9	TU 12
4	Handheld portable outdoor reception / suburban / External antenna (PO-H/Ext)	11.9	TU 12
5	Handheld portable indoor reception / urban / External antenna (PI-H/Ext)	11.9	TU 12
6	Handheld mobile reception / rural / External antenna (MO-H/Ext)	12.6	RA 6

To calculate the minimum median power flux density or equivalent field strength needed to ensure that the minimum values of signal level can be achieved at the required percentage of locations, the following formulas are used:

$$\phi_{min} = P_{s\ min} - A_a + L_f$$

$$E_{min} = \phi_{min} + 120 + 10 \log_{10} (120\pi) = \phi_{min} + 145.8$$

$\phi_{med} = \phi_{min} + P_{mmn} + C_l$ (for portable outdoor reception, mobile reception and, handheld portable outdoor reception and handheld mobile reception)

$\phi_{med} = \phi_{min} + P_{mmn} + C_l + L_b$ (for portable indoor reception and handheld portable indoor reception)

$\phi_{med} = \phi_{min} + P_{mmn} + C_l + L_v$ (for handheld mobile reception)

$E_{med} = \phi_{med} + 120 + 10 \log_{10} (120\pi) = \phi_{med} + 145.8$

Where:

C/N	:	RF signal to noise ratio required by the system [dB]
ϕ_{min}	:	Minimum power flux density at receiving place [dBW/m^2]
E_{min}	:	Equivalent minimum field strength at receiving place [dBμV/m]
L_f	:	Feeder loss [dB]
L_b	:	Building entry loss [dB]
L_v	:	Vehicle entry loss [dB]
P_{mmn}	:	Allowance for man-made noise [dB]
C_l	:	Location correction factor [dB]
ϕ_{med}	:	Minimum median power flux density, planning value [dBW/m^2]
E_{med}	:	Minimum median equivalent field strength, planning value [dBμV/m]
A_a	:	Effective antenna aperture [dBm^2] [$A_a = G_{iso} + 10\log_{10}(\lambda^2/4\pi)$] × G_{iso} is the antenna gain relative to an isotropic antenna.
$P_{s\,min}$	:	Minimum receiver input power [dBW]

For calculating the location correction factor C_l a log-normal distribution of the received signal is assumed.

$$C_l = \mu \times \sigma$$

Where:

μ	:	Distribution factor. See § 3.8.3
σ	:	Standard deviation taken as 4.0 dB for outdoor reception. See § 3.8.4 for σ values appropriate for indoor reception.

While the matters dealt with in this section are generally applicable, additional special considerations are needed in the case of SFNs where there is more than one wanted signal contribution.

5.1.1 Examples of signal levels for planning

This section gives the details of the calculation for the cases listed in Table 23.

In Table 24 (overleaf) the reception height is 1.5 m above ground level (a.g.l.) for all the reception modes. The calculations are performed for one frequency representing Band III (200 MHz) and a bandwidth of 1.7 MHz.

Table 24: DAB+ in Band III			1. (MO) Mobile / rural	2. (PO) Portable outdoor /suburban	3. (PI) Portable indoor / urban	4. (PO-H/Ext) Handheld portable outdoor / suburban / External antenna	5. (PI-H/Ext) Handheld portable indoor / urban / External antenna	6. (MO-H/Ext) Handheld mobile / rural / External antenna
Frequency	Freq	MHz	200	200	200	200	200	200
Minimum C/N required by system	C/N	dB	12.6	11.9	11.9	11.9	11.9	12.6
Receiver noise figure	F_r	dB	6	6	6	6	6	6
Equivalent noise bandwidth	B	MHz	1.54	1.54	1.54	1.54	1.54	1.54
Receiver noise input power	P_n	dBW	-136.10	-136.10	-136.10	-136.10	-136.10	-136.10
Min. receiver signal input power	$P_{s\,min}$	dBW	-123.50	-124.20	-124.20	-124.20	-124.20	-123.50
Min. equivalent receiver input voltage, 75Ω	U_{min}	dBµV	15.25	14.55	14.55	14.55	14.55	15.25
Feeder loss	L_f	dB	0	0	0	0	0	0
Antenna gain relative to half dipole	G_d	dB	-5	-8	-8	-13	-13	-13
Effective antenna aperture	A_a	dBm^2	-10.32	-13.32	-13.32	-18.32	-18.32	-18.32
Min Power flux density at receiving location	Φ_{min}	$dB(W)/m^2$	-113.18	-110.88	-110.88	-105.88	-105.88	-105.18
Min equivalent field strength at receiving location	E_{min}	dBµV/m	32.62	34.92	34.92	39.92	39.92	40.62
Allowance for man-made noise	P_{mmn}	dB	0.90	1.50	5.30	0.50	2.40	0.20
Entry loss (building or vehicle)	L_b, L_v	dB	0	0	10.50	0	10.50	8
Standard deviation of the entry loss		dB	0	0	8.20	0	8.20	2
Location probability		%	90	70	70	70	70	90
Distribution factor			1.28	0.52	0.52	0.52	0.52	1.28
Standard deviation[17]			4	4	9.12	4	9.12	4.47
Location correction factor	C_l	dB	5.12	2.08	4.74	2.08	4.74	5.72
Minimum median power flux density at 1.5m a.g.l.; 50% time and 50% locations (for a location probability of 90 or 70% as indicated)	Φ_{med}	$dB(W)/m^2$	-107.16	-107.30	-90.34	-103.30	-88.24	-91.26
Minimum median equivalent field strength at 1.5m a.g.l.; 50% time and 50% locations (for a location probability of 90 or 70% as indicated)	E_{med}	dBµV/m	**38.64**	**38.50**	**55.46**	**42.50**	**57.56**	**54.54**
Location probability		%	99	95	95	95	95	99
Distribution factor			2.33	1.64	1.64	1.64	1.64	2.33
Standard deviation			4	4	9.12	4.00	9.12	4.47
Location correction factor	C_l	dB	9.32	6.56	14.96	6.56	14.96	10.42
Minimum median power flux density at 1.5m a.g.l.; 50% time and 50% locations (for a location probability of 99 or 95% as indicated)	Φ_{med}	$dB(W)/m^2$	-102.96	-102.82	-80.12	-98.82	-78.02	-86.57
Minimum median equivalent field strength at 1.5m a.g.l.; 50% time and 50% locations (for a location probability of 99 or 95% as indicated)	E_{med}	dBµV/m	**42.84**	**42.98**	**65.68**	**46.98**	**67.78**	**59.23**

[17] The minimum median field strength values calculated use a standard deviation value of 4 dB as being a representative value. However, when making field strength predictions for a particular pixel it is suggested to add the prediction error and therefore to use a standard deviation value of 5.5 dB (see § 3.8.2).

5.2 Protection ratios

5.2.1 DAB vs DAB

5.2.1.1 Co- channel protection ratios

The Co-Channel Interference (CCI) Protection Ratio (PR) is used to plan DAB services on the same channel block or frequency. Generally, though the two transmissions on the same frequency should be from distant locations there will be some 'residual' signal power which propagates between the two areas.

To calculate the maximum allowed interference power in a specific area we must define the minimum power ratio between the wanted and interfering signal. As DAB uses COFDM the interfering signal appears to be AWG Noise added at the front end of the receiver. Consequently, it is reasonable to set the protection ratio at the same value as that used for Rayleigh fading, i.e. a C/N which is generally between 12 and 13 dB.

CRA undertook a number of bench tests to determine the current PR required by modern receivers. Figure 8 shows the results for a very commonly used table top receiver implementation (2016). The results show the power difference to support non-errored audio for a range of input equivalent field strengths and channel types.

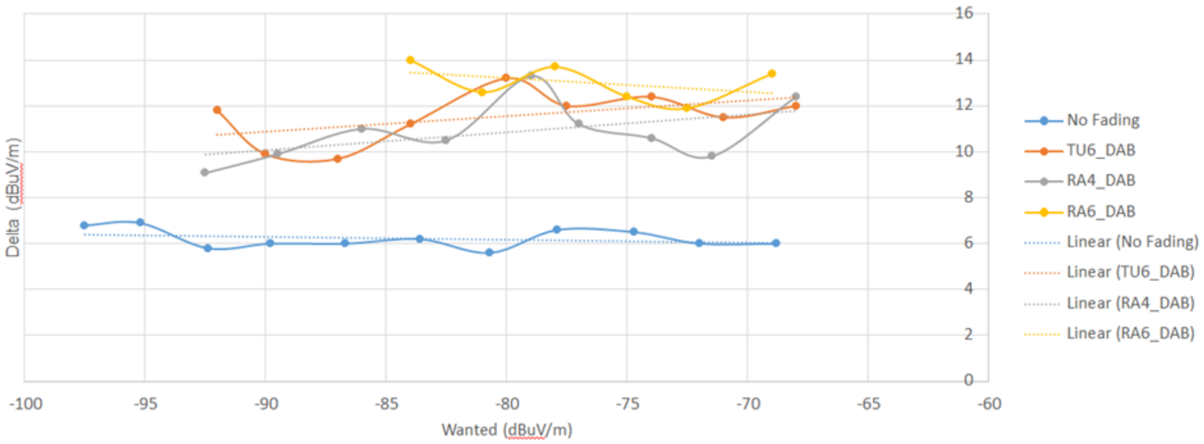


Figure 8: Protection ratio requirements for a range of channel types

The first observation is that the AWGN result is around 6 dB across the input range of -95 to -70 dBµV/m. This can be compared to the commonly used AWGN reference C/N of 7.4 dB and the results may indicate that the required AWGN C/N is less than the standard allowance.

The results for the fading channels show that the required PR is in the range 10 - 14 dB with an average of 12 dB.

5.2.1.2 Adjacent channel protection

The Protection Ratios for adjacent channel use are very important as they will have a large impact upon the design of the DAB network, in particular when adding other non co-located services on an adjacent frequency.

National, Regional and Local broadcast coverage requirements will typically differ leading to alternative network implementations in an area. Introducing a new transmitter into a network has the potential to cause interference not just to co-channel usage elsewhere, but also adjacent channel interference (ACI) in its close vicinity. The level of ACI impact will depend on many factors such as, the new transmitter power, antenna pattern - both Horizontal Radiation Pattern (HRP) and

Vertical Radiation Pattern (VRP), antenna height, whether the new transmitter is in a highly populated area or next to a busy road, and the frequency separation between the new service and the affected service. The level of impact will also depend on the robustness of the affected service and its field strength level in the area around the new transmitter site.

Impact predictions for non co-sited proposed transmitters should be carried out. These predictions must consider the relevant adjacent channel protection ratio plus the additional margin needed to serve the required percentage locations (forming the Protection Margin). Such impact predictions will identify if the existing services are protected to their planned service level.

A field strength measurement survey can be made for the existing services to validate the coverage prediction. BER measurements should also be taken as an indication of the quality of service. These measurements will be a record of the existing service performance.

The predicted field strength difference between the services in each pixel will indicate areas where the protection margin is exceeded, this method will include pixels that would not actually hear any audible interference and therefore it is essentially very restrictive to new services.

Adjacent channel interference can be regarded as degrading the affected service within a certain area around the additional transmitter (so-called 'hole punching'), in which case the impact may be better represented by counting the proportion of users in each pixel that may be affected. This method examines the existing services predicted percentage locations served in each pixel before and after the proposed new service, the drop in predicted percentage locations multiplied by the number of households in that pixel will indicate the severity and number of households likely to be affected. If the coverage in a pixel drops below 50% locations served then receiver blocking can be assumed and all households in that pixel should be counted as lost. Assessment of many ACI situations in the UK has identified these predicted estimates to align closely with reality.

In many cases this proportional counting, combined with careful consideration of the design of the new transmitter, will reduce the predicted impact to a level that the affected broadcaster will find acceptable and hence allow the new non co-sited service to launch.

When the new transmitter is brought to air, drive survey measurements can be taken of both services to validate the impact assessment. The proportion of measurement points within a pixel that exceed the relevant Protection Ratio (from Table 25) should be used to calculate the proportional impact. These results can also be scaled to represent indoor coverage impacts (only counted where the affected service provides enough field strength for an indoor service before the addition of the new transmitter). BER measurements of the affected service should again be taken to indicate where uncorrected errors have increased and to validate the field strength difference results. Annex I provides a worked example of such an ACI assessment carried out in the UK.

The critical and non-critical spectrum masks for DAB were specified to allow a reasonable degree of overlap between service areas using adjacent channels. In deciding the masks, it was important to provide sufficient filtering reducing Out of Band (OOB) emissions from DAB transmissions into adjacent channels, without making filters too expensive. As such the DAB receiver’s adjacent selectivity itself is generally the main limitation when operating non co-sited transmitters.

The IRT has carried out a number of measurements of adjacent channel protection ratios [OS_12] during the last few years. The measurements show that these protection ratios strongly depend upon the spectrum of the interfering signal. Measurements were carried out using three differently filtered interfering signals: fulfilling the non-critical spectrum mask, the critical spectrum mask and using an undistorted signal, shown below in Figure 9.

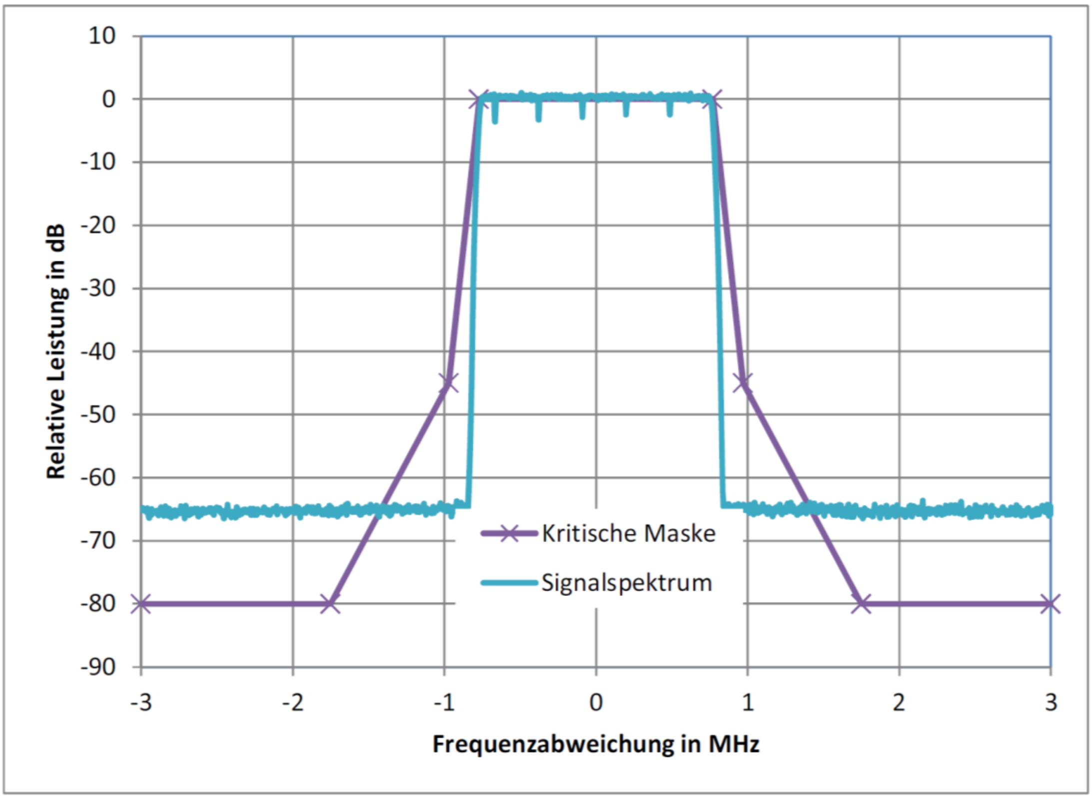


Figure 9: Undistorted signal considered in IRT studies [OS_12]

Based upon on BBC experience (see Annex I) and the IRT's measurements it is suggested that, in the case of the use of the critical spectrum mask, the adjacent channel protection ratios used for planning should be based upon the following values (Table 25):

Table 25: Suggested adjacent channel protection ratios (together with critical mask)

Interfering DAB block	Protection ratio [dB]
N ± 1	-40 dB
N ± 2	-45 dB
N ± 3	-45 dB

5.2.2 DAB vs other broadcasting and non-broadcasting systems

5.2.2.1 General remarks

Protection ratios of DAB vs other broadcasting systems and other non-broadcasting systems are well described in several ITU-R documents: [ITU_1], [ITU_5], [ITU_10]. For Europe, a relevant exception is DVB-T2 since this is a relatively new system for which no or only very few measurements exist.

The situation is different with regard to DAB+. Apart from intra-system measurements (DAB+ vs DAB+), practically no figures are available for protection ratios of DAB+ vs other broadcasting systems and other non-broadcasting systems.

This is not very critical, however, since in most cases an extrapolation from DAB to DAB+ is possible as well as an extrapolation from DVB-T to DVB-T2. The basic ideas for these extrapolations are the following:

a) All cases where DAB+ interferes with other broadcasting or non-broadcasting systems can be treated in the same way as DAB, since both DAB and DAB+ have the same RF characteristics, being OFDM interferers, with the same bandwidth, the same carrier structure, etc.

b) For DVB-T2 being interfered with by DAB/DAB+, it is proposed that the protection ratios of a corresponding DVB-T mode (modulation scheme + code rate) be used; in this case, corresponding means having the same (or a similar) C/N value.

c) For DAB+ being interfered with by DVB-T/DVB-T2, it is proposed that the C/N of DAB+ vs. DAB+ minus 6 dB be used, since the ratio of DAB+ and DVB-T/T2 bandwidths is 1/4.

   Non fully overlapping DAB+ and DVB-T/T2 channels should be treated according to tables A.3.3-13/14 of [ITU_1].

d) For DAB+ being interfered with by other services, it is proposed to use the following procedure:
   The PR for DAB vs the other service (OS) exists: $PR_{DAB\text{-}OS}$, as well as the C/N of DAB: C/N_{DAB}. These values can be taken from [ITU_1] or [EBU_6]; typically DAB mode 'Protection Level 3' is chosen.

   The quantity $\Delta_{OS} = C/N_{DAB} - PR_{DAB\text{-}OS}$ is defined.

   It is assumed that Δ_{OS} is representative for all protection levels, also for DAB+.

   The PR for DAB+ being interfered with by OS is then given by:

$$PR_{DAB+\text{-}OS} = C/N_{DAB+} - \Delta_{OS}$$

This procedure is a pragmatic but qualitative approach, in view of the lack of measurement results. It may be replaced in the future when results of DAB+ measurements become available.

5.2.2.2 DAB vs DVB-T/T2

Protection ratios for DAB vs DVB-T are given in Appendix 3.3 to Annex 2 of [ITU_1], Tables A.3.3-13 - 22.

Protection ratios for DAB vs DVB-T2 and DAB+ vs DVB-T/T2 may be derived by applying the procedure described in § 5.2.2.1.

5.2.2.3 DAB vs other services

Protection ratios for DAB vs Other Services are given in Appendix 4.3 to Annex 2 of [ITU_1], Tables A.4.3-2 - 5.

PRs for DAB+ vs Other Services may be derived by applying the procedure described in § 5.2.2.1.

6. Implementation of DAB

6.1 Frequency planning issues

6.1.1 History of DAB frequency plans in Europe

The first DAB frequency plan in Europe was established in 1995 by the Wiesbaden 1995 agreement WI95 [EU_1]. The plan covered plan entries in VHF Bands I and III and in L-Band. In 2002 the plan was extended regarding the L-Band by the Maastricht agreement MA02 [EU_2]. Since the L-Band part became a separate plan MA02, the old WI95 plan was formally revised and renamed WI95revMA02 [EU_3]; however, no modifications were made regarding the plan entries and the procedures.

In 2006, at the Regional Radiocommunication Conference RRC-06 in Geneva, an ITU frequency plan for ITU Region 1 [ITU_1] and Iran[18], was established for digital audio (DAB) and TV (DVB-T) broadcasting [ITU_1]. This plan is in force and covers most of the VHF plan entries of WI95revMA02. Therefore, the latter was abrogated in 2007 by the Constanta 2007 agreement WI95revCO07 [EU_4], which now covers only the remaining plan entries of WI95revMA02 that are not included in GE06. These are plan entries in channel 13 (230 MHz - 237 MHz) and one plan entry in Band I[19]. Constanta 2007 MA02revCO07, [EU_5], also updated the MA02 plan for the L-Band with additional regulatory procedures.

In the meantime, the EU/EC allocated the L-Band (also) to mobile broadband (supplementary downlink only) [EU_6]. In many European countries, this Band has now been auctioned to the mobile industry and is no longer available for DAB broadcasting - although formally the MA02revCO07 agreement is still in force within the CEPT.

One of the reasons for this EU/EC decision is that over the last 20 years the L-Band was effectively not used by DAB broadcasting - with very few networks implemented and even fewer still operational. This lack of use and reallocation to mobile is also the reason why the new DAB specification [ETSI_2] no longer contains L-Band specific features (this report covers L-Band issues only for completeness with regard to (old) DAB implementations).

6.1.2 Implementation of DAB in the GE06 and WI95revCO07 plans (VHF)

6.1.2.1 General

This section gives a short overview of the DAB frequency plans for Europe in VHF Band III. This is predominately GE06, and to a small extent WI95revCO07. Since for DAB, all in all, the WI95revMA02 plan was transferred to GE06, most principles and procedures are identical for GE06 and WI95revCO07; however, several additional aspects had to be taken into account in GE06 when compared to WI95revMA02; for example sharing with DVB-T. Therefore, GE06 principles and procedures are more complex, details of which are not explained in this section. These can be found in the original agreement texts [ITU_1], [EU_4], and in, e.g., [EBU_11], [OS_13], [OS_14], [OS_15].

6.1.2.2 DAB block raster and bandwidth

A DAB block is a frequency channel 1.536 MHz wide. A 176 kHz guard band separates adjacent DAB blocks. DAB in VHF has been introduced in the pre-existing 7 MHz raster of analogue TV; therefore 4 DAB blocks fit into one TV channel with a guard band of 320 kHz or 336 kHz between TV channel limits. The blocks are designated according to their TV channel position in Band III (channels 5 to 12) and labelled A through D for each TV channel, e.g., 5A for the lowest DAB block in VHF Band III.

Channel 13 (230 MHz - 240 MHz), which is not covered by GE06 and retains to WI95revCO07, contains 6 DAB blocks with a guard band of 176 kHz. There also remains a plan entry in Band I, labelled 4A.

[18] More precisely, the GE06 planning was in parts of Region 1 situated to the west of meridian 170° E and to the north of parallel 40° S, except the territory of Mongolia) and in the Islamic Republic of Iran.

[19] Cyprus Block 4A - Centre frequency: 61.936 MHz.

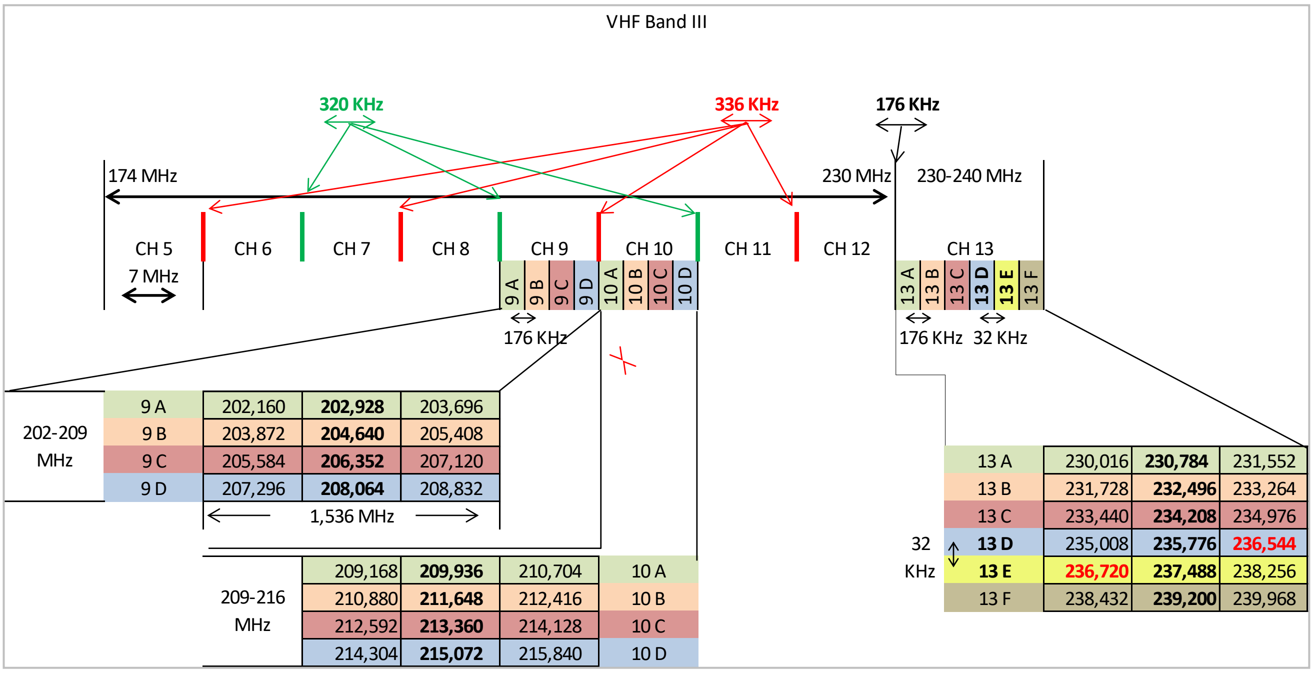


Figure 10: DAB blocks in Band III

6.1.2.3 Allotment plan concept and layer concept[20]

In the allotment concept, geographical areas are identified where a frequency is used with certain restrictions regarding the outgoing interference produced by the network implemented in this area and for which a certain protection is to be respected. No detailed specification of the characteristics of the individual transmitters within the network is necessary. It is left to the particular network implementation to respect the overall restrictions regarding the outgoing interference.

The allotment concept is a suitable frequency planning approach for transmission systems based on single frequency networks. It gives more freedom to the network planner and allows for a better adaptation of the technical aspect of frequency planning to the design of broadcast service areas which are determined by social, cultural and political aspects.

In frequency planning the impact of the outgoing interference originating from a network is relevant. Since with the allotment concept the real network implementation is not yet known at the stage of the establishment of the frequency plan - and it is not even desirable to fix it once and forever - a representative network is defined to describe the expected and, under a regulatory aspect, allowed outgoing interference. The outgoing interference of a network is called its interference potential and the representative, artificial network is called reference network. Based on these assumptions and definitions a frequency plan can be synthesized where certain frequency re-use conditions need to be obeyed.

For DAB two reception scenarios are defined that are termed reference planning configurations: portable indoor reception (RPC 5) and mobile reception (RPC 4). They differ in the assumed required location probability and the required minimum field strength (GE06, table A.3.5-2).

Two different reference networks for the two reference planning configurations are defined. Both describe large SFN with an inter-site distance of 60 km, but differ in their power budget (GE06, table A.3.6-5).

[20] Text of this section is mainly taken from [OS_14].

For the DAB frequency plans in Europe a layer concept was applied. In this approach a homogeneous coverage concept is adopted where in each location of the planning area a similar number of multiplexes are made available. In this way, full area coverage of all countries is achieved. This concept is preferably applied in frequency planning conferences since it allows for a simple realization of the principle of equitable access to the radio spectrum. However, in practice - when a frequency plan is going to be implemented - often a mixture of full area coverage and population centre coverage with aggregation of frequencies in the latter is realised.

On average, GE06 provides three DAB layers for each country in Band III and one layer for DVB-T. In the next section on the envelope concept is described how the latter can be used for further DAB layers.

In addition to the allotment approach, GE06 also provides the possibility for a traditional assignment plan entry, where the individual characteristics of a DAB station are given in detail.

6.1.2.4 Envelope concept

As a new frequency planning aspect, in GE06 as well as in WI95revCO07, the envelope concept was introduced. It provides the possibility to introduce a transmission system other than the one indicated in the plan entry if it does not claim more protection and does not produce more interference than the original plan entry.

The most important application of the envelope concept is the utilization of a DVB-T plan entry for the implementation of DAB networks. This aspect is dealt with in detail in § 6.1.4. Sometimes this is called the “conversion” of a DVB-T plan entry into a DAB implementation.

6.1.2.5 Coordination

When a new plan entry is to be introduced or an existing plan entry is to be modified, coordination with all potentially affected administrations is required. An administration is regarded as affected if the interference potential of the new or modified plan entry exceeds a certain trigger field-strength at the border of the potentially affected country. In this case agreement of the affected administration is required.

Similarly, when a DAB network is to be implemented on basis of an allotment plan entry, the plan management body (ITU BR in the case of GE06) checks whether the interference potential limit of the underlying reference network is kept. Sometimes also this procedure is called a “conversion” of an allotment into one or more assignments.

Similar concepts are realized in the WI95revCO07 agreement, too.

It is to be noted that a vast majority of coordination, at least in Europe, is done on a bi-/multilateral basis, checking interference potential limits as agreed e.g. in additional bi-/multilateral agreements.

6.1.3 Implementation of DAB in the MA02CO07 plan (L-Band)

The principles and procedures applied in MA02revCO07 for DAB in L-Band are (more or less) identical with those established in WI95revMA02 for DAB in VHF (as described in § 6.1.2).

Bandwidth and block raster are the same as in VHF; in total, the plan comprises 16 DAB blocks in L-Band, labelled LA through LP. Two additional reference networks are added which cover smaller service areas and whose interference potentials are reduced; however, no indoor reception mode is defined.

As for the GE06 agreement, an envelope concept was introduced, which in addition includes optional channel aggregation allowing for the implementation of mobile multimedia systems other than DAB.

However, as for some time there have been no implementations of L-Band DAB networks in the CEPT region in the, the MA02CO07 plan and agreement is obsolete in a practical sense. In the meantime, the L-Band was allocated to mobile services in the European Commission implementing Decision (EU) 2015/750[21] [EU_6] and has already been auctioned in some countries.

6.1.4 Conversion of DVB-T allotments into DAB and vice versa

When in 2006 the GE06 Plan was established, the VHF Band III (174 MHz - 230 MHz) was designated for DVB-T as well as DAB. A 7 MHz raster was adopted for DVB-T and a 1.75 MHz raster for DAB. Administrations were free to choose whether to use the Band for audio transmissions (DAB) or for television (DVB-T) and how to divide the Band between the two services.

This division was not, however, fixed forever. The envelope concept of the GE06 agreement allows for the conversion of a previously chosen service into another service as long as certain technical and regulatory conditions are fulfilled. In particular, the conversion of a DVB-T plan entry into DAB entries is possible. The channel rasters of these two services fit seamlessly, one with another (which is not surprising, since at the time, DAB was designed to fit into the analogue 7 MHz TV channel raster of Band III). Thus, one 7 MHz DVB-T channel can accommodate four 1.75 MHz DAB frequency blocks.

The envelope concept requires that the spectral power density of the new entry/entries must not exceed that of the replaced entry, in-band as well as out-of-band. This is not a priori fulfilled with a conversion from a DVB-T entry into a DAB entry, since reference planning configurations (RPC) and reference networks (RN), which are the relevant planning tools for plan modifications, are not identical for the two systems. They differ in their power configuration, network layout and interference susceptibility.

ECC Report 116 [EU_7] gives a detailed analysis of how and under which conditions a conversion can be performed. Two aspects have to be considered. Firstly, the new converted DAB entries must not produce more interference to existing plan entries, and, secondly, with these restrictions the new DAB configurations have to provide sufficient coverage in order to be a feasible option. The considerations are based on DVB-T reference network RN1 which is the relevant reference network for service areas beyond local coverage requirements.

It turns out that for most DVB-T allotment configurations, which are already designed for portable (indoor and outdoor) reception, a conversion into a DAB allotment configurations (for mobile (RPC4) as well as portable indoor (RPC5) reception) is possible. Only with the conversion of DVB-T RPC3 (portable indoor reception) into DAB RPC4 (mobile reception) the DAB service requires a higher protection than provided by the DVB-T entry. However, that can be compensated by an increase of power of the DAB configuration when agreed by the affected services.

DVB-T allotment plan entries for fixed roof-top reception are not well suited for a reasonable conversion into DAB plan entries for mobile and/or portable indoor reception.

The conversion of DVB-T plan assignments into DAB allotments is less flexible. Only DVB-T plan assignments designed for portable indoor reception allow for a reasonable conversion. Otherwise the DAB allotment would have to suffer from remarkable coverage deficiencies.

[21] Decision (EU) 2015/750 on the harmonisation of the 1452 – 1492 MHz frequency Band for terrestrial systems capable of providing electronic communications services in the Union.

ECC Report 116 [EU_7] also deals with adjacent channel issues which arise when DAB allotments are implemented in the same area using adjacent frequency blocks. This (nearly) inevitably occurs with the conversion of a DVB-T allotment into four DAB allotments. Certain mitigation techniques have to be applied in order to guarantee a regular operation of the DAB services. Co-siting of transmitters which use adjacent frequency blocks is one of the major techniques in order to avoid undue interference, in particular hole punching.

6.1.5 Implementation of DAB outside Europe

6.1.5.1 Availability of VHF Band III - DTV migration

Many countries in Asia, the Middle East and Africa are in the process of moving from Analogue Television (ATV) to Digital Terrestrial Television (DTT). The DTT services are generally located in the UHF Band due to the lack of VHF Band III spectrum for the migration process. The result is that at the end of the Digital Switch-Over (DSO) the VHF Band III is left vacant and can be used for digital radio. Countries that are moving their DTT to the UHF Band include Thailand, Malaysia, Indonesia, South Africa and Australia. However, Australia also retains part of VHF Band III for DTT.

In Australia only 2 DTT channels have been allocated for DAB resulting in only 8 DAB blocks being available nationwide. In other countries (e.g. Thailand, Malaysia) the full suite of 8 DTT channels will be generally available allowing around 32 DAB blocks. Higher DAB block availability allows more options for frequency coordination and overall lower implementation costs due to a higher probability of optimal transmitter spacing. As the number of DTT channels (or available DAB blocks) reduces, the transmissions required to cover an area are forced to lower powers to avoid interference, hence increasing the number of transmitter locations and the overall cost of deployment. The DSO process takes some considerable time and it is likely that most South East Asia countries will not complete their DSO and hence vacate VHF Band III until after 2020. A similar timescale is expected in the Middle East and Africa.

6.1.5.2 DAB coexistence with analogue TV

Analogue television was planned in the VHF Band (Bands I and III) and in the UHF Band (Bands IV and V). While Europe has already fully switched from Analogue TV to DTT, many countries in the rest of the world are still planning or undertaking that ASO process. Therefore, Band III might still be used for Analogue TV in many countries.

The deployment of DAB in VHF Band III may be commenced prior to the clearing of Analogue TV in that frequency band. Initial deployment can often be done using low power DAB transmissions for demonstration and trials while Analogue TV services exist, as long as there is adequate physical distance between the DAB and Analogue TV transmissions. Analogue TV networks are more susceptible to co-channel interference and require a high Protection Ratio; consequently the permitted distance between co-channelled transmitters is large. This provides an opportunity for initial low power DAB transmissions. Many such transmissions have been established in the past, including those in Europe during the establishment of DAB in the late 1990s and early 2000s, DAB in Australia prior to their analogue switch-off and the DAB trial transmission in Kuala Lumpur of approximately 5 kW ERP from the KL Tower and five SFN repeaters spread around the city.

Planning for DAB can also start well before a target Analogue TV switch-off date to determine the number of transmitters, their locations and power characteristics required to deliver the coverage needed. Once DAB is planned and an Analogue TV switch-off plan is in place, DAB transmissions can gradually be switched on as Analogue TV is switched off. This provides the quickest route to DAB network deployment.

[ITU_11] provides the Protection Ratios that DAB planning needs to use in order not to interfere with the existing Analogue TV. Additionally, during the commissioning of a DAB service a slow power ramp to full design power can be used and field testing can be employed to check that no interference occurs to the existing Analogue TV services, if interference is detected then the DAB transmission power can be reduced accordingly.

6.2 FM and DAB coverage considerations

As DAB is seen as being the replacement for FM services, it is inevitable that a comparison is made between the coverage of the two. A DAB network would be expected to provide similar or better coverage than the FM networks it is targeted as replacing.

For a comparison of planned coverage between FM and DAB networks the following needs to be considered:

- **Planning -** In most countries coverage planning for FM is based upon directional receiver antennas at 10 m height, though most of the listening today is done using portable (indoor) and mobile receivers. In contrast DAB networks are typically planned for portable/mobile reception at 1.5m height.
- **Failure mode of the service -** Analogue FM has a graceful degradation with, in many cases, receivers switching from stereo to mono. FM-mono reception may still be possible at very low signal levels with a C/N of a few dB. DAB in contrast, has an abrupt degradation characteristic that requires a margin (higher availability) to be built into DAB coverage planning to ensure comparable availability.
- **Frequency difference -** DAB is implemented in Band III (200 MHz) and FM services use Band II (100 MHz). This difference in frequency means that propagation conditions, such as diffraction losses, building entry loss, etc. will be different.
- **Service availability -** Ultimately the listener is the arbiter as to whether the DAB service is a replacement of the FM service. Whilst DAB may offer more choice in terms of programmes, this is of little value if the service is not available in locations a listener was previously able to receive an FM service.
- **Listener satisfaction -** DAB and DAB+ services can be delivered using a wide range of bit-rates. Lower bit rates generally result in relatively reduced audio accuracy or perceived quality. It is important for broadcasters to set the service bit-rate at a high enough value to ensure that the carried audio type is presented with appropriate quality.

These differences between services, planning criteria, operational frequency and failure characteristics, mean there is no straightforward methodology for providing a comparison between the coverage of FM and DAB services.

Some countries, such as Switzerland, aim at respecting the user experience with the present FM coverage today by ensuring that the DAB coverage equals or exceeds the FM coverage.

Other countries define a reference coverage limit for FM that is to be compared with the DAB coverage. Typically, roof-top reception at 10 m with stereo quality and 50% location probability is chosen as the FM reference, e.g. in Norway and Germany. To be regarded as equivalent a DAB network should match this FM reference coverage for both portable (indoor) and mobile reception.

6.3 Practical aspects associated with DAB network implementation

6.3.1 DAB transmitter requirements

To avoid distortion the OFDM signal needs to be transmitted using a linear amplifier. The linear amplifier must also have a sufficiently high Modulation Error Ratio (MER). A poor MER will create degradation in C/N performance before the transmitter output, and may consequently also reduce coverage.

For Digital TV, transmitters with MER values above 40 dB are often suggested. However, the actual loss of performance also depends on the required C/N for the system transmitted. For a robust system such as DAB that requires a C/N of about 12 dB, the MER value will not be as critical as in the case of a DTT transmission requiring a C/N of 23 dB.

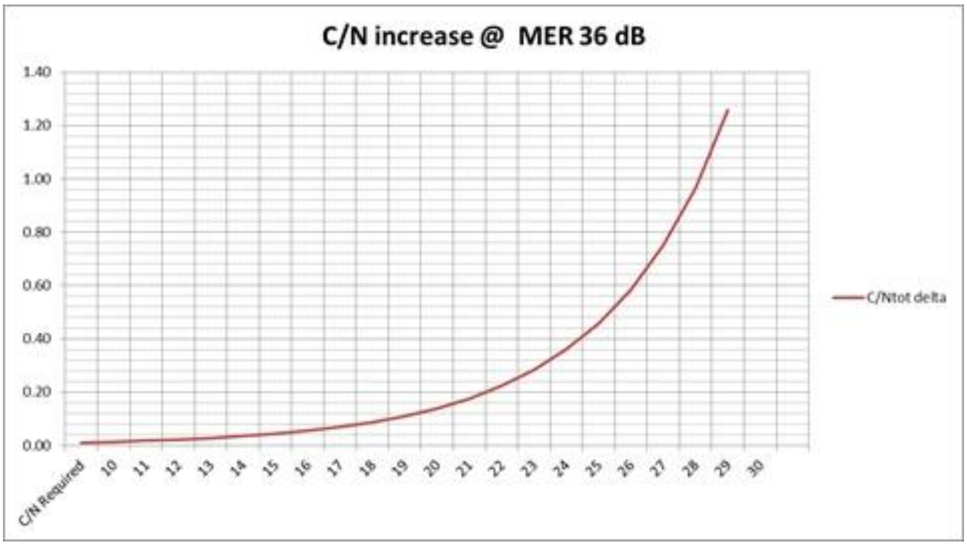


Figure 11: C/N degradation as a function the of required C/N value assuming a transmitter MER of 36 dB

In the example in Figure 11, it can be seen that for a required C/N of 12 dB, the actual C/N loss is about 0.01 dB, i.e. hardly measurable. While at a required C/N of 23 dB the degradation would be about 0.22 dB.

Given the MER of the power amplifier used, the loss in C/N performance can be calculated. The result is shown in Figure 12.

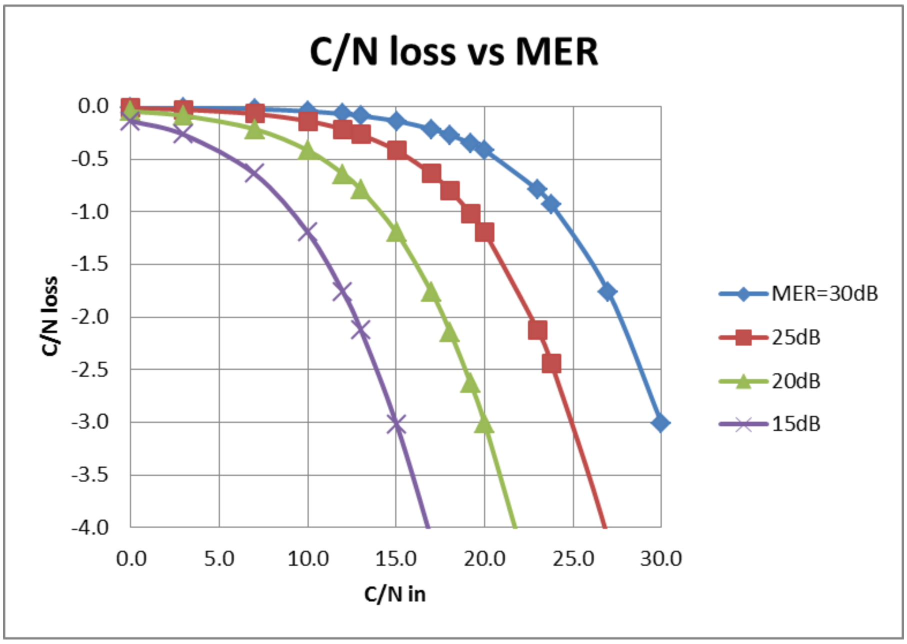


Figure 12: C/N loss as a function of different MER values

In Figure 12 it can be seen that for a C/N value of 12 dB, a MER of 25 dB results in a C/N loss of 0.2 dB while a MER of 30 dB results in a loss of less than 0.1 dB. A C/N loss of 0.1 dB is generally considered to be the maximum acceptable value resulting in a minimum MER of 30 dB.

6.3.2 Examples of receiver requirement specifications

To ensure DAB radios meet the requirements of local markets and provide customers with certainty about the suitability of a radio, certification procedures have been established in a number of countries.

6.3.2.1 Receiver requirements in Italy

In Italy, the standards for digital radio receiver assessment were developed by Rai Way on behalf of ARD[22] (Associazione per la Radiofonia Digitale in Italia), the Italian association responsible for promoting the digital radio. Taking into account the receiver profiles established by WorldDAB, the EBU and DigitalEurope[23], three classes of certification were defined:

- Class A: audio services
- Class B: visual radio services
- Class C: interactive radio services

With respect to these classes, receivers compliant with the specifications defined in the Certification Procedures were allowed to be labelled with one of the following marks:

- ARD white mark for Class A
- ARD blue mark for Class B
- ARD green mark for Class C

The certification procedures were drafted with reference to all types of receivers: portable (such as mp3 players and smartphones including digital radio receivers), kitchen radios and car radios. In order to achieve the ARD marks, receivers had to pass a preliminary test, to prove their capability to operate within the Italian radio context, and then several other tests defined in the specification document, depending on the considered class. All these tests had to be carried out by manufacturers, who had to provide a self-certification document attesting the compliance of their receiver to a specific class. In order to verify the accuracy of the self-certification document provided by manufacturers, ARD periodically performed spot checks to ensure that receivers labelled with ARD marks actually respected requested service requirements.

Passing the preliminary test ensures a correct “radiofrequency access”, that is the capability of a digital receiver to operate within the Italian radiofrequency context. In particular, a receiver has to guarantee a minimum operating level, an adequate protection from signal using adjacent frequency blocks, the ability to tune into the frequency blocks available in Italy for the radio service and a fast and automatic adaptability in case of multiplex reconfiguration (i.e. variation of services contained in the multiplex).

The additional tests depend on the specific class the receiver belonged to. For class A, the capability of audio content decoding and the visualization of station name are requested. For class B, in addition to the features of Class A, a colour screen with a resolution of at least 320 x 240 pixels and a minimum size of 2.2 inches is required, as well as slideshow support and firmware upgradability. For class C, in addition to the features of Class B, the simultaneous decoding of four sub-channels and the visualization of MPEG-4 BIFS (Binary Format for Scenes) contents is required, as well as the capability of browsing web pages via a browser provided in the receiver. In the Certification Procedures, further requirements are specified together with the testing scheme and test processes for each of the three classes. Moreover, specific ETI (Ensemble Transport Interface)

[22] The activities of ARD, Associazione per la Radiofonia Digitale in Italia,were officially ended on December 31, 2015.

[23] The WorldDAB Digital Radio Receiver Profiles can be found at the following link: https://www.worlddab.org/technology-rollout/receivers/worlddab-receiver-profiles.

files are suggested for testing purposes.

As ARD no longer exists[22], Rai Way is willing to provide its experience and competence to any other organization and to manufacturers that support the development of digital radio.

6.3.2.2 UK DAB receiver specification- Tick Mark

In 2010 the UK Minister for Culture, Communications and Creative Industries set out a joint Government-Industry Digital Radio Action Plan, which sought to inform a future decision on digital radio switchover. The Action Plan was to address the key issues of DAB coverage planning, redundant equipment disposal, energy consumption and how a transition could be implemented.

The Action Plan had five key objectives:

1. **Consumer choice** - of content and technology
2. **Quality** - of sound and new functionality
3. **Affordability** - of household and in-vehicle conversion
4. **Accessibility** - coverage and ease of use
5. **Awareness** - through communications and retail advice

The objective of awareness would deliver a public information campaign and develop a common set of standards and testing for digital devices to provide a Certification Mark so that consumers were better informed.

This objective was carried out by the Technical and Equipment Group, comprised of manufacturers, broadcasters and consumer representatives, and it was chaired by Digital Radio UK[24] (DRUK) although a sub-group considering in-vehicle was chaired by the Society of Motor Manufacturers and Traders.

The Digital Radio Certification Mark ("tick mark" [OS_16]) identifies and gives greater assurance to consumers that the DAB digital radio products and services they are buying are future-ready and will enable them to receive the available DAB, DAB+ and FM radio stations. To be granted use of the tick mark, manufacturers must meet the minimum specification. For the manufacturer to prove that they meet the minimum specification, they must put their product(s) through testing.

The tick mark identifies qualifying DAB products and/or digital radio installation services, applying for the mark is voluntary.

The following product types are eligible for the tick mark:

- DAB receivers (domestic and in-vehicle)
- DAB handheld HiFi receivers (domestic)
- DAB head units (in-vehicle)
- DAB adapters (in-vehicle and domestic)
- New vehicles (in-vehicle)

Retailers, franchise dealers, garages and installers are eligible for the in-vehicle installer tick mark.

When used by in-vehicle installers, the mark certifies that the installer has completed and passed

[24] Digital Radio UK works with Government, broadcasters, manufacturers, retailers and a wide range of stakeholders to accelerate digital listening, to enable the expansion of the digital radio platform, and to ensure that industry meets the consumer led criteria to be achieved before a digital radio switchover.

the official IMI (Institute of the Motor Industry) training programme.

The mark can appear at retailer point of sale, on packaging, online and on other marketing materials. Once a manufacturer or installer has been granted use of the mark they will be sent brand guidelines stating how to use the mark.

The certification procedures require a domestic receiver to comply with the Band III provisions of BS EN 62104:2007 [OS_17] with the exceptions of thresholds for Gaussian Sensitivity, Rayleigh sensitivity and adjacent channel interference protection as set out in the minimum receiver specification[25]. The receiver must also decode DAB and DAB+ and be able to receive the FM radio services currently broadcast in the UK.

The minimum receiver specification for in-vehicle receivers and adaptors[26] has the same additional requirements but with different thresholds and the receiver must also support announcement switching and service following.

6.3.3 Local DAB services

The Open Digital Radio Organization (ODR) in Switzerland (www.opendigitalradio.org) maintains and develops a set of tools called ODR-mmbTools originally developed by CRC in Canada that can be used for local DAB services. These tools are an open-source development and completely free to use. The DAB transmission chain consists of ODR-DabMux, ODR-DabMod and the Ettus Research USRP software defined radio (SDR) platform. The encoders for DAB and DAB+ are also realized in software. ODR-DabMux is a DAB multiplexer that combines all audio and data inputs and generates an ETI output. ODR-DabMod is a DAB modulator that generates modulated I/Q data from ETI output und sends it to the USRP.

The second part of the DAB+ transmission chain is the VHF unit comprising of amplifier, filter and antenna. An amplifier is needed to achieve the higher transmission power. The filter is connected after the amplifier to fulfil the spectrum mask defined in the DAB specification. This open source solution is also known as a small scale DAB.

The main characteristics of small scale DAB are:

- Robustness: the tools are very reliable
- Flexibility: It is possible to do software updates and extend the features
- SFN: Tools are capable of SFN using external synchronisation on SDR platform (GPS clock)
- DAB services: Dynamic Label and Multimedia Object Transfer are already implemented
- Protection Ratios in the adjacent channel could be higher than at the professional transmitter due to the uncritical spectrum mask
- It is a cost effective solution compared to professional broadcast equipment
- A commercial solution is not available
- Knowledge of the Linux operating system as well as shell scripting (e.g.: python, bash) is necessary for the installation

At the end of 2015 small scale DAB was tested by the IRT. A ground plane antenna was mounted on the roof of the IRT building in Munich at a height of 22 m. The effective radiated power (ERP) was 25 W. It was possible to receive the DAB signal within a radius of 200 m with a portable receiver outside and inside an older, (not rf-insulated) building. Though it wasn't possible to receive the

[25] The Minimum receiver specification for domestic receivers can be found at the following link: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/207937/Domestic_Min__Spec_v1.1_revisedJune13_.pdf .

[26] The Minimum receiver specification for in-vehicle receivers and adaptors can be found at the following link: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/207935/In_Vehicle_Min_Spec_v1.1_revisedJune13_.pdf .

DAB portable indoor in a recently built (well rf-insulated) building at ground floor.

In Switzerland, UNIKOM, an association of local non-commercial radio, and the company Digris applied for local DAB licenses (the 4th DAB layer) and in 2013, the Swiss Regulator OFCOM granted a license to Digris for building local islands, with 75% of the investment covered by OFCOM. In 2014 the first pilots started in Geneva and Zurich using the open source DAB+ solution.

The Geneva local multiplex is still on air from a 5 kW ERP antenna located on the French border. It distributes 14 local radio programmes to most of the Geneva region. The contribution network to the transmitter is derived from the open internet streams of the radio stations. The transmitter site has a PC with the SDR platform plus a universal software radio peripheral, a power amplifier, a mask filter and an ADSL router.

Today, the other local multiplexes that used the open source DAB+ solution deployed in Zurich and Lausanne are still on air, but they no longer use a platform based on an open source DAB solution.

6.3.4 Tunnel coverage

Broadcasters aim at providing in-tunnel DAB reception with no interruption for all radio programmes. Road authorities of some countries are obliged, for safety reasons, to have an option for voice break-in.

The reception stage, the repeater stage and the voice break-in stage together comprise the DAB tunnel system. The DAB ensembles are received at the reception site and are combined prior to the broadband distribution and amplifying stage. The amplifying stage can be part of the existing infrastructure for FM and PPDR (Public Protection and Disaster Relief) radio services, or it can be provided as a stand-alone solution. The radiation can be based on radiating cables or it can be directly radiated into the tunnel by terrestrial antennas. The advantages of both approaches are described in more detail in Annex J.

Crucial for reliable reception by all car radios is carefully setting the minimum coverage criteria. The minimum field strength should recognise existing car receiver sensitivities, reception antennas, man-made noise in the tunnel and any attenuation of the signal by cars or trucks.

6.3.5 Dynamic reconfiguration of a DAB ensemble to enable regional services within a national SFN

The lack of available frequency blocks for DAB and the necessity to transmit regional services forced Rai Way and the RAI Research Centre to investigate possible solutions.

The most suitable method for broadcasting regional and national content proved to be the dynamic reconfiguration of the DAB ensemble using just a single block in a SFN with frequency reuse 1. The concept is to link the different service IDs of the DAB ensembles to the common national programme content and, after the reconfiguration, to the regional content, alternately.

A detailed description of the technique is reported in Annex K.

7. Specific implementation scenarios/country situation

This section provides examples of how DAB networks have been developed in different countries.

The approaches are often quite dissimilar and also, in a few cases, some of the values used for planning differ from the ones suggested elsewhere in this report.

7.1 UK

The UK Government launched the Digital Radio Action plan in July 2010. The Action Plan was launched to ensure that, if and when a digital switchover occurred, it could be delivered at a time when the market is ready and in a way that protects the needs of the listeners.

The decision on whether to set a date for digital radio switchover would be considered by the government when the following criteria were met:

- When 50% of all radio listening is via digital platforms, and
- When National DAB coverage is comparable to FM and Local DAB reaches 90% of the population and all major roads

As part of this process the UK regulator for spectrum and communications (Ofcom) was asked to chair a DAB coverage and spectrum planning group to determine the current level of FM coverage and develop the options to increase DAB coverage to match FM. The resulting report[27] summarises the UK approach to planning DAB networks.

The Action Plan was finalised in November 2013 and on 16th December 2013 the DCMS (Department for Culture Media and Sport) announced that while there had been steady growth in digital listening it was not yet time to commit to a switchover.

As part of this Action Plan, DAB coverage has been significantly enhanced with the BBC national DAB digital network available to over 97% of the UK population and over 87% of major roads, the Local DAB networks providing local commercial and BBC local stations reaching approximately 90% of the population and over 77% of major roads.

There are now two national commercial digital multiplexes in the UK, one with stations available to approximately 91% of the population and the second which launched in February 2016 serving approximately 81% of the population.

The UK edges closer towards the criteria with RAJAR figures[28] for quarter 4 of 2017 indicating that the Digital platform share of radio listening has reached 49.9%, up 9% year on year with DAB being the driver showing a 36.3% share, followed by online/apps with 8.5% and DTV with 5.1%.

The share of Digital listening[27] within cars is at 24% and data from the Society of Motor Vehicle Manufacturers and Traders (SMMT) shows that since 2017, over 84% of new cars supplied in the UK are equipped for DAB reception as standard[29].

27 https://www.ofcom.org.uk/tv-radio-and-on-demand/information-for-industry/radio-broadcasters/coverage/dab-coverage.

28 http://www.rajar.co.uk/docs/news/RAJAR_DataRelease_InfographicQ42017.pdf.

29 https://www.smmt.co.uk/2017/01/widest-ever-choice-of-listening-for-uk-motorists-as-2-3-million-new-car-buyers-tune-into-digital-radio-in-2016/.

7.2 Germany

In Germany presently (2018), there is one nationwide DAB+ layer implemented and, depending on regional circumstances, one to three additional regional DAB+ layers. The whole of Band III is planned for use by DAB+; there is no usage for DVB-T/T2.

MEDIA BROADCAST is the operator of the nationwide digital radio network which is implemented as one large SFN in DAB block 5C. The launch of the DAB+ nationwide multiplex started in Germany in 2011 with an initial network consisting of 27 sites.

As of the beginning of 2018, this network consists of 120 sites and allows digital radio reception in 94% of the area of Germany (mobile outdoor) as well as for 82% of the inhabitants' portable indoor reception. The coverage of the highways is more than 98%; see Figure 13.

In addition to the nationwide network on block 5C, there are, depending on the area, one to three additional public service and private broadcasters layers implemented.

Figure 14 shows an accumulated coverage as of the beginning of 2018; the value (mobile outdoor or portable indoor) by the best serving DAB block is shown.

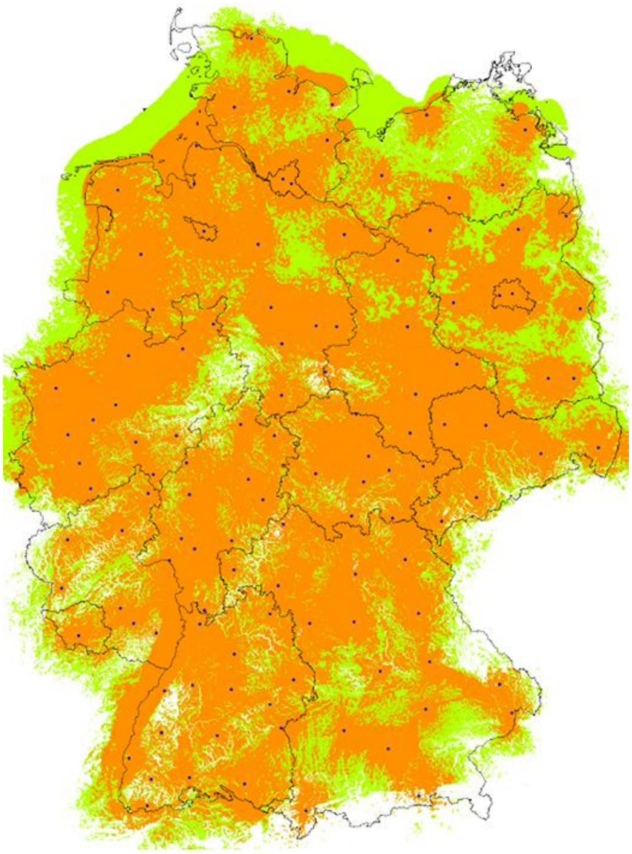


Figure 13: The nationwide network as of beginning of 2018 (120 sites, green mobile coverage, orange portable indoor)

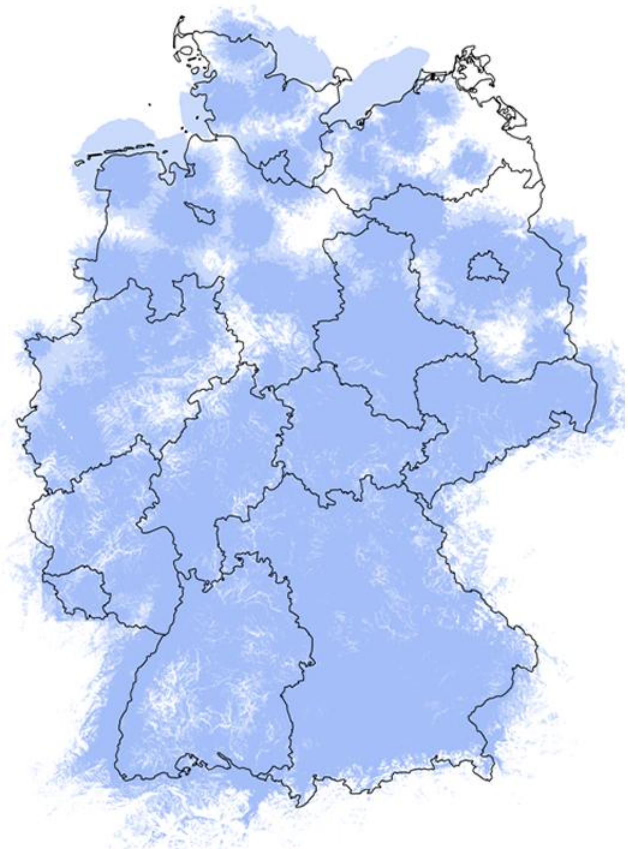


Figure 14: The regional layers as of beginning of 2018 (best serving DAB block presentation, light blue mobile, dark blue indoor)

At the beginning of 2018 coverage by area reached 90% for mobile outdoor and 72% for portable indoor. With this coverage 77% of the population is reached with DAB+ portable indoor by state-wide/regional networks.

Adding coverage by the nationwide network on block 5C, a total of about 90% of the German population can receive at least one DAB+ multiplex indoor.

7.3 Norway

7.3.1 Current situation

On 16th April 2015, the Norwegian government confirmed FM-switch off in 2017. The switchover process started on 11th January 2017 and took place over a 12-month period until 13th December 2017, conducting changes region by region.

Switchover concerned all national radio stations and commercial local radio stations broadcasting in the larger cities. Community-radio and smaller local radio stations continue to broadcast on FM and the licences have been renewed until end of 2021.

7.3.2 Network planning

The current GE06 [ITU_1] for Band III in Norway defined the following layers:

Table 26: Norway regional and national layers*

Type of DAB/DAB+ layer	Number of regions	Current operator	Required pop. coverage for FM-swich-off decision (RPC-5)	Effective pop. coverage as measured (confirmed)	Effective geographic coverage (RPC-4)	Effective road coverage, 4 main road types (RPC-4)
1 regional layer	8 different blocks; 7 different regional content districts	NRK	99.5%	99.8%	89.35%	98.4% (IRT-3D) for RPC-4 (48 dBµV/m) 99.4% for NO-ref. level (42 dBµV/m)
1 national layer	1	Norkring	90%	92.8%	N/A	-
1 local layer	37 (7 currently on-air)	Various	N/A	-	-	-
1 national layer	1	Norkring	N/A	-	-	-

* Note that in Norway a nationwide layer in Band III is reserved for DVB-T (see EBU Tech Fact Sheet Use of Band III).

7.3.3 Planning criteria and comparison with FM

The planning criteria for radio in Norway is based on the GE06 Agreement [ITU_1] for DAB for the frequencies 174 - 230 MHz, on the WI95revCO07 Agreement [EU_4] for the frequencies 230 - 240 MHz, and Stockholm 1961 [ITU_12], rev. Geneva 1984 [ITU_13] for FM. The frequency plan for DAB is using the whole range 174 - 240 MHz, from block 5A to 13F.

The chosen planning configuration for DAB for population coverage is portable indoor reception (RPC-5). The coverage requirement for the public service broadcast NRK was obtained through comparison with the existing coverage of FM stereo for the main NRK channel P1.

Table 27: Norway planning criteria

Planning criteria	RPC 5 (indoor portable)	RPC 4 (mobile)	FM stereo
Location probability	95%	99%	50%
Min. field strength at 10 m	66 dBµV/m	60 dBµV/m	54 dBµV/m
Min. field strength at 1.5 m	54 dBµV/m	48 dBµV/m	-

Even though there was no official requirement for mobile reception, network planning took into account road coverage, corresponding reception levels equivalent to RPC 4 (48 dBµV/m), but even 6 dB lower considering the actual performance of car receivers and antennas. Coverage maps corresponding to 42 dBµV/m are thus available for the public at www.radio.no/dekning.

7.3.4 Network topology

Table 28: Norway transmitter network topology (January 2018)

Network/layer	Number of transmitters	Feeding
Regional layer (required 99.5%)	762	Backbone and satellite
Regional layer (effective; 99.8%)	1020 and counting	Backbone and satellite
National layer (92.8%)	202 and counting	Backbone
Local layer	20 and counting	Backbone
NRK P1 FM (for reference)	(1170)	Backbone, gap fillers, satellite

Some details of design:

- **All the 202 transmitters for the national layer** are co-located with transmitters for the regional layer, preferably at major transmitting sites. Signals come via a backbone network (fibre and radio links).
- The **additional 818 transmitters for the regional layer** (extension from 92.8% to 99.8% coverage) are mainly located at smaller sites rather than high power high tower sites. Signals come through satellite feeds.
- Additional transmitters with small size coverage were launched prior to FM switch-off. Additional small-scale transmitters without guaranteed quality of service were launched as well prior to final FM switch-off. Additional transmitters may come in the future.
- No gap fillers are used in the network.
- Issues of **adjacent channel interference** occurring near regional transmitters affecting reception of the national layer were experienced. This was solved in some cases by lowering the transmitting power of regional transmitters or by relocating them.

Tunnels

Tunnels were provided with DAB coverage prior to FM switch off. All tunnels that previously had FM coverage were equipped with DAB, broadcasting all the channels in the regional and national layers (contrary to FM, where only a few channels had tunnel coverage). In addition, all tunnels longer than 500 m with average traffic per day of over 5000 cars were equipped with DAB; in total 265 tunnels required an upgrade. All tunnels are equipped with bypass communications solutions enabling the authorities to broadcast emergency messages when necessary. The coverage area for DAB is equal to or better than the FM network.

Design of local DAB networks

For local radio in Norway, 37 different SFN areas were assigned that covered Norway’s entire mainland. In 2012 the authorities issued twenty temporary trial licences that lasted up to 31st December 2016. These served the most populated areas and focused on indoor reception as well as the surrounding main roads.

7.3.5 DAB switchover

The switchover plan was a joint collaboration between the public service broadcaster, NRK, and commercial broadcasters.

Table 29: Norway DAB switchover schedule

Region	Broadcaster	Date	Population, 1000s (approx.)	
Nordland	All	11.01.2017	240	= 4.7%
Trøndelag, Møre and Romsdal	NRK	08.02.2017	700	= 13.7%
	P4, Radio Norge, local radio	21.04.2017		
Telemark, Buskerud, Hedmark and Oppland	NRK	26.04.2017	825	= 16.2%
	P4, Radio Norge, local radio	16.06.2017		
Sogn and Fjordane, Hordaland, Rogaland, Agder	NRK	21.06.2017	1365	= 26.8%
	P4, Radio Norge, local radio	15.09.2017		
Østfold, Vestfold, Oslo, Akershus	NRK	20.09.2017	1735	= 34.0%
	P4, Radio Norge, local radio	08.12.2017		
Troms, Finnmark	All	13.12.2017	235	= 4.6%
			5100	100%

The plan involved a successive FM switch-off in six regions and comprised 10 milestones. All the broadcasters had common start (11th January 2017) and common final (13th December 2017) switch-off dates, in the first and last region. In the other regions NRK turned its services off first and commercial and local broadcasters followed 2-3 months later respectively in each region.

When deciding the order of regional switchover, attention was paid to the current FM topology to avoid an early switch-off in a region causing uncontrolled switch-off in neighbouring regions due to the use of repeaters for re-transmission.

Please refer to http://radio.no/2015/04/norway-to-switch-off-fm-in-2017/ for more details about the switch-off plan.

7.3.5.1 Specific considerations and issues

Consideration was given to the following list of specific issues or matters of concern when preparing for the switchover in 2017:

Migration from DAB to DAB+:

In the past few years, the public service broadcaster NRK has launched new services in DAB+ and has started to migrate existing DAB services to DAB+, while keeping the most popular channels in DAB. NRK completed the migration of all its DAB channels to DAB+ on the first switchover date in January 2017.

Automotive solutions for cars:

Most new cars sold in Norway are now factory-fitted with a DAB+ receiver and experience good reception conditions. However new car models do present challenges with sensitivity, mainly due to the replacement of rooftop antenna systems with antennas fitted in other, less favourable locations (windows, bumpers, rear-view mirrors etc.).

A large majority of car owners lacking DAB receivers still have to rely upon an aftermarket solution, such as replacing the original radio, fitting an adapter or a semi-integrated solution. As glass-mount antennas are the primary antenna in aftermarket products, the DAB stakeholders put much effort into benchmarking existing glass mount antennas and other antennas. This activity started in 2014 and was driven by broadcasters and network operators in close cooperation with importers and manufacturers. The aim was to raise awareness of antenna performance and select the best ones, taking into account the accommodation of a minimum field strength of 42 dBμV/m (Rayleigh conditions) as a requirement.

Testing in real conditions was performed with drive tests consisting of listening to end-user equipment while measuring the field strength with a spectrum analyser and a reference antenna. Since the actual reception conditions with glass antennas vary with cars, fitting and antenna diagram, the lowest field strength where stable reception could be achieved in the best conditions was retained as a way of comparing antennas with each other.

This methodology emerged as a key driver for manufacturers to improve their products. In the period 2014 - 2017, differences of up to 20 - 25 dB between the worst and best glass mounted antennas were observed. As a result, as of 2016/2017, the majority of the glass-mount antennas sold in the Norwegian market give good reception down to or below 42 dBµV/m in the best conditions.

Several fitting issues were observed, especially when fitting is done by the customers themselves. Care should be taken when selecting products to ensure they have sufficient RF performance, and clear information about proper fitting, including related pitfalls (polarisation, grounding, metal oxide coating, defrost wires, use of poorly-shielded LED equipment or in-car electronics causing EMC-problems etc.) is essential.

7.4 Switzerland

7.4.1 Current situation

Since its launch with DAB in 1999, Switzerland has been at the forefront of digital radio. With (as of 2017) an outdoor coverage of 99% of the population and an indoor coverage of 98%; a figure that exceeds the geographical coverage of FM, digital radio has, depending on the area, an offering of over 60 stations, with more than three million receivers sold up to 2017.

Since 15th November 2016 all DAB stations were switched to broadcast in DAB+.

In 2015 Switzerland announced its plans for switchover from FM to DAB+ between 2020 and 2024. Based on the recommendations of public, commercial and non-profit broadcasters, the government is now expected to take a decision regarding the FM switch-off date and the proposed roadmap for switchover. Further information is available on www.dabplus.ch.

At regulatory level, a referendum in June 2015 backed the new Radio and TV Act, which allows support for covering up to 80% of the simulcasting costs of the commercial stations and also funds communication initiatives for the digital switchover.

For safety reasons the Swiss road authority will be fitting approximately 300 road tunnels with DAB+ coverage for up to six multiplexes with a voice break-in capability, up until 2019. The system-design is based on the functional and technical reports of the IRT and a proof of concept study performed by the public broadcaster SRG SSR in 2012. The whole rollout will be performed with no costs for public and commercial broadcasters. Again for safety reasons, a standards compliant DAB+ car receiver performance is key. Car and portable radio reselling agencies as well as consumers are informed about the results of the yearly measurement campaign for portable receivers, car receivers and car after market solutions.

This measure clarifies the roadmap for digital radio. In the German- French- Italian and Romansh-speaking parts of the country, public broadcaster SRG SSR now offers nine to sixteen digital-only stations or regional flavours of stations. Today all of the public and commercial FM licensees plus many new services are available in DAB+. In addition to the main DAB+ services, local DAB+ small scale islands of coverage all over Switzerland offer low-cost access to the airwaves to community and ultra-local stations.

The increased penetration and use of digital radio is backed by an agreement between public and commercial broadcasters, in force since March 2015. In Autumn 2017, a study on radio listening habits showed that 57% of all radio listening was digital, with DAB+ and internet equally popular. Digital radio has already overtaken FM at home and at work, with Internet streaming leading at home and DAB+ in the workplace.

The figures for in-car digital radio are likely to increase steadily. By June 2017, almost all new cars sold in Switzerland were equipped with DAB+ tuners as standard in all models. This achievement follows the availability of Traffic Announcement and TPEG services on DAB+ since April 2015 and the official announcement of the Federal Roads Office to equip 300 motorway tunnels with DAB+ by 2019.

Sources and further reading: WorldDAB Global Summary April 2016 [OS_18], EBU-MIS digital radio report [EBU_12].

7.4.2 DAB+ multiplexes

Table 30: List of Swiss DAB+ multiplexes

	ID	Channel	Frequency, MHz	Band	EID
Deutschsprachige Schweiz	SRG D01	12C	227.36	Band III	4001
Deutschsprachige Schweiz	SMC D02	7D	194.064	Band III	4200
Regionalnetz Nordschweiz	SMC D03	7A	188.928	Band III	4201
Regionalnetz Ostschweiz	SMC D03	9B	204.640	Band III	4202
Regionalnetz BE-FR	SMC D03	8B	197.648	Band III	4203
Französischsprachige Schweiz	Romandie Médias SA	10B	211.648	Band III	4241
Französischsprachige Schweiz	SRG F01	12A	223.936	Band III	4041
Italienischsprachige Schweiz	SRG I01	12A	223.936	Band III	4081
Graubünden-Grischun	SRG R01	12D	229.072	Band III	40C1
Regionalnetz VS	SMC D03	11C	220.352	Band III	4204

7.4.3 Digital radio DAB+ coverage planning

The Swiss Digimig working group has set the reference for the comparison to FM coverage at 60 dBµV/m at 1.5 m with stereo quality and 50% location probability. For DAB+ portable indoor a minimum coverage criterion of 61 dBµV/m at 1.5 m was defined. Today an outdoor coverage of 99% with mobile outdoor coverage 48 dBµV/m and an indoor coverage of 98% with portable indoor coverage 61 dBµV/m, both at 1.5 m, are available for the SRG SSR-layer.

To prepare the switchover from FM to DAB+, the criteria for portable indoor coverage may need to be enhanced in urban and suburban areas. This is indicated by feedback from listeners and reports that those areas often need higher allowances for man-made noise and building entry loss. Man-made noise is expected to rise significantly in the future due to digitization of the community. Building entry loss is also expected to raise within the next decade as a result of improved energy efficiency measures. In many cases this enhanced coverage for suburban and urban areas is already there for the public DAB+ multiplex. Enhancing the coverage of urban areas is cost efficient in most of the cases and it is expected that this approach will raise total network costs by only a few percent.

The indoor coverage for rural areas will be pushed over 99.6% for the public multiplexes and up to 98% for the private multiplexes until 2019 when the final stage of the DAB+ network rollout shall be reached for the switch-over.

7.4.3.1 Portable indoor coverage criteria

Urban areas

- Urban population density above 60 persons per 100 x 100 m for living and work-areas
- Minimum field strength 81 dBμV/m (measured at 1.5 m, with omnidirectional antenna, exterior of building)
- Minimum C/N > 12 dB
- Location probability 95%
- This criterion shall be calculated with an accuracy of 100 m. To avoid over-enforcing the coverage in smaller towns with minor areas meeting the urban criteria or for the coverage along the border area of towns, a range of tolerance of up to 200 m or up to three pixels shall be applied. The minimum field strength in this range shall meet 71 dBμV/m.
- Targeted coverage of urban areas: 80% for the public service broadcaster

Suburban areas

- Urban population density above 30 to 59 persons per 100 x 100 m for living and work-areas
- 71 dBμV/m (measured at 1.5 m, with omnidirectional antenna, exterior of buildings)
- Minimum C/N > 12 dB
- Location probability 95%
- This criterion shall be calculated with an accuracy of 100 m. To avoid over-enforcing the coverage in smaller villages with single pixels meeting the suburban criteria, a range of tolerance of up to 300 m or up to fore pixels shall be applied. The minimum field strength in this range shall meet 61 dBμV/m.
- Targeted coverage of suburban areas: 80% for the public service broadcaster

Rural areas

- Rural zones with up to 29 persons per 100 x 100 m for living and work-areas
- 61 dBμV/m (measured at 1.5 m, with omnidirectional antenna, exterior of buildings)
- C/N > 12 dB
- Location probability 95%
- This criterion shall be applied for all regulative obligations
- Targeted coverage 99.6% for SRG, around 98% for commercial multiplexes

Mobile outdoor coverage criteria

- 48 dBμV/m (measured at 1.5 m, with omnidirectional antenna)
- C/N > 12 dB
- Location probability 99%
- Targeted coverage up to 100% for SRG, around 98% for commercial multiplexes
- Remark: almost all new cars sold in Switzerland are line-fitted with a DAB+ receiver. While the majority of line-fitted DAB+ receivers reach a good receiver sensitivity down to 33 dBμV/m in lab conditions, some line-fitted DAB+ receivers as well as aftermarket DAB antennas still have less sensitivity and antenna gain.

Mobile outdoor coverage criteria for tunnels

- 56 dBμV/m typical, 52 dBμV/m minimum (measured at 1.5 m, with omnidirectional antenna, values include allowance for man-made noise and measurement uncertainties)

- C/N > 12 dB
- Location probability 95% (value 95% due to established specification of leaky cables)
- Up to fore multiplexes nominal, up to eight multiplexes maximal
- Voice break-in capability

7.4.3.2 Summary of Swiss digital radio planning parameters

Digital radio planning parameters for rural coverage

Portable Indoor PI 95 1.5 m

Item	**Characteristic**	**Margin**
Reference Receiver (220 MHz, antenna gain -8.1 dBi) E_{min} from “UK tick mark initiative” PL3A Gaussian channel	Table receiver (median of measurements, 2015)	35 dBμV/m
Protection level	EEP-3A	0 dB
Margin for location correction (EBU TR 021)	95%	10.3 dB
Margin for building penetration loss (incl. margin for additional standard deviation)	Light-indoor	9.1 dB
Margin for radio channel model	Rayleigh channel (C/N correction for indoor condition)	5.6 dB
Margin for interference and noise (co-channel, adjacent channel, man-made noise)	Low	1 dB
Total	**Median Field Strength**	**61 dBμV/m**

Digital radio planning parameters for suburban coverage

Portable Indoor PI 95 1.5 m

Item	**Characteristic**	**Margin**
Reference Receiver (220 MHz, antenna gain -8.1 dBi) E_{min} from “UK tick mark initiative” PL3A Gaussian channel	Table receiver (median receiver measurements, 2015)	35 dBμV/m
Protection level	EEP-3A	0 dB
Margin for location correction (EBU TR 021)	95%	10.3 dB
Margin for building penetration loss (incl. margin for additional standard deviation)	Indoor	13.1 dB
Margin for radio channel model	Rayleigh channel (C/N correction for indoor condition)	5.6 dB
Margin for interference and noise (co-channel, adjacent channel, man-made noise)	Normal / medium	7 dB
Total	**Median Field Strength**	**71 dBμV/m**

Digital radio planning parameters for urban coverage

Portable Indoor PI 95 1.5 m

Item	**Characteristic**	**Margin**
Reference Receiver (220 MHz, antenna gain -8.1 dBi) E_{min} from “UK tick mark initiative” PL3A Gaussian channel	Table receiver (median receiver measurements, 2015)	35 dBµV/m
Protection level	EEP-3A	0 dB
Margin for location correction (EBU TR 021)	95%	10.3 dB
Margin for building penetration loss (incl. margin for additional standard deviation)	Deep-indoor	17.1 dB
Margin for radio channel model	Rayleigh channel (C/N correction for indoor condition)	5.6 dB
Margin for interference and noise (co-channel, adjacent channel, man-made noise)	High	13 dB
Total	**Median Field Strength**	**81 dBµV/m**

7.4.3.3 Example for the application of portable indoor criteria

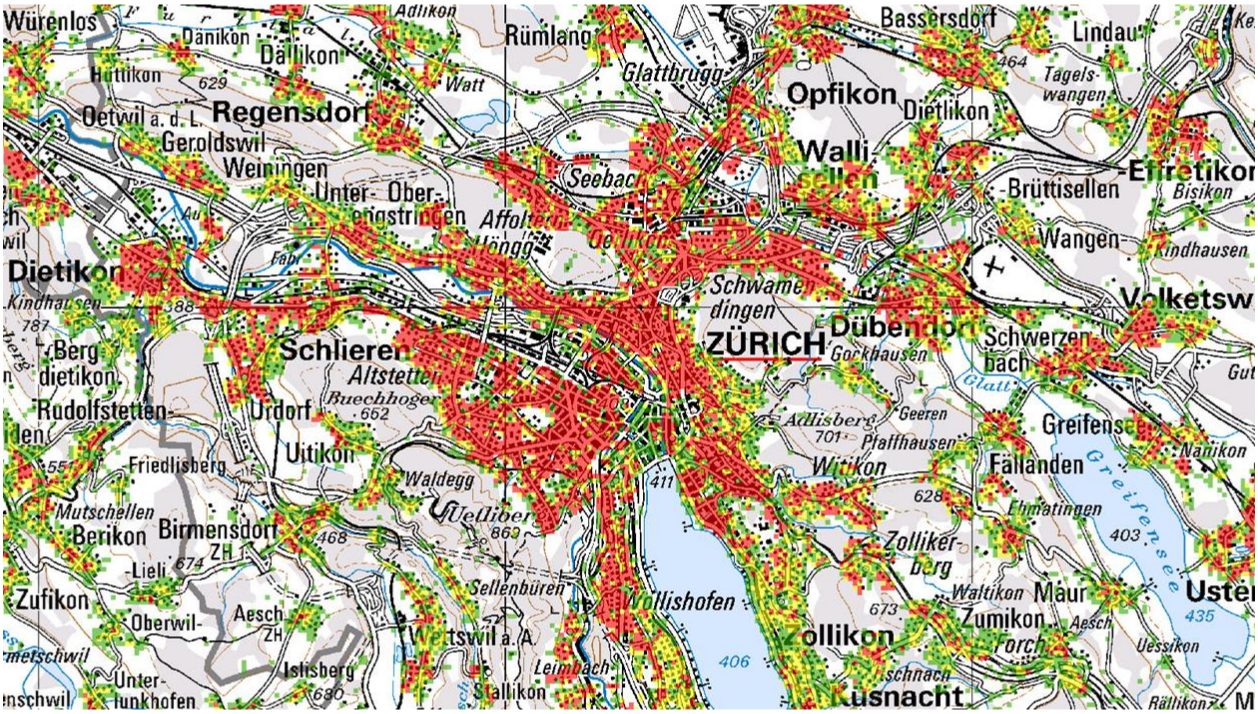


Figure16: Example for the Application of Portable Indoor Criteria urban, suburban, rural

Source: BFS population density layer without working areas (centre of Zurich)

7.5 Italy

7.5.1 Current situation

The first trials of a digital radio service in Italy were made at the end of the nineties by Rai, which started experimental DAB transmissions from a number of stations; these were followed over the years by other operators. Rai Way, on behalf of Rai, set up its first DAB network in 2011.

Currently Rai Way provides the national public radio services with 18 stations broadcasting a DAB+ signal (transmission Mode I) in the VHF band. The network covers more than 40% of the population, especially in the urban areas of the main cities (Rome, Milan, Turin, Bologna, Venice, Naples and

Palermo) and some sections of the main highways.

More than 150 DAB/DAB+ radio stations are also active in Italy among all network operators, providing about 65% of theoretical population coverage (outdoor reception), especially in the Northern part of the country.

An ensemble with both national and regional content is broadcast in Alto Adige and it includes some programmes provided by the RAS (Rundfunk- Anstalt Südtirol), a public radio and television agency for the autonomous province of Bozen.

From the Rai Way station of Paganella, in Trentino, a local ensemble is broadcast that includes programmes of some commercial radios, which are combined in a consortium called Digiloc.

All other stations are managed by local operators, which are generally organized in consortia.

7.5.2 Regulatory aspects

Frequency plan

In May 2012, the national regulator, AGCOM, published the decree *180/12/CONS*, which assigned three blocks in channel 12 (12A, 12B and 12C) for national public and commercial operators and five blocks (12D, 10A, 10B, 10C and 10D) for local radios in the Trentino region; DAB services were officially launched in this region at the end of the same year. The resolution specifies that both national and local networks have to be operated in SFN configuration.

Following the same criteria, in June 2013 and December 2014 AGCOM published the decrees *383/13/CONS* and *602/14/CONS*, which extended regular broadcasting licenses to other regions: Alto Adige, Valle d'Aosta, Umbria and the provinces of Turin and Cuneo in Piedmont.

In July 2015 AGCOM published the decree *465/15/CONS*, that defines the subdivision of the national territory in to 39 different areas, each one composed by one or more provinces and that include regions already taken into account by the previous resolutions. The same decree even included a "Draft frequency plan for digital sound broadcasting" - Annex 2 to the decree - in which are listed the frequency blocks assigned to 8 allotments (named "Bacino" within the document) which correspond to 17 Italian provinces whose inhabitants approximately amount to 13% of national population.

In April 2016 AGCOM published the decree *124/16/CONS* that extended licenses to an additional 8 allotments, which correspond to 21 Italian provinces that are located in the centre and in the south of the country and whose inhabitants approximately amount to 30% of national population.

The Italian draft frequency plan for digital audio broadcasting derived from the above-mentioned decrees is detailed in the following table[30] (Table 31) and the 16 planned allotments are highlighted in green in Figure 17.

[30] Time schedule and conditions of use of frequency blocks in some allotments are still under investigation.

Table 31: Current Italian draft frequency Plan for digital sound terrestrial broadcasting

Allotment Number	Italian Provinces	Frequency Blocks	Network Operator
1	Torino, Cuneo	12A, 12B, 12C	RAI and other national network operators
		10A, 10B, 10C, 10D, 12D	Commercial local network operators
4	Aosta	12A, 12B, 12C	RAI and other national network operators
		12D	Commercial local network operators
8	Trento	12A, 12B, 12C	RAI and other national network operators
		10A, 12D	Commercial local network operators
9	Bolzano	12A, 12B, 12C	RAI and other national network operators
		10B, 10C, 10D	Commercial local network operators
20	Firenze, Arezzo, Pistoia, Prato, Siena	12A, 12B, 12C	RAI and other national network operators
		10B, 11A, 11B, 11C, 11D	Commercial local network operators
22	Roma, Frosinone, Latina, Rieti	12A, 12B, 12C	RAI and other national network operators
		11A, 11B, 11C, 11D	Commercial local network operators
23	Perugia, Terni	12A, 12B, 12C	RAI and other national network operators
		10A, 10C, 10D, 12D	Commercial local network operators
25	L'Aquila	12A, 12B, 12C	RAI and other national network operators
		10C, 10D, 12D	Commercial local network operators
28	Avellino, Benevento	12A, 12B, 12C	RAI and other national network operators
		11A, 11B	Commercial local network operators
29	Napoli, Caserta	12A, 12B, 12C	RAI and other national network operators
		10A, 10B, 10C, 10D	Commercial local network operators
30	Salerno	12A, 12B, 12C	RAI and other national network operators
		11C, 11D	Commercial local network operators
33	Potenza, Matera	12A, 12B, 12C	RAI and other national network operators
		10C, 10D	Commercial local network operators
34	Catanzaro, Cosenza, Crotone	12A, 12B, 12C	RAI and other national network operators
		12D, 11A, 11B	Commercial local network operators
35	Reggio di Calabria, Vibo Valentia, Catania, Messina, Siracusa	12A, 12B, 12C	RAI and other national network operators
		10A, 10B, 10C, 10D, 11D	Commercial local network operators
37	Palermo, Trapani	12A, 12B, 12C*	RAI and other national network operators
		12D*, 11A*, 11B*, 11C*	Commercial local network operators
39	Cagliari, Nuoro, Ogliastra, Carbonia-Iglesias	12A, 12B, 12C	RAI and other national network operators
		10A, 10B, 10C, 12D	Commercial local network operators

* The use of these frequency blocks is subject to international coordination.

Figure 17: Green: allotments included in the draft frequency plan for DAB+. Red: areas not yet planned

It is important to point out that, to date, DAB+ transmitters are even active in areas not yet planned (i.e. in the red areas in Figure 17: the regions of Lombardy, Veneto, etc.), on the basis of specific authorization provisions of the Ministry of Economic Development.

Operators' obligations

In February 2016 AGCOM published the decree 35/16/CONS, which introduces some modifications for the launch of the DAB service in the new areas. It defines a new procedure for the assignment of blocks to local operators and establishes the obligation for national and local commercial broadcasters to achieve 40% of population coverage within the first two years, 60% of population coverage within the first four years and 70% of population coverage within the first five years (*portable outdoor* reception) after receiving the “rights of use” in a specific area.

L-Band

In September 2015 two mobile operators were awarded frequency blocks in L-Band (originally allocated to DAB) for mobile broadband use. Therefore in Italy DAB transmissions are now allowed only in VHF band, according to GE06 Agreement [ITU_1].

7.6 France

Presently, digital radio only operates in Band III. A call for tender for digital radio in the L-Band (1452-1479.5 MHz) was launched in December 2011 and through an auction process Onde Numerique was awarded a licence for the terrestrial segment using SDR - but no services have subsequently been launched.

Two standards, T-DMB and DAB+, are allowed for digital radio broadcasting in Band III on frequency blocks 5A to 11D; VHF channel 12, frequency blocks 12A to 12D are restricted to military use in

France. While T-DMB allows the broadcasting of video content in addition to audio content, DAB+ is the only standard used since digital radio was launched in June 2014,; it has been optimized for audio content (with 12 radio programmes per multiplex) and it is widely used in neighbouring countries. In addition, some receiver manufacturers do not want to integrate T-DMB chipsets into their products due to the increased cost it represents.

The current use of Band III is limited to three areas: Paris, Marseille and Nice-Cannes. It follows a call for tender in April 2012 and the auction of 19 multiplexes in the designated zones in March 2013. Currently, 14 multiplexes are effectively on air (some for a use in an extended zone covering the corresponding area, some for use in an intermediate zone and some for use in a local zone - up to 3 or 4 per area): 6 in Paris, 4 in Marseille and 4 in Nice-Marseille. Several multiplex operators share the market, two of them stemming from network operators: RMUX (founded by TDF) and France Multiplex (founded by VDL and ITAS).

Further multiplexes are authorized to start their transmissions in the area of Lille in April 2018, and new ones will follow in the areas of Strasbourg and Lyon in September 2018. This is the result of a former call for application in early 2017 to develop the local coverage of those new areas. Additional areas (Rouen and Nantes) made a selection of the applicants in January 2018, and a call for applications will be launched for the Bordeaux and Toulouse areas during the first quarter of 2018, resulting in additional new emissions in 2018 and mid 2019.

It is to be noted that with the start of Lille, Lyon and Strasbourg coverage, the officially estimated population covered will reach 20%, hence enforcing the legal obligation to have DAB+ receivers in all new equipment that is sold.

Following a consultation on DAB+ in late 2017, the CSA publicly announced on December 27th 2017 that new multiplexes would be launched in the period 2018 - 2020, firstly with 30 additional zones, the major highways and the roads connecting them. Each zone will be able to benefit from up to 4 layers, starting with local / extended layers to allow a fast and economically viable deployment of DAB+ programmes. A first multi-regional call in mid 2018 for 15 zones was centred on agglomerations of more than 175 000 inhabitants. A second call for the remaining 15 zones will occur one year later, i.e. in mid 2019. Two metropolitan layers will benefit from a separate call for application in mid 2018, after consultation with stakeholders and realization of an impact study. Given the usual 15 months delay in France between a call and the start of corresponding emissions, the first 15 zones will have on-air programmes by late 2019 and the remaining zones by late 2020.

7.7 Denmark

7.7.1 Current situation

On 28th April 2015, there was a political decision to retract a previous decision aimed at *switching off FM in 2019, if by 2018, 50 % of all radio listening is done on a digital platform (Internet, DAB or cable networks)*. Instead it was agreed to follow the development of the digital radio platform and come up with a decision, when digital radio listening reaches 50%. From this date, FM switch off can be done after two years at the earliest. In April 2018, the Danish government proposed to switch off FM radio by 2021, or within two years after digital listening has exceeded 50%, in a move to accelerate the transition to DAB+ digital radio.

Denmark has three national DAB-layers, one of which is owned by the commercial gatekeeper Digital Radio Teracom, one owned by the public broadcaster DR and one that is owned by several local radio associations. Since 1st October 2017 all three multiplexes have been DAB+. The commercial gatekeeper has built a new network with at least 81.3% acceptable[31] indoor geographical coverage, replacing DR's existing network in this multiplex. The coverage of the second multiplex owned by DR has 96.7% acceptable indoor coverage. The third multiplex consists of several individual sites/networks with regional coverage; there is no information for national geographical coverage of this multiplex at present.

An information campaign started in 2017, which will inform the population about the benefits of digital radio and the switch to DAB+. This campaign is scheduled to end in 2019 by which time the remaining DR DAB+ multiplex should have reached coverage comparable to present FM coverage.

7.7.2 DR's DAB-network

DR's national network consists of 66 transmitters, illustrated in Figure 18. For further information as to how coverage is calculated; please see Table 32.

Table 32: Danish DAB+ planning parameters

DAB+	DAB+ (useful)	DAB+ (robust)
Reference documents		
Coverage levels height	1.5 m	1.5 m
- Mobile reception	43	43
- % of locations	99	99
- Indoor reception (suburban)	51.9	56.7
- % of locations	80	95
- Indoor reception (urban)	55.3	60.5
- % of locations	80	95
- Indoor reception (dense urban)	59.3	64.5
- % of locations	80	95
Planning Height		
- coverage	1.5	
- CCI / ACI	1.5	
Planning models		
- coverage	CRC-predict	
- CCI / ACI	ITU-R 1546	
Parameters		
- 1.5 to 10m height allowance	10	
- DAB-DAB CCI PR	13	
- DAB-DAB ACI PR	-35 (1st adj), -40 (2nd adj), -45 (3rd adj)	
- DAB to DVB-T ACI		
- man-made noise allowance	0	
- interference allowance	0	
- Location variation SD - outdoor	4	
- In building entry loss		
- suburban - loss	8	
- suburban - SD	4.4	
- urban - loss	11	
- urban - SD	5	
- dense urban - loss	15	
- dense urban - SD	5	
Signal and antennas		
Rayleigh allowance	3.6	
Car antenna gain	-2.9	
Portable antenna gain	-8.1	

[31] Acceptable coverage is used as a definition for when using a location probability of 80%, robust = 95%.

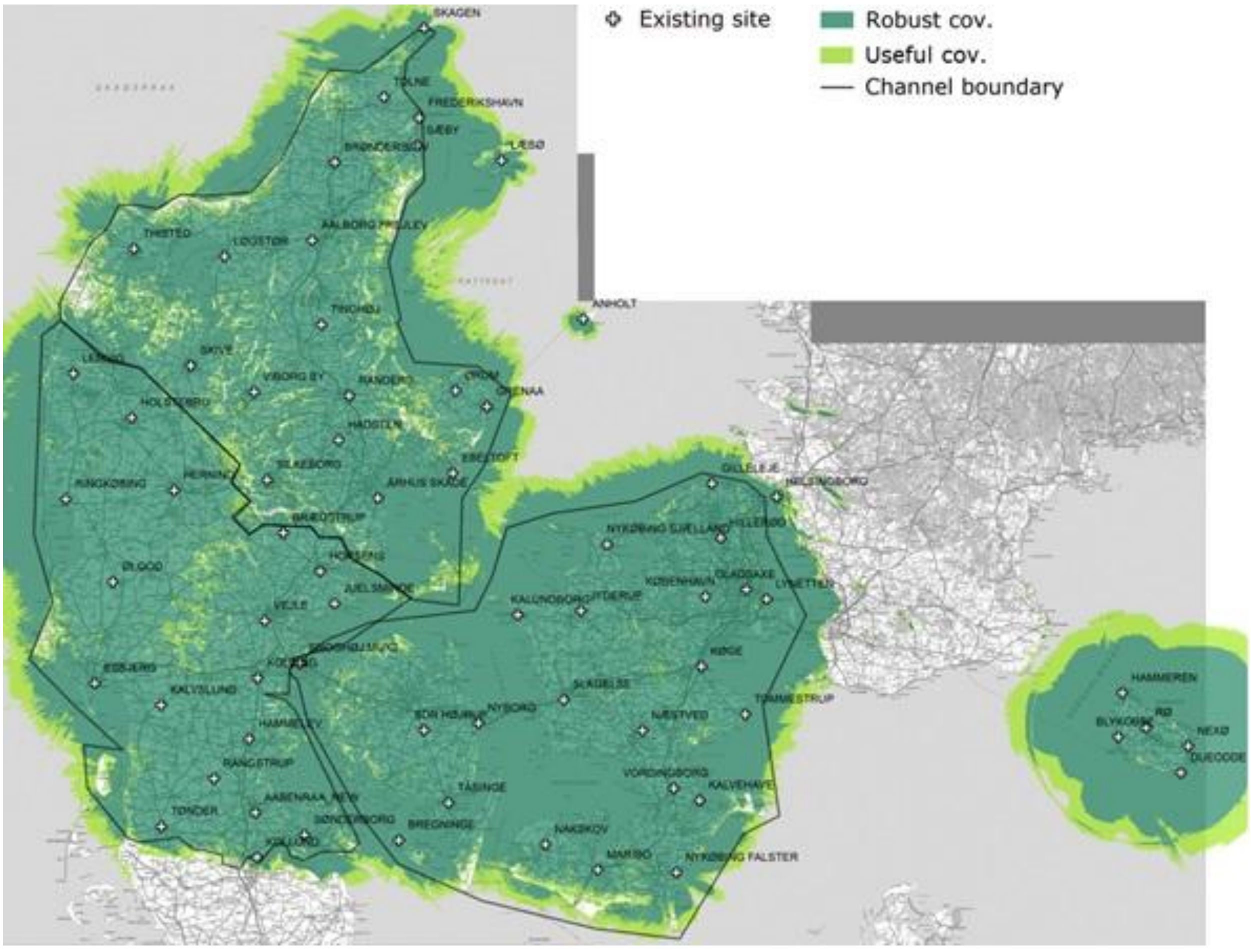


Figure 18: Coverage map for DR's national DAB+ network

7.8 Sweden

DAB transmissions in Sweden started in 1995 and today's coverage is 35% of the population with services from public service broadcaster Swedish Radio (SR). The licence under which SR operates is valid until 31 December 2019. DAB+ trial transmissions have been in operation with both SR and commercial radio since 2010.

In 2013 the Government put forward a bill for the benefits of digitization of the Swedish terrestrial radio network. Government Industry Coordinator Nina Wormbs was appointed to draft a transition plan with the goal to abandon FM in 2022 for the benefit of DAB+. Following this direction the Swedish Broadcasting Authority in October 2014 awarded 21 national and 4 regional DAB+ licenses for commercial radio. The licenses are valid until 30th September 2022.

In December 2014, the Industry Coordinator put forward the FM to DAB+ switchover plan to the Government. However, in June 2015, in light of the responses from the consultation bodies, the Government decided not to proceed with the transition. The Government's conclusion was to not move forward with a transition to DAB+ since such a transition was associated with many uncertainties. The Government said that this decision may be reviewed, depending on the development of digital radio in the rest of Europe - especially in neighbouring Norway. Given this situation the launch of commercial radio has been pushed forward several times. The date when commercial radio should have started regular DAB+ transmission was set to 1st October 2017. The ongoing FM-frequency re-planning and relicensing, followed by an expansion of the commercial FM-networks, has currently stopped the expansion of the DAB networks in Sweden. Swedish Radio has asked the Government for clarification on how and if to proceed with their DAB broadcasts.

7.9 Australia

7.9.1 Overview of radio in Australia

Australian radio broadcasting started in 1923 and has continued to adapt to changes in society and technology by being highly innovative, adaptive and engaged.

The adoption of DAB+ digital radio was seen by Australian commercial, public service and community broadcasters as a way to future proof already successful operations and maintain a robust free to air radio system. In particular the DAB+ standard:

1. Provided access to new Band III spectrum;
2. Was designed to work well in mobile and built environments;
3. Allowed them greater functionality and capacity for new content.

Australia has a diverse range of AM/FM radio stations including commercial, public service and local community stations.

1. 103 commercial radio licence areas - with more than 260 free to air radio services on analogue;
2. Seven government-funded public service broadcasters, 5 services by the Australian Broadcasting Corporation (ABC) include 4 national footprint services and 1 local service in 60 different areas and 2 national services by the Special Broadcasting Service (SBS);
3. 380 community stations - local area or niche format.

In 2017, 95% of Australians listened to radio, and 81% of all radio listeners aged 10+ listening to commercial radio.

7.9.2 Digital radio

Australia was the second market, after Malta, to start permanent DAB+ broadcasts on 6th August 2009. DAB+ coverage of the five major capital (metro) cities of Adelaide, Brisbane, Melbourne, Sydney and Perth is approximately 63% of the national population. The metro transmissions deliver 50 kW ERP (except Brisbane on 23 kW and Sydney on 45 kW) and were the highest powered transmissions on air at that time.

In 2010 additional low power trial services were added in Canberra and Darwin.

In 2017 and 2018 Canberra, Darwin and Hobart DAB+ permanent transmissions were established by the commercial, national and community broadcasters with two ensembles being provided in each city.

Additional regional DAB+ transmissions are now being planned across Australia as shown in Figure 19.

Source: CRA

Figure 19: Australian DAB+ transmission areas in 2018

During 2013 - 2018 fourteen (14) repeaters were added in Sydney, Melbourne, Brisbane and Perth to improve grades of coverage across the cities and fill in black-spot areas on the edge of the licensed coverage area. Additional repeaters will also be established in Canberra, Darwin and Hobart in 2018.

7.9.3 DAB+ adoption in Australia

Adoption has been rapid, as at May 2018:

1. Over 4 million listeners (30%);
2. Over 4 million DAB+ devices have been sold in Australia;
3. More than 300 different DAB+ receiver models are available;
4. Over 1.4 million new vehicles sold with DAB+ since 2011;
5. 42 automotive manufacturers offer DAB+ in vehicles in Australia including Mazda, Toyota, Mercedes, Mitsubishi, Ford and General Motors with over 51% of all new vehicles including DAB+ receivers.

All national and commercial AM and FM services in each DAB+ transmission area are simulcast on DAB+. These are supplemented with digital only services typically on at least a 1 to 1 basis. For example, in Sydney there are 7 national services (5 ABC and 2 SBS), 12 commercial services and 6 wide area community services which are simulcast on DAB+. The national broadcasters have 12 digital only services while the commercial broadcasters provide an additional 19 digital only services and community radio 1 additional digital only service for a total of 57 services.

At the beginning of 2018 there were 49 DAB+ only additional digital stations in Australia, 31 of which are commercial, 14 are national and 4 community.

There are also pop-up and branded stations, which cater to event programming (such as Elf Radio at Christmas) or specific retailer radio services, such as Coles Radio or The Chemist Warehouse radio. Emergency stations are also provided in times of natural disasters, for example 4TAB Flood during the Queensland Floods in 2011.

The Commercial Radio Australia (CRA) Board has now released DAB+ only station listening figures to allow broadcasters to sell inventory to advertisers and agencies. This helps build a business case for private broadcasters to invest in DAB+ as they can now monetise the technology and generate new revenue streams.

Broadcasters are now exploring increasing the time spent listening to their services with the creation of niche or targeted stations, to which listeners can go to after listening to the most popular presenters on the main stations. This encourages new advertisers to come into the radio space to access targeted audiences. Some commercial radio networks are also using brand extension methods to add value to their advertising content. Innovation continues.

7.9.4 DAB+ spectrum

In Australia, VHF Band III (174 MHz – 240 MHz) has television channels 9 and 9A allocated for DAB+, a total of 14 MHz of spectrum carrying 8 DAB channels across Australia on international DAB channel designations 8A to 9D. DAB+ radio is broadcast on DAB channels 9A, 9B and 9C in metropolitan cities.

7.9.5 Listening statistics

Listening statistics are collected by GfK under contract from CRA.

Australian DAB+ listening in the five metro cities was measured at over 4 million people in GfK listening survey 3, 2018[32] corresponding to over 30% of radio listening each week.

7.9.6 New features

All Australian broadcasters deliver Programme Associated Data (PAD) including both Text information (DLS) and SlideShow images (SLS). The PAD is seen as added value to the services delivered providing the listener with more information than just the audio itself. Australian broadcasters continue to innovate and are committed to further increasing the value of their content through new advanced features such as Categorised Slideshow, Interactivity and Hybrid delivery of PAD and Service and Programme Information (SPI). Receivers with these capabilities are currently being developed, including Smartphone products, which will fuel the next generation of connected digital radio.

7.9.7 Next steps

A Digital Radio Planning Committee (DRPC) was established in 2015 as an industry-wide body to support the design and deployment of DAB+ in regional Australia. The DRPC has representatives from the Department of Communications, the Australian Communications and Media Authority, Commercial Radio Australia, the Australian Broadcasting Corporation, the Special Broadcasting Service and the Community Broadcasters Association of Australia and the Australian Competition and Consumer Commission. A Technical Sub-Committee (TSC) was also established to examine the technical aspects of DAB+ planning and make recommendations to the main DRPC in the form of planning principles.

[32] Listening survey results may be found at: www.radioalive.com.au/surveys.

Regional deployment is now focused on completing the regional capital cities of Canberra, Hobart and Darwin in 2017/18 each of which will have one commercial and one national ensemble.

Planning will continue in 2018 and focus on deployments in larger population centres during 2019 - 2020. This is expected to increase coverage in Australia to over 20 licence areas and population coverage in excess of 75%.

7.9.8 Summary

The growth of DAB+ radio listening in Australia has been one of the fastest adoption rates of any newly introduced technology. This is largely due to the strong leadership provided by the broadcasters and particularly by CRA. This includes the innovation of broadcaster owned Joint Venture Companies, strong marketing commitment and strong industry leadership across the entire ecosystem including suppliers, retailers and the automotive sector. This is now being extended to the mobile phone sector to incorporate DAB+ receivers into smartphones.

Progress continues with strong interest from broadcasters in regional Australia to deploy DAB+ before 2020, and further deployments into the 2020s.

8. References

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[OS_8] DAB+ Field Strength Location Variation Standard Deviation Investigation. *CRA, Les Sabel and Wilson NG, September 2016*

[OS_9] Signal in Band III.*OFCOM/BBC/Arqiva. Version 1.0, 30 April 2012* (http://stakeholders.ofcom.org.uk/binaries/broadcast/radio-ops/coverage/Location_Variation_for_TDAB.pdf)

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Annex A: Historical information about DAB transmission modes

Modes I, II and III are the original transmission modes. Mode IV was added in 1997. As of 2017, only Mode I is retained due to the lack of available spectrum for radio above 300 MHz.

Mode I is most suitable for a terrestrial single-frequency-network (SFN) in the VHF range. It has the longest guard interval and it allows the largest distances between transmitters. It can be used for Multiple Frequency Networks (MFN) as well.

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

Mode III was 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 was a mode bridging the gap between Modes I and II. It is also optimized for operation at 1.5 GHz and has 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.

Table A1: DAB Modes

	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	1536	768	384	192
Carrier spacing [kHz]	1	2	4	8
Useful Symbol duration [μs]	1000	500	250	125
Guard interval [μs]	246	123	62	31
Total Symbol Duration [μs]	1246	623	312	156
Max Speed if used in Band III [km/h]	260/390	520/720	Na	Na

Annex B: Types of DAB receivers

B1 Vehicle mounted receiver (MO)

Mobile reception assumes a receiver mounted in a vehicle with an antenna mounted outside the vehicle situated at no less than 1.5 m above ground level. Figure B1 shows the type of receiver inside a car and Annex C includes pictures of the adapted antennas mounted outside the car. The values of the associated antenna gains are provided in § 3.3.1.

Figure B1: DAB receiver mounted inside a car

B2 Stand-alone receiver (PO/PI)

A stand-alone DAB receiver is a table top or kitchen radio with a built-in antenna (folded or telescopic). Figure B2 shows a stand-alone receiver with a built-in antenna (telescopic). The values of the associated antenna gains are provided in § 3.3.2.

Figure B2: Stand-alone portable receiver with a built-in (telescopic) antenna

B3 Stand-alone handheld receiver

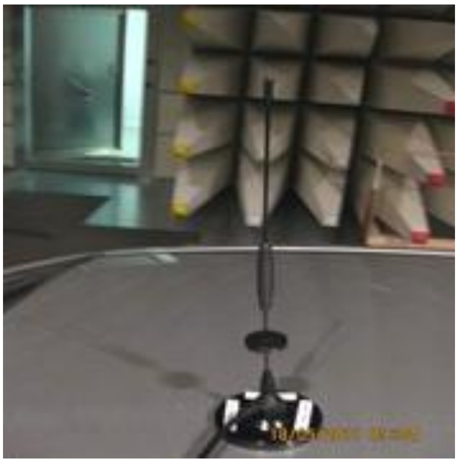
As defined in § 3.1.4, a stand-alone handheld DAB receiver is a '*personal wireless device, normally of a very small size, similar to that of a mobile phone or PDA (Personal Digital Assistant), with the capability of receiving audiovisual streams and data services, often with facilities for bidirectional voice/data communication*'. Figure B3 shows two stand-alone handheld receivers with an external antenna (wired headset and telescopic). The values of the associated antenna gains are provided in § 3.3.3.

Figure B3: Stand-alone handheld receivers with an external antenna (wired headset, on the left and telescopic, on the right)

Annex C: Car antenna patterns

C1 Ideal antenna

This type of antenna is a quarter wave monopole mounted near the roof centre, or with at least ¼ wavelength of ground plane (metallic roof) in all directions. The pattern is approximately omnidirectional in azimuth and the gain is typically -2 dBi [C1].



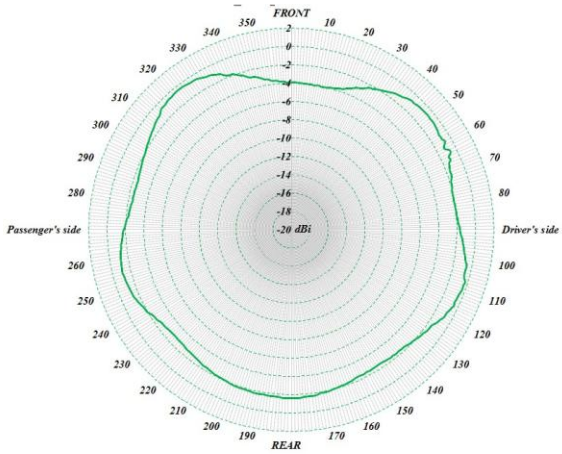


Figure C1: 'Ideal' Quarter wave monopole on car roof

C2 ¼ wave slant whip

This type of antenna is slanted, typically at around 30 degree from vertical and can be a good solution with performance near that of the ideal antenna above. It does however suffer from deep notches in the horizontal antenna pattern if placed close to the roof edge [C1].

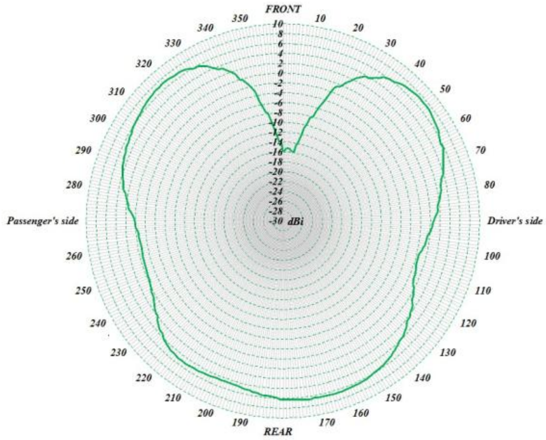


Figure C2: Quarter wave slant whip on car roof

C3 Shark's fin antenna

This type of antenna is aesthetically pleasing and a reasonable omnidirectional pattern but it has a low gain of approximately -8 dBi (-10.2 dBd) [C1].

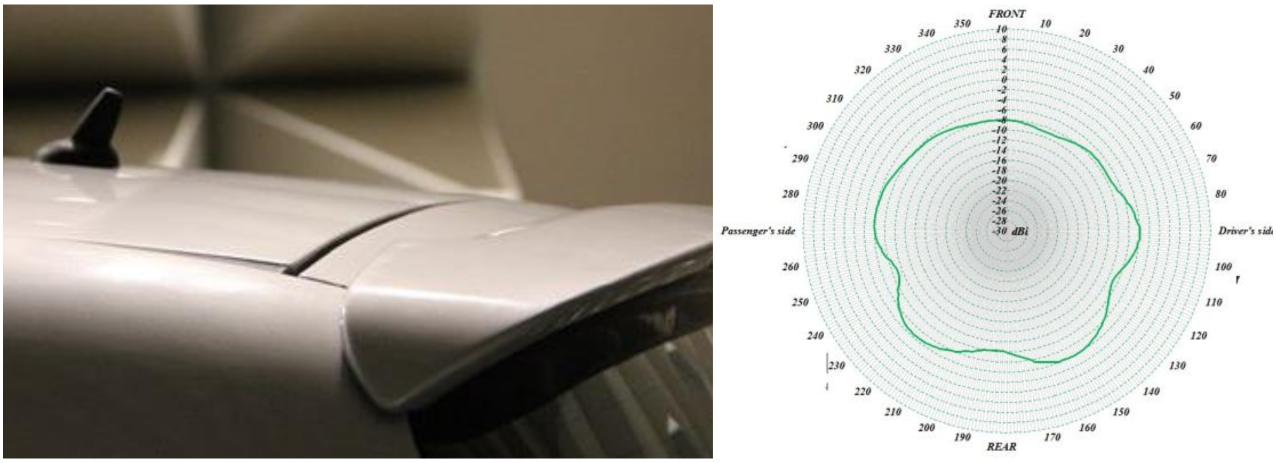


Figure C3: Shark's fin antenna on car roof

C4 In-glass antenna

In-glass antennas are usually placed on side and rear windows and consequently usually have notches in the horizontal antenna pattern. They also usually have low gain.

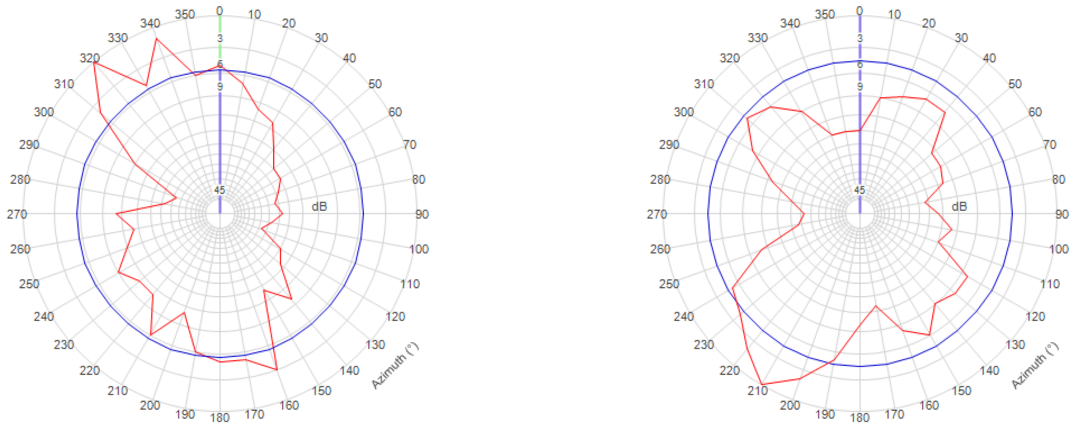


Figure C3: Typical in-glass antenna patterns

C5 References

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Annex D: Height loss calculations from recommendation ITU-RP.1546

The following text is an extract from Recommendation ITU-R P-1546-5 'Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 3 000 MHz' [ITU_4].

Some worked example calculations are also provided.

D1 Text from Annex 5 of Recommendation ITU-R P.1546

§ 4.3 Negative values of transmitting/base antenna height, h_1

$$J(v) = \left[6.9 + 20 \times log\left(\sqrt{(v-0.1)^2+1}+v-0.1\right)\right] \; for\; v > -0.7806 \qquad (12a)$$

$$J(v) = 0 \qquad otherwise \qquad (12b)$$

§9 Correction for receiving/mobile antenna height

The field-strength values given by the land curves and associated tabulations in this Recommendation are for a reference receiving/mobile antenna at a height equal to the greater of the representative of the height of the ground cover surrounding the receiving/mobile antenna, R_2, and 10 m.

Examples of reference heights are 20 m for an urban area, 30 m for a dense urban area and 10 m for a suburban area. For sea paths the notional value of R_2 is 10 m.

Where the receiving/mobile antenna is on land account should first be taken of the elevation angle of the arriving ray by calculating a modified representative clutter height R_2' , given by:

$$R_2' = (1000dR_2 - 15h_1)/(1000d - 15) \quad m \qquad \textbf{(27)}$$

where h_1 and R_2 are in units of metres, and horizontal distance d in km. The representative clutter height R_2' is calculated in such way, that it represents the reference point of height for a receiver which is situated 15 m behind the clutter encountering grazing incidence of the ray from the transmitter.

Note: Height R_2' adjusts the clutter height at the receive location by a very small amount and will be discounted from the examples below.

When the receiving/mobile antenna is in an urban environment the correction is then given by:

$$Correction = 6.03 - J(v) \quad dB \qquad for\; h_2 < R_2' \qquad \textbf{(28a)}$$

$$= K_{h_2} log(h_2/R_2') \quad dB \qquad for\; h_2 \geq R_2' \qquad \textbf{(28b)}$$

where J(ν) is given by equation (12a)

and:

$$v = K_{nu}\sqrt{h_{dif2}\theta_{clut2}} \qquad \textbf{(28c)}$$

$$h_{dif2} = R_2' - h_2 \quad m \qquad \textbf{(28d)}$$

$$\theta_{clut2} = arctan(h_{dif2}/27)$$ *degrees* ***(28e)***

$$K_{h2} = 3.2 + 6.2log(f)$$ ***(28f)***

$$K_{nu} = 0.0108\sqrt{f}$$ ***(28g)***

f: *frequency (MHz)*

Where the receiving/mobile antenna is on land in a rural or open environment the correction is given by equation (28b) for all values of h_2 with R_2' set to 10 m.

The above complete correction for receiver/mobile antenna height can be summarized by the flowchart given in Figure 27.

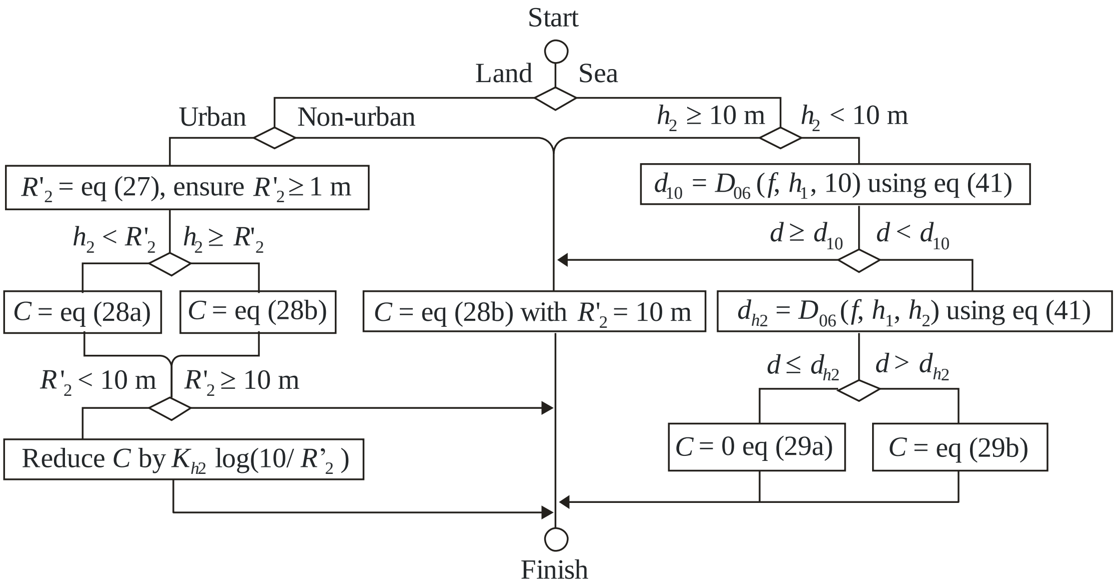


Figure 27: Flowchart for receiver/mobile antenna height correction

D2 Example calculations

Rural

For Rural locations (Land, Non-Urban) the Correction is calculated by equation 28b with R_2' = 10 m and h_2 = 1.5 m

i.e.

K_{h2} log(1.5 m/10 m) = K_{h2} x (-0.824)

For 200 MHz K_{h2} would be 17.46 and the Correction becomes -14.39 dB

UK Suburban (clutter height 9 m)

h_2 = 1.5 m

Assume worst case of the modified representative clutter height, so that R_2' = clutter height of 9 m

K_{nu} = 0.1527 for 200 MHz

θ_{clut2} = 13.5 or 15.5

Therefore v = 1.43 or 1.64 from equation 28c

K_{h2} = -1.08

J(v) = 16.4 or 17.46 from equation 12a

From equation 28a the Correction = 6.03 - 17.46 = -11.4 dB for Suburban at 200 MHz for 9 m

UK Urban (clutter height 18 m)

h_2 = 1.5 m

Assume worst case of the modified representative clutter height, so that R_2’ = clutter height of 18 m

K_{nu} = 0.1527 for 200 MHz

θ_{clut2} = 31.4

Therefore v = 3.477 from equation 28c

K_{h2} = -1.08

J(v) = 23.66 from equation 12a

From equation 28a the Correction = 6.03 - 23.66 = -17.6 dB for Urban at 200 MHz

UK Dense Urban (clutter height 27 m)

h_2 = 1.5 m

Assume worst case of the modified representative clutter height, so that R_2’ = clutter height of 27 m

K_{nu} = 0.1527 for 200 MHz

θ_{clut2} = 43.36

Therefore v = 5.077 from equation 28c

K_{h2} = -1.08

J(v) = 26.94 from equation 12a

From equation 28a the Correction = 6.03 - 26.94 = -20.9 dB for Dense Urban at 200 MHz

Austria Dense Urban (clutter height 30 m)

h_2 = 1.5 m

Assume worst case of the modified representative clutter height, so that R_2’ = clutter height of 30 m

K_{nu} = 0.1527 for 200 MHz

θ_{clut2} = 46.54

Therefore v = 5.56 from equation 28c

J(v) = 27.7 from equation 12a

From equation 28a the Correction = 6.03 - 27.73 = -21.7 dB for Dense Urban at 200 MHz

As height R_2’ is reduced the height loss decreases, so if R_2’ was calculated as 29.9 m then the height loss correction for Dense Urban at 200 MHz would reduce from 21.7 to 21.67 dB

Austria Low Urban and Suburban (clutter height 10 m)

h_2 = 1.5 m

Assume worst case of the modified representative clutter height, so that R_2’ = clutter height of 10 m

θ_{clut2} = 17.47

K_{nu} = 0.1527 for 200 MHz

Or 0.108 for 100 MHz

Therefore v = 1.86 from equation 28c

J(v) = 18.46 from equation 12a

From equation 28a the Correction = 6.03 - 18.46 = -12.43 dB for Suburban at 200 MHz

As height R_2’ is reduced the height loss decreases, so if R_2’ was calculated as 9.9 m then the height loss correction for Suburban would reduce from 12.43 to 12.34 dB

D3 Conclusion

The calculated height losses using Recommendation ITU-R P.1546-5 for 200 MHz give results that can be used for carrying out planning exercises. However the simplified equation (28b) for Rural cases produces a height loss that is greater than Suburban and would likely be overly pessimistic when planning a network. This may be due to compensating for the ground reflection component which would likely not be considered in a planning tool.

Annex E: Measurement in Stockholm of attenuation for VHF signals in building outer wall

(This Annex has been adapted from a PowerPoint presentation)

E1 Measurements

The first set of measurements was predominantly made in blocks of flats in the centre of Stockholm. The second set of measurements was carried out in town houses and detached houses.

Figure E1: Stockholm measurement locations

E2 Measurements - definitions

BWL - Building Wall Loss

The difference in field strength one metre outside the building and inside the building.

BWL for wall X (front, side, back), $BWL = F_{XOut} - F_{XIn}$

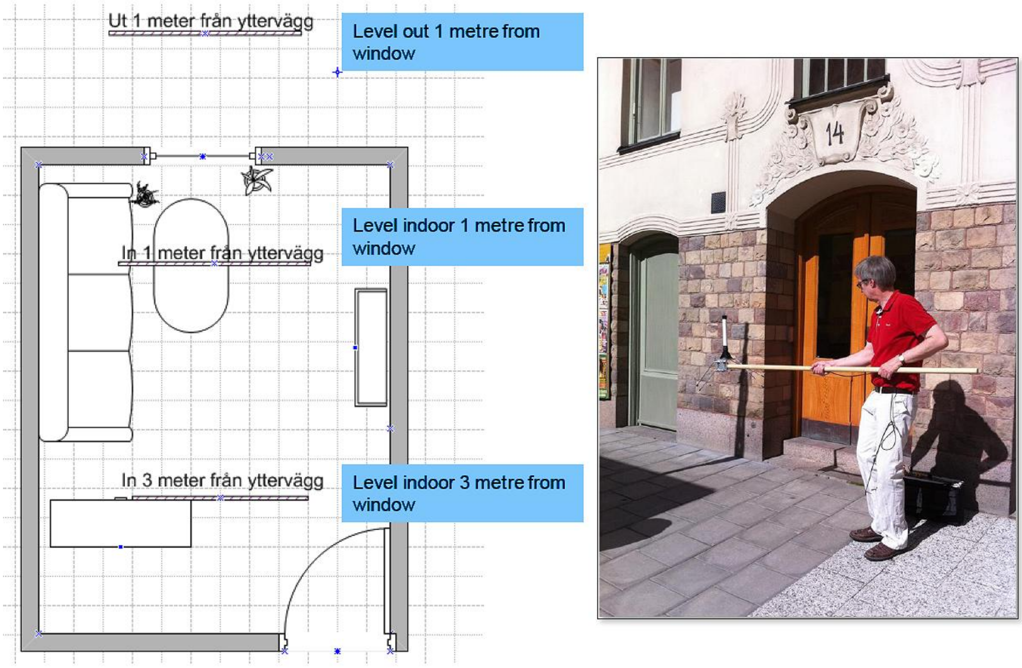


Figure E2: BWL3 = average level 1 m outside - average level 3 m inside

BEL - Building Entry Loss

The difference between the highest measured field strength outside by the house wall and the lowest measured field strength 1 m from a window, indoors.

$$BEL = MAX\ (F_{FO}, F_{BO}, F_{SO}) - MIN\ (F_{FI}, F_{BI}, F_{SI})$$

BAL – Building Additional Loss

The difference between the mean field strength measured at a road close to the house (F_{MOB}) and the lowest measured field strength 1 m from a window, indoors.

$$BAL = MEAN\ (F_{MOB}) - MIN\ (F_{FI}, F_{BI}, F_{SI}, F_{FO}, F_{BO}, F_{SO})$$

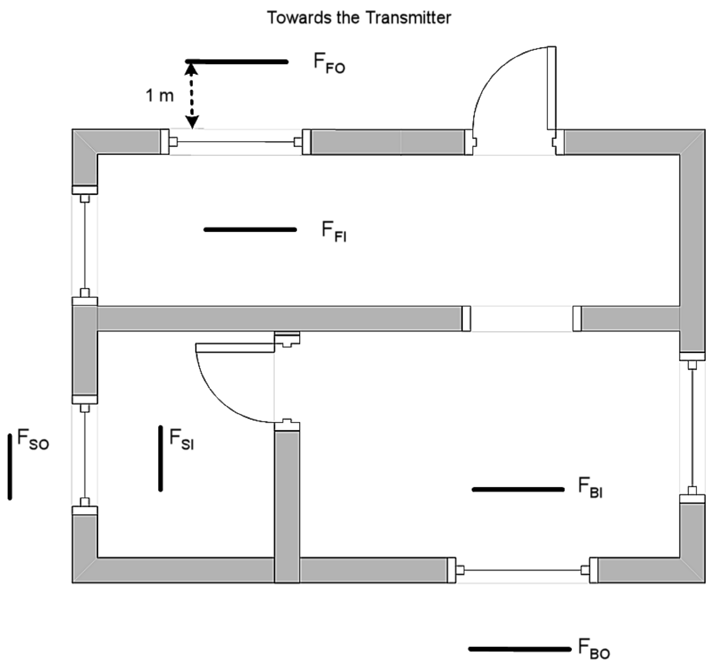


Figure E3: Field strength measurement points inside and outside a building

E3 Measurement of BWL in Stockholm blocks of flats

The first measurement, done predominantly in blocks of flats in central Stockholm involved the calculation of BWL.

Figure E4: Measurement of BWL in block of flats (set 1)

E3.1 Measurement sites in central Stockholm

First measurements were taken at a total of twenty-two sites in central Stockholm.

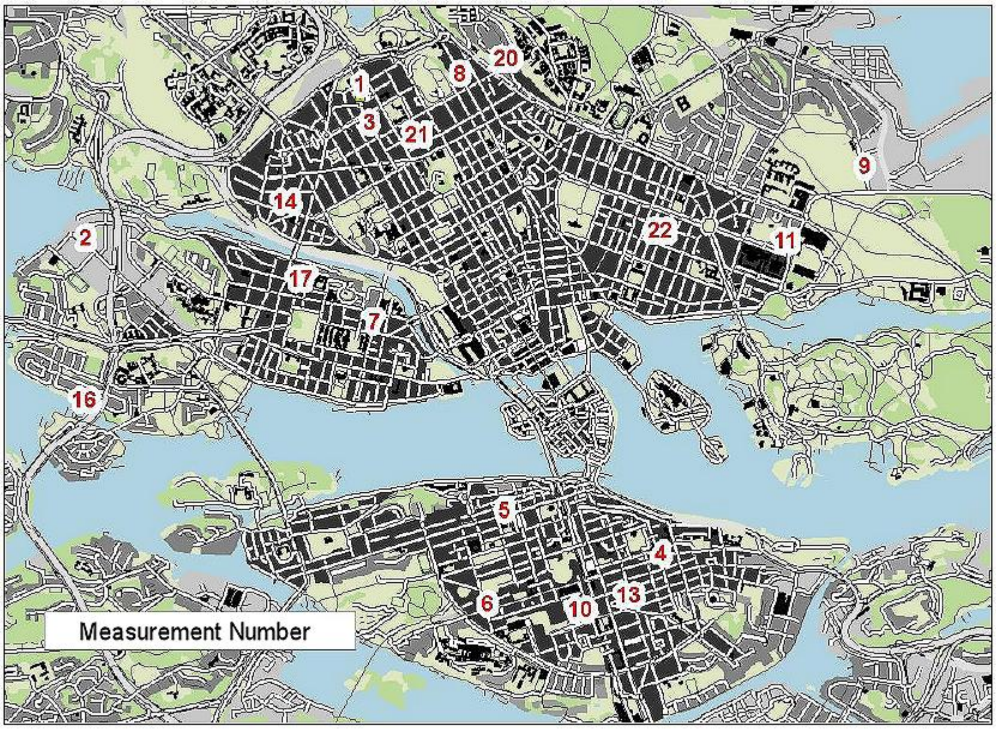


Figure E5: Stockholm measurement sites 1 – 22 (set 1)

E3.2 Site 1 transmitter direction and floorplan of flat

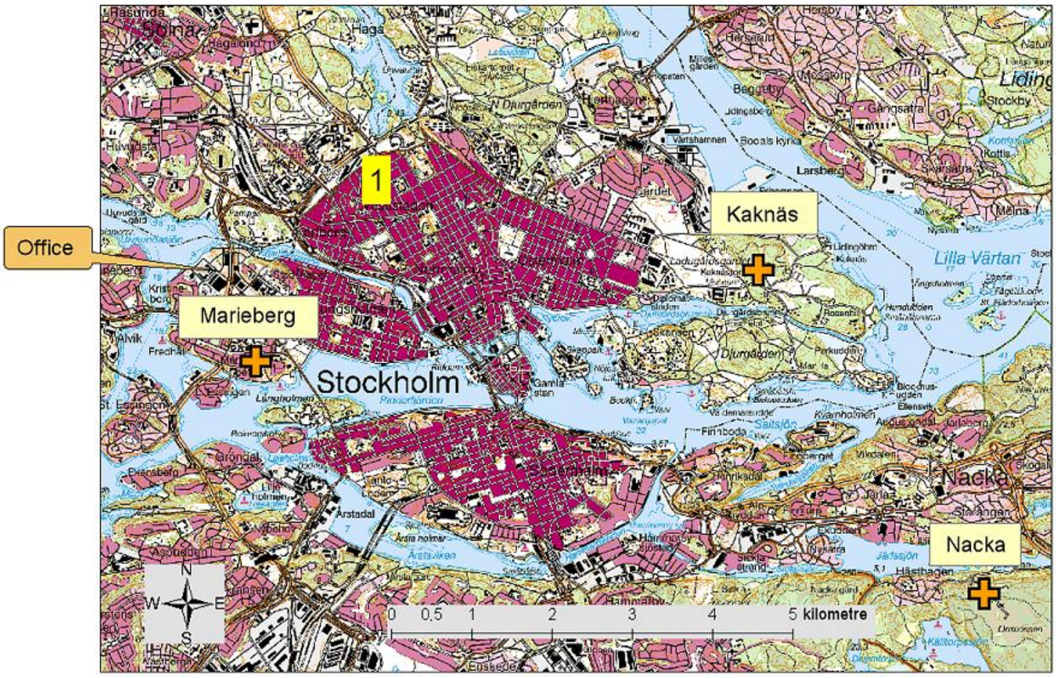


Figure E6: DAB transmitters in the Stockholm area and measurement site 1 (Teracom office)

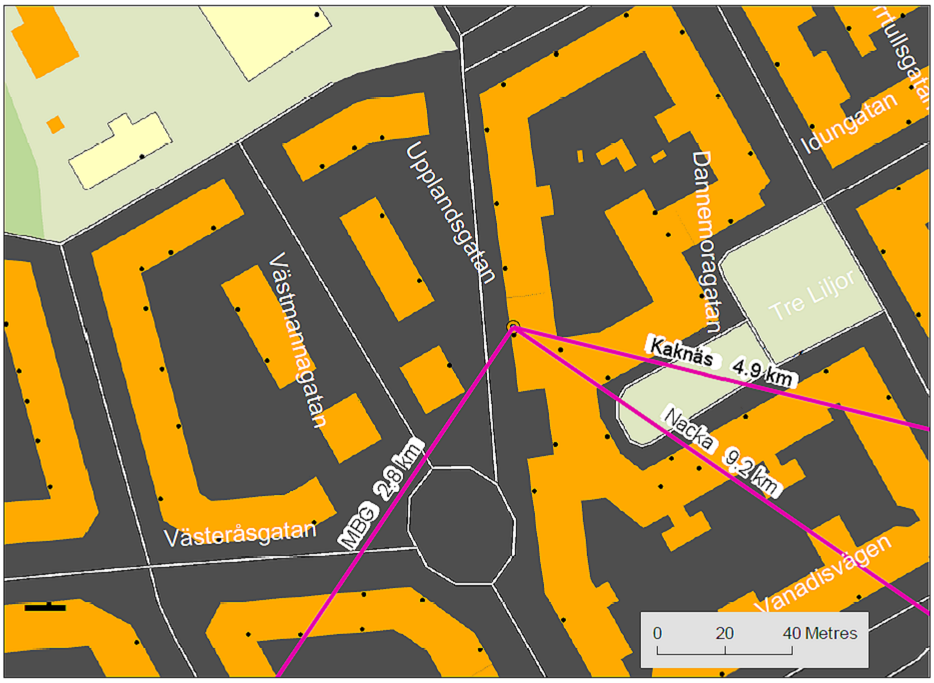


Figure E7: Direction to transmitters from site 1

Room	12B dBµV/m	STD dB	12D dBµV/m	STD dB	Δ (12D - 12B) dB
"MOA" 1 m	57		62		4.8
"KÖK" 1 m	59		62		3.5
"SOV" 1 m	62		62		0.7
"VARD" 1 m	63	3.1	61	2.5	-2.0

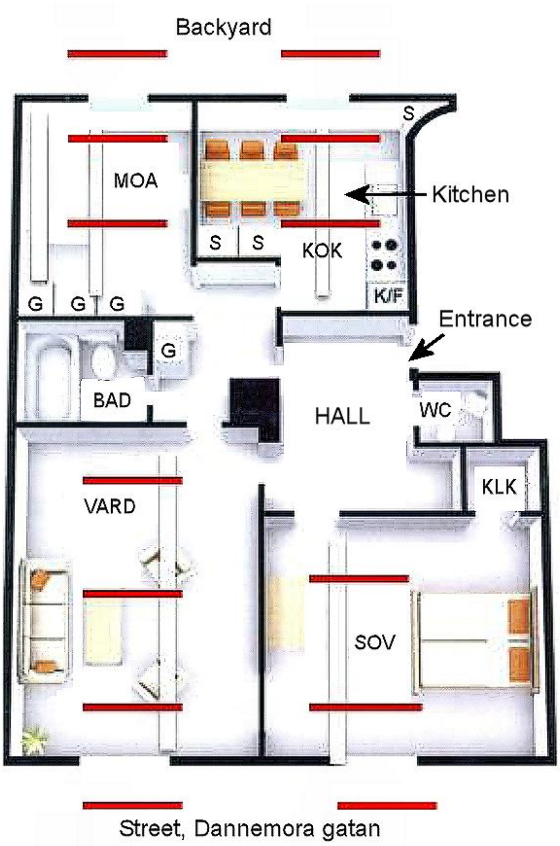
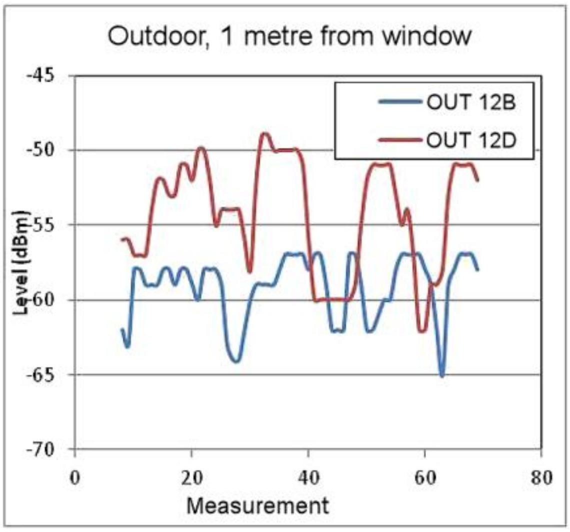


Figure E8: Floorplan of flat (site 1)

E3.3 Site 1 BWL measurement, kitchen



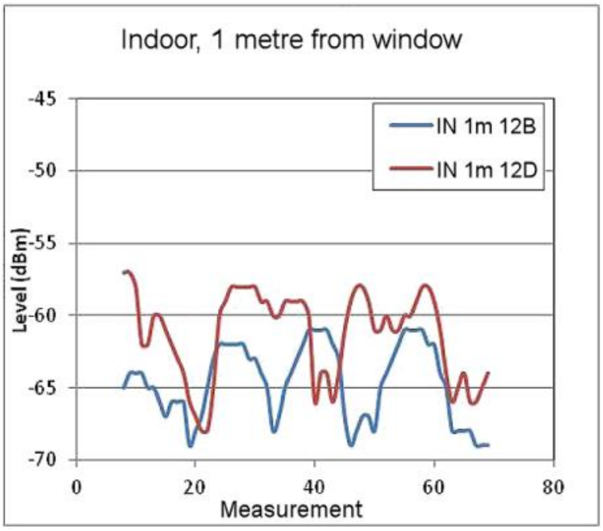


Figure E9: Indoor and outdoor signal measurements of channels 12B and 12D

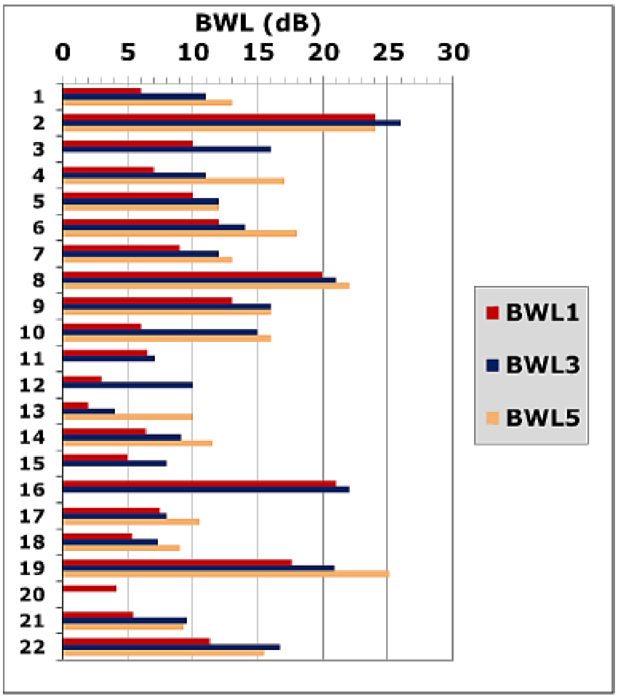
BWL1 (12B) = 5.5 dB	BWL1 (12D) = 7.1 dB	Average BWL, kitchen = 6.3 dB

E3.4 Site 1 BWL measurement for flat

Room	BWL1 (dB)	BWL3 (dB)
“MOA”	7.6	10.3
“KÖK”	6.3	9.8
“SOV”	6.1	11.0
“VARD”	5.3	11.2
Average	**6.3**	**10.6**

E3.5 Measured BWL for the 22 measurement sites

Figure E10: chart showing BWL for 22 Stockholm sites (set 1)



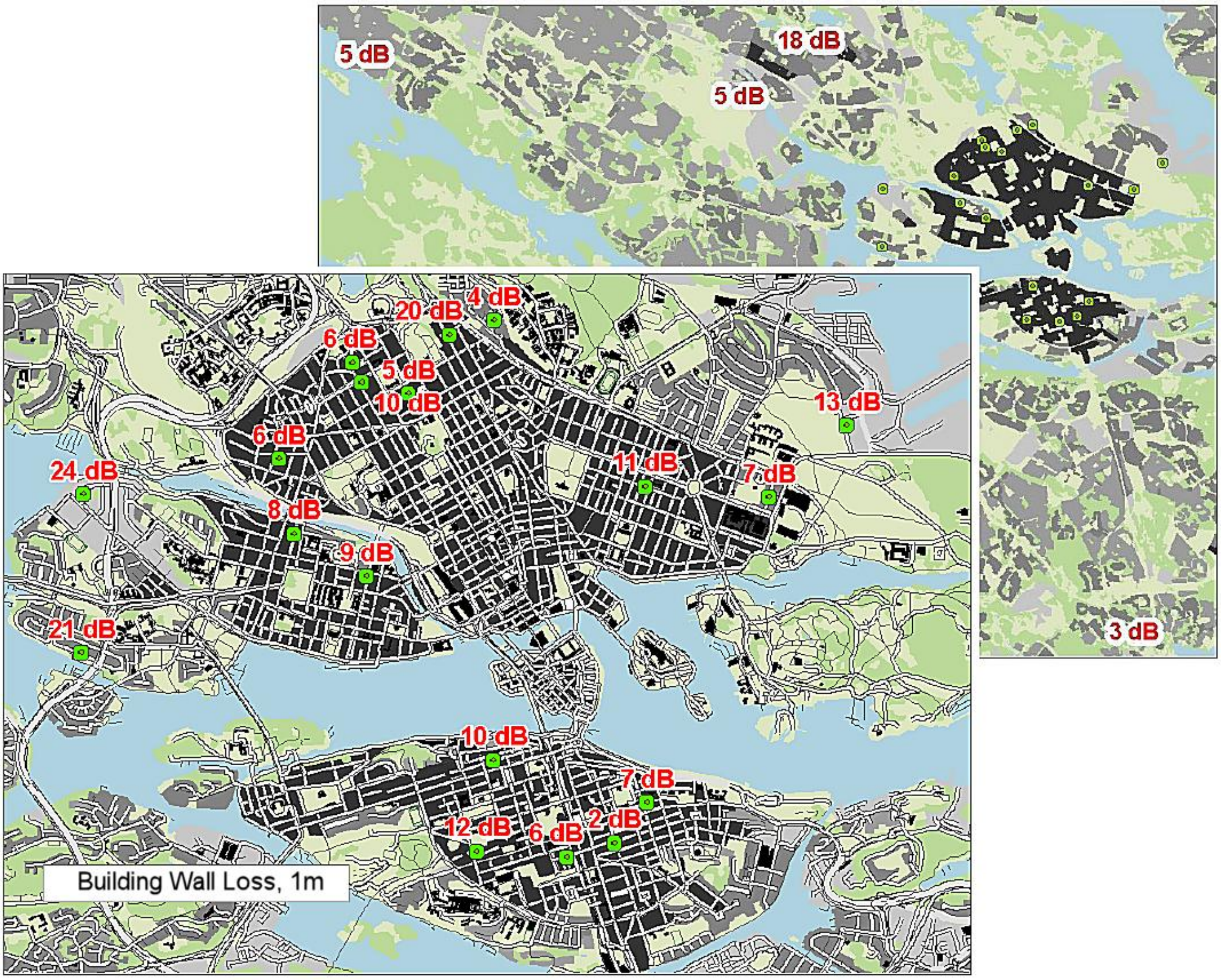


Figure E11: Map showing BWL1 for 22 Stockholm sites (set 1)

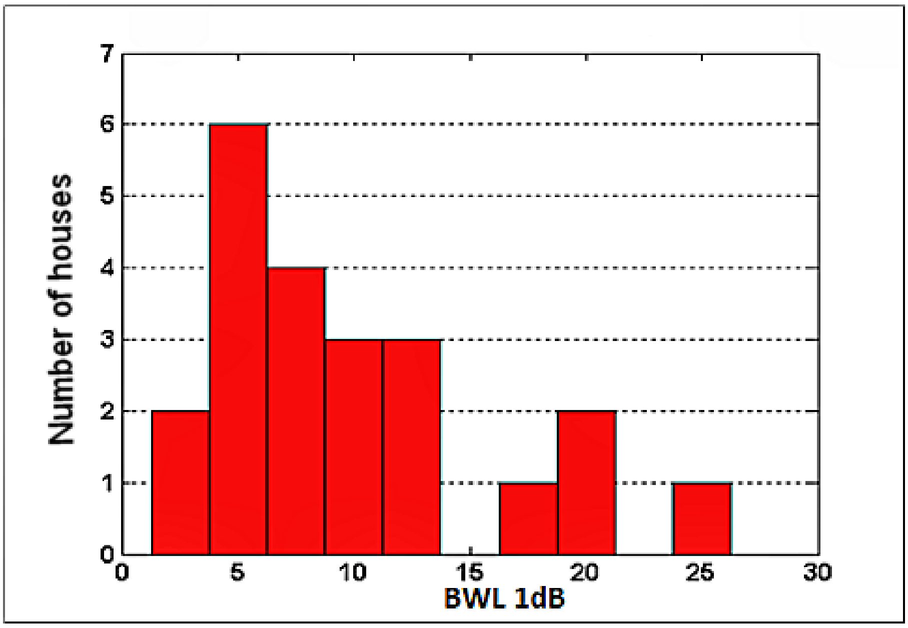


Figure E12: BWL1 distribution amongst 22 sites (set 1)

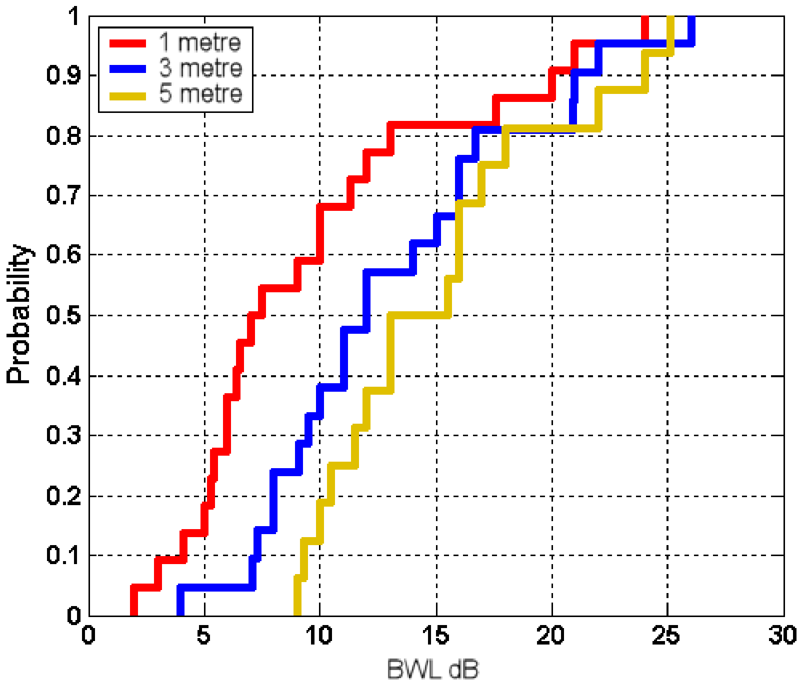


Figure E13: Cumulative distribution of building loss for DAB (set 1)

E3.6 Conclusions on BWL

- The measured Building Wall Losses (BWL) has a very large spread.
- The internal field strength, one metre from a window, is 2 – 24 dB lower compared to outside the building.
- The internal field strength, three metres from a window, is 4 – 26 dB lower compared to outside the building.
- The large spread in BWL makes the use of a single average value unfeasible for coverage calculations.
- The statistical distribution of the BWL between different houses seems not to have a Gaussian distribution

E4 Measurement in Stockholm of detached and town houses

The second set of tests was made in town houses and detached houses in the Stockholm area.

Figure E14: Stockholm measurement locations (set 2)

E4.1 Example (measurement 1)

Freq. = 229 MHz	Direction	FS OUT	FS IN	BWL
Living room (downstairs)	Against Nacka	82	81	1
Bedroom	Against Nacka	85	77	8
Kitchen	From Nacka	68	77	-9
Car		75		
BEL (dB)	8			
BAL (dB)	7			

Figure E15: Example measurement of BEL and BAL (set 2)

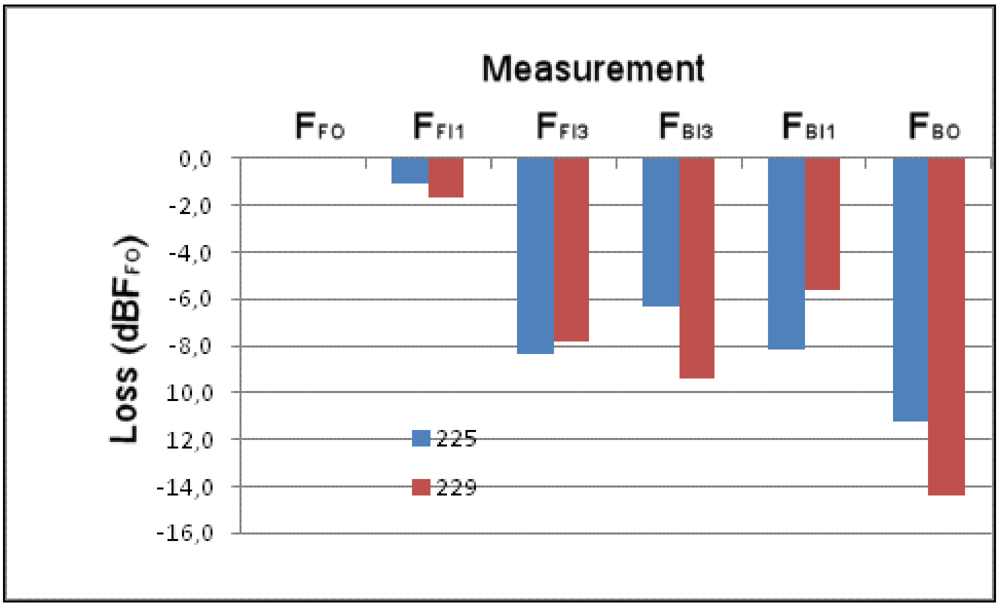


Figure E16: BWL for 225 MHz and 229 MHz (set 2)

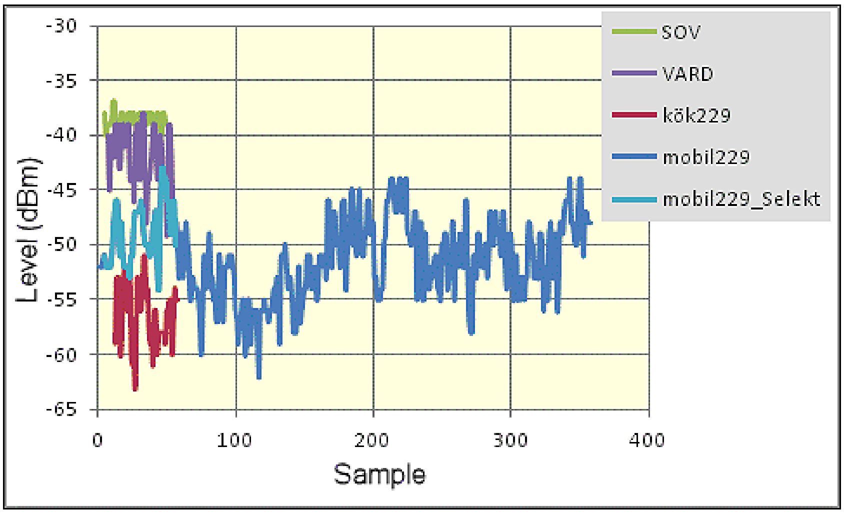


Figure E17: Levels measured in various rooms and car (set 2)

	Material	BWL1	BWL2	BWL3	BEL	BAL
1	Wood + (Brick)	1	8	-6	11	7
2	Wood with pitch facade	4	-4		5	11
3	Wood	11	6	12	14	19
4	Lekablock, polished	26	22	15	27	29
5	Wood	2	-1	2	5	NM
6	Wood	7	8		15	NM
7	Concrete	3	11		14	13
8	Wood	6	0	-4	8	5
9	Wood + Brick	1	2		8	12
10	Tin facade	12	9	-2	15	14
11	Wood	4	1		5	11
12	Concrete tile, triple glazing	4	9		9	9
13	Brick	1	5		5	5
14	Brick	7	-3		8	5
15	Wood	6	-2		7	5
16	Wood	4	11	2	14	10
17	Wood	-3	2		9	11
18	Wood	5	6		11	8
19	Brick	7	-2		11	NM
20	Blue concrete	6	-2		6	7
21	Wood + gold plating (?)	3	2		4	7
22	Wood	9	0		9	6
23	Wood	4	2		7	9

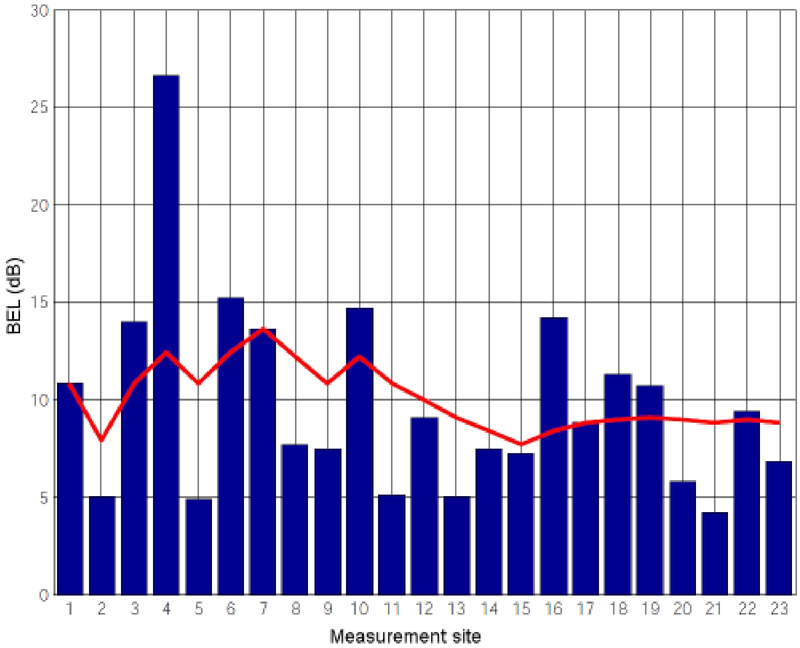


Figure E18:BEL measurements with average (red line)

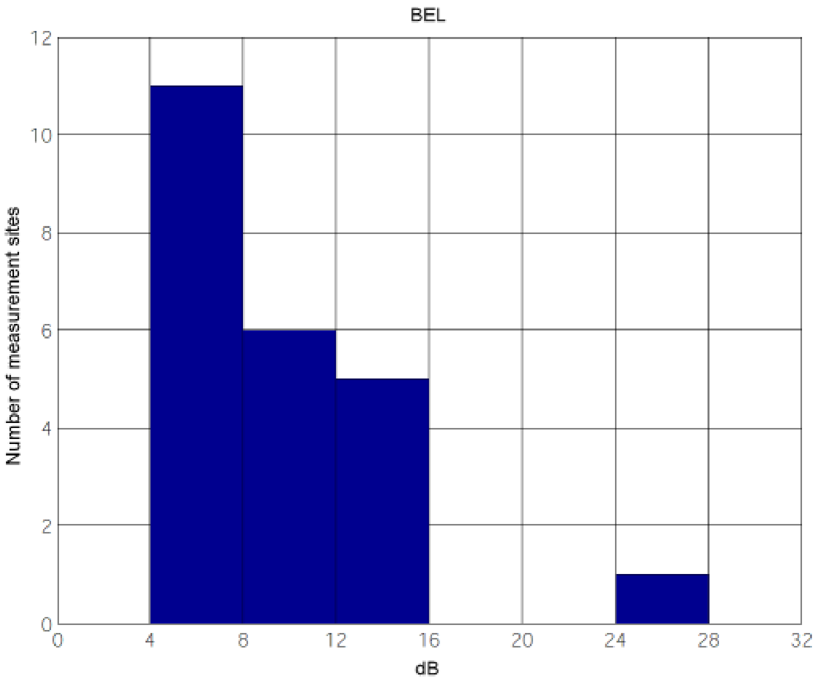


Figure E19: BEL

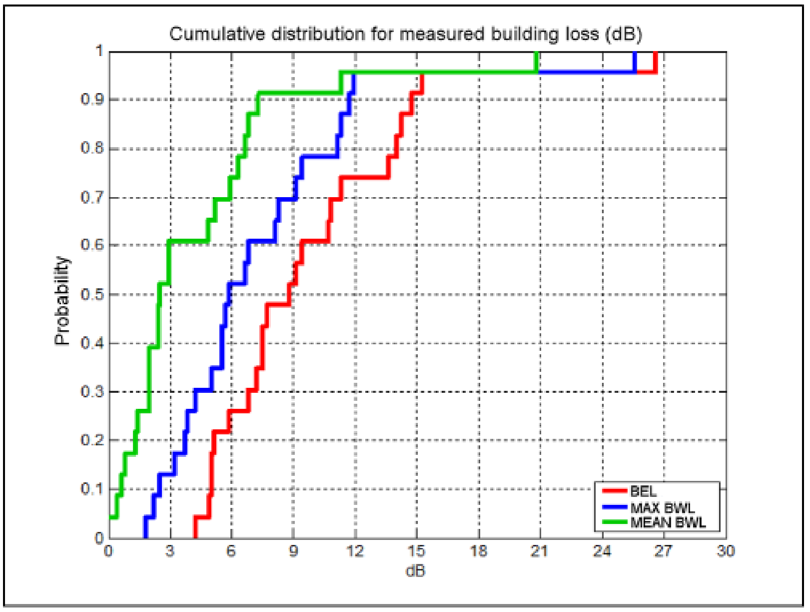


Figure E20: Results from 23 town houses and detached houses

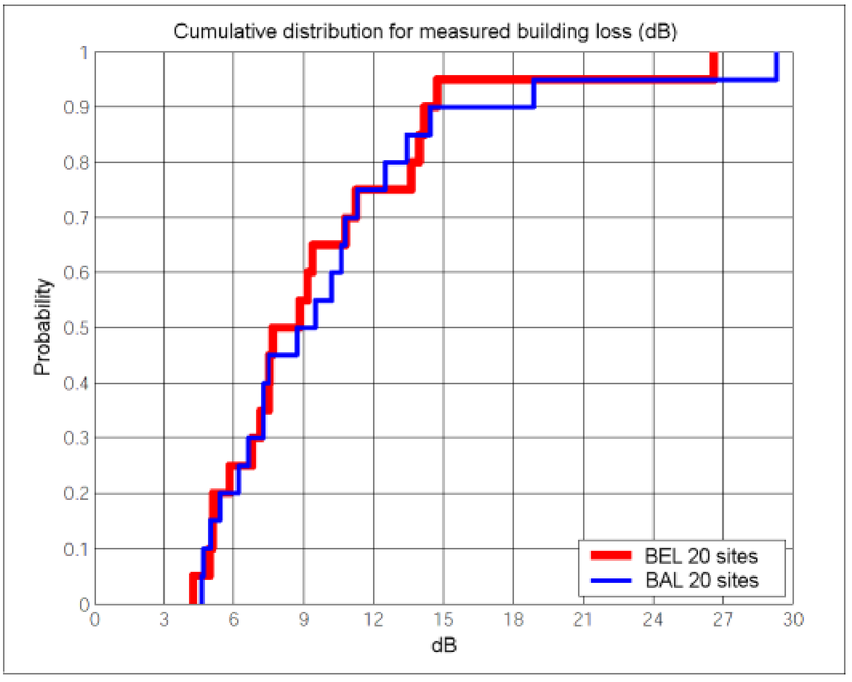


Figure E21: Comparison between BEL and BAL

E4.2 Conclusions

- Your prediction model and coverage aim indoor must be considered when deciding which loss figure you should use.
- BEL looks like being a good value to use if you use a prediction model for 1.5 m calibrated with mobile measurements - at least for detached houses and town houses.

Annex F: DAB+ field strength location variation standard deviation investigation

F1 Introduction

The Location Variation Standard Deviation (LV SD) parameter is used in the determination of the field strength value required to provide a specified percentage of locations.

The LV is considered to be a log-normal distribution, i.e. a normal distribution of logarithmic values. The larger the SD of that distribution the higher the median field strength must be to ensure a specified percentage of locations will exceed the target value.

A LV SD value of 5.5 dB is currently used in many planning documents, e.g. [F2] - [F4] and in several countries including Australia [F1] for DAB coverage and interference planning. Studies of other investigations, e.g. [F6] and field measurements undertaken by Commercial Radio Australia (CRA) have shown that the currently used value of LV SD appears to be high.

This Annex provides the details and results of an investigation undertaken by CRA into the observed value of LV SD.

F2 Field testing overview

The field testing was conducted in the Brisbane area in 2015 and focused on three areas around Brisbane metropolitan area.

The field testing was undertaken in standard family car using a RadioScape Field Monitor (FMON). The FMON was set to sample the received field strength every 25 ms. The signal was received using a (approximately) quarter wave monopole antenna located in the centre of the vehicle roof at approximately 1.5 m a.g.l..

The measurements were made along a number of predefined routes as well as some additional ‘random’ investigations based on listening experience during the trials themselves.

The LV SD analysis of the data collected focused on a number of typical clutter types in the areas around Brisbane

1. Ipswich
    a. Focused on suburban housing areas. These are typically single storey and a limited number of two storey dwellings on moderate land holdings, typically around 15 x 50 m. The area also has a reasonable cover of trees

    b. Field strength was moderate, typically 50 - 60 dBµV/m

    c. Ipswich 2 data set is over 41 km, Ipswich 4 is over 52 km

2. Nambour
    a. The Nambour track covered a number of rural areas with some mountainous sections with forest as well as rural open and rural towns

    b. Field strength was low, typically 30-60 dBµV/m

    c. Nambour data set is over 112 km

3. Gold Coast
    a. The Gold Coast highway provides a snapshot of road performance where the typical width of the highway was around 100 m with multiple overpasses, field strengths from good to low, typically 70 to 40 dBµV/m

    b. The rural area in the north of the Gold Coast region is flat and open with mainly sugar cane covering, this is a low field strength area with typically 40-55 dBµV/m

    c. Gold Coast suburban areas are also fringe coverage with variable field strengths of <40 to 55 dBµV/m

    d. Gold Coast highway data set is over 27 km, rural over 43 km and suburban over 6 km.

Figure F1: Field test vehicle

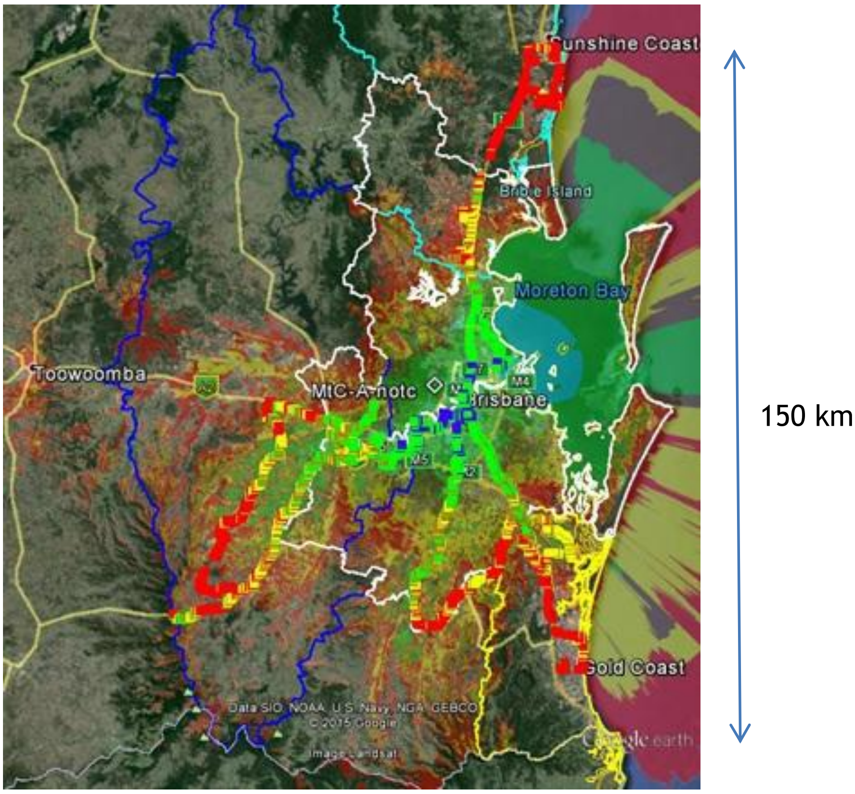


Figure F2: Coverage prediction after tuning with measurement overlay

>=dBu/OAA	Label
40	poor vehicle
50	vehicle
57	suburban
63	urban
83	dense urban

Figure F3: Coverage Field Strength palette

F3 Analysis and results

F3.1 Analysis method

The analysis was undertaken using the following procedure:

1. The received field strengths are logged against GPS position every 25 ms

2. The received data is filtered to remove stationary points (i.e. less than 3 km/h)

3. The resulting dataset is then decimated to ensure that all data points are independent. This requires the points to be at least 0.8 wavelengths apart. As the source signal was on frequency block 9B, the wavelength is 1.47 m.

4. The decimated data was then filtered using the Lee Criteria [F5] where all data points within ±25 wavelengths are averaged; the average value was then used instead of the central data point of the averaged data window.

5. The decimated and Lee filtered data was then segmented into pixels and the SD and mean of the received signal field strength for each pixel is determined for pixel sizes of 10, 20, 50, 100, 200, 500 and 1000 m.

6. Finally the SD values for each pixel size were averaged.

The Lee filtering procedure described above was used to remove the impact of fast fading as experienced in Rayleigh channels. The link budget used to calculate the minimum median field strength target already makes allowance for such fading channels by increasing the required minimum C/N from 7.4 dB for a Gaussian channel to 13 dB for a Rayleigh channel, an allowance of 5.6 dB.

F3.2 Data sets

The drive tracks are shown below for each data set.

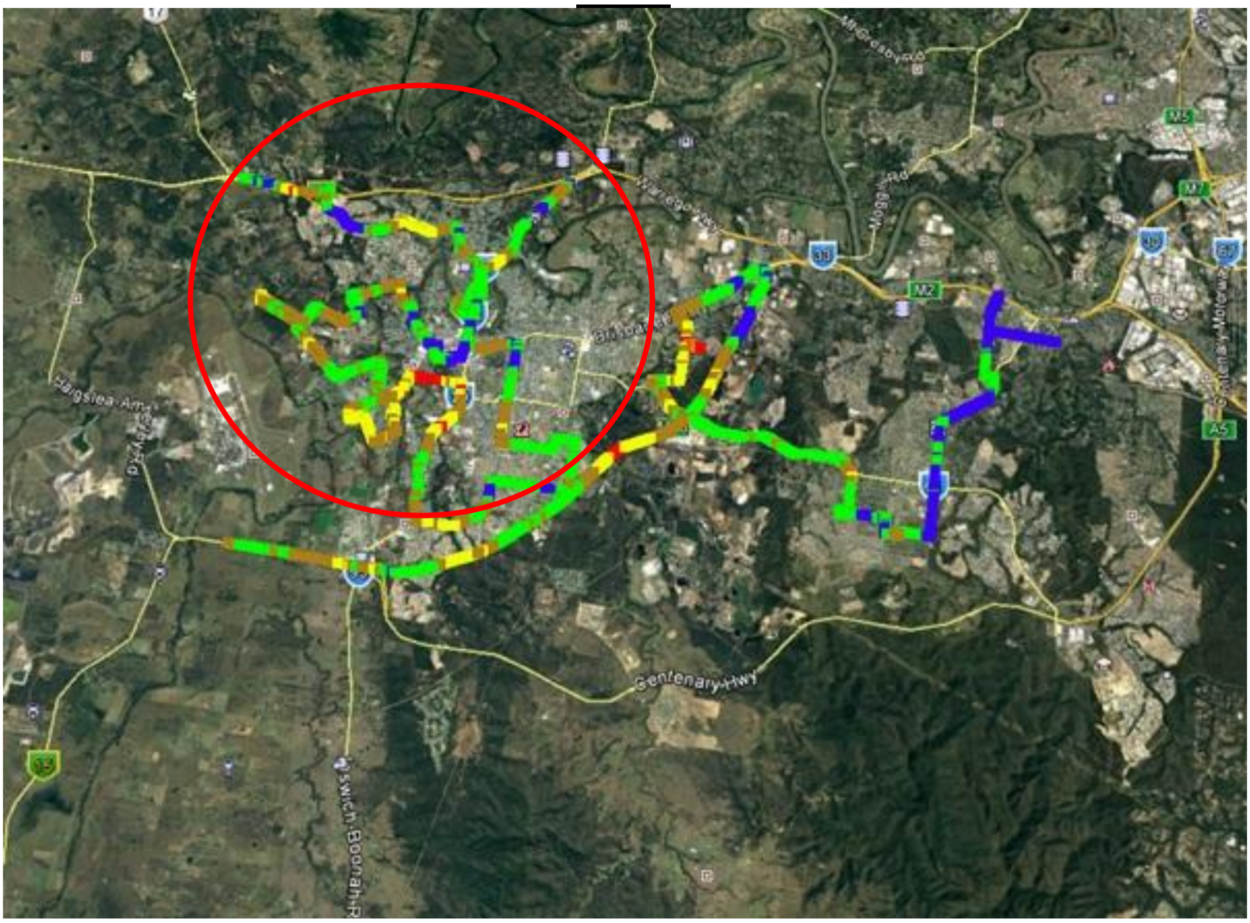


Figure F3: Ipswich area studied (red outline is Ipswich 4 dataset, the rest is Ipswich 2)

Figure F4: Gold Coast highway

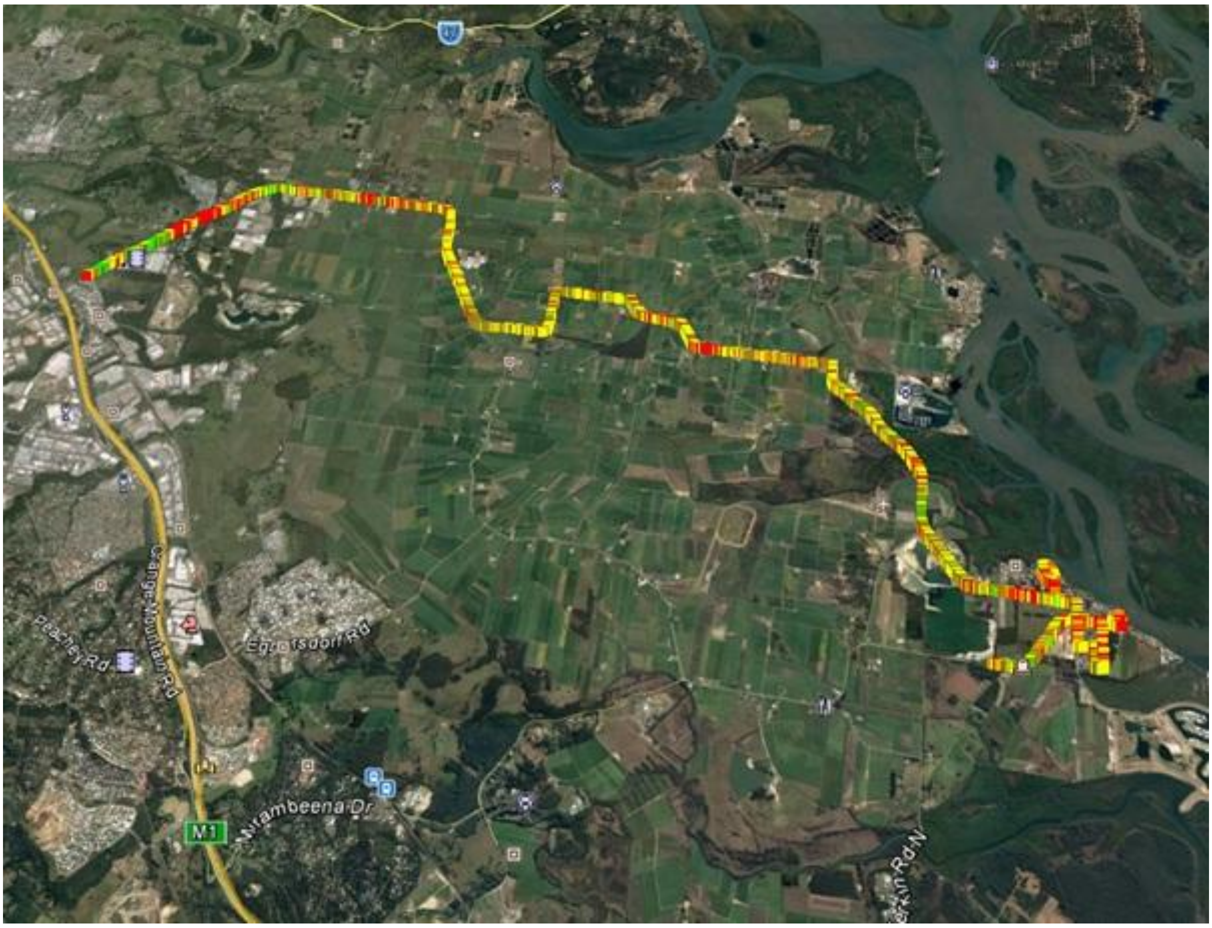


Figure F5: Gold Coast rural

Figure F6: Gold Coast suburban

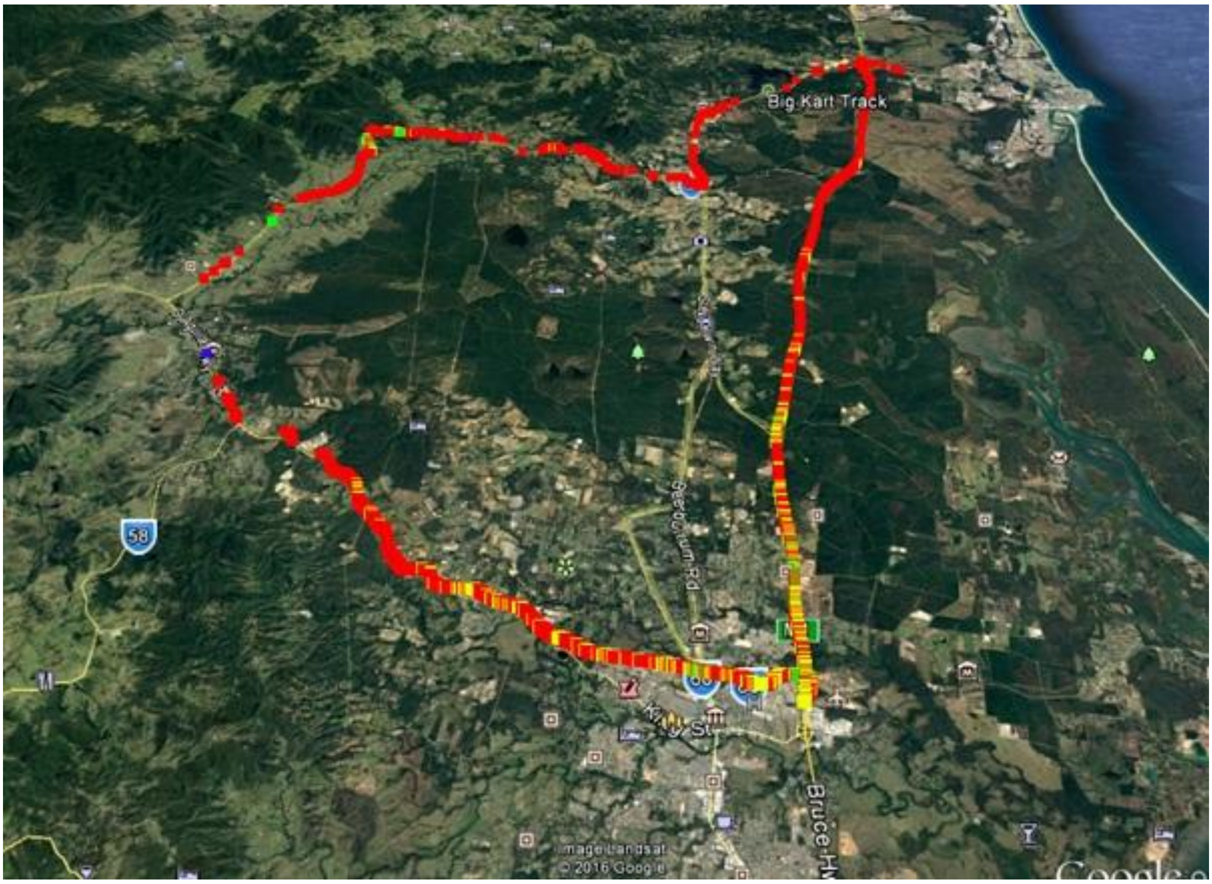


Figure F7: Nambour rural

F3.3 Results

The results for the Lee filtered data, when the data sets are decimated to ensure that the samples used are always greater than 0.8 wavelengths apart, are shown in Figure F8. The mean value of the SD calculated for each pixel size is shown for the different areas. The results show that the suburban areas in Ipswich and the Gold Coast have a higher SD than those for more open environments such as the highway and rural areas.

In Figure F9 we show the pdf (probability density function) of the SD values for the Ipswich 4 data set. The figure shows that as the pixel size increases so does the mean value of the distribution and its spread. The pdf plot is shown in steps of 1 dB where the point at, say, 1.5 dB represents all SD values that fell in the range between 1 and 2 dB.

The corresponding cdf (cumulative distribution function) graph is shown in Figure F10. If we wish to be 95% confident that our LV SD value will not result in a pessimistic target field strength then for pixel size of 20 m the corresponding LV SD value is less than 1 dB, for 100 m pixels it is 2.2 dB and for 1000 m pixels it is 5.3 dB. This last value is very close to the standard value used of 5.5 dB.

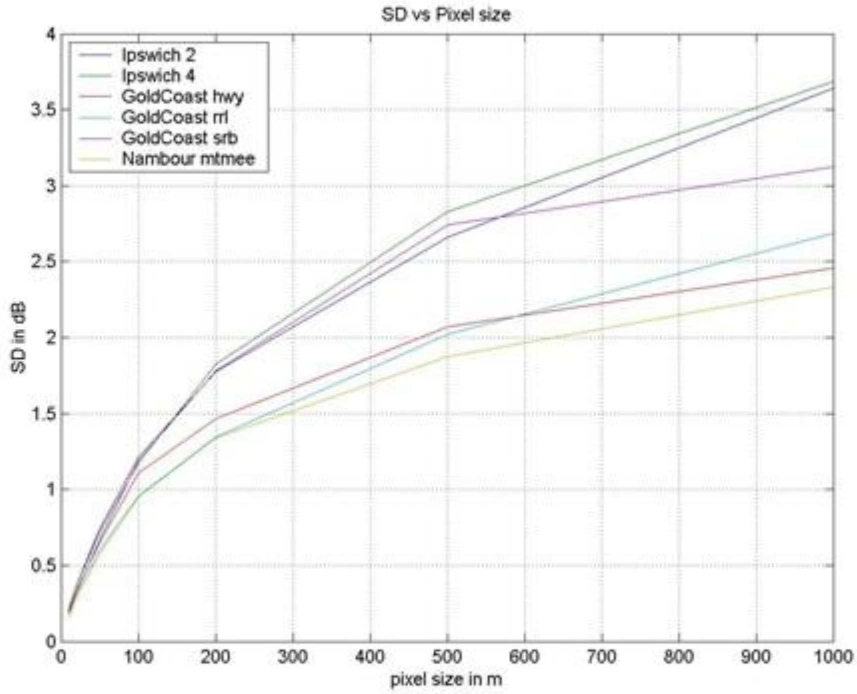


Figure F8: SD mean values vs pixel size for Lee filtered using 40 wavelengths and uncorrelated data samples

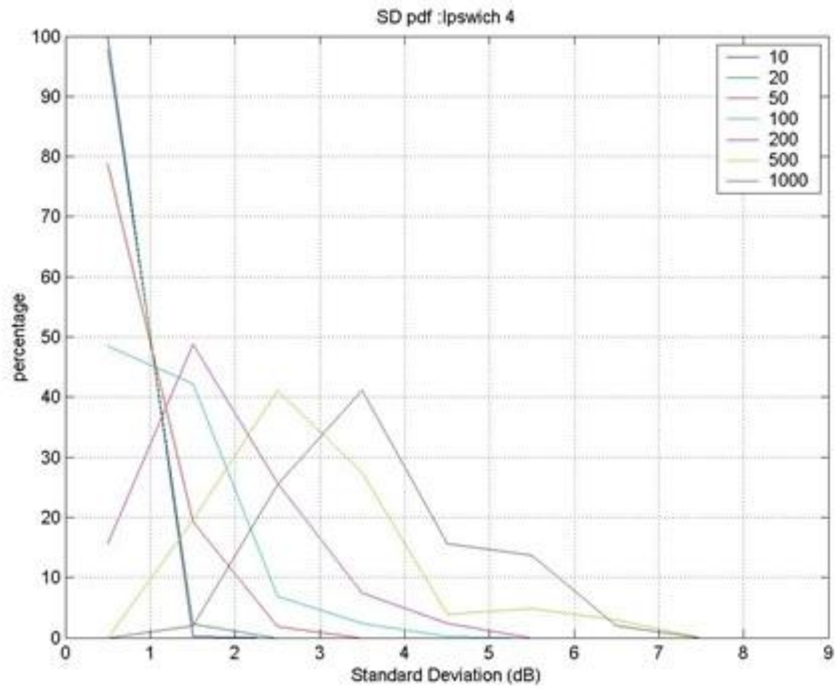


Figure F9: Ipswich 4 data set (suburban) - pdf results for each pixel size

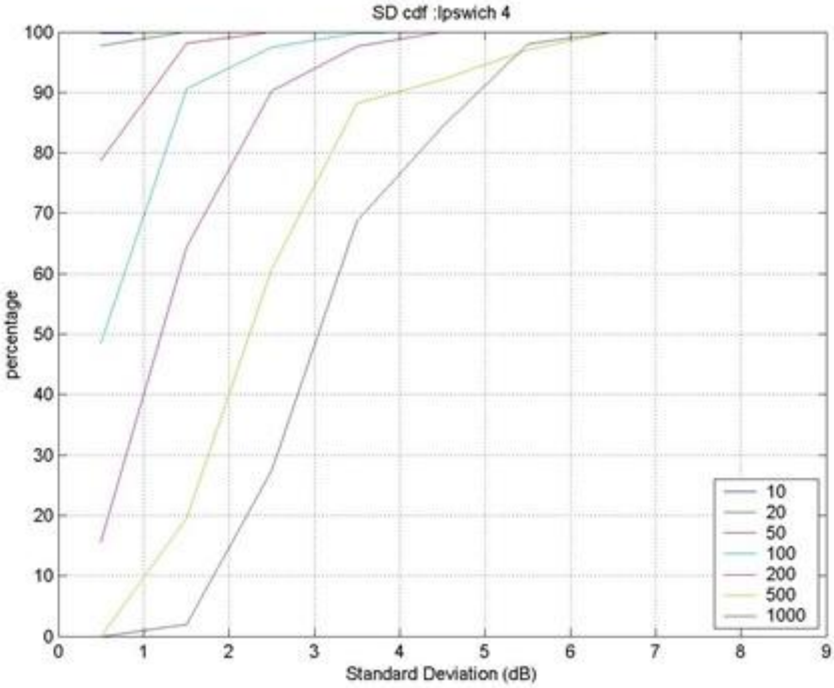


Figure F10: Ipswich 4 data set (suburban) - cdf results for each pixel size

Figure F8 shows the mean field strength and SD per pixel analysed for the Nambour data set and a pixel size of 100 m. The overall mean value of SD shown in Figure F5 is approximately 1 dB, which correlates well with the values shown in Figure F8.

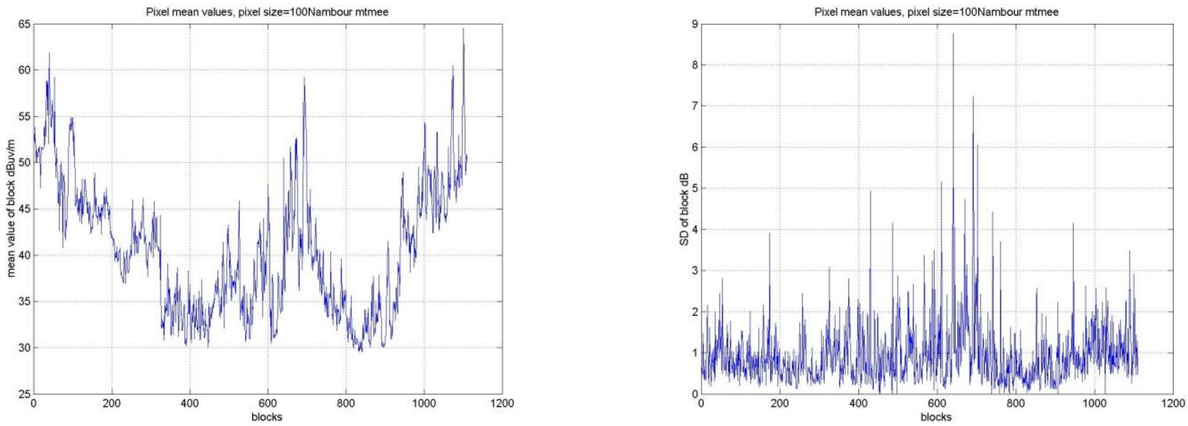


Figure F11: The mean field strength per 100 m pixel and the corresponding SD for 100 m block using the Nambour data set.

Comparing the cdf results shown in Figure F12 for Nambour which is rural in nature and those shown in Figure F10 for Ipswich 4, which is suburban, we see that the rural values are slightly lower, e.g. for 95% confidence and 100 m pixel size Nambour has a SD of 1.9 dB while Ipswich 4 has a SD of 2.2 dB. This is to be expected given that the suburban area studied has higher clutter than the Nambour rural environment.

As a reference point, the value of LV SD used in EBU TR 021-2012 (§ 4.2.2) states for 100 m pixel size:

"For digital wide band signals the standard deviation (s) of the field strength is assumed to be 5.5 dB, which has been confirmed by a number of measurements. In some cases the standard

deviation has been measured to be even lower, down to 3.5 dB for Band III."

Our field test results show that even 3.5 dB appears to be high in many situations when using small pixel sizes; however to ensure that all SD values are captured a figure of 4 dB should be considered in line with the UK report [F6].

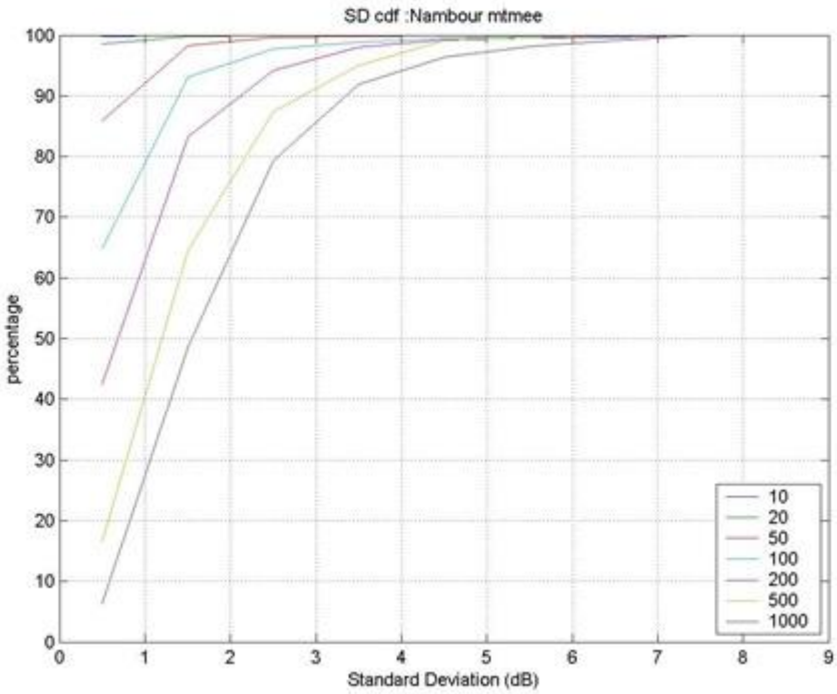


Figure F12: Nambour data set (rural) - cdf results for each pixel size

F4 Discussion and conclusions

The results of the SD field trials have shown that the Location Variation factor Standard Deviation is generally significantly lower than the currently used value of 5.5 dB. This is not unexpected considering that the original figure of 5.5 dB was based on larger pixel sizes, possibly as large as 500 m or even 1000 m, and certainly no less than 100 m [F6].

The Lee filtered results show, for the suburban, rural and open/highway classes, that the mean value of SD in 100 m pixel is typically below 2 dB with 95% confidence.

The field testing did not cover the more challenging case of urban and dense urban environments found in major cities. Given that such environments have dense clutter it is reasonable that the SD in those clutter classes would be greater than the suburban and rural/open classes.

The results to date support the reduction of the LV SD value. This is particularly the case when undertaking coverage analysis using terrain and clutter data of less than 100 m pixel size, with 50 m and 20 m resolutions becoming increasingly common.

F5 References

[F1] ACMA, Broadcasting Services (Technical Planning) Guidelines 2007 (as amended in 2009)

[F2] EBU TR 021, *Technical bases for T-DAB services network planning and compatibility with existing broadcasting services*, October 2013

[F3] EBU TR 024. *SFN frequency planning and network implementation with regard to T-DAB and DVB-T*, October 2013

[F4] ITU-R BS.1660-6 *Technical basis for planning of terrestrial digital sound broadcasting in the VHF band*, 08/2012

[F5] William C. Y. Lee, "*Estimate of Local Average Power of a Mobile Radio Signal*", IEEE Transactions on Vehicular Technology, February 1985

[F6] OFCOM report Annex F, "*Location Variation for a T-DAB signal in Band III*", April 2012

Annex G: Location variation of field strength and its implementation for coverage prediction

G1 Coverage prediction

G1.1 Basic facts

Field strengths are characterized by a statistical nature concerning time and location. The traditional treatment of field strengths in prediction tools takes account of effects due to topographic, morphographic and meteorological conditions, not deterministically, but in a statistical way. Therefore, field strength prediction is based on distributions that indicate the probability of occurrence of a certain field strength value instead of a constant value.

In the case of location variability a log-normal distribution is found for the absolute values of the field strength, resulting in a normal distribution for the logarithm of the field strength. In the context of coverage prediction, the term field strength usually means the median of the field strength distribution.

From the perspective of the receiver, a minimum field strength is required to guarantee a particular reception quality against noise. This value is determined by the system and is not a statistical value. In addition, interference from co- and adjacent channel transmitters has to be taken into account. A minimum difference between useful and interfering field strength has to be met for a certain reception quality. This minimum value is defined as the protection ratio, which is also determined by the system and is not a statistical value.

The first task of the planning tool is to calculate the wanted and the interfering field strength. If different signals are involved, a sum of field strengths has to be calculated. For this a few methods for summation (statistical and non-statistical) are available in the broadcasters' toolboxes. A short overview of different methods is given in § G1.2. Based on the field strength predictions, the probalility value has to be calculated according to the following requirement [G1]:

$$\mathrm{P}\left(\sum F_{i,use} > \sum\left(F_{i,int} + PR_i\right) + F_{min}\right) \qquad (1)$$

where
$F_{i,use}$: useful field strength
$F_{i,int}$: interfering field strength
F_{min}: minimum field strength
PR_i: protection ratio for related interfering system

It won't be necessary for the sum of useful field strengths to comply with formula (1) for each point of time and location. It will be sufficient to fulfil the criterion by a certain value of probability. The required probability depends on the reception quality demand for the distribution. For the time probability, usually high availability for the wanted field strength and high protection against interference is required. The following time percentages are typically used for broadcast service coverage predictions:

Wanted field strength: 50% time probability
Interfering field strength: 1% time probability

The use of 50% time probablity for the wanted signal looks like a reduction in quality requirement. Nevertheless, the assumption of 50% seems to be feasible, since the distribution function for time variation is highly asymmetrical: the differences between 50% and 99% are much smaller than those between 50% and 1%.

For the location probability the appropriate values depend on the intended reception mode and quality. Typically the following are used:

Mobile reception:	99% location probability
Portable reception:	95% location probability (good coverage)
	70% location probability (acceptable coverage)

Based on formula (1), three different coverage conditions occur:

1) field strength limited: $$\sum F_{i,use} < F_{\min} \qquad (1a)$$

2) interference limited: $$F_{min} < \sum F_{i,use} \leq \sum (F_{i,int} + PR_i) + F_{min} \qquad (1b)$$

3) covered: $$\sum F_{i,use} > \sum (F_{i,int} + PR_i) + F_{min} \qquad (1c)$$

A schematic representation and an example of coverage prediction concerning the three cases are given in Figure G1.

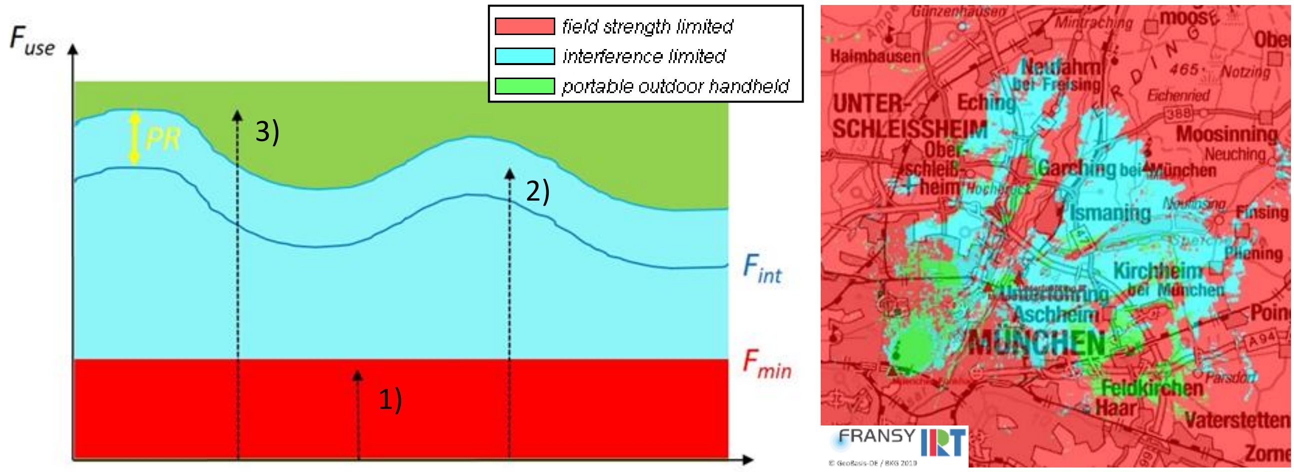


Figure G1: Different coverage conditions

G1.2 Methods for field strength summation

There are several options for the summation of field strength, which are commonly accepted in the broadcaster's world. The most common methods are briefly described in the following sections. Further details on the calculation methods are given in [G2], [G3], [G4] and [G5].

G1.2.1 Power sum method

The power sum method is the simplest way of field strength summation. It is an approach, for which any statistical characteristics are neglected, assuming the mean value of the field strength as sufficient for approximations. The method is diminished to a simple summation of the mean values for both, useful and interfering signals, in terms of power.

The unwanted signals are added to the minimum field strength that is representing the noise contribution, leading to a total nuisance field. The sum of wanted signals must be at least the same level as the nuisance field to guarantee a coverage probability for 50% of locations. Since the statistical effects are not taken in to account, this summation method provides the lower limit concerning coverage probability.

G1.2.2 Log-normal method

The log-normal method describes a procedure for the aggregation of field strengths on a simplified statistical basis. The method is characterized by the assumption, that the sum of log-normal distributions is log-normally distributed; too, which itself is a kind of approximation. Furthermore, the operations are based on the supposition of only uncorrelated signals, which is not necessarily true for real networks.

To determine the parameters of the log-normal distribution for the sum of field strengths, the expected values and variances of the individual field strengths are determined using the distribution parameters of the single log-normal distributions. Afterwards, the expected value and variance of the field strengths are calculated.

Based on the resulting parameters of this sum distribution, the distribution parameters of an equivalent log-normal distribution are recalculated. It is assumed that the equivalent log-normal distribution is a good representation of the requested sum distribution of the field strengths.

$$\sigma_\Sigma^2 = \log\left(\frac{S^2}{M^2} + 1\right) \tag{2a}$$

$$F_\Sigma = \log(M) - \frac{\sigma_\Sigma^2}{2} \tag{2b}$$

where
M: the expected value of the sum field
S^2: variance of the sum field
σ_Σ^2 : variance of the equivalent log-normal distribution of the sum field
F_Σ : the expected value of the equivalent log-normal distribution of the sum field

For the calculation of coverage probability, the sum of the interfering field strengths as well as the noise is compared separately with the sum of the useful field strengths, in terms of a split-up of formula (1). The corresponding coverage probabilities are determined and subsequently multiplied to determine the total coverage probability.

Different standard deviations of field strength distributions are applicable within this approximation procedure. This allows a pixel related treatment of location variation within the calculation area and account of influences from environmental data or pixel sizes (see also § G2.2.1). Furthermore, network gain effects such as the decrease of standard deviation due to multipath propagation or SFN (single frequency network) operation, (see also § G6) are represented in the simulation.

G1.2.3 Monte-Carlo method

The Monte-Carlo Method is considered as the most accurate kind of treatment. A set of random values for the logarithm of field strength are generated according to a Gaussian distribution with known statistical parameters (mean and standard deviation) for both the useful and interfering fields.

For each pixel a large number of samples, representing various reception situations, have to be gathered to guarantee reliable statistics. For all locations, the wanted signals as well as the unwanted signals are summed and transformed to power. Afterwards, the interfering power is complemented by noise, and a signal/(noise + interference) ratio (SINR) is calculated. These outcomes are sorted within a histogram, leading to a distribution density *g(x)* and a probability distribution *P(x)*, which can be used for calculating coverage probability.

The term (3) corresponds to formula (1), and specifies the relevant value for coverage probability at the location under consideration.

$$P\left(\frac{C}{N+I}\right) = P(PR) \qquad (3)$$

where
C: signal
N: noise
I: interference
PR: protection ratio for related interfering system

Since the distribution functions of the individual components are definable by input parameters very flexible, a large number of potential reception and interference scenarios can be mapped, including the consideration of signal correlation. For this purpose, mutual dependencies concerning the samples need to be taken into account.

G2 Types of fading concerning the location variation

Typically, it is not possible to take in to account general information on topography and clutter type exactly. Therefore, this information needs to be considered in a more general way, leading to an estimate of median field strength and its variance, which is measured in equivalent situations for a specified area. More information on measurement procedures for location variation is given in § G3.

The location variation of field strength results from two main fading effects: Fast fading due to multipath and slow fading due to changes in the clutter data. Fast fading superimposes the slow fading with regard to field strength characteristics, as it is shown in Figure G2, taken from [G6].

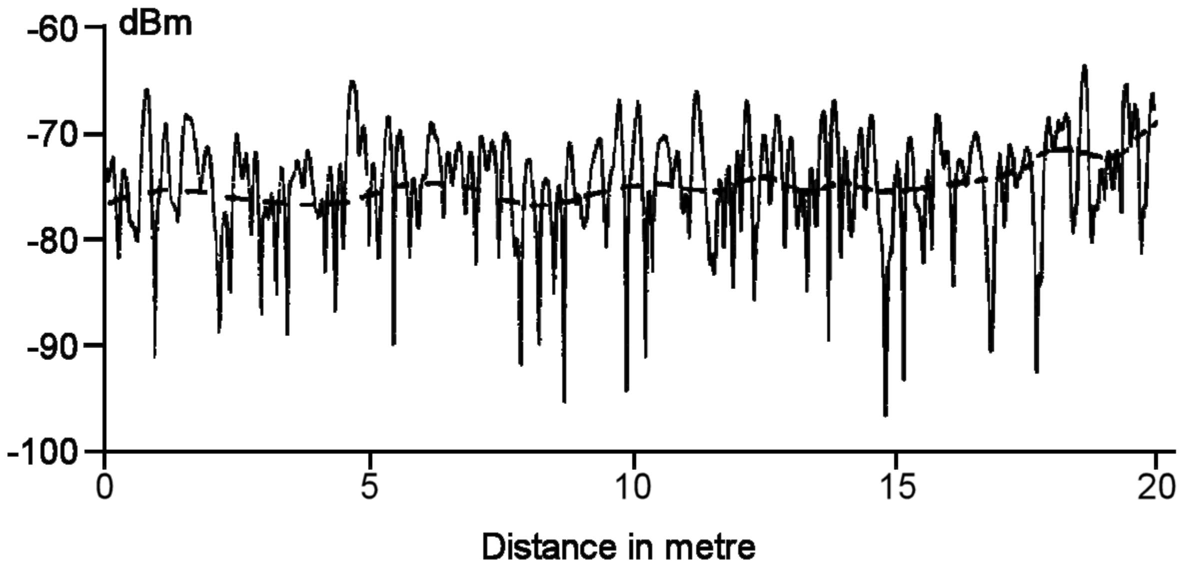


Figure G2: Superimposed fading effects [G6]

Since the sources of the two fading effects differ, also the statistical distributions are different. More information on the differences of the two fading effects and their corresponding field strength distributions are given in the following sections. More detailed information on this topic can be found in [G7], [G8].

G2.1 Fast fading

The signal arrives at the receiving place via many different paths. In most cases, there will be a direct path as well as further signal paths affected by shadowing, diffraction or reflection. Due to this multipath propagation, destructive and constructive interference occurs, leading to a fast variation of field strength, called “Fast Fading” or “Multipath Fading”. These effects are observed over a distance of a few wavelengths [G7] and they are not negligible in practice. Fast fading effects decrease with increasing correlation of the incoming waves, resulting in a smaller variation of field strength. The fast fading effect depends on the bandwidth of the system, since the cancellation of signals is frequency selective, which leads to a lower impact on wideband signals than on narrowband signals.

The total of multiple paths describes the channel profile, formed by numerous waves with various amplitudes, phases and delays. Since these characteristics cannot be described deterministically, they are usually described in a statistical way. Therefore, field strength distributions are taken in to account for coverage predictions. Detailed information on probability density functions and cumulative distribution functions relevant to propagation modelling are given in [G9], [G10].

G2.1.1 Channel profiles

Depending on the receiving location and situation, numerous different channel profiles are formed by the incoming waves. However, typical field strength distributions can be found for a certain kind of reception mode. Therefore, representative channel profiles are assumed according to those particular receiving situations. A brief description of classification is given below. A more detailed definition of the different types of channel profiles as well as their scope of application can be found in [G4].

Portable or mobile reception - Rayleigh

In the case of portable or mobile reception, it would be likely that a scattered wave field is formed due to many reflections and no line of sight. The components are assumed to be uncorrelated and without any dominant part. Under these conditions, the channel profile is characterized by a Rayleigh distribution of the field strength. Usually, the parameter of the Rayleigh distribution is supposed as time-invariant, even though that is not necessarily true in practice, especially for the mobile case.

Fixed reception - Rice

For fixed reception, usually a directed receiving antenna is used, the focus of which is adjusted to the transmitter with highest field strength or to the direction providing best coverage. Moreover, the antenna height goes far beyond that of a portable antenna. Due to those conditions, line of sight or one strong reflection is often predominant at the receiving antenna, leading to a channel profile, which is characterized by a Rice (also called Nakagami-n) distribution of the field strength.

Lab conditions (theory) - Gaussian

A Gaussian distribution of the field strength is formed if only one signal path is present. This case is merely theoretical, because this situation is achievable just under lab conditions. Nonetheless, this channel profile is often used for theoretical studies as a basis, since this assumption facilitates analysis due to missing fading effects. The Gaussian channel is also called AWGN (Additive White Gaussian Noise) channel, referring to a superposition of the transmitted signal with noise, which is characterized by a constant power density spectrum.

G2.2 Slow fading

As described in [G6], [G9], [G10], [G11], slow fading effects are due to ground cover variations, which are important when pixel size is substantially greater than the relevant morphography.

Therefore, the slow fading is often called “Shadow Fading”. Since the local distribution of morphographic influences within the pixel will usually be homogenous and their effects come across a multiplicative way along the path, the loss due to slow fading fits a log-normal distribution, independent of the bandwidths. Measurements validate this assumption. The slow fading is often also called “Log-normal Fading”.

Due to the log-normal distribution of the slow fading, the logarithm of the field strength (including slow fading only) fits a normal distribution. The field strength is characterized by a median value and its standard deviation, or rather location variation, within the area of one pixel. For planning purposes of digital wideband signals a standard deviation of 5.5 dB is often used. For example, this value is specified for the planning procedures within the scope of GE06 [G12]. The location variation is presumed as a constant value, independent of pixel size, frequency or clutter type.

G2.2.1 Influencing criteria for location variation

Even though most of the traditional planning methods assume a constant value of the location variation, experience and measurements have shown a dependence of this value on frequency and environment.

A method for consideration of both factors is described in [11]. For a pixel size of 500 x 500 m the following formula is given:

$$\sigma_L = K_L + 1.3\log(f) \qquad (4)$$

where
f: required frequency in GHz
σ_L: location variability

KL = 5.1	for receivers with antenna below clutter height in urban or suburban environments for mobile systems with omnidirectional antennas at car-roof height
KL = 4.9	for receivers with rooftop antennas near the clutter height
KL = 4.4	for receivers in rural areas

Studies on this topic, as given in [G10], [G13], verified this dependence on frequency and environment, in terms of different clutter types. Moreover, the studies have shown a dependence of the location variation on pixel size. Location variation decreases for smaller pixel sizes and vice versa. This is to be expected, since the number of terrain obstructions increases with pixel size. On the other hand, the standard deviation of the slow fading will achieve a value near zero, if the pixel size is very small (less than the size of relevant obstacles).

G3 Measurement procedures

Since the location variation results from two main effects, which are treated in different ways within the coverage prediction tools (see § G4), the two fading types need to be separated. For field strength calculations only slow fading effects need to be taken in to account. Consequently, the fast fading effects should be eliminated from measured field strengths. For coverage predictions the fast fading effects need to be taken in to account.

G3.1 Eliminating fast fading effects

A procedure for smoothing out the fast fading from the measured field strength is given in [G14]. Many measurement campaigns in past and present, e.g. [G8], [G15], are based on this method.

For separating slow fading from fast fading effects, it is recommended to average the signal data over a small measuring section, calculating median values for every section. As a consequence, the resulting curve characteristics of the median values represent the variation due to slow fading effects only. There are two main aspects to be followed when smoothing out the fast fading effects: the length of signal data averaging and the number of independent samples required for averaging over this length.

Length: Concerning the length for signal data averaging, it should be a compromise between too short and too long. On the one hand, the length should be long enough to smoothing out the fast fading, on the other hand, slow fading has to be preserved and therefore the length should not be too long. According to [G14] a length between 20 and 40 wavelengths will be feasible to fulfil these requirements.

Samples: The required sampling rate should be as small as possible for practical reasons. Nevertheless, a minimum sampling rate is required to ensure high accuracy for the measurement results. Therefore, the sampling rate is a function of the maximum acceptable relative measurement error. According to [G14] 36 uncorrelated samples will be sufficient to restrain the error to less than 1 dB within a 90 percent confidence interval.

G3.2 Eliminating slow fading effects

A procedure for smoothing out the slow fading from measured field strength is applied in [G8]. Within the measuring sections, defined in § G3.1, a classification of the field strength values is made and median values are calculated. Afterwards the content of the classes for all sections are aggregated, centred to the median value. Since the median values are always included in the same class, the slow fading is eliminated and only the variation compared to the median value remains, representing the fast fading effect.

G4 Methods for consideration of location variation in coverage predictions

As already described in § G3, fast fading and slow fading effects can be distinguished by appropriate measurement procedures. Also for coverage prediction, the fast fading and slow fading is taken in to account at different points of the calculation process. In the following section, the different methods with regard to fading effects are explained in more detail.

G4.1 Consideration of fast fading effects

Within the coverage prediction procedure fast fading effects traditionally are taken in to account by the C/N value (carrier to noise ratio). The C/N usually is determined by lab measurements. These measurements are based on numerous receivers, which are tested for different reception modes, represented by different channel profiles (see § G2.1.1). C/N measurements are typically based on channel models, which are well defined, to ensure general and replicable conditions. As an example, [G16] specifies channel_models for fixed (Rice) and portable (Rayleigh) DTT reception. For all receivers and test scenarios the minimum required C/N value is measured, leading to a typical, representative reference value for each channel profile or rather reception mode. The C/N value is part of the minimum field strength F_{min}, which is required to guarantee a particular reception quality against noise, as given in formula (1).

G4.2 Consideration of slow fading effects

Slow fading effects are taken into consideration within the field strength prediction procedure. The propagation model calculates a median field strength value. In combination with the standard deviation of the slow fading the median value fits a normal distribution, this enables a prediction of coverage probability for a given minimum field strength F_{min}. For a simplified scenario without any interference, the coverage target will be achieved if the following formula is fulfilled:

$$F_{\sum use}^{med} > F_{min} + \mu_{x\%} \times \sigma_{\sum} \qquad (5)$$

where

$F_{\sum use}^{med}$: median value of the sum of useful field strengths

$\sigma_{\sum}$: standard deviation of the sum of useful field strengths

F_{min}: minimum field strength

$\mu_{x\%}$: percentile value of the normal distribution for a probability value of $x\%$ (e.g. $\mu_{99\%}$=2.33)

The value $\sigma_{\sum}$ is the result of the statistical field strength summation. The summed standard deviation is lower than that assumed for a single signal. This effect is part of the so-called network gain and will be described in more detail in § G6. The standard deviation of the slow fading for the single signals is usually assumed as one fixed value for the whole coverage area, independent on frequency, environment or reception scenario. Very often a value of 5.5 dB is used for planning purposes of digital wideband systems. As already mentioned before, this value of 5.5 dB is also specified for the planning procedures within the scope of GE06 [G12].

G4.3 Consideration of the variation at indoor locations

For indoor reception, the standard deviation is a combination of outdoor variation due to slow fading effects and indoor variation due to building entry loss. It is assumed, that the variations are uncorrelated, therefore the combined result for indoor reception is the square root of the sum of the squares of the two standard deviations.

$$\sigma_{in} = \sqrt{\sigma_{out}^2 + \sigma_{build}^2} \qquad (6)$$

where

σ_{in}: variation for indoor reception

σ_{out}: variation due to slow fading

σ_{build}: variation due to building entry loss

The assumption of uncorrelated variations takes for granted, that σ_{build} means the variation of different building types, which are taken into consideration when determining a mean value of field strength variation. If the main reason for the variation in the building entry loss is the different entry paths into the building (window, door, wall, etc.), the variations σ_{out} and σ_{build} would be partly correlated. For this case, the treatment of standard deviation for indoor reception would be more complex and the variation would no longer be given by formula (6).

The same treatment of standard deviation is used for handheld reception in vehicles, simply replacing the variation due to building entry loss by the variation due to vehicle entry losses.

G5 Prediction error

In addition to the physical location variation of the field strength, which is basically treated in a statistical way, as described in the previous sections, there is one more statistical component, which needs to be considered in the coverage prediction. Each propagation model, used for the prediction of field strength, is affected by a prediction error.

G5.1 Definition

The prediction error is defined as the difference between measurement and prediction of the median value of field strength (50% location probability and 50% time probability) [G17]. The formula is given in (7). This error is based on the propagation model, and is therefore a kind of quality issue concerning its accuracy.

$$\Delta F = F_m - F_c \qquad (7)$$

where
ΔF: prediction error
F_m: measured field strength
F_c: calculated field strength

In the main, the values for the prediction error are normally distributed; therefore, the prediction error is characterized by a median value and its standard deviation. The median is taken in to account by adjusting the prediction model correspondingly, leading to a median of zero concerning the prediction error. Nevertheless, the standard deviation remains as a statistical component, relevant for the accuracy of field strength prediction.

G5.2 Global predictions

Since the variance due to the prediction error will be well balanced concerning positive and negative effects over the whole coverage area, it is feasible to make coverage predictions concerning the whole coverage area (like percentage of covered area in total) without any consideration of the prediction error.

G5.3 Precise prediction at specific test points

For a precise prediction of coverage at specific test points, the prediction error of the propagation model needs to be taken in to account. The statistical consideration of the standard deviation of the prediction error will ensure that the coverage, which is predicted by the calculation tool for the specific test point, will be actually achieved.

Since the variation due to slow fading and the variation of the prediction error are assumed to be uncorrelated, the combined result of both standard deviations is the square root of the sum of the squares.

$$\sigma_{prec} = \sqrt{\sigma_{out}^2 + \sigma_{pred}^2} \qquad (8)$$

where
σ_{prec}: variation for coverage prediction at specific test points
σ_{out}: variation due to slow fading
σ_{pred}: variation of the prediction error

G6 Network gain

The OFDM technology applied by digital systems enables a constructive use of delayed signals. This is valid for signals from one transmitter reaching the receiver with various delays due to multipath propagation, as well as for signals deriving from different transmitters, synchronized within a single frequency network.

The signal delay after receiver synchronization determines the Mode of signal combination, either constructive or destructive. Within the guard interval, delayed signals are fully decoded as useful signals. Inside a real receiver this useful span is followed by a further range, splitting signals into useful and interfering components depending on their incoming delay. This splitting process can be described by a theoretical weighting function. Further information on this topic is given in [G18].

Due to the constructive combination of signals, the median of the field strength increases. Moreover, in many cases the additional signals will fill up some minima of field strength from the single signal. Because of this, the variation of field strength for the sum of signals is reduced compared with the variation of field strength for the single signal. The extent of this impact depends on the particular situation, leading, more or less, to a reduction of fading effects.

Statistical methods for the summation of field strength, as described in § G1.2, also take into consideration these multipath effects. Both the increase of the median of the useful field strength and the decrease of the standard deviation are part of the so-called network gain. Due to this network gain, the coverage requirements given in formula (5) become easier to fulfil, leading to a higher percentage of coverage. An example of network gain calculation can be found in [G1].

A detailed description concerning the calculation of field strength under consideration of multiple signals is given in [G2]. A verification of the reduction of standard deviation due to network gain by measurement took place in [G8]. A decrease of slow fading as well as a decrease of combined fading (including slow and fast fading effects) was found in this measurement campaign. Further measurements in this context are given in [G13]. It has been shown that the standard deviation in a single frequency network decreases the most when all wanted signals are of comparable levels.

The network gain effect of slow fading reduction is also considered in the statistical field strength summation methods, such as the log-normal method, described in § G1.2.2. An example is given in Figure G3, representing a single frequency network with three transmitters. The standard deviation of the useful field strength is presented, based on a standard deviation for single transmitter of 5.5 dB.

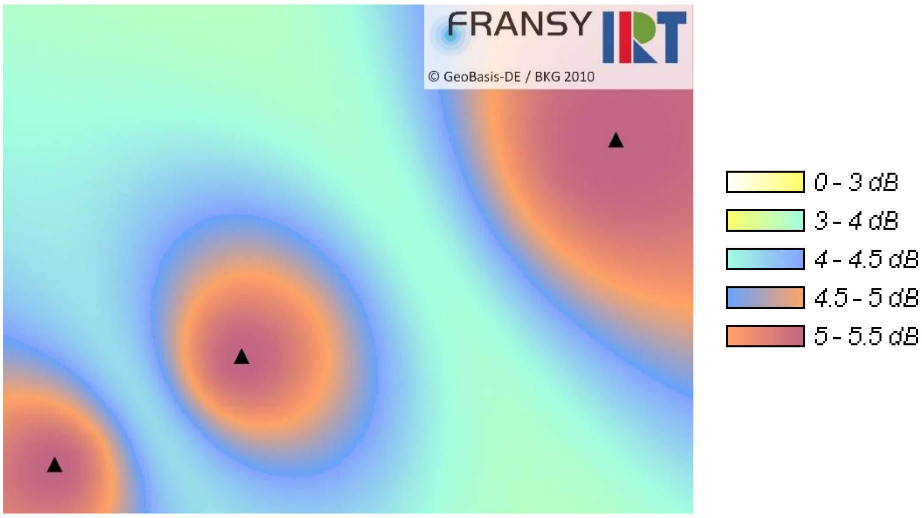


Figure G3: Standard deviation in a single frequency network

Another kind of network gain is merely a statistical effect, developed as a part of the network planning process. Under the usual assumption of statistical independence of individual signals, the probability for providing a specified minimum field strength level may be reached by combination of signals, even though the single transmitter signals are not individually sufficient to provide the required probability. This gain primarily results from the combination of the individual probability values, which leads to an increased combined probability value. This statistical network gain is valid for SFN operation as well as for multi-frequency networks (MFN).

G7 Upcoming research issues concerning location variation

From the previous discussion, a few open questions remain and some points should be clarified in the future.

Investigations have shown a dependency of location variation not only on frequency and clutter type, but also on pixel size. Therefore, the pixel size should be also taken in to account. A first proposal for this issue is provided in [G10]. A verification of this approach by means of further measurements would be helpful.

A further important topic would be the consideration of signal correlation within the treatment of location variation. Approximation methods concerning the field strength summation are based on the assumption of uncorrelated signals; this will be rarely the case in practice. Therefore, a consideration of signal correlation would be reasonable. A procedure for the simulation of such effects must be a compromise between accuracy and complexity. In the context of signal correlation the treatment of indoor variation is also an important aspect.

Another issue to be examined in future should be the prediction error and its relevant dependencies. Investigations to identify those dependencies should be a first step. Based on the findings, it may be necessary to develop an appropriate method for consideration of the prediction error in coverage predictions.

Last, but not least, an interesting subject to deal with would be the linkage between the variation in location and time. Concerning broadcasting systems, usually both kinds of variation are dealt with separately. Due to the fact that no detailed information on distribution functions of time variation are available, only discrete values for percentages of time (corresponding to quality requirements) are presently used. For a linkage between the variation in location and time it would be essential to investigate the time variation with regard to its distribution function. For this purpose, long-term measurements would be required.

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Annex H: Performance characterization of DAB receivers in SFN mode

H1 Introduction

In Single Frequency Networks (SFNs) transmitters are required to radiate the same OFDM symbol at the same time. This comes from the fact that "echoes" generated by co-channel transmitters should be confined within the guard interval period. The OFDM receiver needs to set up 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. If the transmitters of the SFN deliver the same OFDM symbol at the same instant, or with a sufficiently small delay, the differential propagation path delay to the OFDM receiver will remain inside the guard interval period. Accordingly, the sum of all received signals will be constructive because they constitute the same OFDM symbol (with no inter-symbol interference).

Ideally, therefore, in the design of SFNs, the inter-transmitter distance is proportional to the maximum echo delay acceptable by the transmission system that depends on the guard interval. Actual transmitter spacing can be increased beyond that defined by the guard interval with network optimization in terms of static delays, antenna patterns and power of transmitters.

The effective planning of the required radiated power and the optimization of static delays at the secondary site(s) will improve SFN performance and eliminate most potential interference problems. However, taking into account that in some countries large area SFNs will be required due to frequency constrains, an experimental verification of the behaviour of DAB receivers in presence of signals beyond the guard interval is required to optimize the setup of this kind of network.

H2 Characterization of DAB receivers

Rai Way performed several tests on this issue in the laboratory and within the service area.

H2.1 Laboratory tests

Some models of commercial receivers sold in Italy (*Continental* and *Pure*) have been laboratory tested using a DAB signal generator. An instrument able to operate as a spectrum analyzer and a signal detector was used to monitor the "simulated" relative delay between DAB signals (also referred to as "echoes" in SFN contexts). In fact, one of the main scopes of the tests was to evaluate the capability of receivers to correctly demodulate the content in critical reception conditions; that is, when one echo is beyond the guard interval and/or the main signal has the same power level. For these tests the transmission Mode I was considered as a reference, as it is used in real DAB deployment in Italy where networks operate in the VHF Band. Therefore, the theoretical value of the guard interval is about 246 µs.

The following list summarizes the main results achieved in the laboratory:

1) signals having the same power level within the guard interval are correctly demodulated with good/very good audio quality;

2) under certain conditions commercial receivers are able to correctly demodulate the content in presence of an echo beyond the guard interval, even if it has the same power level as the main signal; relative delays and power levels are specified below,

3) with an echo beyond the guard interval, the protection ratio associated with the considered transmission mode is needed well before the end of the theoretical equalization interval which lasts 1000 µs for transmission Mode I. In fact, for a certain delay, the echo is computed as a completely destructive interference by receivers;

4) when a receiver loses synchronization due to the presence of a signal well beyond the guard interval, it is necessary to considerably reduce the delay of the echo to allow the receiver to re-synchronize and correctly demodulate the content. For example, if a receiver loses synchronization when the delay of an echo is 400 μs, it may be able to recover synchronization when the delay of the echo is reduced, for example, to 350 μs.

Basically, the theoretically expected behaviour beyond the guard interval has not been displayed by any of the tested receivers.

With reference to point 2), above, laboratory tests were then focused on the identification of the “minimal condition” under which commercial receivers can correctly demodulate the content when one or more echoes are beyond the guard interval, taking into account the power levels of the signals and their relative delays.

In more detail, the tests performed in several reception conditions showed that far beyond the guard interval, it is the difference in the signal levels of the transmitters that represents the discriminating factor guaranteeing good reception quality. Therefore, this difference was named the required *protection ratio* that makes the reception feasible in presence of signals beyond the guard interval.

For example, when the power sum of echoes beyond the guard interval is 4 dB lower than the useful signal, all the receivers were still able to synchronize and correctly demodulate the content until the relative maximum delay was over 350 μs. It is worthwhile to consider that, as the relative maximum delay decreases, the required *protection ratio* could be less than 4 dB.

On the whole, Rai Way derived the following table which defines the conditions that make audio reception possible with good quality, in terms of *protection ratios* as previously defined and relative delay between transmitters.

Table H1: Conditions to be respected by DAB signals in SFN Mode to make good quality audio reception feasible with commercial receivers, as achieved by laboratory tests

Required protection ratio	Relative delay
0 (i.e. not required)	0 ≤ t ≤ 246 μs (i.e. inside the guard interval)
4 dB	246 < t ≤ 350 μs
13.5 dB	t > 350 μs

This table represents a first conservative outcome of several laboratory tests. Further analysis might help to derive a mathematical function that could better describe the behaviour of commercial receivers in presence of signals beyond the guard interval (for example, as stated before, for t > 246 μs and t << 350 μs it is expected that receivers are able to correctly demodulate the content even when the *protection ratio* is lower than 4 dB). The value of 13.5 dB is the one commonly used as co-channel protection ratio for a DAB signal interfered by a DAB signal, in every reception class (both portable and mobile).

H2.2 Tests in service area

For the tests performed in the service area, two DAB transmitters which operate in SFN on block 12D (229.072 MHz) in the Veneto region, between the provinces of Venice and Padua, were considered: M.VENDA (operating power 1 kW) and VENEZIA CAMPALTO (operating power 250 W), as shown in Figure H1.

Rai Way performed several tests in this area using a vehicle equipped with different commercial

DAB receivers (*Continental*, *Blaupunkt* and *Pure*) and an "ad hoc" receiver board developed in partnership with a world leader in electronic components and semiconductor solutions. This equipment allowed Rai Way to evaluate the performance of the SFN both statically and on the move. Figure H2 shows the measurement set up.

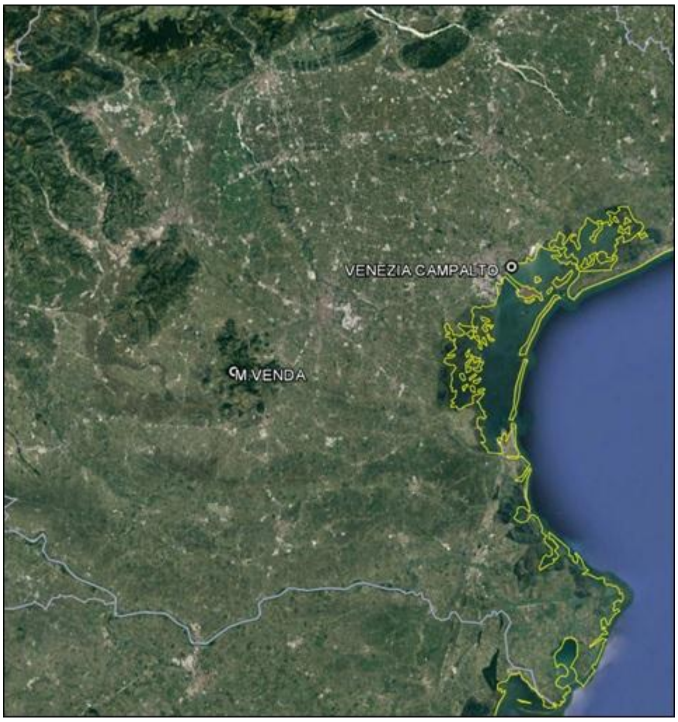


Figure H1: Geographical location of M.VENDA and VENEZIA CAMPALTO within the Veneto

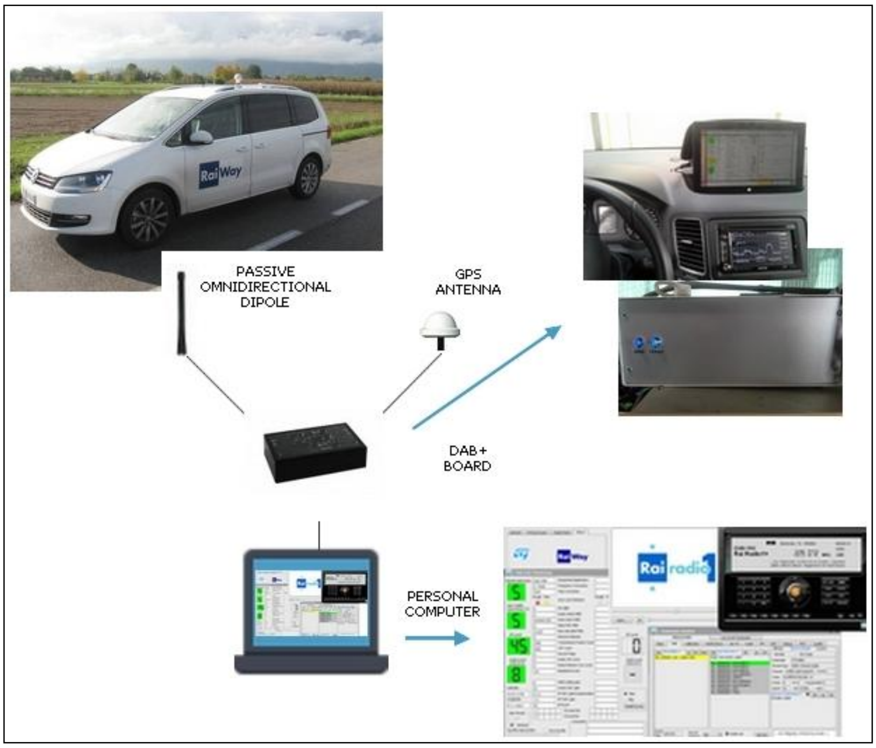


Figure H2: Measurement set up

At the beginning of the tests, the signals from the two transmitters were synchronized in time, that is, both of them were inside the guard interval. In this situation all the receivers were able to correctly demodulate the content and the detected audio quality was very good with all the receivers Figure H3 gives an example of the relative delay between the two transmitters in the city of Mestre, which is about 10 km away from Venice.

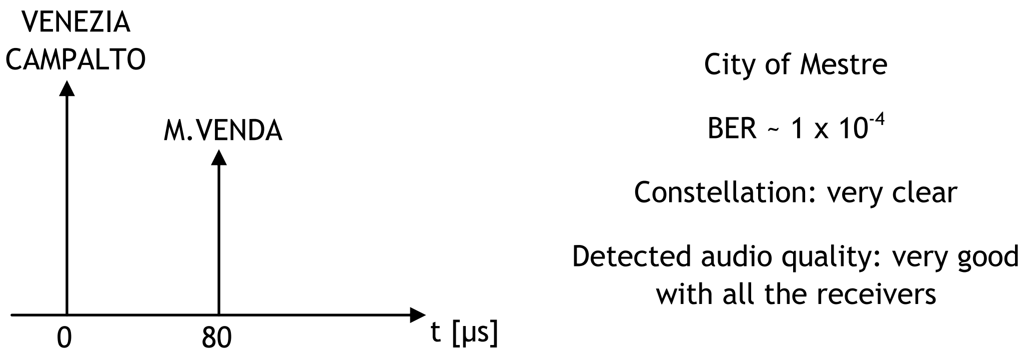


Figure H3: Relative delay in Mestre from the two transmitters in test

With this configuration of the static delays assigned to the transmitters, the audio quality measured travelling on the highway in Veneto was very good with all the receivers, as well.

Then, in order to characterize the behaviour of the receivers when one of the two signals was beyond the guard interval (246 μs), the static delay assigned to VENEZIA CAMPALTO was increased step by step and the responses of the receivers were collected, both statically and on the move.

In order to simulate very critical reception conditions for SFNs, several variations of the signal levels were investigated, up to signals having the same power level and beyond the guard interval.

As long as the relative delay between the two transmitters was about 300 μs, that is 50 μs beyond the guard interval, all the receivers were able to correctly demodulate the content and the detected audio quality was good, even if the signals of the two transmitters had about the same power level. Figure H4 gives an example of this kind of reception condition at the toll booth of Mestre, on the highway.

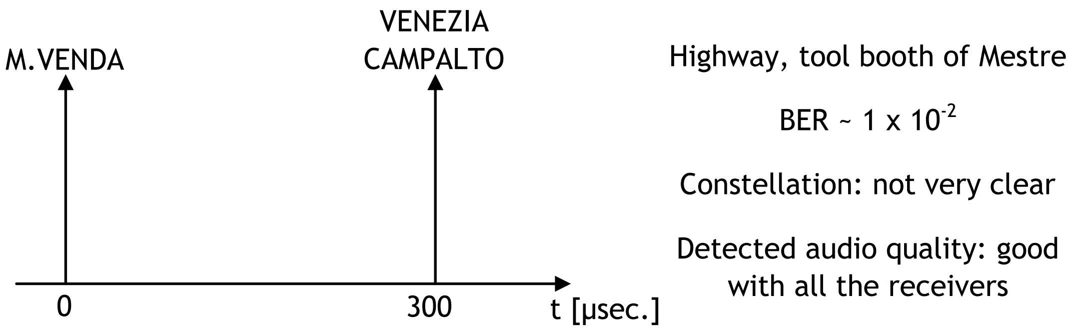


Figure H4: Reception at Mestre from the two transmitters in test (300 μs delay)

With a further increase of the relative delay between the two transmitters beyond 350 μs, maintaining the two signals at the same power level, no reception was possible for all receivers. However, with this relative delay, if a difference of about 5 dB between the signal levels is introduced, a reception with fair quality is still possible with all the receivers. These measurements were repeated in several reception conditions and, as already observed in the laboratory, beyond the guard interval, the difference in the power levels of transmitters is the key factor that defines if the reception is feasible or not. Figure H5 shows the results along the Veneto highway of the detected audio quality which remains good or, at least, fair within the red area between the target areas of M.VENDA and VENEZIA CAMPALTO, where one of the two signals is beyond the guard interval and both of them have about the same power level.

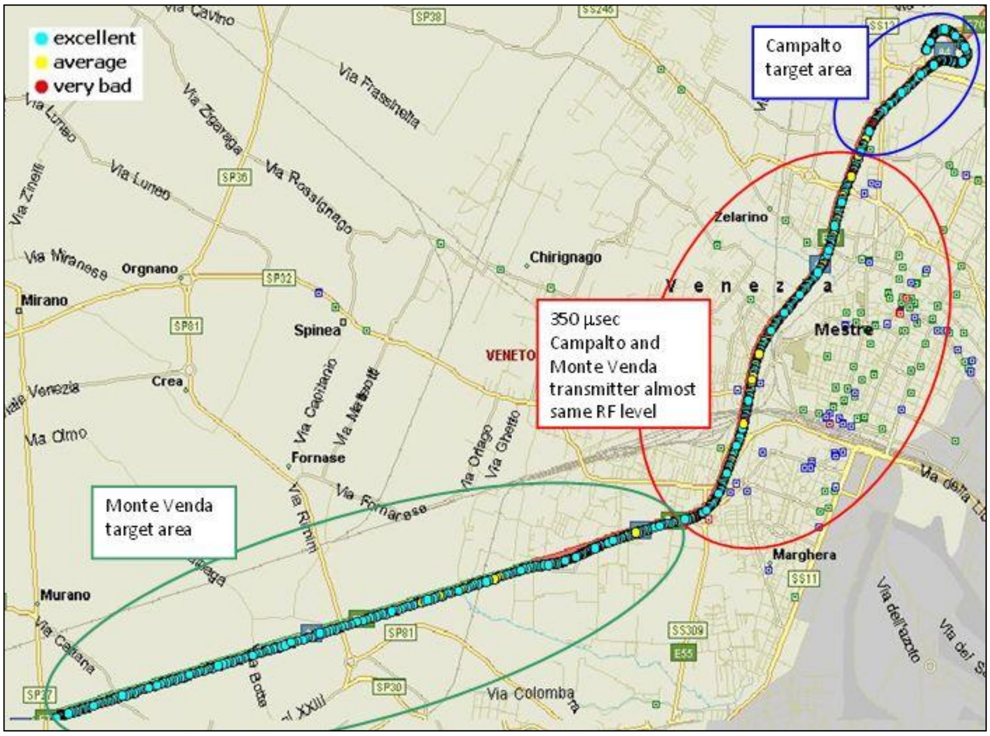


Figure H5: Audio quality measured travelling on highway

At the end of the field trials on the commercial DAB receivers (*Continental*, *Blaupunkt*, *Pure*), as done for the laboratory tests for both static and mobile data, Rai Way derived the conditions that allow audio reception with good or, at least, fair quality, see Table H2.

Table H2: Conditions to be respected by DAB signals in SFN mode to make audio reception feasible with good quality with commercial receivers, as achieved by service area tests

Required protection ratio	Relative delay
0 (i.e. not required)	0 ≤ t ≤ 246 μs (i.e. inside the guard interval)
0	246 < t ≤ 280 μs
2 ~ 3 dB	280 < t ≤ 320 μs
4 ~ 5 dB	320 < t ≤ 350 μs
6 ~ 7 dB	350 < t ≤ 380 μs
13.5 dB	t > 380 μs

H3 Conclusions and final remarks

Making a comparison between Table H1 and Table H2, it is possible to notice that the behaviour shown by commercial receivers in the service area is very similar to that revealed in the laboratory; the laboratory results were confirmed in the service area. Starting from this comparison, Rai Way finally derived the values shown in Table H3 that express the conditions required within an SFN by commercial DAB receivers so that they may correctly demodulate the audio content with good quality.

Table H3: Conditions to be respected by DAB signals in SFN configuration (transmission Mode I) to make audio reception feasible with good quality with commercial receivers.

Required protection ratio	Relative delay
0 (i.e. not required)	$0 \le t \le 246$ μs (i.e. inside the guard interval)
5 dB	$246 < t \le 350$ μs
13.5 dB	$t > 350$ μs

As already stated, Rai Way considers these conditions quite conservative: they might be slightly adjusted after performing further tests on commercial receivers and a more complex mathematical function that describes the real behaviour of receivers in the presence of echoes beyond the guard interval could be derived.

Additional tests should be also performed with echoes “in advance”, i.e. for $t < 0$. To date, Rai Way does not rely on the symmetry of the theoretical DAB model with respect to the time axis for planning analysis and the considered *protection ratio* for $t < 0$ should be 13.5 dB.

H4 Bibliography

EBU Tech 3317 *Planning parameters for hand held reception*. Status: version 2.0. Geneva, July 2007.

EBU TR 024 *SFN frequency planning and network implementation with regard to DAB and DVB-T*. Geneva, October 2013.

Annex I: An example of ACI assessment in the UK

I1 Introduction

When assessing the potential impact of a newly proposed DAB site that is not co-sited with other DAB services it is necessary to ascertain the potential impact. In the UK, two assessments are carried out;

1. the potential impact to mobile reception on major roads
2. the potential impact to indoor reception.

Predictions are used to estimate the likely impact and these results are discussed with interested parties; survey measurements of existing coverage can be carried out to validate the predictions. If agreement cannot be reached then the proposing broadcaster has to decide whether to proceed with the new site at risk of having to provide filler transmitters to repair coverage of any impacted services. If proceeding to build the new site the following sections describe the methods used in the UK to assess the real impact.

I2 Mobile coverage

To verify predictions and establish a baseline for any impact assessments the existing coverage of the existing services close to the proposed new site are measured for Field Strength and Bit Error Rate. This is to ascertain whether the road is served prior to the possible impact from ACI. Only Motorways and main A roads are considered, although for some B class roads, traffic flow rate is sometimes assessed to determine the daily/weekly use and grade impacts (especially close to road junctions).

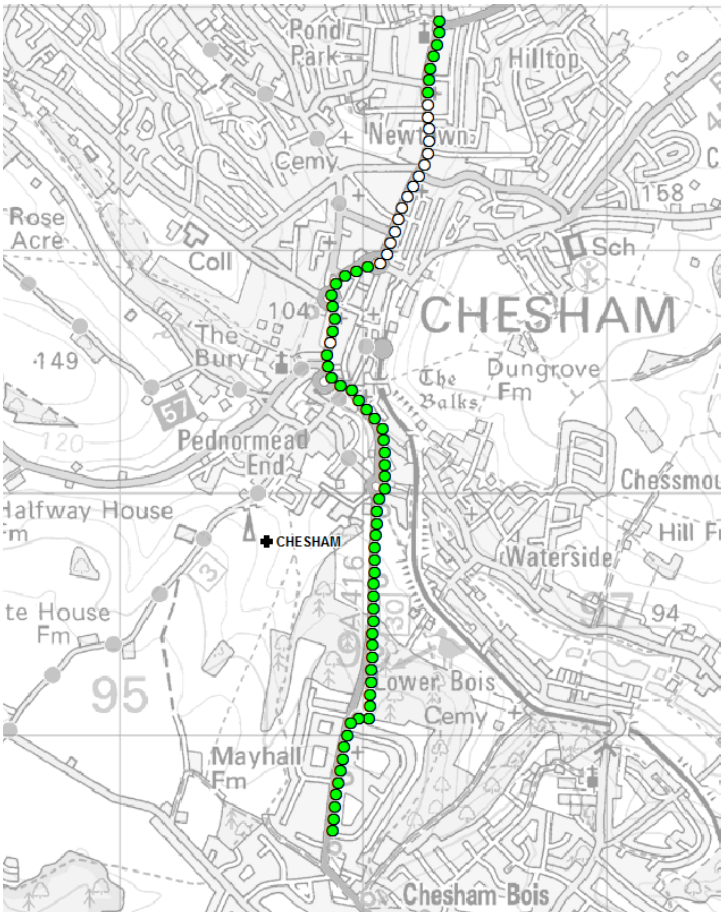
In this example a new site for Chesham was proposed for a channel 12B service and the potential impact to channel 11D services assessed.

The initial coverage survey for the channel 11D service demonstrated that while all roads in the area - including the main A416 Amersham Road - are predicted to be served, measurements suggested that parts of the A416 remain unserved. This is illustrated in Figure I1 for a calibrated measurement survey.

Coverage was found to be particularly poor in the north of the town centre, including a stretch of some 700 m of the A416.

To test consumer experience of in-car reception of the channel 11D DAB service, a Toyota Avensis with factory fitted DAB radio was driven along the A416 in Chesham, subjective listening of the DAB service was carried out and the result is plotted in Figure I2.

Areas highlighted **green** indicate that audio was decoded without audible errors; **yellow** areas had some noticeable degradation (burbling); **red** areas indicate complete loss of reception (silence).



- Field strength equal to or greater than the derived minimum field strength for a mobile service
- Field strength less than the derived minimum field strength for a mobile service

Figure I1: Drive survey calibrated measurement results (mobile reception)

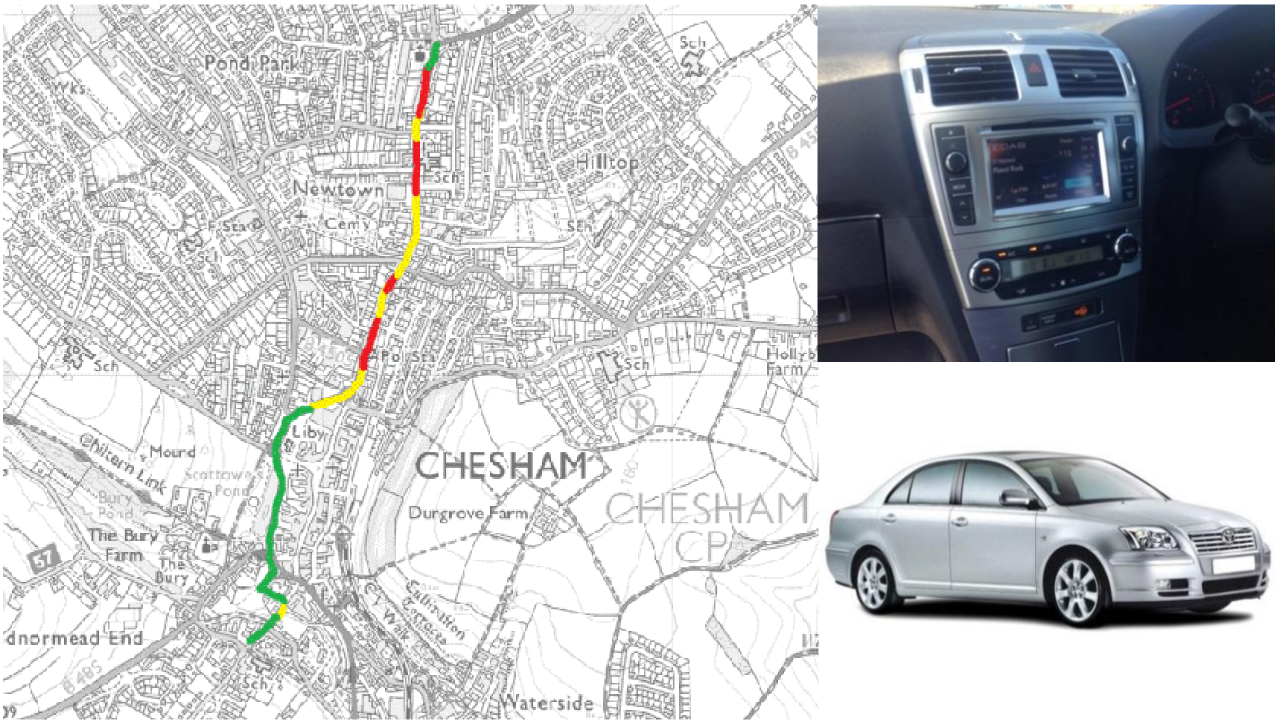


Figure I2: Subjective Drive test results (mobile reception from a Toyota Avensis with DAB radio)

The prediction method used in the UK (the UKPM) power sums the contribution of transmitters. In most areas, a dominant server is reinforced by a number of secondary servers. Typically the dominant server provides sufficient field strength to provide a service in its own right; while other transmitters in the SFN provide diversity of reception, which is particularly beneficial for robust indoor coverage and mobile coverage in built-up areas. In general, receivers synchronise to the dominant server, and that is where the receiver synchronisation window is assumed to begin; secondary servers contribute within this window.

In the Chesham area, the channel 11D network has a number of transmitters contributing to coverage. Predictions indicate that the SFN mobile coverage is near complete - however, neither of the two most dominant servers (Crystal Palace and Hemel Hempstead) provides a service in their own right, which is supported by the drive survey measurements as illustrated in Figure I3.

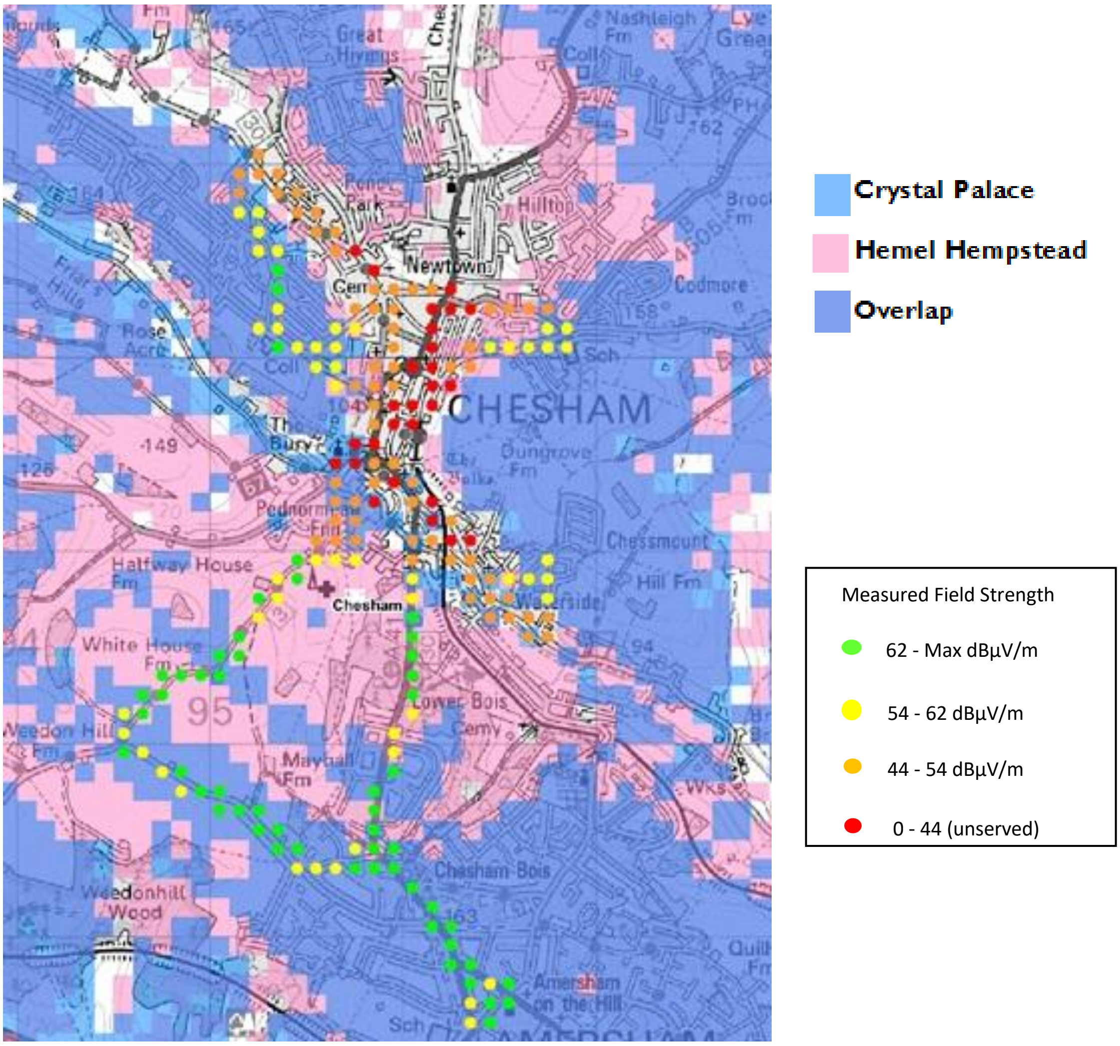


Figure I3: Predicted mobile coverage for channel 11D in Chesham from the two dominant servers, Crystal Palace and Hemel Hempstead (Gross transmitter coverage - No SFN gain). Drive survey measured Field Strength for channel 11D is also shown (measured at 1.5 m a.g.l. and averaged into 100 m pixels)

The antenna pattern for the proposed channel 12B service from the Chesham site is shown in Figure I4.

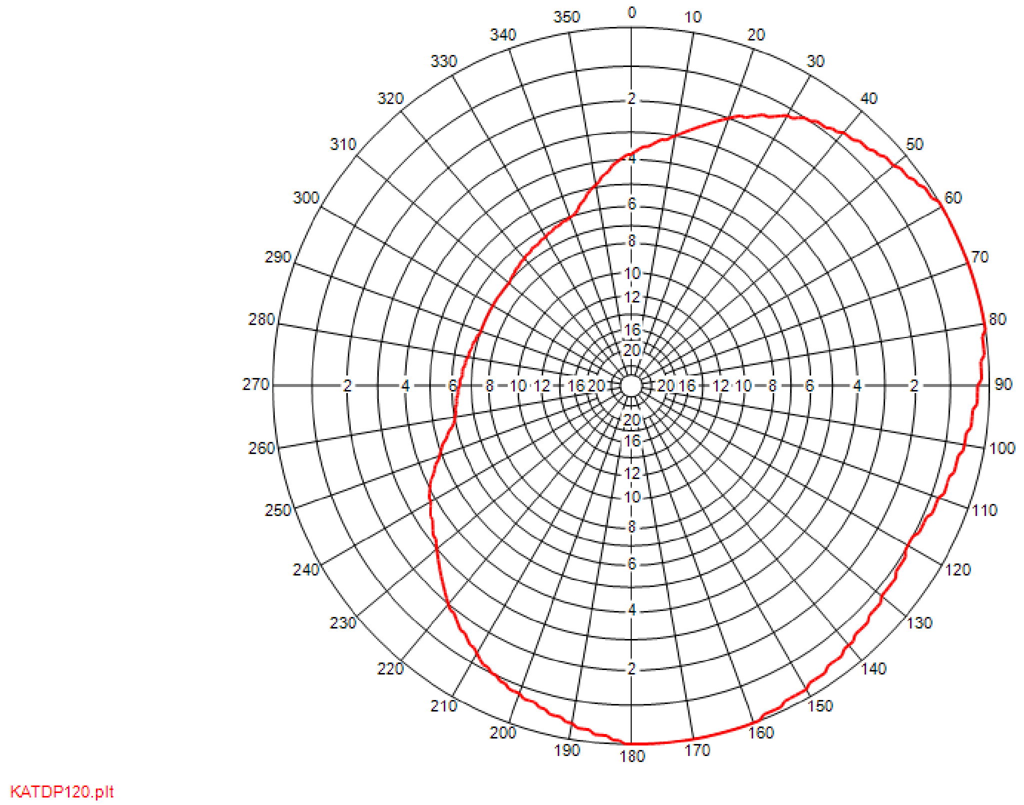


Figure I4: Antenna HRP for the proposed Channel 12B service at the Chesham transmitter

The transmitter has the following parameters.

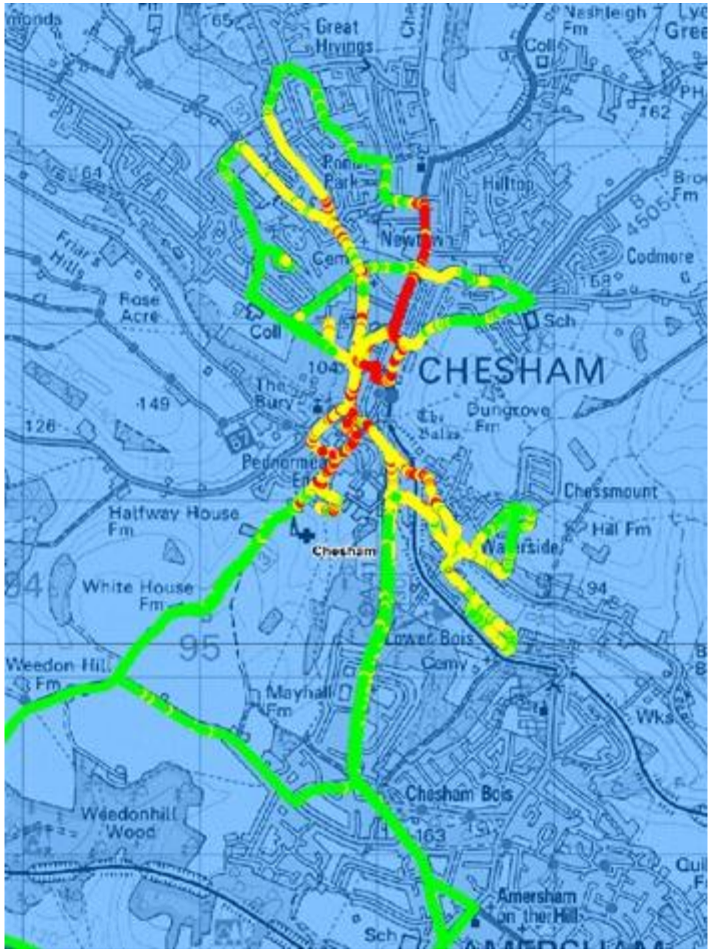
Table I1: Transmitter parameters

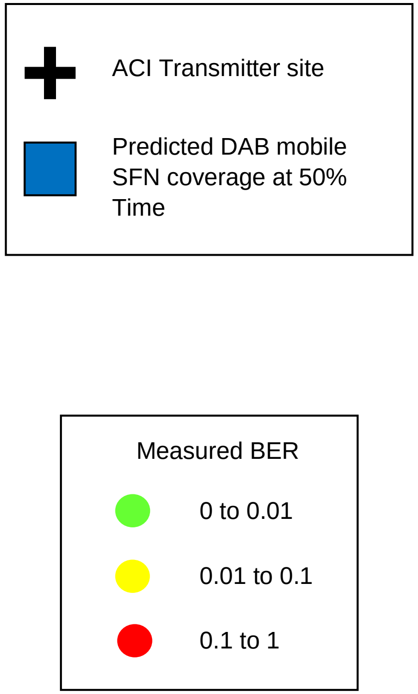
ERP	100 W
Site Height	127 m
Antenna height	52 m
Site Location (NGR)	SP956008

In Figure I5, the Bit Error Rate measurements made before bringing to air the 2nd Adjacent interfering transmitter are plotted over the predicted mobile 50% time coverage. It can be seen that the existing channel 11D DAB service already has a high level of errors within Chesham.

In Figure I6, the Bit Error Rate measurements made after bringing to air the 2nd Adjacent interfering transmitter showing that the error rate of the channel 11D service is increased close to the transmitter but in some areas the results look better due to the variation typical in BER measurements.

Figure I5 demonstrate the erratic behaviour of BER measurements and the difficulty of interpreting these for ACI. In general in the UK we do not use BER as the key identifier of adjacent channel interference but rather use Field Strength difference instead. There is another benefit of measuring Field Strength difference, which is that a calibrated vehicle is not completely necessary; just a vehicle with a relatively omnidirectional antenna installation.





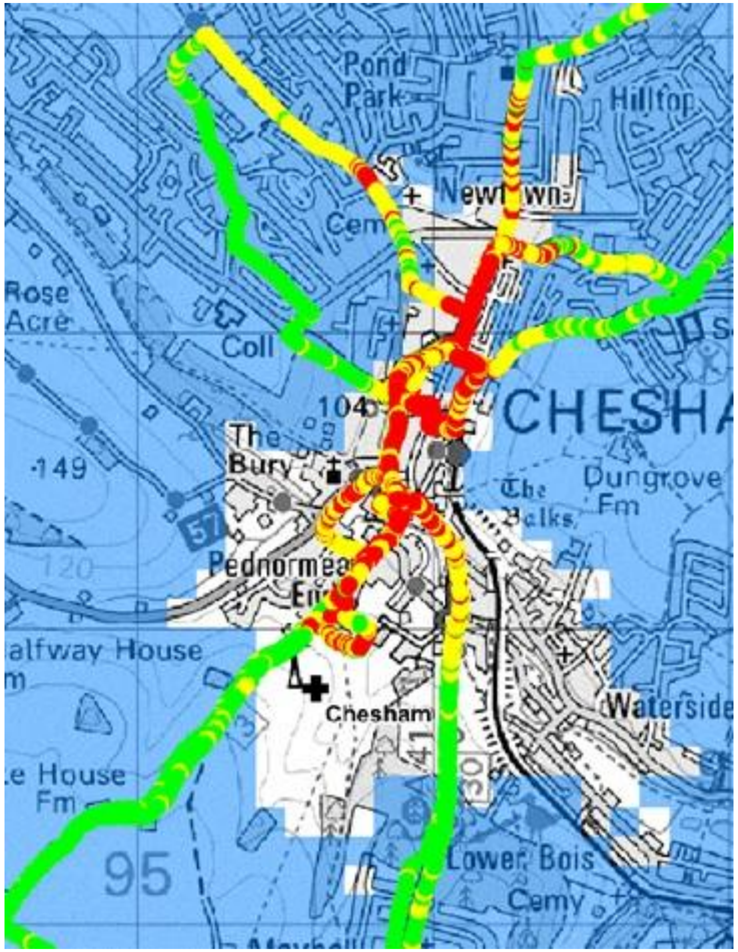


Figure I5: Predicted mobile coverage and channel 11D BER with No Adjacent Channel Interference

Figure I6: Predicted mobile coverage and channel 11D BER with 2nd Adjacent Channel Interferer at 100 W ERP

In the Chesham example measurements showed that when aggregated into 100 m pixels the Median field strength levels for channel 11D were below the minimum required for a mobile service along parts of the A416 through the town.

When the new transmitter is brought into service, measurements can be taken to identify where the field strength differences between the Median field strength of the 2nd adjacent interferer within a pixel and the Median wanted field strength in that pixel is greater than the 2nd adjacent protection Margin (27 dB in the UK, as shown in Table I3). When this is true that pixel is likely to be affected, providing it was served previously.

Table I2: Industry agreed ACI Protection Ratio figures used in the UK

Channel Relationship	Protection Ratio (dB)
1st Adjacent	-35
2nd Adjacent	-40
3rd Adjacent and higher	-45

The protection ratios in Table I2 apply for a receiver at a single location and are based on historical BBC measurements. When comparing predicted median field strengths an additional correction needs to be included to ensure the service is protected from interference at the required percentage of locations. This correction is added to the Protection Ratio to produce a Protection Margin.

The correction is calculated using equation 3.3 for the standard deviation of the difference between wanted and unwanted signals. In the UK a standard deviation within 100 m square pixels of 4 dB is used for outdoor reception (and 5.95 dB for combined indoor reception), the wanted and unwanted signals are assumed to be uncorrelated (ρ=0).

$$\sigma_{res} = \sqrt{\sigma_{wanted}^2 + \sigma_{uwanted}^2 - 2\rho\sigma_{wanted}\sigma_{unwanted}}$$

$$\sigma_{res} = 5.6 \text{ dB for outdoor and } \sigma_{res} = 8.4\ dB \text{ for indoor}$$

The resulting Location Correction Margin *(LCM) based on the required percentage locations is subtracted from the Adjacent channel protection ratio to produce the Protection Margins in Table I3.*

Table I3: Protection Margin figures used in the UK

Scenario	Percentage Locations (%)	Protection Margin (dB)		
		1st Adjacent	2nd Adjacent	≥3rd Adjacent
Outdoor Mobile	99	22	27	32
Indoor Robust	95	21.2	26.2	31.2
Indoor Marginal	80	27.9	32.9	37.9

In Figure I7 the predicted Mobile coverage loss is displayed along with the difference between the Median wanted and the Median unwanted measured field strengths within 100 m pixels. These results are plotted for the 27 dB Protection Margin to show pixels that may be affected by 2nd Adjacent Channel Interference.

These measurements compare well with the prediction. However it is also necessary to confirm whether the measured Median wanted field strength for channel 11D is strong enough to provide a service as shown in Figure I8.

These measurement results show that much of the centre of the town and particularly on the A416 does not have a mobile service and that the additional interference from a 2nd adjacent service from the new Chesham transmitter would only slightly increase the unserved section of the A416. It was considered that the Mobile interference case was not sufficient to require a filler transmitter to be provided.

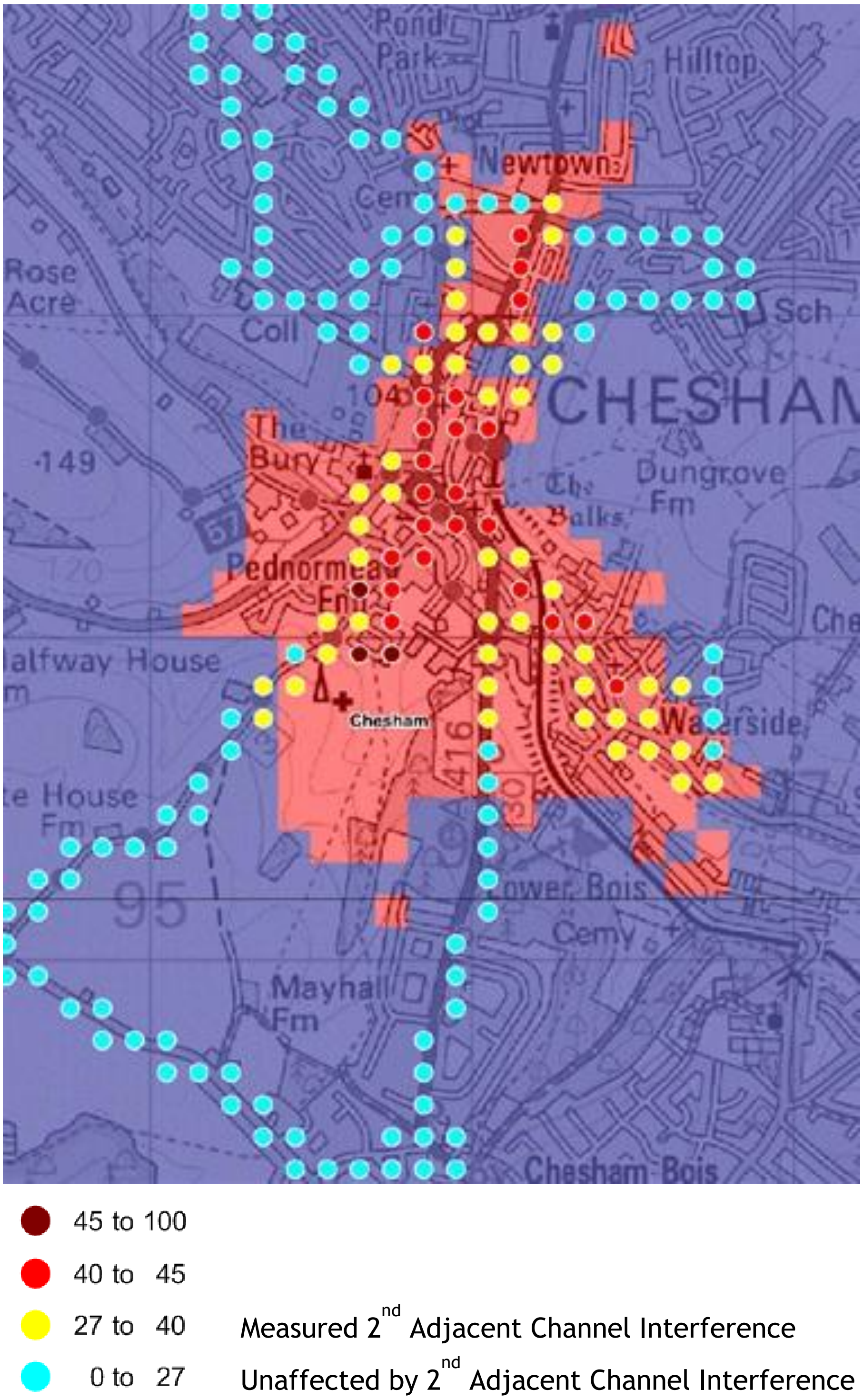
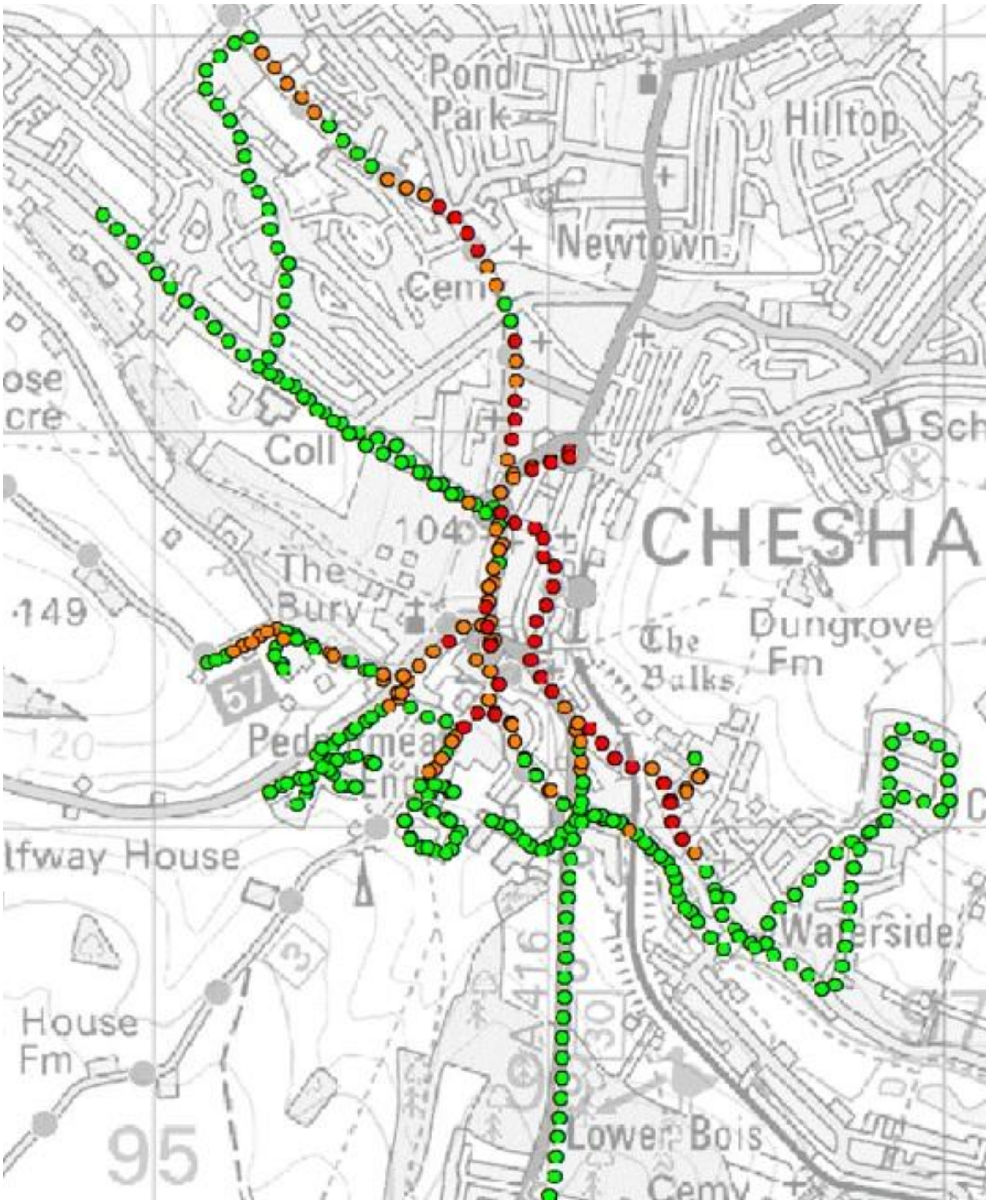


Figure I7: Predicted channel 11D mobile SFN coverage in Chesham before and after the channel 12B transmitter is brought to air at 100 W ERP compared with the Measured Field Strength Difference.



🟢	Field strength equal to or greater than the derived minimum field strength for a mobile service (44 dBuV/m at 1.5m a.g.l.)
🟠	Field strength with less than 3 dB margin (i.e. lower than 47 dBuV/m at 1.5m a.g.l.)
🔴	Field strength lower than the derived minimum field strength for a mobile service

Figure I8: Measured field strength data for the channel 11D service in Chesham before any ACI but showing areas considered unserved for a mobile service.

I3 Indoor coverage

Some indoor coverage for channel 11D is predicted at populated areas close to the site. Figure I9 highlights the change in predicted coverage pre- and post-ACI.

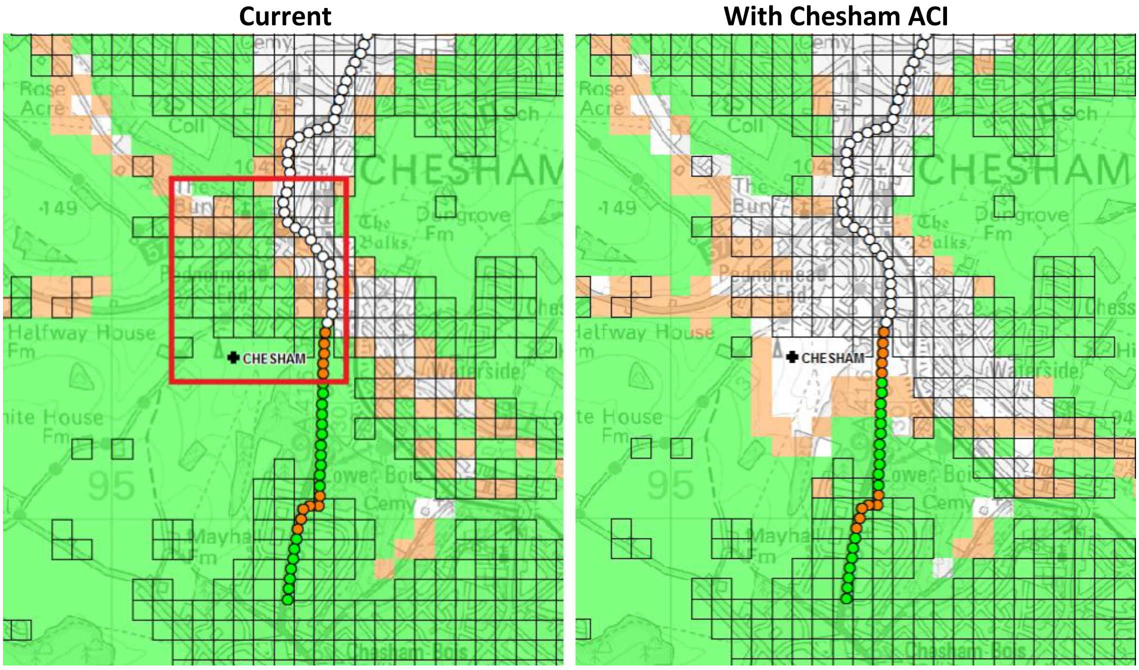


Figure I9: Predicted indoor coverage overlaid with surveyed field strength corresponding to good and robust indoor reception, and with □ populated pixels

While the area highlighted in the red box is at an elevated position and is predicted to be served, predominantly by Hemel Hempstead, measurements from the drive survey suggest a sharp drop in field strength to the north of the site, consequent with the steep drop in elevation from around 125 m above ordnance datum to 90 m in the centre of the town.

When assessing new transmitters for potential Indoor ACI the process is adapted to allow for areas where the service is not completely lost, this is because an indoor receiver can be moved around to recover reception. Obviously the closer to the interfering transmitter the more likely it is that ACI will be a problem.

Those households that may drop from a predicted robust service (95% locations served) to a predicted Good/Marginal service (80% locations served) are still considered served. The difference in predicted coverage in Chesham for the channel 11D service is 785 households. This figure is investigated further by banding the results to show what level of service is left for those households that have degraded below the Good/Marginal service (80% of locations served indoor). This is again sensitivity tested for radios with a Protection Ratio 5 dB better than assumed (to allow for more recent radio performance). The results for this analysis are shown in Table I.

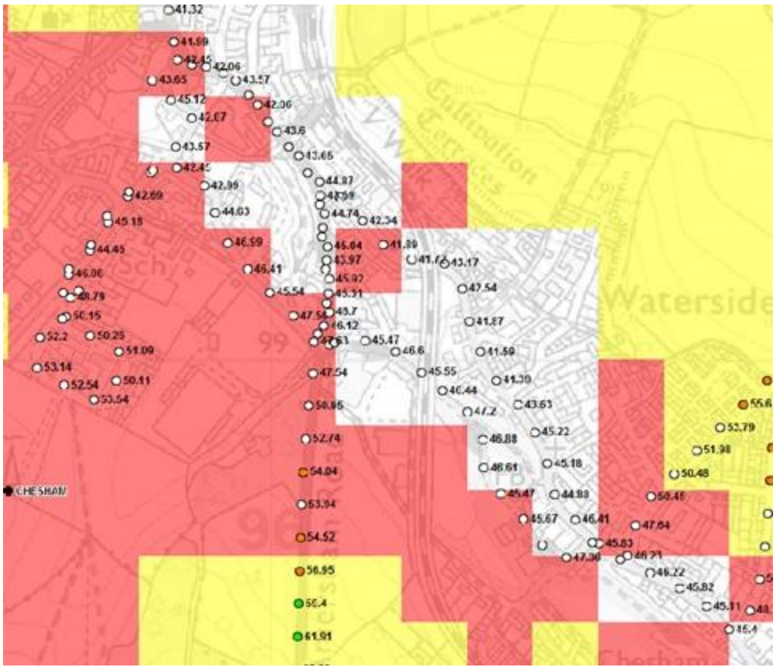
The table shows that of the 785 households predicted to fall below 80% locations served many remain in the 60 - 80% locations served categories. The bands below 50% locations are taken as fully lost and all households counted, the bands between 50% and 80% are counted proportionally (% locations remaining served in pixel x number of households in pixel) and summed to produce a degradation count, which can be seen in the total impact row.

For the case of the standard UK Protection Ratio 233 households are predicted to be impacted and for the Protection Ratio +5 dB case the impact is predicted to be 50 households.

Table I4: Predicted ACI impact to an indoor service banded by percentage locations remaining served

Predicted ACI impact by banded percentage locations		
Percentage Locations Range	Predicted Loss in Households	
	Standard Protection Ratio (40 dB)	Protection Ratio + 5 dB (45 dB)
0 - 9.9	0	0
10 - 19.9	0	0
20 - 29.9	1	0
30 - 39.9	73	0
40 - 49.9	64	1
50 - 59.9	34	15
60 - 69.9	235	179
70 - 79.9	378	82
Total impact	233 households	50 households

Figure I10 shows that from the survey measurements the channel 11D service is not strong enough to provide an indoor service within some of the pixels predicted to be served.



Field strength equal to or greater than the derived minimum field strength for a robust indoor service
Field strength equal to or greater than the derived minimum field strength for a good/marginal indoor service
Field strength less than the derived minimum field strength for an indoor service
predicted loss due to ACI and predicted to remain served with ACI

Figure I*10*: Measured field strength of channel 11D in areas predicted to be affected by ACI

The process used in the UK for counting an Indoor ACI impact from survey measurements is:

a) Make as many mobile measurements in as many locations as possible recording the channel 11D and channel 12B field strength values simultaneously.

b) Identify 100 m pixels where the channel 11D Median field strength is greater or equal to the Minimum Median Field Strength for a Marginal indoor service (80% Locations indoor). These have been identified in Figure I11 with Green or Yellow dots.

c) Of these identified pixels count the proportion of measurement points within each 100 m pixel, that have a field strength difference exceeding the 2nd Adjacent Protection Ratio (40 dB in the UK).

d) Multiply the proportion result for each pixel by the number of households in that pixel. These are the Blue squares in Figure I11.

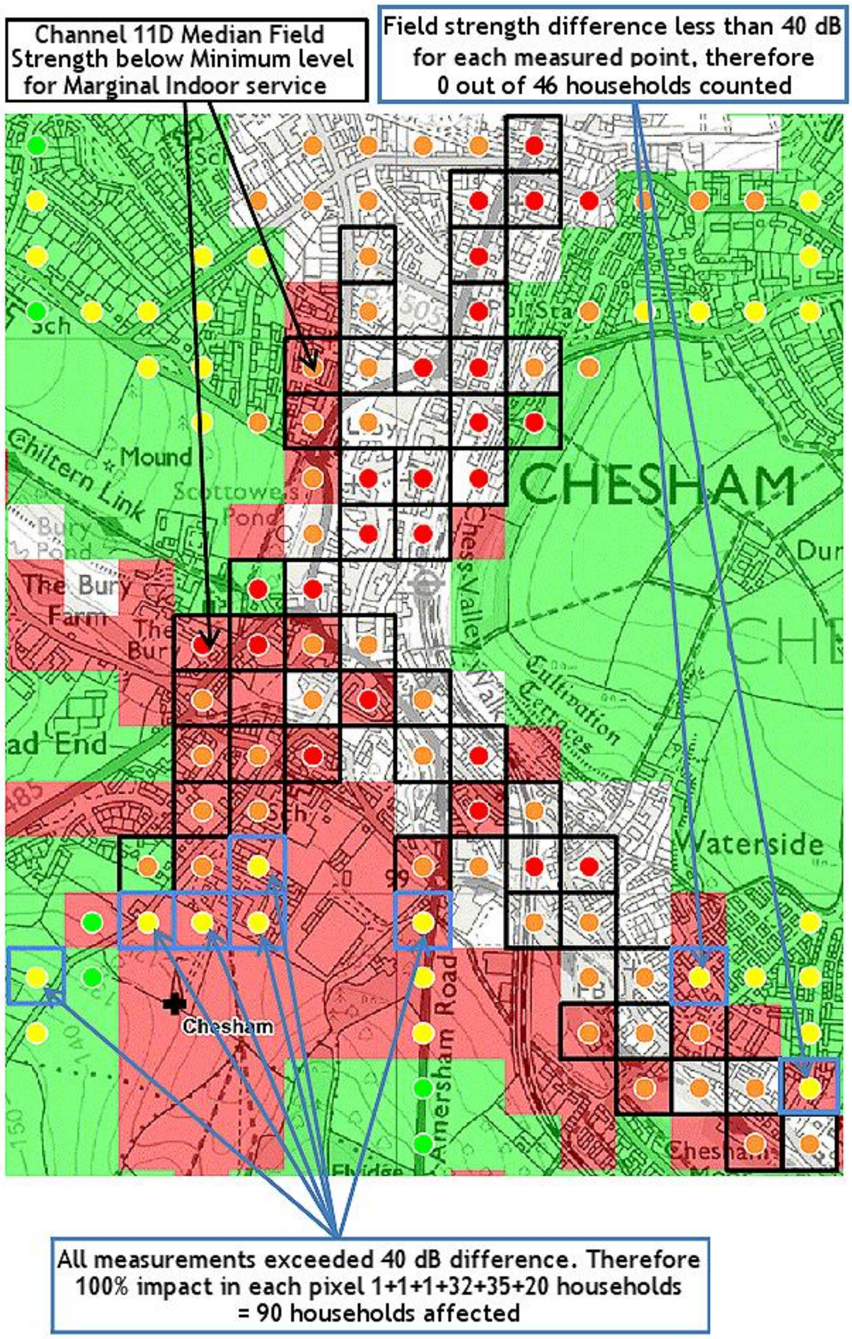
e) Sum the number of affected households to compare with banded prediction result.

Figure I11 summarises the Chesham example with the above method for indoor counting.

Predictions indicated the Red squares to be affected by ACI, when considering the measurements 8 populated pixels have been highlighted as having at least the Minimum Median field strength for a Marginal Indoor service. Of these 8 pixels only 6 pixels had any measurement points with a difference in field strength greater than the 2nd adjacent protection ratio (40 dB in the UK). Within those 6 pixels all measurement points were found to have a field strength difference of greater than the 40 dB ratio and hence 100% of households were counted for each, resulting in a total of 90 households

The resulting impact from measurements was counted as 90 households that may not be protected. This is compared with the resulting impact from predictions which was 785 households for an 80% locations threshold count, this was reduced to 233 households by applying the percentage locations banding in Table I and reduced further to 50 households when the Protection Ratio was increased by 5 dB.

It can be seen that the measured impact of 90 households is between the two prediction results based on percentage locations banding and was closer to the figure when +5 dB is added to the protection ratio. However it is more likely that it reflects those households that are predicted to be heavily degraded (i.e. below 50% or 60% locations remaining served). This has been found to be the case for other examples and a balanced approach is adopted for making the decision between interested parties as to the need for an ACI filler transmitter based on indoor reception. Typically broadcasters are concerned when the banded impact is heavily degraded (majority of impacted households falling below 60% locations) or the total banded result is greater than approximately 200 - 300 households and only reduces slightly with the Protection Ratio +5 dB sensitivity test.



- Field strength ≥ the derived minimum field strength for a Robust indoor service
- Field strength ≥ the derived minimum field strength for a Good / Marginal indoor service
- Populated Pixel affected by 2nd Adjacent Channel Interference
- Populated Pixel Unaffected by 2nd Adjacent Channel Interference

Figure I11: Populated pixels to be analysed based on measured field strength of channel 11D overlaid on areas predicted to be affected by ACI

It can also be noted in Figure I11 that one pixel to the West of the new site was predicted to remain served but actually the measurements showed this pixel was 100% impacted.

The comparison of measurements to prediction showed that 379 households that were predicted to be lost were not actually served to begin with.

Annex J: Tunnel coverage

J1 *Radiating cable system*

J1.1 DAB tunnel system

DAB tunnel coverage and, for safety reasons, voice break-in is provided by the DAB tunnel system in Switzerland. The system is comprised of two functional blocks, the repeater stage and the voice break-in stage. Both functional blocks use common elements such as the reception antenna, preamplifier, channel selection, filtering, voice-break-in stage, distribution to amplifying sites, amplifying and radiation of the signal into the tunnel. Several DAB ensembles are combined into the broadband distribution and amplifying stage; in most cases this already exists for FM and PPDR radio services.

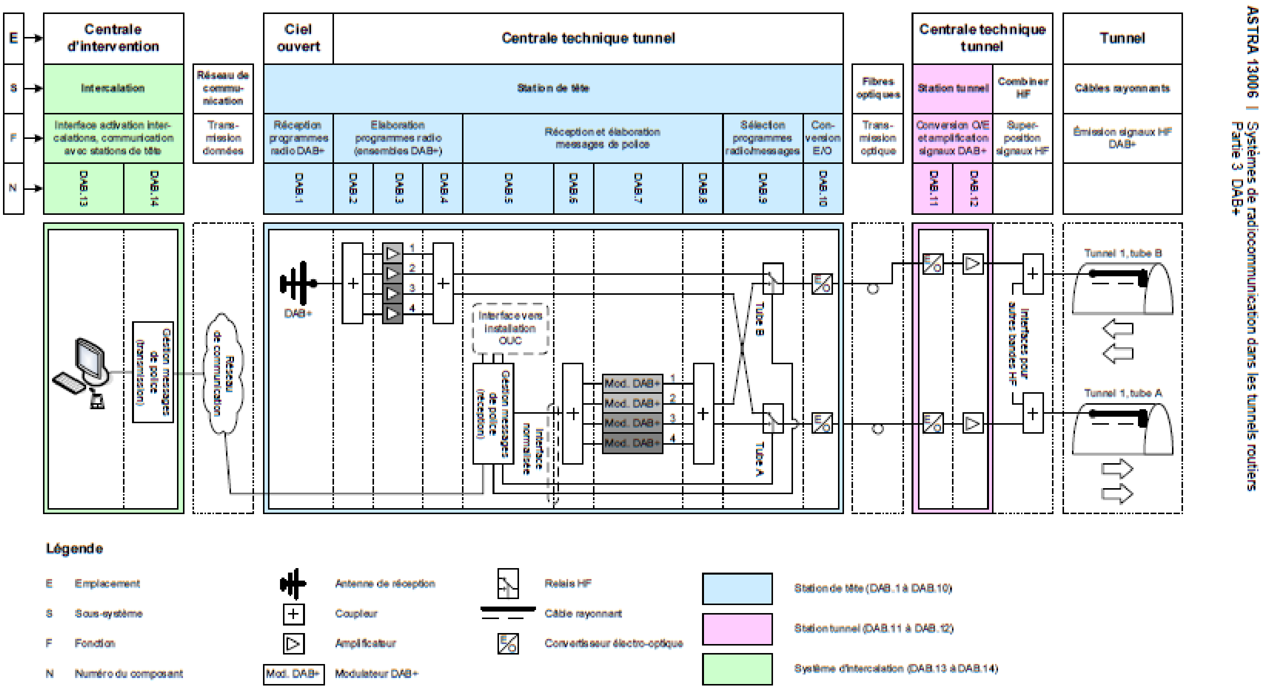


Figure J1: Overview of a DAB tunnel-system (courtesy of Swiss Federal Roads Authority)

J1.2 Minimum coverage criteria for DAB+

The minimum field strength shall reach 52 and 56 dBµV/m typical to ensure minimum coverage in case of higher man-made-noise levels within the tunnel. In any condition, the minimum C/N for mobile reception depicted in Table 8 of this report shall be fulfilled.

The minimum coverage criterion is based on the following vehicle receiver specification. A DAB digital radio in-vehicle receiver with integrated antenna shall provide audio reception when receiving a DAB signal with a field strength signal greater than FSRmin in a Rayleigh transmission channel. FSRmin=[34.7 + 20 log(F/220)] dBµV/m, where F is the frequency in MHz. Receivers supplied without an antenna shall be capable of providing audio reception with an input power level of -92.2 dBm when fed by a DAB signal with Rayleigh transmission channel characteristics. The external antenna shall reach a gain of -2.9 dBi or greater to produce this power at the required minimum field strength.

J1.3 Measuring coverage

For measuring the minimum coverage criteria within the tunnel, a set of consecutive measurement samples shall be calculated to a floating average value. The window for this floating average shall be carefully limited in order not to hide the result of the minimas. The optimum window length is seen at around 20 m.

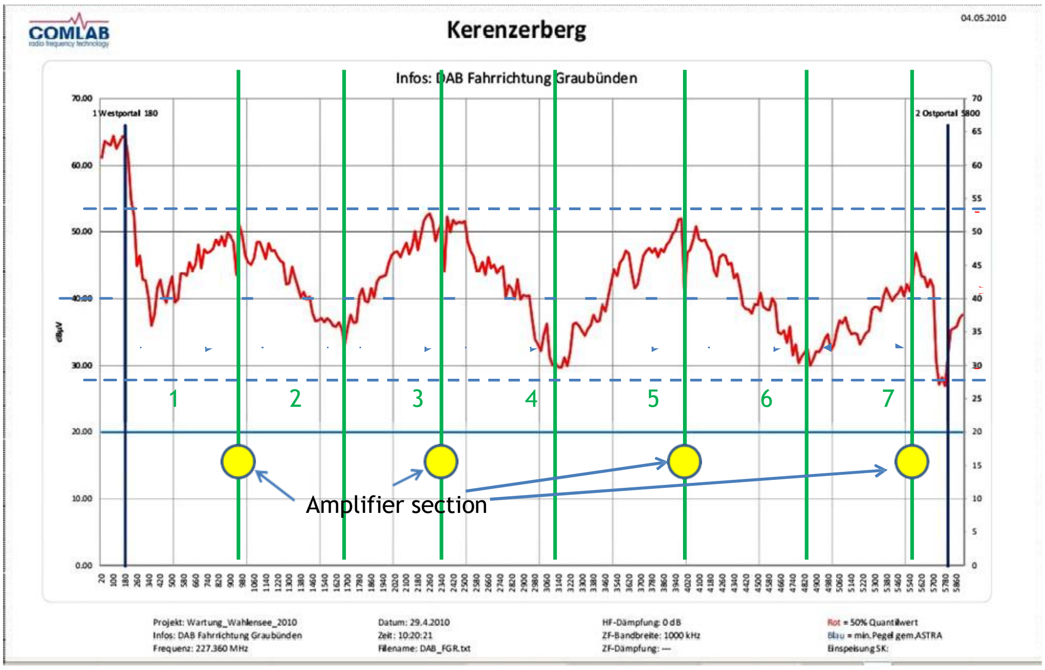


Figure J2: Sample measurement for minimum coverage criteria for DAB
(courtesy of Comlab AG, measurements performed with a rooftop quarter wave antenna with k factor of 16 dB/m)

J1.4 Maximum signal delay

For a very long tunnel or a series of tunnels connected to the same reception site the delay within the tunnel-system shall be limited or respected in the SFN-planning of the terrestrial network. To allow any positioning of the receivers FFT window, delays of more than half of the guard interval shall be avoided. Relevant delays between terrestrial and in-tunnel signal may occur if the reception site is at the far end of the tunnel and the signal flow is pointing in direction of the feeding transmitter.

J1.5 Additional criteria for DAB+ voice break-in

The voice break-in system shall be able to follow any change of services within a DAB-ensemble as defined by the broadcaster.

In order to ensure voice break-in functionality within the full length of the tunnel, the in-tunnel radiated signal shall reach the minimum C/N over the terrestrial signal at the entrance of the tunnel. At the tunnel entrance where a strong terrestrial signal of the same channel might be present the field strength of the in-tunnel signal has to be raised accordingly.

J1.6 System integration

Due to the low spectral density of the DAB signal, any risk of interfering with existing PPDR radio services is significantly lower compared to FM.

The radiating cable should be installed underneath the top of the tunnel in order to ensure an optimum coverage of all lanes.

J2 Tunnel coverage by terrestrial antennas

Radio service diffusion inside tunnels requires specific methods. The most popular and reliable techniques are based on the radiating cable; unfortunately, its installation and maintenance costs become greater as the tunnel length increases. Furthermore, adding DAB services over an existing radiating cable (already serving other radio services) requires the modification of the RF branching system which increases its costs and complexity.

Because of the high implementation and maintenance costs of this solution, RAI Research Center investigated the possibility of proving coverage inside tunnels using the direct transmission by means of antennas situated inside or nearby the tunnels [EBU Technical Review March 2017 - A. Morello, S. Ripamonti, M. Tabone, G. Vitale - "DAB+ Signal Propagation in Tunnels"].

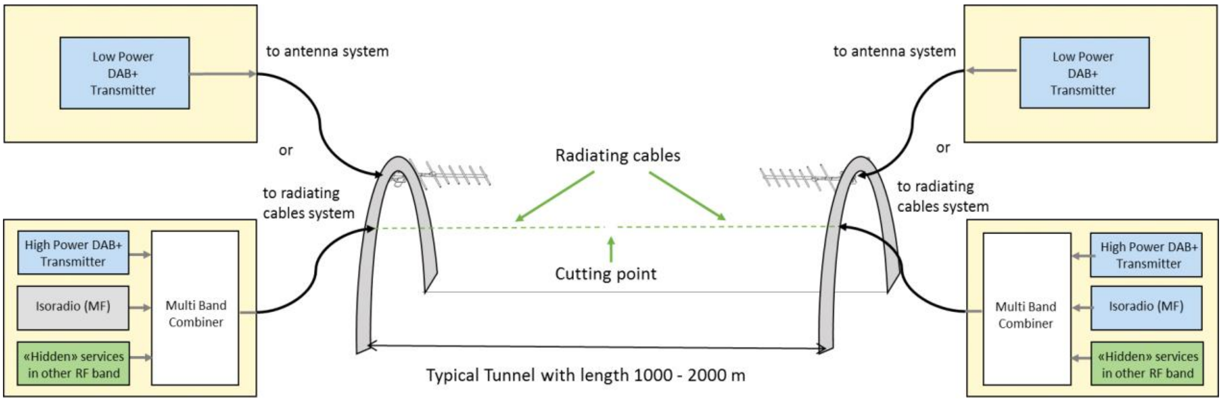


Figure J3: Radiating cable VS directive antenna

Since the technical literature on this subject is sparse, Rai performed an extensive measurement campaign in order to obtain some preliminary results about strengths and weaknesses of the direct antenna irradiation into tunnels. Since November 2015 a lot of tests were run in the Apennine section of the Italian A1 highway, focusing on DAB system on 226 MHz.

Preliminary tests on the A5 highway between Turin and Aosta, using a transmission from HPHT sites (Col Courtil and Saint-Vincent-Salirod transmitting sites) showed that RF signal penetration within tunnels of about 180 m occurred. A further measurement campaign was executed on the A1 highway between Bologna and Florence, in order to define some general design parameters and a simple network infrastructure for the implementation of DAB radio services diffusion in tunnels.

To ensure DAB signal coverage in tunnel environments by means of HPHT and complementary LPLT networks (in mountainous areas), an RF signal was transmitted from just outside (max. distance 300 m.) both sides of the tunnel entrance.

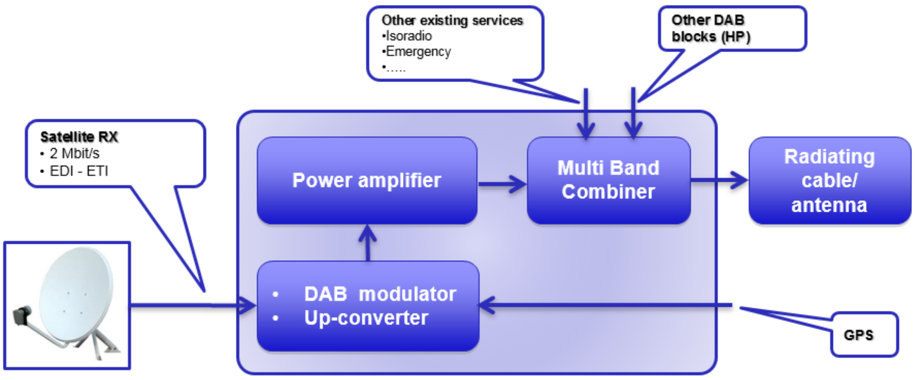


Figure J4: Hypothetical LPLT system serving the tunnels

Several tests were run with and without vehicular traffic, at different transmission powers (1 W and

4 W) and signal polarizations (H/V). The data collected were:

1) Electro-Magnetic (EM) field strength was sampled every 10 cm by a professional measurement test set, with GPS + odometer high accuracy position recording.

2) EM field measurements sampled every second by using a DAB+ professional receiver.

3) Subjective signal evaluation by listening to an integrated on board consumer receiver, in order to identify the real service threshold in terms of signal power.

The RF signal was received using a roof-top vertical whip antenna ($\lambda/4$). Supported by a statistical analysis of signal fluctuations, tests were based on the "45 dBμV/m criterion", according to the conventional open-air HPHT planning (Recommendation ITU-R P.1546).

Polarization, *morphology* and *traffic* are the main factors influencing the signal propagation inside tunnels.

Tests indicate that horizontally polarized signals always propagate better than vertically ones, providing a simplified rule to fix some maximum tunnel coverage parameters.

Table J1: DAB coverage inside tunnel with traffic

Worst case coverage with traffic	
TX from tunnel entrance (D=0)	700 m
External TX (D<300 m approx.)	300 m

D = distance from the tunnel entrance

Transmitting from both sides of the tunnel entrances could provide coverage of between 1400 m and 600 m if the antenna is placed within 300 m of the tunnel entrance.

Traffic also has an important role in tunnel propagation, depending on its intensity. Tests revealed that light traffic (cars only and/or few heavy vehicles) has a low impact on signal propagation. In such conditions the increase in propagation loss (linear degradation in regular trunks) is about 0.5 dB/100 m. The substantial presence of heavy vehicles (i.e. trucks, buses, etc.) deeply influences the signal propagation and, in some cases i.e. congested tunnel and trucks overtaking each other, a sort of service blockage/unlocking has been observed. This last case is still under investigation: a new ad hoc measurement campaign is planned in order to observe, from a statistical point of view, the impact of very dense traffic conditions on tunnel propagation. For this purpose, a fixed test bed will be installed in a highway tunnel on the A1 between Bologna and Florence, in order to get long term measures.

Additional studies will be done on tunnel morphology, trying to find out if this simplified approach could be limited by tunnel materials, presence/typology of curves, number of lanes, etc.

Annex K: Dynamic reconfiguration of a DAB ensemble to enable regional services within a national SFN

In some countries the number of frequency blocks available for DAB could be very limited and, by contrast, the number of programmes to be transmitted could be very high. The broadcasters are also requested to make efficient use of the scarce available spectrum.

Moreover, in some countries, public broadcasters need to transmit national and regional or local content and these latter can be time-limited, consuming only a only few hours a day. Different solutions can be chosen to meet these requirements and one of them, devised by Rai Way and RAI Research Centre, is the dynamic reconfiguration of the DAB ensemble.

This method is realized through a DAB Single Frequency Network with frequency reuse 1, on which both national and regional/local contents are conveyed.

The scheme of the broadcasting Mode is shown in Figure K1.

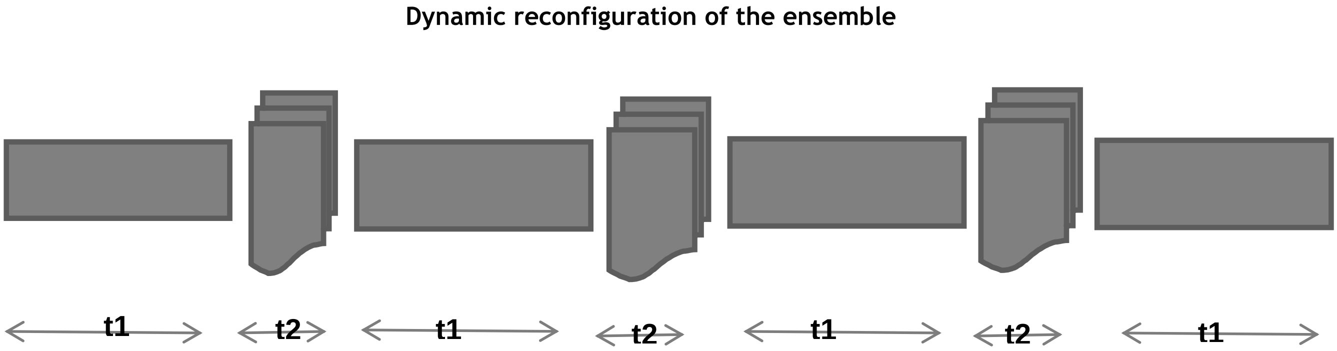


Figure K1: Scheme of the broadcasting method

During the time intervals t1, the national programme only, is broadcast; during the time intervals t2, regional and national programmes are broadcast together.

The dynamic reconfiguration is useful when t1 is much greater than t2, for example t1 = 7 hours and t2 = 1 hour.

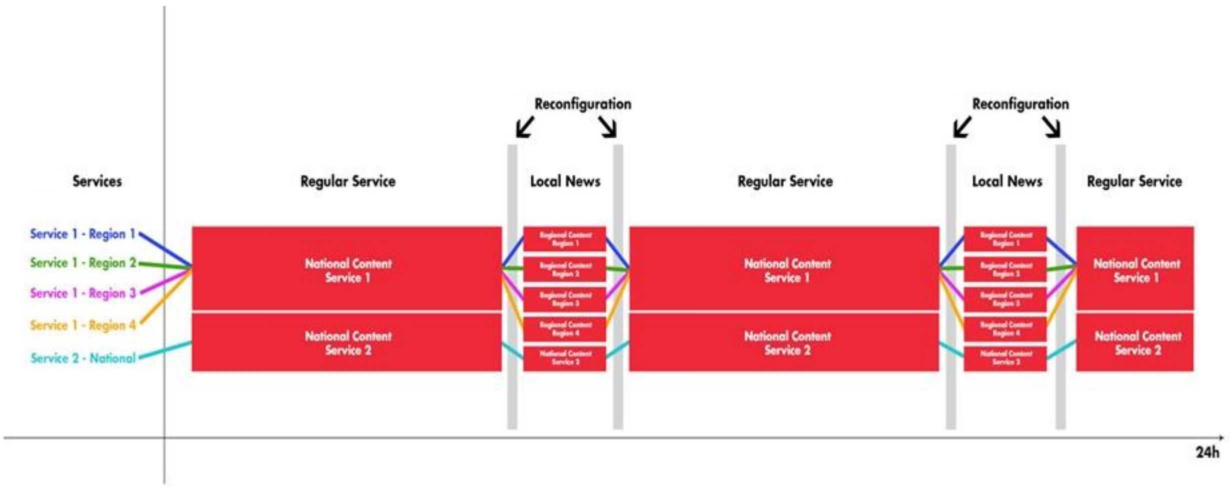


Figure K2: Scheme of the ensemble reconfiguration

The working principles are very simple. The DAB ensemble can be considered as being composed of services and contents. Only one multimedia content can be associated to each service but, conversely, one multimedia content can be associated to more than one service.

The assumption is that all the services are continually declared regardless the configuration that is in force at a specific time.

After the first tuning or after any re-tuning of the receiver, all services are listed in the service list, i.e. S1 - R1, S1 - R2, ... S1 - Rn, S2.

When the national programme is transmitted, each S1 - Ri service is linked to the same content. Moving from one S1 - Rx service to another S1 - Rz service, the listener hears the same programme.

The reconfiguration of the ensemble from national to regional mode links each S1 - Rn service to its own content. Therefore, after the reconfiguration, different programmes can be listened to moving from one S1 - Rx service to another S1 - Rz service.

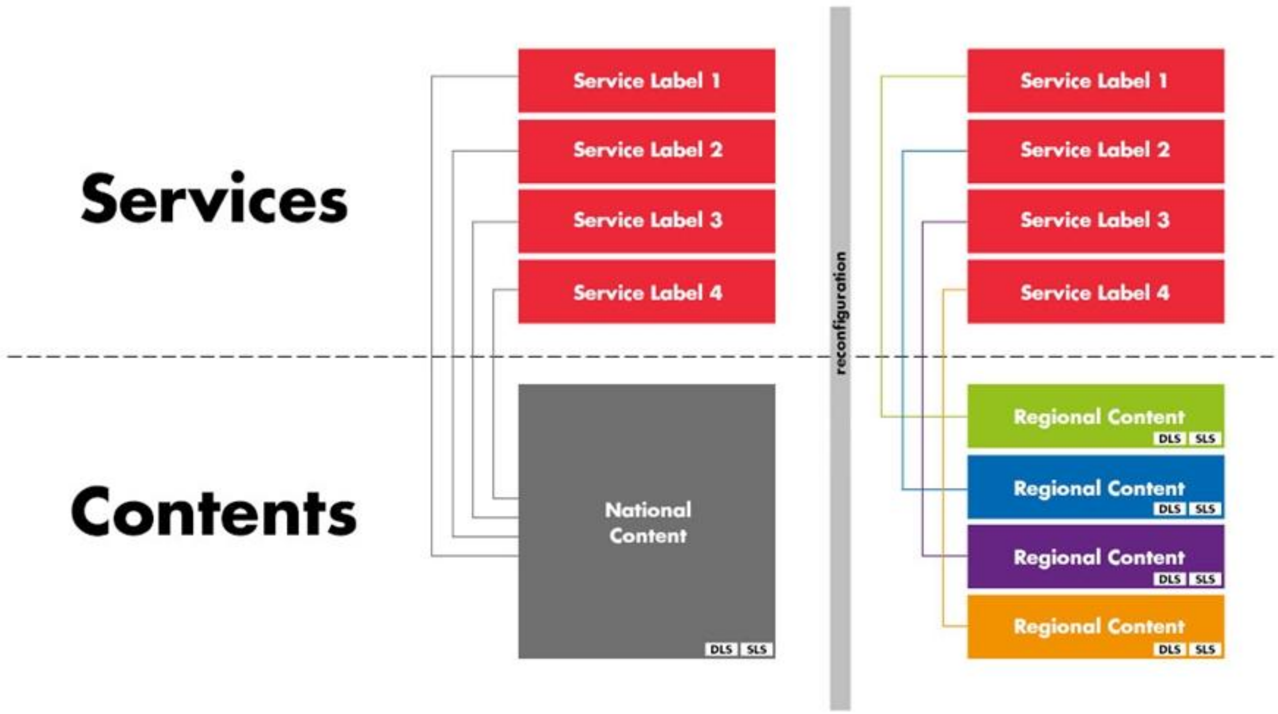


Figure K3: Scheme of the ensemble content before and after the reconfiguration

The maximum number of different contents that could be transmitted depends on the bit rates chosen for the services. The capacity available for a DAB multiplex is of 864 Capacity Unit (CU) and such capacity cannot be exceeded.

For example, Rai Way had some tests, also reported in the following figures, using 96 CU (128 kbit/s) for the national service that was split into four regional services of 24 CU (32 kbit/s) each.

In Figure K4 and in Figure K5 the results of the ETI analysis are reported. In the first figure the services and the content of the national service are identified.

In the second figure, after the regional reconfiguration, four regional services with different contents and languages are displayed.

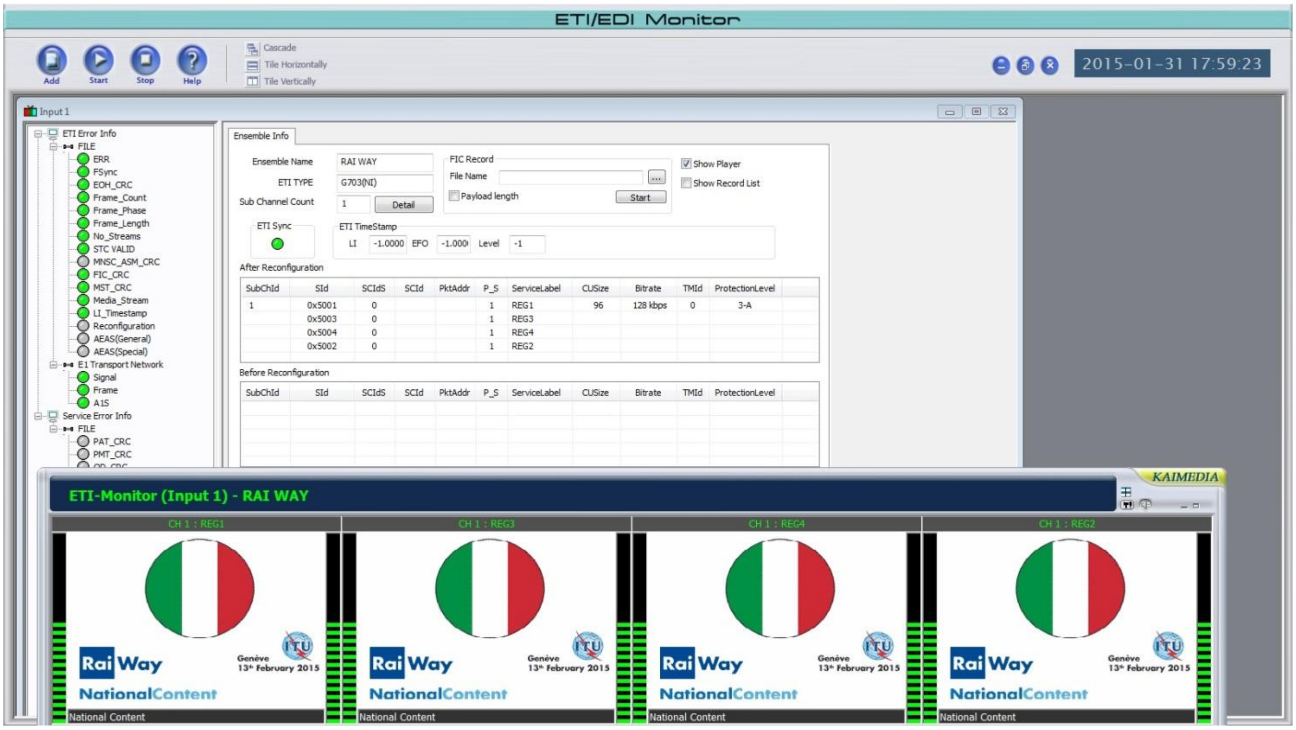


Figure K4: ETI analysis with the national service

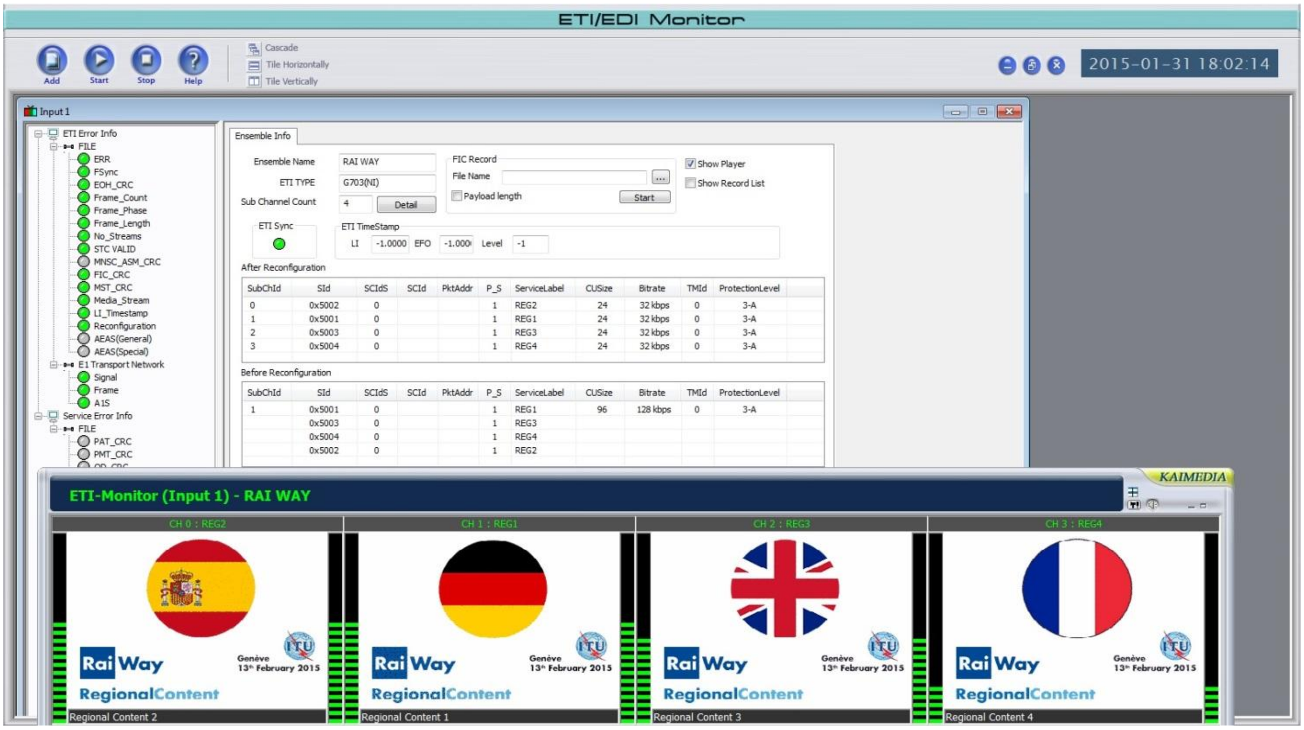


Figure K5: ETI analysis with regional services