HD Radio™ System
Planning Parameters for VHF Band II

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Table of Contents

Contents

List of Figures

List of Tables

1. Introduction

The HD Radio hybrid configuration makes use of the existing VHF Band II allocations and embeds new audio and data services along with the existing analogue FM. The IBOC implementation preserves the analogue broadcast located on the main frequency assignment and adds low-level digital signals immediately adjacent to the analogue signal. These digital signals, immediately adjacent to the analogue, may be on either side of the analogue signal or on both sides. This approach, as mentioned previously, is known as In-Band On-Channel (IBOC).

IBOC, as implemented by the HD Radio system, retains the power of the analogue signal, while adding digital carriers within a controlled bandwidth and at lower power levels. This design allows for adjustment of the bandwidth and power of the digital signal, making possible controllable tradeoffs between coverage of the digital signal and adjacent channel availability.

For the purpose of deploying the HD Radio FM system in the VHF Band II, certain reception performance may be considered.

This document provides a summary of requirements in order to allow for adequate reception performance. The analysis follows the guidance in the applicable ITU requirements documents. However, ITU documents that were available when the HD Radio system was designed did not cover all reception aspects and evolving devices. Therefore, as a complementary measure and where applicable, the analysis follows other applicable guiding documents and practices from Region 1 and from the USA.

2. Configurations and Definitions

The HD Radio system is designed to allow for numerous configurations. The configurations allow for different bandwidth settings, frequency positioning, band combining, and different throughput. These configurations are captured in standard documents, such as NRSC-5-C or other design documents. While the system has provision for several configurations, only a subset is initially implemented and proposed for deployment in Brazil. However, at a future time, additional configurations may be implemented as suitable for one location or another. A subset of these configurations is briefly described in the present document in conjunction with the provided planning parameters and deployment aspects.

2.1. HD Radio System Configurations

This analysis includes the configurations that are considered suitable for initial deployment in Brazil. At a future time, additional configurations may be considered for deployment in Brazil. The analysis can then be expanded to include such additional configurations.

The system can be configured to use a single frequency block that employs 70-kHz digital signal bandwidth or a single frequency block that employs 100-kHz digital signal bandwidth. The configuration is defined by system modes, and provides various combinations of logical channels, bit rates, and protection levels.

When configured to use a single frequency block that employs 70-kHz bandwidth, the system may be configured by mode MP9. It then employs logical channel P1 and provides a throughput (net bit rate) of 98.3 kbit/s. The employed modulation is QPSK.

When configured to use a single frequency block that employs 100-kHz bandwidth, the system may be configured to mode MP8 or mode MP19, which allows for a tradeoff between throughput (net bit rate) and robustness. When configured to mode MP8, the system employs logical channel P1 and provides a throughput (net bit rate) of 98.3 kbit/s. When configured to mode MP19, the system employs logical channels P1 and P3, and provides a throughput (net bit rate) of 122.9 kbit/s. The employed modulation is QPSK.

The HD Radio system also supports joint configurations of two digital bands. These two digital bands are treated as two independent signals, in the context of planning, sharing, and compatibility for Band II. The joint configurations provide higher robustness or otherwise support higher throughput (net bit rate). When configured to use 2 x 70-kHz bandwidth, the system may be configured by mode MP1. It then employs logical channel P1 and provides a throughput (net bit rate) of 98.3 kbit/s. When configured to use 2 x 100-kHz bandwidth, the system may be configured by mode MP11. It then employs logical channels P1, P3, and P4, and provides a throughput (net bit rate) of 147.5 kbit/s.

The essential characteristics of the HD Radio system configurations (operating modes) are summarized in Table 2-1.

Table 2-1: Characteristics of various HD Radio System Operating Modes

System Mode	Used BW [kHz]	Total[1] bit rate	Channel P1		Channel P3		Channel P4		Comments
			Code rate	Bit[1] rate	Code rate	Bit[1] rate	Code rate	Bit[1] rate	Interleaver span
MP9	70	98.3	4/5	98.3	-	-	-	-	P1: ~1.5s
MP8	100	98.3	4/7	98.3	-	-	-	-	P1: ~1.5s; additional diversity delay
MP19	100	122.9	4/5	98.3	1/2	24.6	-	-	P1: ~1.5s; P3: ~3s
MP1[2]	2x 70	98.3	2/5	98.3	-	-	-	-	P1: ~1.5s
MP11[2]	2x 100	147.5	2/5	98.3	1/2	24.6	1/2	24.6	P1: ~1.5s; P3/P4: ~3s

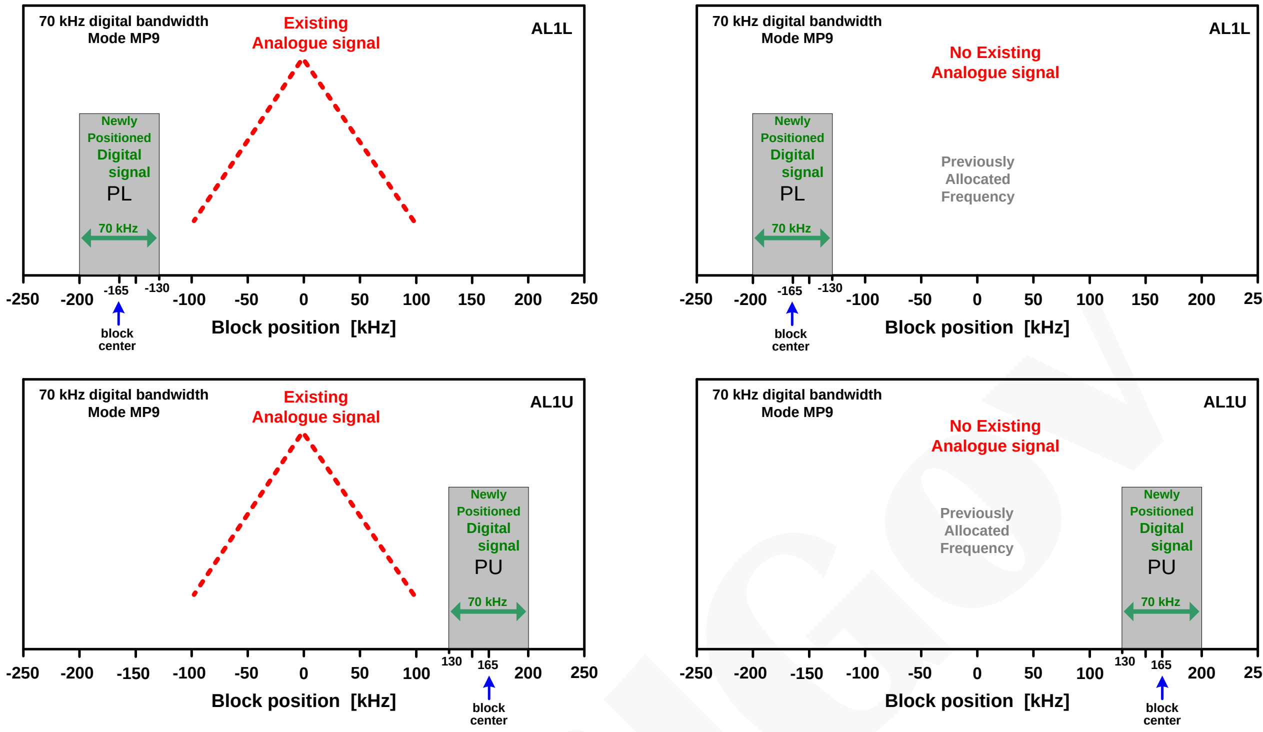
Note 1: the bit rates reflect the throughput ('net' bit rate) by the application layer, and do not include the overhead used by the physical layer.

Note 2: Joint configuration of two digital signal blocks for enhanced performance or features. The digital blocks may be adjusted independently for power level.

Additional HD Radio system signal parameters (physical layer) for VHF Band II are provided in Table 2-2.

Table 2-2: HD Radio System Physical Layer Parameters

Parameter Name	Computed Value (rounded)
Cyclic Prefix Width α	0.1586 ms
Symbol Duration (with prefix) T_s	2.902 ms
Number of symbols in a block	32
Block Duration T_b	9.288 ms
Number of blocks in a frame	16
Frame Duration T_f	1.486 s
OFDM Subcarrier Spacing Δf	363.4 Hz
Number of carriers	70 kHz band : 191 100 kHz band: 267
Used bandwidth	70 kHz band : 69.4 kHz 100 kHz band: 97.0 kHz



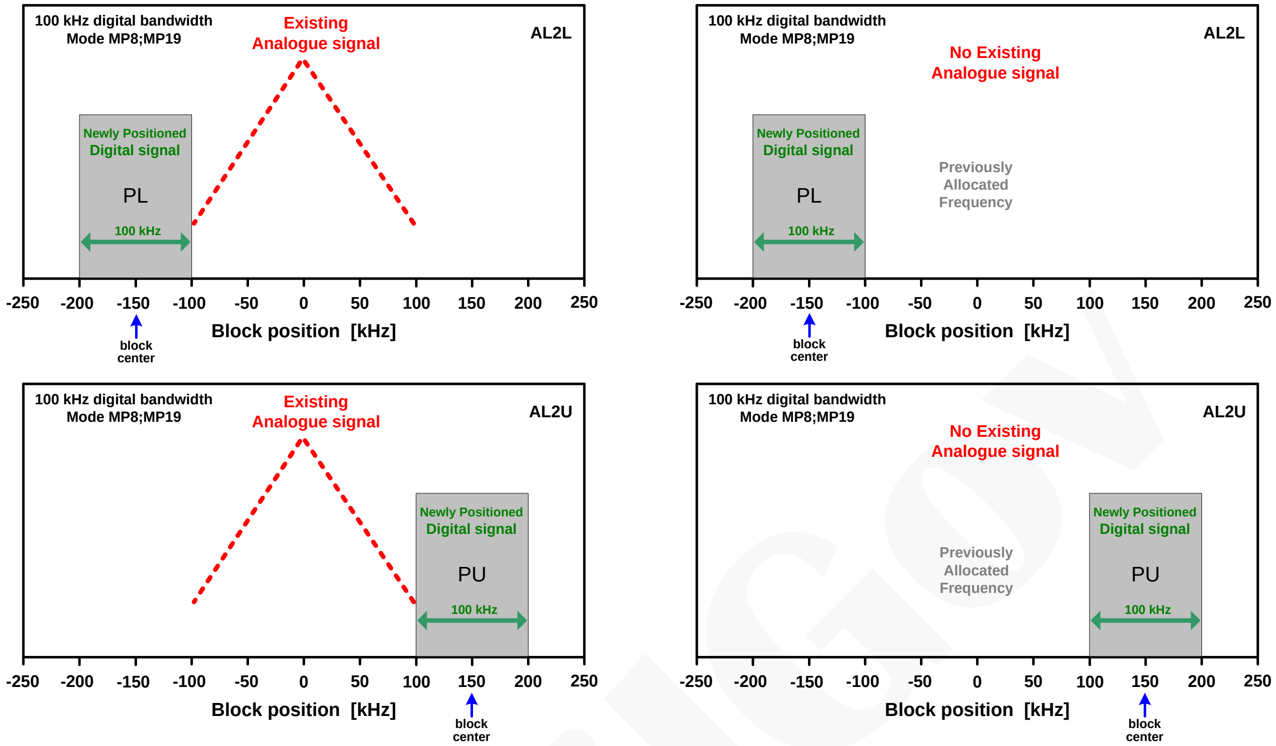
Note: PL and PU are used for indicating lower positioning and upper positioning (respectively) of the digital block. The indication is for convenience only, and does not suggest an actual difference in the signal.

Figure 2-1: HD Radio System 70-kHz Digital Block Positioning Examples

In the US, the fundamental channel raster in VHF Band II is based on 200-kHz spacing. The HD Radio system presumes that the digital signal blocks are at pre-defined positions. As can be seen from the diagrams in Figure 2-1 and Figure 2-2 that these positions are not centred on the 200-kHz raster but in between. It has to be noted that the block position of 0 kHz in the figures below corresponds to the reference analog frequency for the HD Radio signal.

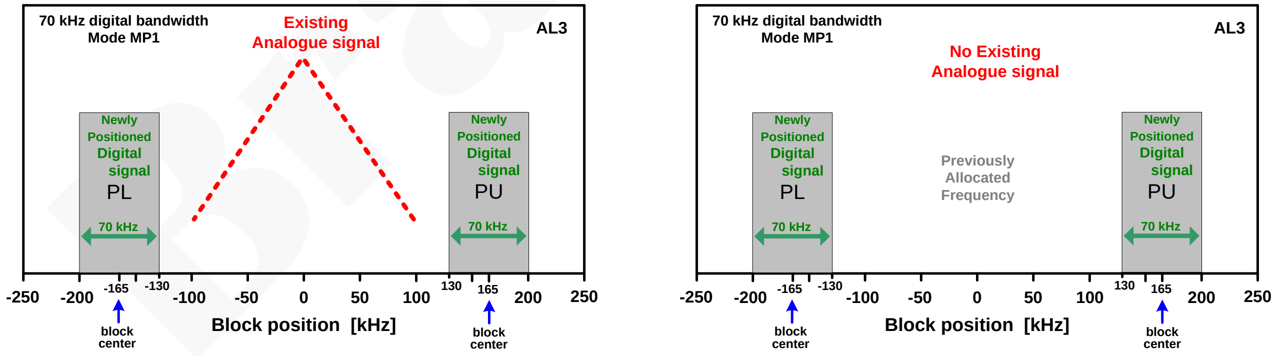
The reference analog frequency may represent an actual analog host signal when operating in hybrid configuration and employing a composition of either two signals (one analog and one digital band) or three signals (one analog and two digital bands). The analog reference frequency may represent the center frequency of a vacant band of a previously existing analog host signal, while the system operates in all digital configurations. Such reference also demonstrates that a transition from hybrid configuration to all digital configurations does not have to change the digital signal allocation or configuration. Practically, it is expected to be followed by increasing the digital signal power.

Additional configurations allow for expanded signal composition, where two digital blocks of 70 kHz each as shown in Figure 2-3, or two digital signal blocks of 100 kHz each as shown in Figure 2-4, are employed jointly for providing more options for tradeoff between throughput (net bit rate) and robustness.



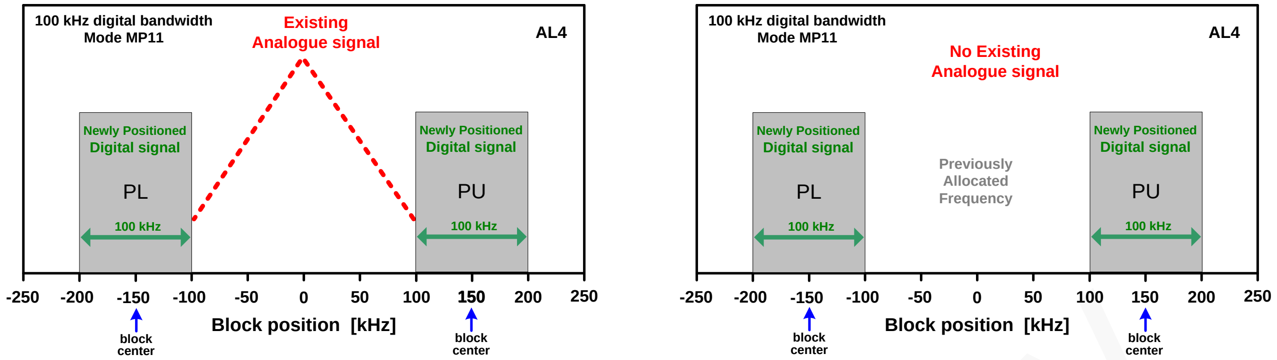
Note: PL and PU are used for indicating lower positioning and upper positioning (respectively) of the digital block. The indication is for convenience only, and does not suggest an actual difference in the signal.

Figure 2-2: HD Radio System 100-kHz Digital Block Positioning Examples



Note: PL and PU are used for indicating lower positioning and upper positioning (respectively) of the digital block. The indication is for convenience only, and does not suggest an actual difference in the signal.

Figure 2-3: HD Radio System 2 x 70-kHz Digital Block Positioning Examples



Note: PL and PU are used for indicating lower positioning and upper positioning (respectively) of the digital block. The indication is for convenience only, and does not suggest an actual difference in the signal.

Figure 2-4: HD Radio System 2 x 100-kHz Digital Block Positioning Examples

3. Analysis Parameters

The performance is provided for several scenarios and reception conditions. The conditions are related to the signal path, the specific reception scenario and the receiving device category.

In order to properly analyze reception performance of the different receiving modes and circumstances, certain correction factors have to be applied to the calculations of required (median) minimum field strength, as reflecting the received signal power. The foundations for such corrections are established in [5]. However, certain adjustments for scenarios that are not addressed in [5], are devised from related technologies and environments, as indicated where applicable.

The correction factors may be divided into two groups. One group is related to the signal path and the reception location, and is independent of specific receiver implementation. The second group may be related to specific receiver design methodology and needs to be analyzed accordingly.

3.1. Reception Modes

A total of six reception modes can be distinguished and include fixed portable and mobile, where portable reception is further sub-divided.

Reception availability as addressed by ITU in [5] and [2] considers certain percentile ranges over time and locations but does not attempt to address the practical modes or usage scenario with specific percentile or minimum requirements. Therefore, the analysis derives availability requirements from other related broadcasting areas and broadcasting technologies, and best practices, as broadly recognized.

3.1.1. Fixed Reception (FX)

Fixed reception is defined as reception where a roof level mounted receiving antenna is used (i.e., fixed antenna reception). For calculating the required field strength levels for fixed antenna reception, a receiving antenna height of 10 m above ground level is assumed, following [5] and [2]. However, the location probability of 50% as often indicated in [5] is considered insufficient. Instead, a location probability of 70% is assumed to obtain ‘acceptable’ reception situation as suggested in [13] and [12].

3.1.2. Portable Reception

Portable reception is defined as reception where a portable receiving device is used. Such portable device may also be hand-held. That implies the use of portable, smaller, limited performance antenna, at limited elevation above ground level. As indicated in [13] and [12], different combinations of antenna and locations may be translated to different reception modes.

A distinction is made over location in association with speed and the employed antenna:

- Portable / Hand-held outdoor reception
    - At 1.5 m or more above ground level, at rest or at very low speed
    - With external antenna (i.e. telescopic, wired headset, etc.) or integrated antenna
- Portable / Hand-held indoor reception
    - At 1.5 m or more above ground level, at rest or at very low speed
    - With external antenna (i.e. telescopic, wired headset, etc.) or integrated antenna
    - On the ground floor, in a room with window in an external wall

A distinction is made over location and perceived/desired reception quality:

- Quasi-static
    - Approximately 0.5 m x 0.5 m, with antenna moving up to 0.5 m

    - 99% reception
- Small area
    - Approximately 100 m x 100 m
    - 95% reception
- Large area
    - Consists of sum of small areas

3.1.3. Mobile Reception

Mobile reception is defined as reception by a receiver in motion, at speeds ranging from approximately two km/h and up to 300 km/h. Speeds in the range of 50 km/h to 60 km/h are of particular interest, as they may represent urban vehicular motion. For this reception category, the antenna is considered matched and situated 1.5 m or more above ground level. While not specifically addressed in [5] but yet allowed along with providing valid guidance for calculations, a reception location probability of 99% is assumed, in order to guarantee ‘good’ reception. Such choice is further supported in [13] and [12].

In order to cover all of the indicated combinations by using as few cases as possible while providing realistic reception scenarios, only six reception modes are analyzed, as indicated in Table 3-1.

Table 3-1: Definition of Reception Modes for Performance Analysis

Reception Mode	FX	MO	PO	PI	PO-H	PI-H
Antenna type	Fixed	Mounted	External	External	Integrated	Integrated
Location	Outdoor	Outdoor	Outdoor	Indoor	Outdoor	Indoor
Speed [km/h]	0 (static)	2-150	2 (walking)	0 (quasi static)	2 (walking)	0 (quasi static)
Reception percentage	70%	99%	95%	99%	95%	99%

3.2. Reception Location Related Correction Factors

This section provides the basis and the calculations for correction factors that are only related to signal path and reception location.

3.2.1. Reference Frequency

The correction factors and related analysis are done for a reference frequency of f = 100 MHz.

3.2.2. Feeder Loss

The feeder loss L_f represents the signal attenuation from the receiving antenna to the receiver’s RF input. This is not covered by [5] but is specifically addressed in [13] for f = 200 MHz. Since it is indicated to be proportional to f_2, it is then adjusted for the reference frequency and indicated in Table 3-2.

Table 3-2: Feeder Loss versus Reception Mode

	FX	MO	PO, PI, PO-H, PI-H
Cable length, [m]	10	2	0
Feeder loss, L_f, [dB]	1.4	0.3	0

3.2.3. Height Loss

The effective receiving antenna height depends on the reception mode. For mobile reception and for portable reception, a receiving antenna height of 1.5 m above ground level (outdoor) or above floor level (indoor) is assumed. The common propagation prediction methods typically provide field strength values at 10 m. To correct the predicted value from 10 m to 1.5 m above ground level, a height loss factor Lh [dB] has to be applied. Height loss in VHF Band II can be calculated using [5]. However, the proposed correction may apply to specifically situated antenna, which may be considered acceptable for certain portable reception cases. This may not be properly representing other cases such as hand-held devices, where the antenna situation (spatial orientation) varies and impacts the effective height. More realistic scenario and applicable losses for VHF Band II are indicated in [12]. The resulting height loss correction factor L_h for all reception modes is provided in Table 3-3.

Table 3-3: Height Loss Correction Factor

	FX, MO, PO, PI	PO-H, PI-H
Height loss, L_h, [dB]	10	17

3.2.4. Building Penetration Loss

Building penetration loss reflects the mean ratio between the mean field strength inside a building and the mean field strength outside the building, at the same height above ground level. No direct recommendations were provided by ITU regarding applicable penetration loss values for VHF Band II. More recent activities and documents [13] and [12] have resulted in recommended values for VHF Band III. As indicated in [13], these values are applicable to the wide range of frequencies over VHF Band III. Therefore, it is assumed that these values are also applicable to VHF Band II, and are provided in Table 3-4.

Table 3-4: Building Penetration Loss Factors

Building penetration loss, L_b, [dB]	Building penetration loss standard deviation, σ_b, [dB]
9	3

3.2.5. Implementation Loss

Implementation loss, as indicated in this document, reflects the correction factor to the minimum input power in order to compensate for the non-ideal receiver. Choosing such a factor may be subjective. For receivers that are internally spacious (i.e., reception circuitry not significantly limited by device size) and non-power-restricted (i.e., have constant or frequent access to durable power source), it is often considered to be 3 dB.

Advanced and highly integrated small receivers, such as handheld devices and particularly inclusion in smart phones, may experience additional higher implementation losses. Such losses may be due to the small physical dimensions, limited battery capacity, and co-existence with several additional hardware and radio wave-based functions. Therefore, the implementation loss, L_{im}, for such receivers are considered to be 5 dB. The implementation losses per reception mode are provided in Table 3-5.

Table 3-5: Implementation Loss Factor

	FX, MO, PO, PI	PO-H, PI-H
Implementation loss, L_{im}, [dB]	3	5

3.2.6. Location Variability Correction Factor

Location variability loss is often defined as reflecting the excess path loss over the service area of a transmitter, due to terrain effects and obstacles, in addition to more local shadowing. The variability discussions refer to the terrain as a finite area, typically represented by a square with a side length of 100 m to 1 km.

Field strength predictions are typically provided for 50% of time and 50% of locations. In order to derive the field strength value that is required for higher location probability, a location correction factor has applied, according to ITU recommendations as indicated in [5].

3.2.6.1. Location Standard Deviation

As indicated in [5], values of the standard deviation of the signal strength at a location are dependent on frequency and environment, and empirical studies have shown a considerable spread. Representative values for areas of 500m-x-500m are given by the following expression in Equation (1):

$$\sigma_L = K + 1.3\log(f) \quad (1)$$

Where

σ_L	standard deviation of the Gaussian distribution of the local means in the study area [dB]
K = 1.2	for receivers with antennas below clutter height in urban or suburban environments for mobile systems with omnidirectional antennas at car-roof height
K = 1.0	for receivers with rooftop antennas near the clutter height
K = 0.5	for receivers in rural areas
f	required frequency (MHz)

The standard location deviation has been calculated according to Equation (1). Excess effects that may be differently resulting from different mobility scenarios, and may be potentially differently mitigated by different receivers, are accounted for by separate calculation for each channel model, thus not added here. The calculated standard deviation is provided in Table 3-6.

Table 3-6: Location Standard Deviation

Standard deviation for digital broadcasting, σ_L, [dB]	
In urban and suburban locations	3.8
In rural locations	3.1

3.2.6.2. Location Distribution Factor

The distribution factor is defined as "inverse complementary cumulative normal distribution as a function of probability". It is used to correct the standard deviation for the desired location probability. For the location probabilities as indicated for each reception mode, the applicable distribution factor, as recommended in [5] is provided in Table 3-7.

Table 3-7: Location Distribution Factor

	FX	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
Reception percentage	70%	99%	95%	99%	95%	99%
Distribution factor, µ	0.52	2.33	1.64	2.33	1.64	2.33

It is noted that the HD Radio system's approach to signal reception considers 99% for 'good' indoor reception, while certain other approaches may require only 95%. This higher requirement (of 99%) results in a higher distribution factor of 2.33 as opposed to a distribution factor of only 1.64 for 95% indoor reception.

3.2.6.3. Adjusted Location Deviation

The location deviation which has been calculated for outdoor locations has to be adjusted for the desired location probability and for any environment that is other than outdoor.

The reception modes include indoor reception environment. The excess variations (i.e., beyond the outdoor location variation) of the signal impeding on the quasi-static indoor antenna are assumed to be affected solely by the building penetration deviation; thus the antenna location deviation is assumed to be the same as the building penetration deviation. The outdoor field strength and the building penetration are assumed to be statistically independent, and both follow log-normal distribution. Similarly to the calculations in [13], their combined deviation may be calculated as follows in Equation (2):

(2) $$\sigma_C = \sqrt{(\sigma_L^2 + \sigma_b^2)}$$

Where

σ_c combined standard deviation [dB]

Then, adjusting the deviation with the distribution factor according to [5] is calculated as follows in Equation (3):

(3) $$\sigma_S = \mu \cdot \sqrt{(\sigma_L^2 + \sigma_b^2)}$$

Where

σ_S The adjusted location deviation [dB]

σ_L Outdoor location deviation [dB]

σ_r Antenna location deviation [dB]. For outdoor reception $\sigma_r = 0$

For indoor reception $\sigma_r = \sigma_b$

In order to reduce the number of calculations, all reception modes are either defined in urban and suburban areas or otherwise performance are assumed to be a larger interest in these areas over rural areas. Therefore, a location correction of σL = 3.8dB is used for all cases, ignoring the ‘lower’ correction of 3.1 dB which applies only to rural areas, according to [5]. The calculated adjusted location deviation is provided in Table 3-8.

Table 3-8: Adjusted Location Deviation

Reception mode	**FX**	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
Reception percentage	70%	99%	95%	99%	95%	99%
Distribution factor, μ	0.52	2.33	1.64	2.33	1.64	2.33
Standard deviation, σ_L	3.8	3.8	3.8	3.8	3.8	3.8
Specific antenna location deviation, σ_r	0	0	0	3	0	3
Adjusted location deviation, σ_s, [dB]	**2**	**8.8**	**6.2**	**11.3**	**6.2**	**11.3**

It is noted that the HD Radio system’s approach to signal reception considers 99% for ‘good’ indoor reception, while certain other approaches may require only 95%. This higher requirement (of 99%) results in considering a higher adjusted location deviation of 11.3 dB as opposed to an adjusted location deviation of only 7.9 dB for 95% indoor reception.

3.2.7. Adjusted Reception Location Loss

The total reception location loss accounts for the signal path loss and the reception location signal variability. Both depend on the reception modes. The calculations are as follows:

(4) $L_{rl} = \sigma_s + L_h + L_f + L_b$

Where

L_{rl} The total adjusted reception location loss [dB]

The results are summarized in Table 3-9.

Table 3-9: Adjusted Location Loss

Reception mode	**FX**	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
Reception antenna location	Outdoor	Outdoor	Outdoor	Indoor	Outdoor	Indoor
Adjusted location deviation, σs, [dB]	2	8.8	6.2	11.3	6.2	11.3
Height loss factor, L_h	0	10	10	10	17	17
Feeder cable loss L_f	1.4	0.3	0	0	0	0
Building penetration loss L_b	**0**	**0**	**0**	**9**	**0**	**9**
Total reception location losses, L_{rl}, [dB]	**3.4**	**19.1**	**16.2**	**30.3**	**23.2**	**37.3**

It is noted that the HD Radio system's approach to signal reception considers 99% for 'good' indoor reception, while certain other approaches may require only 95%. This higher requirement (of 99%) results in considering higher total location losses of 3.4 dB more than the total location losses for only 95% indoor reception.

3.3. Design Related Correction Factors

This section provides the basis for the calculations approach for correction factors that are related to receiver design methodology.

Receiver design approaches, in the specific context of best matching the received signal for minimizing the antenna related path loss, may vary across the different systems. This is typically characterized by different analysis and design methodology of the antenna system and the RF front end. A legacy distributed approach was established and largely, though not completely, addressed by reference documents. However, more recent integrated approach is also employed and needs to be accommodated.

The distributed approach separately addresses the antenna and the RF front end. For each reception mode and its applicable antenna structure, analysis and numerical references are provided by either calculations or measurements. As a result, a set of different antenna gains was provided and was further followed by different sets of matching (or otherwise mismatching) losses, and then followed by allowable man-made noise in combination with discrete (provided separately) receiver noise figure.

The integrated approach follows more recent design methodology, where an antenna, followed (optionally) by dynamically adjustable matching circuitry and then a low noise amplifier of buffer are integrated in whole or in part. Whether the antenna is actually integrated or not, it may be constantly (i.e. dynamically) matched, and therefore the entire chain may be viewed as having one gain value but different overall noise figure. The applicable calculations and specific values for this approach are used in this document for calculating the mean minimum field strength.

3.3.1. Correction Factors for Integrated Methodology

For the purpose of sensitivity calculations, antennas are often represented by gains, and then attached to receivers with separately calculated noise figure. Several legacy design and analysis approaches, as well as certain measurements, refer to the entire gain by a single factor. Then, only the LNA noise figure (referred to as receiver noise figure) is applied to the overall gain and noise calculations. However, an antenna gain consists of fixed physical structure gain, which can be calculated, and additional gain (typically attenuation) component that depends on attached circuitry. While the physical positive gain higher than 0 dBi (-2.2 dBd) corresponds to radiation patterns, negative gains are related to impaired antenna efficiency, which is caused typically by mismatch between the antenna and the receiver, as described in [12].

Advanced receiver implementation techniques, may employ dynamically adjustable circuitry that may improve the matching of the receiver input network, including the LNA. Therefore, for such implementations it may be useful to calculate the combined receiver system noise figure, as resulting from the receiver input network, while separating it from the physical antenna gain. Then, a reference physical antenna gain (typically the lowest realistic gain) is used, and any further antenna attenuation is expressed by a combined noise figure. When a higher physical antenna gain is available, it may then be used to adjust the calculations, without affecting the combined noise figure calculations.

The effect of the matching circuitry on the overall noise, or otherwise on the integrated antenna gain, may be derived from Appendix A. Required adjustments for the physical antenna gain are further described in this section.

3.3.1.1. Antenna Gain Adjustment

The sensitivity (required field strength) based on the overall receiver system NF, already assumed antenna gain of 1.5 (‘net physical’ isotropic element of 1.8 dBi / -0.4 dBd, separate of matching loss), as indicated in Appendix A. Therefore, antenna gain correction factor Δ_{AG} is applied where the physical element is different (noticeably larger). For fixed reception, an antenna gain of 4 dBd is used, as recommended in [14]. In all other reception modes, no physical antenna gains are available, and therefore are assumed to have no gain over the reference antenna.

The applicable antenna gain correction for all reception modes is provided in Table 3-10.

Table 3-10: Antenna Physical Gain Correction

	FX	MO, PO, PI, PO-H, PI-H
Antenna gain correction. Δ_{AG}, [dB]	4.4	0

3.3.1.2. Allowance for Man-Made Noise

The allowance for man-made noise, P_{mmn} [dB], takes into account the effect of the man-made noise received by the antenna on the system performance.

The legacy approach to calculating certain antenna noise F_a is described in [15] and is also indicated in [13]. However, these values are based on measurements taken in 1974, under completely different RF environments and different antenna system implementation approaches, and may not be considered realistic anymore; and thus, not applicable for reliable calculation for man-made noise allowance.

The approach in [15] views an external antenna noise figure and separately a receiver noise figure (as opposed to integrated systems). Such an approach considers the antenna gain for calculating P_{mmn}. While it may be applicable to positive gains that relate the antenna radiation patterns, it may not be suitable for negative antenna gains which typically relate the matching between the antenna and the receiver (typically the LNA section). The integrated receiver system methodology mitigates that problem.

More recent studies (2001-2003) by OFCOM, as indicated in [16] and [17], and by others in [18] show that the realistic noise may be substantially higher. For example, for the purpose of calculating MMN allowance, a reference F_a value of 21 dB (equivalent to a noise temperature of approximately 360,000 K) for 100 MHz is derived from OFCOM [17] and corresponds to a 'quiet' rural environment. The measurements for that environment resulted in the lowest standard deviation and may be considered the most repetitive. The use of that higher and much more realistic value has been extended to reception modes.

A similar approach of adjusting the man-made noise allowance for cases with noticeable antenna losses (i.e. high integrated NF) is used in [12] and employed in this document.

Applying the methodology in [12] to an antenna with a gain higher than -2.2 dBd results in a P_{mmn} of 14.1 dB. This is considered applicable to the cases where the receiver system structure is reasonably physically controlled, such as in a fixed installation, automotive, and larger portable devices.

Respectively, applying an adjusted methodology in [12] to handheld devices that employ an antenna system with significantly lower gain or equivalently high NF (as applicable to integrated systems methodology) does not produce realistically considerable P_{mmn}.

The applied P_{mmn} is listed in Table 3-11.

Table 3-11: Allowance for Man-Made Noise for Integrated Design

	FX, MO. PO, PI	PO-H, PI-H
Man-made noise allowance, P_{mmn}, [dB]	14.1	0

3.4. Channel Models and Fading Margins

The specific EIA-approved channel (fading) models used in this analysis are provided in Appendix B. Attempting to address all the reception modes along with the possible channel models may result in a significant number of combinations, thus prolonging the analysis work. For the specific purpose of providing planning parameters and in order to cover all of the combinations by using as few analysis cases as possible, the analysis brings forward the more demanding cases (in terms of required CNR and the resulting field strength), while assuming that the less demanding cases are then accounted for. For example, it may be assumed that reception under urban slow fading is more demanding than reception under suburban slow fading; therefore only the case of using the urban slow fading model has to be analyzed. In another example, while considering the urban multipath profile in comparison to the suburban multipath profile, it may be assumed that reception under urban fast (60 km/h) fading is more demanding than reception under suburban fast (150 km/h) fading; therefore only the case of using the urban fast fading model is analyzed for planning purposes.

In accordance with the analysis of a reduced number of cases, the reception modes and channel models combinations for planning purposes (referred to by their symbols in Appendix B) are provided in Table 3-12.

Table 3-12: Definition of Reception Modes and Channel Models

Reception mode	**FX**	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
Antenna type	External	External	External	External	Integrated	Integrated
Antenna location	Outdoor	Outdoor	Outdoor	Indoor	Outdoor	Indoor
Environment	Suburban/Urban	Suburban/Urban	Suburban/Urban	Suburban/Urban	Urban	Urban
Reception percentage	70%	99%	95%	99%	95%	99%
Analysis speed, [km/h]	0 (static)	60 (driving)	2 (walking)	0 (quasi-static)	2 (walking)	0 (quasi-static)
Analysis channel model	FXWGN	UFRM	USRM	FXWGN	USRM	FXWGN

4. Field Strength Requirements Analysis

4.1. Minimum C/N Ratio

CNR calculations for various reception scenarios employed various channel models. Followed by long term experience with commercial HD Radio receivers, the models correlation with actual reception conditions has been observed. As a result, the more performance impacting (i.e., requiring higher CNR) models are provided for planning purposes.

CNR values (f = 100 MHz) are provided for an average decoded BER of 0.5×10^{-4} as a reference operating point for providing services.

In considering the approach for planning parameters as indicated in [12] and based on potential (and actual) usage scenarios of various HD Radio receiver types, the following is assumed for planning:

1. Handheld portable receivers may be used while walking or while driving. Slow (up to 2 km/h) fading conditions are likely to affect reception at a walking speed, while fast (60 km/h) fading conditions likely to affect reception while driving. The slow urban fading conditions are expected to have much more severe impact on the reception than fast fading conditions and therefore will be used for planning purpose.
2. Portable receivers may be used in quasi-static (0 km/h) conditions or while driven. Due to their larger form factor in comparison to handheld receivers, it is assumed that they are likely to be used for quasi-static reception. Therefore, quasi-static reception is used in conjunction with portable receivers for planning purposes.
3. For mobile receivers, typical usage is more likely to be experienced in urban areas. In addition, calculations and actual tests have not shown significant difference of impact on reception, between urban conditions (60 km/h) and rural conditions (150 km/h). Therefore, urban reception conditions analysis, which employ more aggressive multipath profiles, are used for planning purposes.

The cases (and models) and their related required C_d/N_0 (digital power to noise density ratio) as analyzed for planning purposes are provided in Table 4-1.

Table 4-1: HD Radio Receiver Required CNR for Various Reception Modes

Reception mode	**FX**	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
Channel model symbol	FXWGN	UFRM	USRM	FXWGN	USRM	FXWGN
Environment	Fixed	Urban	Urban	Indoor	Urban	Indoor
Speed, [km/h]	0	60	2 (walking)	0 (quasi-static)	2 (walking)	0 (quasi-static)
MP9 **Required C_d/N_0 [dB-Hz]**	55.3	59.7	64.3	55.3	64.3	55.3
MP8 **Required C_d/N_0 [dB-Hz]**	54.4	58.5	62.5	54.4	62.5	54.4
MP19 **Required C_d/N_0 [dB-Hz]**	56.8	61.2	65.8	56.8	65.8	56.8
MP1 **Required C_d/N_0 [dB-Hz]**	53.8	57.2	61.3	53.8	61.3	53.8
MP11 **Required C_d/N_0 [dB-Hz]**	56.3	58.7	62.8	56.3	62.8	56.3

4.2. Receiver Integrated Noise Figure

Based on calculations and certain deployments, the HD Radio receiver system noise figure (NF) for link budget calculations is shown in Table 4-2. Considering the reality of constant device miniaturization and integration, it is believed that for handheld reception, both external (ear bud) antenna and internal integrated antenna should be considered for planning purposes.

The integrated noise figure calculations employ conservative practical values, in accordance with the methodology for antenna for maximum voltage transfer (to the LNA), as indicated in Appendix A and in [19].

In portable devices, power constraints are assumed to result in LNA noise figures that may be slightly higher (approximately 1 dB) than LNA noise figures for fixed or automotive reception which may not have power constraints.

In handheld devices, the best achievable antenna matching may be impacted by limited radiating element dimensions, varying elements and varying spatial orientation, which may collectively result in relatively high integrated noise figures. In all other cases (where the physical antenna, receiver structure, and their spatial orientation may be considered stable and reasonably defined), the antenna matching network is assumed to achieve the best required matching for maximum voltage transfer; thus resulting in values that may be common to those of the receiver only, as indicated in [12].

Table 4-2: HD Radio Overall Receiver System Noise Figure

Reception mode	**FX**	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
Antenna type	External fixed	Adapted	External telescopic / ear bud	External telescopic / ear bud	Internal	Internal
Receiver System NF, [dB]	7	7	8	8	25	25

The sensitivity (required field strength) based on the overall receiver system NF already assumed antenna gain of 1.5 (‘net physical’ isotropic element, separate of matching loss), while all losses are included in NF. Therefore, the antenna gain correction factor Δ_{AG} is applied only where the physical element is different (noticeably larger).

4.2.1. Receiver Noise Input Power

This section does not include any operational values and is provided only as a place holder for reiterating that such a legacy approach is irrelevant for HD Radio field strength calculations, since an integrated NF approach is used.

4.3. Minimum Wanted Field Strength used for Planning

The minimum median required field strength calculations are according to the integrated approach, as described in Appendix A.

In certain configurations (i.e., system modes) where both channels P1 and P3/P4 are active, and where field strength requirements for channel P1 are different from the field strength requirements for channels P3/P4, the more demanding requirements (higher CNR) are used for planning and are provided in the tables in this section.

The minimum median field strength E_{med} for the HD Radio system is indicated in Table 4-3 to Table 4-7.

It is noted that while the calculations follow the ITU guidelines as indicated in the respective sections in this document, the chosen values are intended to ensure adequate reception in realistic conditions. Specifically, the following is noted:

- The HD Radio system's approach to signal reception considers 99% for 'good' indoor reception, while certain other systems' approaches may consider only 95% for indoor reception, potentially leading to inadequate reception. This higher requirement (of 99%) results in considering higher field strength requirements of 3.4 dB more than the field strength for only 95% indoor reception. This is relevant for reception modes PI and PI-H (and reflected in higher total reception location losses for these modes).
- Broad industry experience with advanced and highly integrated small receivers, such as those in handheld devices and particularly their inclusion in smart phones, may require considering higher implementation losses than the implementation losses for discrete classes of receivers (i.e., automotive, portable). These higher losses result in considering higher field strength requirements of 2 dB more than the field strength for only discrete classes of receivers. This is relevant for reception modes PO-H and PI-H.
- The technological advances over the last tens of years have resulted in increased man-made noise, as has been indicated in certain published referenced documents. The HD Radio system's analysis approach employs such man-made noise data from the year 2000 or later while certain other systems' approaches may consider other data from referenced documents which have been established in 1974 or earlier. The HD Radio system's approach considers such old data to be outdated and potentially leading to an inadequate reception. The consideration of the higher man-made noise data results in considering higher field strength requirements of 6.2 dB more than the field strength considered for the lower and potentially non-realistic man-made noise. This is relevant for all outdoor reception modes: FX, MO, PO, and PI.
- The HD Radio system's analysis approach considers the often outdoor use of handheld and portable receivers in both walking speed and driving speed. Adverse reception conditions for walking speed are considered much more demanding (requiring higher CNR) due to the slow fading impacts. While certain other systems' approaches may consider analysis in driving speed to be sufficient, the HD Radio system considers the field strength requirements for walking speed to be adequate for planning. The consideration of walking speed reception results in considering higher field strength requirements of up to 4.6 dB more than the field strength considered for driving. This is relevant for all outdoor reception modes PO and PO-H.

The HD Radio system's analysis for deriving field strength requirements considers the most probable usage scenarios along with conservative assumptions regarding adverse channel conditions, environmental noise (man-made), and deployment margins. Considering less conservative parameters or outdated data may lead to potential reduction of more than 10 dB in field strength requirements, which may potentially lead to inadequate planning and then inadequate reception.

Table 4-3: HD Radio Mode MP9 Minimum Median Field Strength versus Reception Modes

Reception mode	**FX**	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
MP9 Required **Cd/N$_0$** [dB-Hz]	55.3	59.7	64.3	55.3	64.3	55.3
Antenna gain correction, Δ_{AG}, [dB]	4.4	0	0	0	0	0
Reception location losses, L_{rl}, [dB]	3.4	19.1	16.2	30.3	23.2	37.3
Implementation loss, L_{im}, [dB]	3	3	3	3	5	5
Receiver System NF, [dB]	7	7	8	8	25	25
Man-made noise allowance, P_{mmn}, [dB]	14.1	14.1	14.1	14.1	0	0
Minimum median field strength, [dBµV/m]	19.9	44.4	47.1	52.2	59.0	64.1

Table 4-4: HD Radio Mode MP8 Minimum Median Field Strength versus Reception Modes

Reception mode	**FX**	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
MP8 Required **Cd/N$_0$** [dB-Hz]	54.4	58.5	62.5	54.4	62.5	54.4
Antenna gain correction, Δ_{AG}, [dB]	4.4	0	0	0	0	0
Reception location losses, L_{rl}, [dB]	3.4	19.1	16.2	30.3	23.2	37.3
Implementation loss, L_{im}, [dB]	3	3	3	3	5	5
Receiver System NF, [dB]	7	7	8	8	25	25
Man-made noise allowance, P_{mmn}, [dB]	14.1	14.1	14.1	14.1	0	0
Minimum median field strength, [dBµV/m]	19.0	43.2	45.3	51.3	57.3	63.2

Table 4-5: HD Radio Mode MP19 Minimum Median Field Strength versus Reception Modes

Reception mode	FX	MO	PO	PI	PO-H	PI-H
MP19 Required **Cd/N₀** [dB-Hz]	56.8	61.2	65.8	56.8	65.8	56.8
Antenna gain correction, Δ_{AG}, [dB]	4.4	0	0	0	0	0
Reception location losses, L_{rl}, [dB]	3.4	19.1	16.2	30.3	23.2	37.3
Implementation loss, L_{im}, [dB]	3	3	3	3	5	5
Receiver System NF, [dB]	7	7	8	8	25	25
Man-made noise allowance, P_{mmn}, [dB]	14.1	14.1	14.1	14.1	0	0
Minimum median field strength, [dBµV/m]	21.4	45.9	48.6	53.7	60.5	65.6

Table 4-6: HD Radio Mode MP1 Minimum Median Field Strength versus Reception Modes

Reception mode	FX	MO	PO	PI	PO-H	PI-H
MP1 Required **Cd/N₀** [dB-Hz]	53.8	57.2	61.3	53.8	61.3	53.8
Antenna gain correction, Δ_{AG}, [dB]	4.4	0	0	0	0	0
Reception location losses, L_{rl}, [dB]	3.4	19.1	16.2	30.3	23.2	37.3
Implementation loss, L_{im}, [dB]	3	3	3	3	5	5
Receiver System NF, [dB]	7	7	8	8	25	25
Man-made noise allowance, P_{mmn}, [dB]	14.1	14.1	14.1	14.1	0	0
Minimum median field strength, [dBµV/m]	18.4	41.9	44.1	50.7	56.0	62.6

Table 4-7: HD Radio Mode MP11 Minimum Median Field Strength versus Reception Modes

Reception mode	**FX**	**MO**	**PO**	**PI**	**PO-H**	**PI-H**
MP11 Required **C_d/N_0** [dB-Hz]	56.3	58.7	62.8	56.3	62.8	56.3
Antenna gain correction, Δ_{AG}, [dB]	4.4	0	0	0	0	0
Reception location losses, L_{rl}, [dB]	3.4	19.1	16.2	30.3	23.2	37.3
Implementation loss, L_{im}, [dB]	3	3	3	3	5	5
Receiver System NF, [dB]	7	7	8	8	25	25
Man-made noise allowance, P_{mmn}, [dB]	14.1	14.1	14.1	14.1	0	0
Minimum nedian field strength, [dBµV/m]	20.9	43.4	45.6	53.2	57.5	65.1

A. Appendix: Calculation of Minimum Median Field Strength Level – Integrated Method

For the systems that employ the integrated method for calculating the minimum median field strength, this appendix provides the background for the reference calculations, followed by the required steps / expressions.

Background for calculating the reference minimum field strength

Receiver sensitivity, being the minimum required signal field strength at the receiver antenna (E) is expressed as a function of the required pre-detection C/N_0, the noise, the effective length h_e of the antenna (h_e is a function of radiation resistance), and the antenna matching circuit $H_a(f)$. For a given signal field strength E (µV/m) impinging upon the antenna, C/N_0 is expressed as a function of the field strength, the antenna effective length $h_e(f)$, the transfer function of the antenna circuit (matched) filter $H_a(f)$, and the sum of noise sources comprising N_0.

NOTE: The expression is provided for the lowest realistic directivity antenna, which is the one of a short dipole (length, l << λ) and it has the gain value of 1.5 (1.76 dBi; -0.4 dBd). Any gain higher than -0.4 dBd has to be separately applied to the link budget calculations. Any gain lower than -0.4 dBd is assumed to result from reduced efficiency that is caused by a mismatched network, and is already included in the calculations, as provided in this section.

The signal power C (V^2) applied to the LNA input is given by

$$C = \left[E(\mu V/m)\cdot 10^{-6}\cdot h_e(f)\cdot\left|H_a(f)\right|\right]^2 \tag{1}$$

The noise power spectral density (PSD) at the LNA input (for a conjugately matched antenna) as a function of the ambient noise and the LNA noise figure (NFLNA) is given by

$$No = \kappa\cdot T_0\cdot R_{LNA}\cdot 10^{NF_{LNA}/10} + \kappa\cdot\left(T_{amb} - T_0\right)\cdot R_{LNA} \tag{2}$$

For reference temperature (T_0) discussion, $T_{amb} = T_0$ is assumed. In addition, the LNA input is frequency dependent and may not be conjugately matched to the antenna. The combined noise PSD is given by

$$No(f) = \kappa\cdot T_0\cdot\left[R_{LNA}\cdot\left(10^{NF_{LNA}/10} - 2\right) + 4\cdot\mathrm{Re}\{Z_{in}(f)\}\right] \tag{3}$$

where Z_{in} is the input impedance seen at the LNA input, including the LNA input impedance, and NFLNA is the Noise Figure of the LNA. The receiver system NF is the ratio (in dB) of the overall noise to the noise produced by the antenna's radiation resistance

$$NF = 10\cdot\log\left(\frac{\kappa\cdot T_0\cdot\left[R_{LNA}\cdot\left(10^{NFlna/10} - 2\right) + 4\cdot\mathrm{Re}\{Z_{in}\}\right]}{4\cdot\kappa\cdot T_0\cdot R_a(f)\cdot\left|H_a(f)\right|^2}\right) \tag{4}$$

or equivalently

(5) $$NF = 10\cdot\log(No) + 204 - 10\cdot\log\left(4\cdot R_a(f)\cdot\left|H_a(f)\right|^2\right)$$

The carrier to noise density ratio at the output of the LNA is given by

(6) $$\frac{C}{No} = \frac{\left[E(\mu V/m)\cdot 10^{-6}\cdot h_e(f)\cdot\left|H_a(f)\right|\right]^2}{No}$$

This is expressed in dB as

(7) $$C/No = 10\cdot\log\left(\frac{C}{No}\right) = E(dBu) - 120 + 10\cdot\log\left(h_e(f)^2\cdot\left|H_a(f)\right|^2\right) - 10\cdot\log(No)$$

or equivalently

(8) $$C/No = E(dBu) + 78 + 10\cdot\log\left(\frac{h_e(f)^2}{R_a(f)}\right) - NF$$

Then the required field strength E (dBu) as a function of the required CNR

(9) $$E(dBu) = C/No - 78 - 10\cdot\log\left(\frac{h_e(f)^2}{R_a(f)}\right) + NF$$

Using the antenna's effective length h_e as related to its radiation resistance R_a is given by

(10) $$h_e = 2\cdot\sqrt{\frac{R_a\cdot A_e}{Z_0}}$$

where $A_e = \frac{\lambda^2}{4\cdot\pi}\cdot G$, $Z_0 = 120\cdot\pi$, and G = 1.5 (1.8 dBi; -0.4 dBd) is the constant directivity for small antennas ($h_e << \lambda$)

(11) $$10\cdot\log\left(\frac{h_e(f)^2}{R_a(f)}\right) = 10\cdot\log\left(\frac{\lambda^2}{120\cdot\pi^2}\cdot G\right) = 20\cdot\log(\lambda) - 29$$

Then the required field strength, as a function of λ and receiver system NF is given by

(12) $$E(dBu) = C / No - 49 - 20 \cdot \log(\lambda) + NF$$

Determining the minimum required field strength

For each system configuration and for each reception mode, the applicable CNR and the applicable NF where:

NF is the receiver system integrated noise figure in dB

CNR is the carrier to noise density ratio in dB-Hz

The following relationship may be used for convenience

(13) $$C / No = 10 \cdot \log\left(\frac{C}{No}\right) = SNR + 10 \cdot \log(BWn)$$

where BWn is the receiver noise bandwidth (ideally the signal bandwidth).

When using λ = 3 m for 100 MHz, the minimum required field strength E_r is given by

(14) $$E_r\,(dBu) = C / No - 58.5 + NF$$

Physical antenna gain adjustment

Since the reference calculation in expression (14) is using the minimum realistic gain, of -0.4 dBd, then the difference should be calculated for any other higher indicated physical gain as follows

(15) Δ_{AG} [dB] = Ag [dB] + 0.4

where Δ_{AG} is antenna gain correction in dB.

Determining the minimum median required field strength

The minimum median field strength is calculated as follows

(16) $E_{med} = E_r + MMN - \Delta_{AG} + L_{rl} + L_{im}$

or otherwise

(17) $E_{med} = C/N_0 – 58.5 + NF + MMN – \Delta_{AG} + L_{rl} + L_{im}$

where:

L_{rl} is the reception location loss in dB,

L_{im} is the implementation loss in dB,

MMN is man-made noise allowance, calculated according to the recommended method in [12], but based on integrated NF rather than on antenna gain.

B. Appendix: Channel Models

The channel models included in this section may apply to the reception modes.

Table B-1: Fixed Reception under White Gaussian Noise (FXWGN) Channel Model

Ray	Delay (µsec)	Attenuation (dB)	Doppler Frequency (Hz)
1	0.0	0.0	0

Table B-2: Urban Slow Rayleigh Multipath (USRM) Channel Model

Ray	Delay (µsec)	Attenuation (dB)	Doppler Frequency (Hz)
1	0.0	2.0	0.174 (reflects ~2 km/h
2	0.2	0.0	
3	0.5	3.0	
4	0.9	4.0	
5	1.2	2.0	
6	1.4	0.0	
7	2.0	3.0	
8	2.4	5.0	
9	3.0	10.0	

Table B-3: Urban Fast Rayleigh Multipath (UFRM) Channel Model

Ray	Delay (µsec)	Attenuation (dB)	Doppler Frequency (Hz)
1	0.0	2.0	5.231 (reflects ~60 km/h
2	0.2	0.0	
3	0.5	3.0	
4	0.9	4.0	
5	1.2	2.0	
6	1.4	0.0	
7	2.0	3.0	
8	2.4	5.0	
9	3.0	10.0	

Table B-4: Rural Fast Rayleigh Multipath (RFRM) Channel Model

Ray	Delay (µsec)	Attenuation (dB)	Doppler Frequency (Hz)
1	0.0	4.0	13.08 (reflects ~150 km/h
2	0.3	8.0	
3	0.5	0.0	
4	0.9	5.0	
5	1.2	16.0	
6	1.9	18.0	
7	2.1	14.0	
8	2.5	20.0	
9	3.0	25.0	

Table B-5: Terrain Obstructed Fast Rayleigh Multipath (TORM) Channel Model

Ray	Delay (µsec)	Attenuation (dB)	Doppler Frequency (Hz)
1	0.0	10.0	5.231 (reflects ~60 km/h
2	1.0	4.0	
3	2.5	2.0	
4	3.5	3.0	
5	5.0	4.0	
6	8.0	5.0	
7	12.0	2.0	
8	14.0	8.0	
9	16.0	5.0	

C. Appendix: IBOC Conversion of C/N$_0$ to SNR

The **carrier-to-noise ratio**, often written *CNR* or ***C/N***, is the signal-to-noise ratio (SNR) of a modulated signal. The noise power *N* is typically defined in the signal's processing (reception) bandwidth.

The **carrier-to-noise-density ratio (*C/N$_0$*)** is similar to **carrier-to-noise ratio,** except that the noise ***N$_0$*** is defined per unit Hz bandwidth.

For analysis, the digital modulation power of the signal ***Cd*** is often distinguished from the total signal power ***C***. This is used in, for example, an FM Hybrid IBOC signal where the digital-only power ***Cd*** is distinguished from the FM analog power ***C***.

IBOC FM Conversion of Cd/N$_0$ to Digital CNR or SNR Example

For a single 70-kHz digital signal bandwidth system configuration,

$$SNR_{dB} \equiv (Cd / N)_{dB} = Cd_{dB} - N_{dB}$$

$$N_{dB} = No_{dB} + 10 \cdot \log(70\,\mathrm{kHz}) = No_{dB} + 48.45\,\mathrm{dB}$$

Then

$$SNR_{dB} \equiv (Cd / No)_{dB} - 48.45\,\mathrm{dB}$$

List of Reference Documents

[1] ITU-R BS.1114-7: Systems for terrestrial digital sound broadcasting to vehicular, portable and fixed portable, and fixed receivers in the frequency range 30-3000 MHz.

[2] ITU-R BS.412-9: Planning standards for terrestrial FM sound broadcasting at VHF.

[3] ITU-R BS.704: Characteristics of FM sound broadcasting reference receivers for planning purposes.

[4] ITU-R BS.415-2: Minimum performance specifications for low-cost sound-broadcasting receivers.

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[6] U.S.A FCC Title 47, Part 73, Section 73.215: Contour Protection for Short Spaced Assignment.

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Revision History

ITEM	Change Description	Section(s) Affected	Revision
1	Content Creation / Document Development	All	SOURCE
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