International Telecommunication Union



Report ITU-R BS.2482-0 (02/2020)

Planning analysis for the HD Radio system in the MF band

BS Series Broadcasting service (sound)



Telecommunication

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REPORT ITU-R BS.2482-0

Planning analysis for the HD Radio system in the MF band

(2020)

1 Introduction

The HD Radio hybrid configuration makes use of the existing MF Band allocations and embeds new audio and data services within an analogue 10 kHz frequency raster. The system characteristics for the HD Radio system can be found in Recommendation ITU-R BS.1514 [1].

The MF HD Radio system operates in two modes: hybrid and all-digital. In hybrid mode, this in-band on-channel (IBOC) implementation preserves the analogue broadcast located on the main frequency assignment and adds low-level digitally-modulated signals immediately adjacent to either side (or both sides) of the analogue signal. In all-digital mode, the system takes advantage of a previously vacated analogue broadcast and employs digitally-modulated signals immediately adjacent to either side (or both sides) of the analogue carrier.

2 HD Radio system configurations

The system can be configured to use multiple frequency blocks that employ up to 30-kHz digital signal bandwidth. Such spectral configurations are shown for hybrid signal composition in Fig. 1, and for all-digital signal composition in Fig. 2.





NOTE – PL/SL/TL and PU/SU/TU are used for indicating lower and upper positioning of the digital block respectively. The indication is for convenience only, and does not suggest an actual difference in the signal.

The configuration is defined by system modes and power settings, and provides various combinations of logical channels, bit rates, and protection levels.

Three different digital block-pairs or blocks may be employed. The Primary block-pair, indicated by PL (Primary Lower) and PU (Primary Upper), occupies 10-kHz, is present in all the configurations and carries logical channel P1. The Secondary block-pair, indicated by SL (Secondary Lower) and SU (Secondary Upper), may be present in the 20-kHz configuration MA3 and in the 30-kHz configuration MA1. The Tertiary block-pair, indicated by TL (Tertiary Lower) and TU (Tertiary Upper), may be present in the 30-kHz configuration MA1. Logical channel P3 is carried solely by the

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Secondary block-pair in the 20-kHz configuration MA3, and jointly by the Secondary block-pair and Tertiary block-pair in the 30-kHz configuration MA1.



FIGURE 2 HD Radio AM system digital-only block positioning examples

NOTE – PL/SL and PU/SU are used for indicating lower and upper positioning of the digital block respectively. The indication is for convenience only, and does not suggest an actual difference in the signal.

The essential characteristics of the HD Radio system configurations (operating modes) are summarized in Table 1. Additional time-frequency information may be found in Table 2.

TABLE 1

Characteristics of various HD Radio AM system operating modes

Swatam	Used BW (kHz)	Total bit rate ⁽¹⁾	Channel P1		Channel P3			Analogue	Comments	
Mode			Code rate	Bit rate ⁽¹⁾	Modulation	Code rate	Bit rate ⁽¹⁾	Modulation	signal support	Interleaver span
MA1	10	20.4	5/12	20.4	64 QAM	-	_	—	Yes	P1: ~4.5 s
MA1 ⁽²⁾	30 (3)	36.4	5/12	20.4	64 QAM	2/3		16 QAM / QPSK	Yes	P1: ~4.5 s P3: ~4.5 s
MA3	10	20.4	5/12	20.4	64 QAM	-	-	-	No	P1: ~4.5 s
MA3 ²	20	40.4	5/12	20.4	64 QAM	5/12	20	64 QAM	No	P1: ~4.5 s P3: ~4.5 s

⁽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.

⁽²⁾ Joint configuration of two or more digital signal block-pairs for enhanced services or features. Each digital block-pair may be adjusted independently for power level.

⁽³⁾ This value includes shared (overlapped) bandwidth with the analogue host signal.

Parameter name	Computed value (rounded)		
Symbol duration (with prefix), T_s	5.805 ms		
Frame duration, T_f	1.486 s		
OFDM subcarrier spacing, Δf	181.7 Hz		
Number of carriers	10 kHz band:5420 kHz band:10430 kHz band:156		
Used bandwidth	10 kHz band: 9.8 kHz 20 kHz band: 18.9 kHz 30 kHz band: 28.4 kHz		

TABLE	2
HD Radio System Time-Frequence	cy Parameters for MF band

3 Considerations and analysis parameters for deriving useful field strength requirements for HD Radio system

In order to provide adequate reception performance for the different receiving modes and circumstances, the calculations of minimum useful (median) field strength, as they reflect the received signal power, may be derived from Recommendations ITU-R BS.703 and ITU-R P.1321. These calculations may require certain adjustments (corrections) related to the technology and the environments.

The correction factors may be divided into two groups. One group is related to the signal path and the reception conditions and is independent of specific receiver implementation. The second group may be related to specific receiver design methodology and needs to be analysed accordingly. Whether it is needed or not needed to consider the receiver design methodology, such a decision may result from the reception conditions. In the case where the reception conditions dominate the reception capability, the effect of specific design methodology may be deemed negligible and may not need to be considered.

The reception conditions including signal path, reception scenarios, and potential sources for adjustments (corrections) are discussed in the present section of this Report.

Annex 1 links the reception conditions and scenarios to the system reception performance and implementation technology, by providing applicable equations for calculating the minimum useful (median) field strength.

3.1 Reception conditions

Reception conditions result from several factors that are related to the signal propagation and the reception environment. Additionally, reception location may be considered and potentially may require adjusting the required signal level for adequate reception.

3.1.1 Ground wave propagation

Ground wave propagation represents the main propagation mode in the MF band. Reference conditions for assessing the propagation loss are provided in [2]. Far-field propagation graphs are provided and are based on reference field strength of 300 m/V, assumed at a distance of 1 km from the radiating antenna over a near perfect conducting ground. The received field strength at a given

distance depends on several parameters. Seasonal temperature changes may lead to field strength variations of 5 dB at 100 km from the transmitter.

Ground conductivity, ranging from 1 S/m for salt water to 10^{-3} S/m for typical mostly (semi-dry) ground (also indicated in NTIA Report 99-368, titled "Medium frequency propagation prediction techniques and antenna modelling for intelligent transportation system (ITS) broadcast applications"), contributes to path loss variations of over 30 dB at a distance of 100 km from the transmitter.

Frequency-dependent path loss variations of over 10 dB at 100 km from the transmitter are indicated in Recommendation ITU-R P.368 for propagation over land with ground conductivity of 3×10^{-3} S/m.

It is reasonable to assume that a non-homogenous path, consisting of different conductivity and different permittivity is expected over an assessed distance thus making the path loss analysis further complicated, resulting in large variations.

For predicting the path loss, various methods are proposed and employed. As indicated in Recommendation ITU-R P.368, the Millington method is recommended for non-homogenous path loss prediction. However, that method which employed forward and reciprocal path calculations may be sufficiently accurate for line-of-sight or for limited obstruction. When terrain obstruction and beyond line-of-sight are involved, large errors which may be in the amount of 15 dB per reference [15], may occur.

Alternative prediction methods are offered and include the following:

- 1 BBC method (in the UK)
 - Based on recursive calculation that includes the points along the path from the transmitter to the receiver
- 2 NTIA method (in the USA)
 - Based on path profiles (as described for ITS)
- 3 UPV-EHU method
 - The method indicated in [15] applies weighted conductivity where a different weight is provided for the length of each conductivity section along the path. It is then accompanied by attenuation estimates which are based on the path irregularities (i.e. obstacle distance and height). This alternative method is claimed to provide better prediction accuracy than other methods.

However, path loss prediction still depends on varying conditions and results in large mean error. Thus, prediction methods must be considered for the specific reception circumstances.

3.1.2 Skywave propagation

After sunset, ionosphere E-layer and F-layer (region) propagation cause multi-hop reflection of the broadcast signals in the MF band. As a result, these time-delayed signals may result in the reception of a composite signal, consisting of components with different magnitude and different delay. The relative delay of sky-wave signal to ground-wave signal at 100 km from the transmitter, for a single hop (which is the dominant component at that distance), is indicated in Recommendation ITU-R P.1321 to be between 0.4 ms and 1.2 ms. The relative magnitude of the sky-wave component may be approximately -25 dB compared to the ground-wave, when the path is over sea water. However, it may be +15 dB compared to the ground wave when the path is over typical (mostly semi-dry) ground.

Since the absorption of the ionosphere layers varies with time, the reflected magnitude is time-variant and it includes 'hourly loss factor' which provides correction relative to sunset or sunrise time. While this is significant at 750 km, reaching up to 30 dB for less absorptive levels per Recommendation ITU-R P.1147, it is insignificant at 100 km.

Another sky-wave magnitude variation is given in Recommendation ITU-R P.1147 as 'day-to-day' variation. This variation is normally expressed in 1-day change and 10-day change. For the MF band, it is indicated to be between 6 dB and 10 dB for 10-day variation, and between 11 dB and 15 dB for 1-day variation.

Solar activity may also contribute to the sky-wave path loss. However, it is assumed to be 0 for latitudes $|\text{Lat}| < 45^{\circ}$ and relatively small for larger latitudes and distance much larger than 100 km.

Daytime sky-wave propagation in the MF band may be practically ignored, as it is indicated in Recommendation ITU-R P.1147 to be approximately 43 dB lower than the similar distance/route night-time sky-wave propagation at the highest occurrence of 6 hours after sunset.

3.1.3 Composite wave propagation

The receiver is likely to exhibit a composite signal, consisting of the original ground wave signal and the deflected sky-wave signal. The sky-wave signal amplitude adheres to log-normal distribution. Assuming (per Recommendation ITU-R P.1321) the same distribution for the ground wave signal amplitude, the composite amplitude adheres to the following power summation:

$$A_c = \sqrt{(A_g^2 + A_s^2)} \tag{1}$$

where:

 A_c : composite amplitude

 A_g : ground amplitude

 A_s : sky-wave amplitude.

The composite signal also adheres to log-normal distribution. Using this assumption, the following example results are provided in Recommendation ITU-R P.1321 and Table 3.

The example assumes a standard deviation of 0 dB for the ground wave, and 3 dB for the sky-wave.

TABLE 3

A_s / A_gComposite mean level comparing to ground
wave mean levelComposite signal
standard deviation0.5 (-6 dB)1.3 dB0.72 dB1 (0 dB)4.4 dB1.35 dB2 (+6 dB)5.7 dB2 dB

Composite wave statistical parameters

3.1.4 Signal variability during daytime

Ground wave propagation varies with seasonal temperature. The variations increase along with the increase in summer-winter temperature difference. The long-term measurements, as reported in Recommendation ITU-R P.1321, indicate summer-winter daytime signal strength variations as small as 4 dB where the average winter temperature is 4° C and as high as 15 dB where the average winter temperature is -16° C.

3.1.5 Signal variability during night-time

Sky wave signal magnitude is subjected to night-to-night variations. The reported semi-interdecile hourly median distribution is up to 9 dB and the standard deviation across the measurements is approximately 3 dB. The measured fading rate is 10 to 30 fades per hour.

The nature of fades and excesses over the link (composite wave) has been measured as reported in Recommendation ITU-R P.1321 over long range, while short range information is not provided. The measurements indicate that at the peak hour (typically 24:00) the median rate is 3.5 fades or excesses per hour, with statistically close rates for each. The results also indicate that the duration of approximately 70% of the excesses is up to 5 minutes per hour, and the duration of approximately 90% of the excesses is up to 12 minutes per hour.

3.1.6 Terrain irregularities and obstruction

For signal propagation in the MF band, it is assumed (in NTIA report 99-368 on ITS) that smooth-earth ground wave propagation models and composite propagation models may be used as long as terrain irregularities (variations) are smaller than the wavelength. When such irregularities are of the size of the wavelength or larger, location dependency becomes significant and modelling becomes complicated and often too inaccurate. These irregularities have led to reliance on actual field measurements, use of actual field data, and even attempts to apply modelling to test results.

Location related signal variability, at a reference distance of 1 km between two locations outside of urban areas, is assumed Recommendation ITU-R P.1321 to exhibit a standard deviation of 3.7 dB. In urban street areas, the indicated standard deviation is 4 dB and reaches 8 dB in densely built urban areas. Inside buildings, resulting from absorption (penetration loss), it may reach 20 dB.

Measurements of the irregular terrain attenuation in Madrid are reported [16] for assisting with planning for digital broadcasting systems. The results were analysed for cells of the size of 500 m x 500 m. The results have suggested the possibility of differences exceeding 10 dB from one place to another at the same distance from the transmitter due to various obstructions where the dominant obstructions are close to the receiver. In an extreme case, such as a tunnel, fades (also known as 'shadowing') in excess of 20 dB were recorded. The report suggests a formulated method (with certain curve fitting) for representing the variations. The suggested method does not specifically relate to the variations' cause/nature and occurrence density. The accuracy and suitability of the formulated method to environments other than Madrid is not proven and is unclear.

An expanded characterization of spatial medium wave variability includes measurements in Delhi, Madrid, and Mexico City and is reported [17]. The results were analysed for square cells with diagonal length less than 1 km. As related to street dimensions, the report indicates that obstructionrelated fading in medium streets (up to seven lanes) have resulted in mean signal difference in excess of 11 dB with standard deviation of near 7 dB. The report indicates that obstruction-related fading in narrow streets (up to three lanes) have resulted in mean signal difference of nearly 20 dB with standard deviation of more than 8 dB. The analysis has separated the field strength variability into long term and short-term components. The report has pointed to the street width (within the cell) as the dominant cause for the long-term variability, while suggesting the use of the measured median field strength in the street (within the cell) for the purpose of deriving that component value. The report points to other conductive or absorptive (shadowing) structures, such as high buildings, tunnels (and over-paths), bridges, panels (signs), squares, power lines, and more, as the cause for short term variations. The processed results have shown that approximately 13% of measured cell segments were affected by short term variations, while spanning a range of over 30 dB. It has also been suggested that the short-term variations were practically of the same cause/nature and magnitude across all the tested areas, thus, the variations were independent of the specific urban environment. The combined variation range of both components is not specifically indicated but is likely to be wider than that of each component.

ITU Recommendations [2][3][4] for signal propagation analysis often refer to analysis methodology of one point at a time or to limited size cells. Similarly, some of the alternative propagation analysis proposals [5][15] as well as reported test data and modelling pertaining to obstruction related variability [16][17] followed the intra-cell methodology.

When considering urban and suburban mobility, the variability data for across longer segments (routes) may need to be considered. The HD Radio team has recorded and analysed data for signal strength variability due to obstruction from several routes. It was reiterated that multipath (i.e. Rayleigh statistically adhering fading) is rarely seen in the MF band because of the low frequency and large structure size required to reflect an incident wave. However, certain grounded conductive structures have proven to cause the magnitude and phase of the incident wave to change, sometimes as much as 60 dB in magnitude and 180° in phase.

For the purpose of analysis and planning for HD Radio broadcasting, specific data is used by and provided in Annex 2.

3.1.7 Noise

Noise in the MF band includes multiple sources, including ambient noise, low-noise amplifier (LNA) (and circuitry), and antenna circuitry. Each noise source has different characteristics. While some sources or requirements may be characterized, others may only be assumed or measured or remain unknown and variable.

3.1.7.1 Specified radio noise considerations

The recommended terms for noise calculations are provided in Recommendation ITU-R P.372. Without specifying the external noise source, the receiver noise factor at the receiver port is defined by:

$$f = f_a + f_c - 1 + l_c \cdot (f_t - 1) + l_c \cdot l_t \cdot (f_r - 1)$$
(2)

where:

- f_a : external noise factor, often expressed by the ambient temperature ratio $f_a = t_a / t_0$
- f_c : antenna circuitry noise factor due to the circuitry loss and circuitry temperature
- f_t : feeder (transmission line) noise factor due to the line loss and line temperature
- f_r : receiver noise factor, being typically the LNA noise factor.

When the transmission line actual temperature and the antenna circuitry actual temperature are close to the nominal temperature, then the receiver noise factor is reduced to:

$$f = f_a + f_c \cdot f_r \cdot f_r - 1 \tag{3}$$

For a short monopole antenna of length *h* relative to wavelength λ (*h* << λ) over a sufficient sized ground plane, the noise field strength (vertical component) may be calculated per Recommendation ITU-R P.372 as follows:

$$E_n = F_a + 20 \cdot \log(f_{MHz}) + 10 \cdot \log(b_{Hz}) - 95.5 \quad dB\mu V/m$$
(4)

where:

$$F_a = 10 \cdot \log\left(f_a\right) \tag{5}$$

Considering a reference frequency of 1 MHz and 530 kHz and receiver bandwidth of 10 kHz, then the noise field strength becomes:

$$E_n = F_a - 55.5$$
 dBµV/m@ 1 MHz (6)

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$$E_n = F_a - 61 \quad dB\mu V/m@~530 \text{ kHz}$$
 (7)

The results suggest that the noise factor (caused by atmospheric noise) sets the above values (55.5 dB and 61 dB) as the lower bound for the expected noise factor at various frequencies (respectively) in the MF band.

The various noise factors are indicated in Recommendation ITU-R P.372. The minimum noise factor from man-made noise in a 'quiet receiving site' (typically rural) is 53 dB at 1 MHz, while the man-made noise for a city area is 77 dB. Similarly, the atmospheric noise at 1 MHz is 100 dB.

3.1.7.2 Audio protection related requirements

Reception requirements for analogue signal audio protection, per Recommendation ITU-R BS.703, define the minimum input carrier signal (receiver sensitivity) for obtaining output Audio Frequency SNR (signal-to-un-weighted noise) of 26 dB for a 400-Hz tone at 30% modulation.

The 400-Hz, 30%-modulated AM test signal can be represented as:

$$s(t) = \left[1 + 0.3 \cdot \cos\left(2 \cdot \pi \cdot 400 \cdot t\right)\right] \cdot \cos\left(2 \cdot \pi \cdot f_c \cdot t\right) \tag{8}$$

The computed modulated (audio) power relative to the main carrier power:

$$10 \cdot \log(0.3^2) = 10 \cdot \log(0.09) = -10.5 dBc \tag{9}$$

Therefore, the required carrier-to-noise for the required audio is:

$$C/N = 26 \text{ dB} + 10.5 \text{ dB} = 36.5 \text{ dB}$$
(10)

The noise density over the entire signal bandwidth (10 kHz) is $N_0 = 40$ dB-Hz. Therefore, for analogue audio demodulation requirement in Recommendation ITU-R BS.703, the receiver sensitivity must conform to:

$$C/N_0 = 36.5 \text{ dB} + 40 \text{ dB-Hz} = 76.5 \text{ dB-Hz}$$
 (11)

The required receiver sensitivity (per the same reference) for the calculated C/N is 60 dBµV/m. Therefore, the specification-based calculated receiver input noise level is:

$$N_f = 60 \text{ dB}\mu\text{V/m} - 36.5 \text{ dB} = 23.5 \text{ dB}\mu\text{V/m}$$
(12)

Using the calculated receiver input noise level in conjunction with the noise field strength calculations as indicated in Recommendation ITU-R P.372 is as follows:

$$F_a = E_n + 55.5 \text{ dB} \quad @ 1 \text{MHz}$$
 (13)

$$F_a = E_n + 61 \text{ dB}$$
 @ 530 kHz (14)

Then, the audio related per Recommendation ITU-R BS.703 antenna noise factor at various frequencies (respectively) in the MF band, is as follows:

$$F_a = 79 \text{ dB} \quad @ 1 \text{MHz}$$
 (15)

$$F_a = 84.5 \text{ dB} \quad @ 530 \text{ kHz}$$
 (16)

3.1.7.3 Supplemental noise information

The man-made noise information indicated in Recommendation ITU-R P.372 is related to data recorded during the 1970s or prior to the 1970s. Some of the atmospheric-related data may be from

several years prior to that time. The information provided in Report ITU-R SM.2055 classifies the noise sources. It specifically indicates:

- 1 Atmospheric noise, mostly coming through sky wave, and from nearly any azimuth. It is strongly affected by time, season, frequency, weather and more.
- 2 Thermal noise, mainly from earth, but also from stellar bodies.
- 3 Equipment noise.
- 4 Man-made noise of different variants.

The levels of measured noise at the MF band are not indicated, but recommendations are provided to ensure that the receiver LNA NF (Noise Figure) is bounded by 15 dB, and preferably by 10 dB. It also assumes that NF in the range of 2 dB to 3 dB may be considered. This indirectly infers that the expected ambient noise far exceeds the receiver noise, thus reception is limited by the noise sources indicated above.

Additional atmospheric noise data (from 1988) is provided in [19]. The indicated atmospheric noise field strength for various angles exceed the 'quiet receiving site' (typically rural) man-made noise that is indicated in Recommendation ITU-R P.372, thus again pointing to it as the dominant noise source. In concentrated urban and business locations, man-made noise is indicated to be 20 dB to 30 dB higher than in rural areas. It then may become the dominant noise source, exceeding atmospheric noise levels.

More recent man-made noise measurements, made specifically while considering digital broadcasting systems in the MF band, were reported in [20] for indoor locations and in [21] for outdoor locations. Man-made noise is found to be the dominant noise in indoor locations, at least during daytime. The in-door measurements (as referenced above) point to an indoor external noise factor (Fa) which may be nearly 50 dB above the Recommendation ITU-R P.372 indicated noise factor for outdoor locations. These measurements also indicate nearly the same relative tendency across the entire MF band. The outdoor results (as referenced above) point to noise (mainly man-made) levels that are higher by at least 10 dB as measured in Madrid and higher by up to 40 dB as measured in Mexico City, when compared to the Recommendation ITU-R P.372 indicated noise levels for outdoor locations. That study's conclusions specifically state that the minimum field strength requirements for MW band services have to be increased by several decibels.

3.1.8 Reception paradigm layout

From the receiver point of view, antenna type is considered as the signal source (and noise source) for given or expected field types and ambient noise. Antenna location, antenna height, and feeder are considered sources for losses. Receiver location and potential motion need to be considered in the paradigm layout. Coupling the signal source with the reception layout allows for examining the most probable reception paradigm, and therefore its potential relevancy (or degree of contributing adjustments) to the minimum field strength requirement.

The considered reception paradigms are summarized in Table 4.

3.1.8.1 Fixed (FX) reception

This reception mode is considered for indoor only. The commonly used antenna (provided by most receiver manufacturers) for fixed location indoor reception is an air loop. Although it is referred to as 'magnetic loop' in the near field, both electrical and magnetic fields are used for (far field) reception. For some rare cases where certain receivers include a ferrite rod antenna, the magnetic field is assumed to dominate the reception. While both antennas may be oriented towards the desired direction and avoiding undesired signals, they have no effect on the ambient noise. Similarly, antenna orientation may be often inaccurate or non-ideal, thus further degrading the reception. The feeder loss

may consist of minimal-length low-capacitance cable between the receiver and the co-located loop antenna or may consist of negligible-length internal ferrite rod connected antenna.

Large signal variations outside the reception location have been predicted and measured. These large variations are further affected by a non-homogenous urban environment, building conductivity (modern business structures) and density. The reception elevation typically contributes to an increase in field strength.

Indoor signal level may be related to outdoor signal level by the penetration loss factor, distance from the walls, and adverse signal paths from the surrounding buildings/structures. There are no specific recommendations regarding the penetration loss. It may be significantly affected by the wall structure type (wood, concrete, metal with heat radiation deflecting material, etc.). It is indicated in Recommendation ITU-R P.1321 to exhibit values of 20 dB.

Ambient noise levels are provided in ITU documents only for outdoor reception, while they are provided by independent research for indoor reception. This situation may require expending indoor noise considerations for planning with either environment-specific (non-ITU) or geographically-specific (non-ITU) information.

3.1.8.2 Mobile (MO) reception

Mobile reception is defined as reception by a receiver in motion, at speeds ranging from approximately 2 km/h and up to 300 km/h. Speeds in the range of 50 km/h to 60 km/h are of interest as they represent urban vehicular motion. Additionally, speeds in the range of 90 km/h to 110 km/h are of some interest as they represent urban freeway (bypass urban 'highway') vehicular motion.

For this reception category, the antenna is considered situated at approximately 1.5 m or more above ground level. It typically consists of a whip (telescopic or fixed), mounted over the vehicle ground plane. It is considered omnidirectional, but it may be unevenly (directionally) affected by the vehicle. Electrical field is then used for reception.

Ambient noise levels are provided in ITU documents for outdoor reception and are also provided by independent research.

3.1.8.3 Portable (PO) reception

This mode of reception is relatively uncommon for broadcasting in the MF band.

While no typical receiver features or size are assumed, it is assumed that a common ferrite rod antenna may be used. The magnetic field is then considered to be used for reception. The antenna may be oriented toward the desired direction and avoiding undesired signals, but it has no effect on the ambient noise. Similarly, antenna orientation may be often inaccurate or non-ideal, thus further degrading the reception.

Ambient noise levels are provided in ITU documents for outdoor reception and are also provided by independent research.

_	_	_	
Reception mode	FX	МО	РО
Antenna type	Fixed air-loop	Mounted whip	Ferrite loop
Location	Indoor	Outdoor	Outdoor
Speed (km/h)	0 (static)	2-150	0 (quasi static)

TABLE 4

Reception Paradigm for Planning Considerations Parameters

3.2 Design related correction factors

This section provides the basis for the calculations approach for correction factors that are related to receiver design methodology. Some of the numerical expressions for adjustment calculations may only be provided for specific cases and cannot be provided in general form. This is because certain reception chain structures and reception locations/topology in the MF band are non-ideal and may be subjected to many parameters.

Receiver design approaches, in the 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 receiver approach was established and addressed by several publications and used for analysis of analogue signal reception and receiver implementation. Such a legacy approach has been often employed for analysis of digital signal reception. However, a more recent integrated receiver approach is also employed and is provided for planning purposes.

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 factors (for the antenna alone) were provided and were further followed by different sets of matching (or otherwise mismatching) losses, and then followed by discrete (provided separately) receiver noise figures.

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

3.2.1 Correction factors for integrated methodology

Several legacy design and analysis approach separately address the antenna and the RF front end. For sensitivity calculations in such designs, antennas are often represented by antenna factor ('gain'), and then attached to receivers with separately calculated noise figures. 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 factors (for the antenna alone) were provided and were further followed by different sets of matching (or otherwise mismatching) losses, and then followed by discrete (provided separately) LNA noise figure (referred to as receiver noise figure).

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 factor, as resulting from the receiver input network, while including the specific physical antenna that is assumed for that design. Then the combined antenna factor may be calculated.

Since each antenna type and receiver front end type may be differently modelled and then specifically analysed, the effect of the matching circuitry on the overall receiver sensitivity allows for adjustment only for each specific antenna and is provided in Annex 2.

3.2.1.1 Common antenna information

For the fixed location indoor reception, a loop antenna that is commonly provided by many receiver manufacturers has been used as reference for planning. The antenna consists of a rectangle air loop with a typical side length in the range of 10 cm to 15 cm.

For mobile reception a fixed or telescopic whip antenna that is often installed in a vehicle has been used as reference for planning. The antenna consists of an approximately 75-cm (30-inch) long whip

and is mounted over the vehicle which acts as the ground plane. Such an antenna is normally optimized for VHF band II (FM services) signal reception and is used for MF band signal reception while employing the best matching practices.

For portable reception a ferrite rod antenna has been used as reference for the purpose of planning. While no typical implementation is suggested, such an antenna may be considered due to its small dimensions, which can be considered for inclusion inside compact portable devices. Such an antenna is assumed to be approximately 7.5 cm (3 inches) long with a diameter of approximately 1.25 cm (0.5 inches).

3.2.1.2 Integrated receiver antenna noise factor – Specific cases

This section is informative only and may not be required for planning. However, it provides practical considerations for assisting with planning.

Field measurements and performance tests that are associated with planning often employ professional front-end equipment. Such equipment may include a special antenna (often specially sized, amplified) that may be specially placed (car rooftop, indoor window or centre place) and potentially followed by a special processing chain or professional receiver. While such tests provide correct and useful information, including the field strength, it may not always reflect the actual reception capabilities of various commercial-grade receivers for the very same technology. This section aims to assist with determining when the reception may be limited by noise (ambient, man-made) and therefore considers the noise-driven minimum field strength requirements, or otherwise when the reception may be limited by configuration and therefore considers the receiver integrated noise-factor-driven minimum field strength requirements.

The integrated noise figure calculations employ conservative practical values in accordance with the methodology for an antenna with maximum voltage transfer (to the LNA). In all the integrated antenna topologies, the LNA noise is assumed to be approximately 1 nV/ \sqrt{Hz} at the reference frequency. Even deviation from the assumed value is far below the integrated antenna noise. The noise factors are provided in Table 5.

Reception mode	FX	МО	РО
Specifically chosen antenna type	Fixed air-loop	Mounted whip	Ferrite loop
Antenna noise factor F_a (dB) (integrated receiver)	85	64.5	91.5

TABLE 5

HD Radio Antenna Noise Factor for Specific Integrated Receivers

3.2.2 Implementation loss

Implementation loss 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.

Small receivers, such as handheld devices, 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 functions. Therefore, the implementation loss, L_{im} , for such receivers is slightly higher, at approximately 4 dB. The implementation loss per reception mode is provided in Table 6.

Implementation loss factor

	FX, MO	РО
Implementation loss, <i>L_{im}</i> , (dB)	3	4

3.3 Channel models and applicable margins

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.

Multipath based on only speed modelling is rarely seen in the medium wave frequencies because of the large structure size required to reflect an incident wave continuously consistent with the tendency and direction of the vehicle's motion. However, certain ground conductive structures (GCS) can cause the magnitude and phase of the incident wave to change, sometimes as much as 60 dB in magnitude and 180° in phase.

Therefore, considering a reduced number of models, it may be assumed that reception under urban driving speed (55 km/h) while experiencing multiple GCS related abrupt fading is more demanding than reception under suburban driving speed (100 km/h) with potentially less often or relatively shallow fading; therefore, only the case of using the urban driving speed fading model needs to be considered for the purpose of planning.

For planning purposes, it is assumed that obstruction-related attenuation variability in the USA may be changing with the heterogeneity degree of the urban environment, as also shown in [17] for other locations (referring to using the long-term variability component). For the same reason, it is assumed that attempting to formulate the variability and accurately calculate such attenuation for all the medium wave reception areas in the USA may be impractical. Therefore, the HD Radio system has taken a different approach that includes recorded data and the use of fading margins as is assumed applicable for specific reception modes.

Similarly, a simplistic model for ground wave and sky wave combinations bounded by dispersion as indicated in Recommendation ITU-R P.1321 and even beyond, or otherwise certain deflection (or diffraction) related non-homogenous signals have been considered. However, the transitions from one propagation (thus signal reception) scenario to another vary noticeably, and it is assumed that it may be impossible to precisely distinguish when each scenario applies (and possibly follow by applying real-time system configuration changes) for practical operation. Therefore, the system configuration includes one extended signal time spread and coding depth, thus covering the more demanding conditions.

A lightning model has also been employed for system analysis but has not resulted in any significant impact that may require adjustments in SNR calculations.

In accordance with the analysis of a reduced number of cases, the reception mode and channel model combinations for planning purposes (referred to by their symbols in Annex 2) are provided in Table 7.

Definition of Reception Modes and Channel Models

Reception mode	FX	МО	РО
Antenna type	Fixed air-loop	Mounted whip	Ferrite loop
Antenna location	Indoor	Outdoor	Outdoor
Environment	Suburban/Urban	Suburban/Urban	Suburban/Urban
Analysis speed (km/h)	0 (static)	55, 100 (driving)	0 (quasi static)
Analysis channel model	FXWGN	UFGCS/RFGCS	FXWGN

4 Spectrum management considerations and control

The HD Radio system promotes spectrum management by allowing the introduction of digital broadcasts without the need for additional spectrum allocations. Special attention is given to adequate operation of the legacy analogue services while adding the digital signals. That includes also the prevalence of older receivers alongside with better performing newer receivers that can benefit from the digital services. Therefore, the system is often introduced with nominal power setting, but it allows for individually adjusting the power level of each digital block-pair ('sub-bands').

The power settings of each digital signal block-pair are provided in terms of dBc. The values indicate the ratio of the total power of the digital block-pair to the analogue (or otherwise measurable reference) carrier frequency power. Such an approach allows for hybrid signal composition to easily relate the signal components to each other in terms of power, as well as in terms of relating performance to the carrier power (being a single power parameter).



FIGURE 3 HD Radio digital signal power settings for AM system mode MA1

In system mode MA1, the transmitted digital power is separately defined for each block-pair. The definition is in dBc, relative to the existing analogue host carrier frequency power (which is the reference at 0 dBc). The values apply to the digital signal power density over a specified bandwidth.

The specified bandwidth is typically one subcarrier bandwidth of 181.7 Hz. That bandwidth is often converted to 300 Hz in order to simplify practical settings and field measurements.

The parameters in Fig. 3 apply to the AM mode MA1 configuration as follows:

- 0 dBc indicates the analogue host carrier frequency power level
- A_p indicates the power density setting of the primary block-pair in dBc/181.7 Hz
- As indicates the power density setting of the secondary block-pair in dBc/181.7 Hz
- A_t indicates the power density setting of the tertiary block-pair in dBc/181.7 Hz

The term L_p indicates the ratio of the analogue frequency power to the total power of the primary digital block-pair may be calculated from the power density as follows:

$$L_p = -(A_p + 10 \cdot \log(9200/181.7))$$
(17)

Similarly, the ratio of the analogue carrier power to the secondary block-pair L_s , and tertiary block-pair L_t can be calculated from the power density. However, in the full MA1 system mode, the secondary and tertiary block-pairs are only used jointly. Therefore, only the ratio L_{st} of the analogue carrier power to the joint power of these block-pairs is of interest.



FIGURE 4
HD Radio Digital Signal Power Settings for AM system mode MA3

The parameters in Fig. 4 apply to the AM mode MA3 configuration as follows:

- 0 dBc indicates the power level of the included carrier frequency (at 0 Hz)
- A_p indicates the power density setting of the primary block-pair in dBc/181.7 Hz

- A_s indicates the power density setting of the secondary block-pair in dBc/181.7 Hz

Then for MA1,

- For the nominal settings of $A_p = -30 \text{ dBc}$, $L_p \sim 13 \text{ dB}$

- For the nominal settings of $A_s = -43$ dBc and $A_t = -44$ dBc $\div -50$ dBc, $L_{st} \sim 24.5$ dB Then for MA3,

- For the nominal settings of $A_p = -15 \text{ dBc}$, $L_p \sim -2.5 \text{ dB}$
- For the nominal settings of As = -30 dBc, $L_s \sim 12.5 \text{ dB}$

- For these nominal settings, the total power of the digital subcarriers (including the reference subcarriers and the PIDS subcarriers), exceeds the power of the included frequency carrier at 0 Hz by approximately 2.3 dB.

These power ratios (L_p, L_s, L_{st}) are further used for planning, thus allowing for flexibility and adjustment if and when such need arises.

5 Field strength considerations

The calculations of minimum field strength are provided twice where each time a different approach is considered.

The first is a legacy audio protection noise-level-based approach which follows ITU-based information.

The later approach is the receiver practice approach, which applies to the highly integrated receivers and follows practical considerations as often apply to more recent receiver implementations.

Specifically, the following is noted:

 The noise driven approach solely considers the information provided by Recommendations ITU-R P.368, ITU-R P.1321, ITU-R P.1147, ITU-R P.372, ITU-R BS.703, ITU-R BS.415 and Report ITU-R SM.2055, regarding both noise sources and wave propagation.

The referenced ITU-R Recommendations and Reports that provided data regarding noise were established in the 1970s and updated only to a limited degree. Technological advances in recent decades have resulted in increased man-made noise, as has been observed and indicated in certain independent (non-ITU) published documents.

While certain other systems' approaches may consider only the noise data from referenced documents for deriving the minimum usable field strength, the HD Radio system's analysis applies also a supplementary approach, where receiver design practices are considered in order to determine the reception limiting factors for a given field strength. This may be considered informative but has the potential for assisting with realistic planning regarding minimum usable field strength, rather than only referring to potentially increased noise as the sole cause for reception performance.

- Large signal variability is indicated in the referenced documents due to the limited accuracy of the propagation analysis and due to dispersion and GCS impacts. In attempting to predict reception in mobile mode, the signal strength over a large reception area is often measured in limited size squares and/or over several static location points. While certain other systems' approaches may consider such quasi-static information sufficient for mobile reception analysis, the HD Radio system's approach to signal reception considers 'good' mobile reception as the reception in motion. As a result, the HD Radio system applies an additional (on top of already considered propagation and noise information) GCS-related fading margin of 3 dB to mobile reception mode for adequate reception in true motion.
- Broad industry experience with advanced and highly integrated and/or small receivers indicates that such receivers may be optimized for a wide range of functionalities other than medium wave reception. Therefore, considering implementation losses may be required. Such losses are included in the receiver practices approach for deriving the minimum usable field strength.

The HD Radio system 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 partial data may lead to potential reduction of more than 10 dB in minimum usable

field strength requirements, which may potentially lead to inadequate planning and then inadequate reception in realistic conditions.

The various channel models, reception modes, and details related to the analysis and calculations for deriving the minimum required field strength for allowing an adequate operation of HD Radio receivers are provided in § 3.

In certain HD Radio system configurations (i.e. system modes) where both channels P1 (included in PL+PU digital block-pair) and P3 (included in SL+SU and TL+TU) are active, and where power level settings for each block-pair are different, separate requirements (C/N) are used for planning and are specifically indicated in the Tables in this section.

5.1 Minimum *C*/*N*

C/N values (at f = 1 MHz) are provided for an average decoded BER of 1×10^{-4} as a reference operating point for providing services. These values are provided in terms of *C/N*₀ (dB-Hz), reflecting the ratio of the analogue (or otherwise measurable reference) carrier frequency power to the noise density (in 1 Hz).

In considering the propagation factors and noise-related information, as provided in Recommendation ITU-R P.1321, and particularly their large variability or their level of uncertainty, and based on potential (and actual) usage scenarios of various HD Radio receiver types, the following approach is applied for planning:

- 1 A single coding rate and an interleaver span that far exceeds the indicated composite wave time span are employed (see Table 1). Therefore, no significant dependency on the wave composition variants is considered.
- 2 For fixed reception, only noise (ambient, man-made) is considered.
- For mobile receivers, typical usage is more likely to be experienced in urban areas. In addition, analysis and actual tests have not shown significant differences of impact on reception, between urban conditions (55 km/h) and suburban conditions (100 km/h), with often urban environment causing more signal disruption. Therefore, urban reception conditions analysis, which employs more aggressive GCS dispersive profiles, is used for planning purposes.
- For portable receivers, it is assumed that they are likely to be used for quasi-static reception, thus quasi-static (0 km/h) outdoor conditions. Therefore, such reception is used in conjunction with portable receivers for planning purposes. Only noise (ambient, man-made) is considered.

The signal-to-noise requirements for the HD Radio system are provided in terms of C/N_0 (carrier power to noise spectral density ratio). The carrier frequency power is an easily measurable reference. These values consider the ratio of the analogue host carrier frequency power to the total power of the digital block-pair for the hybrid configurations. Similarly, these values consider already the ratio of the transmitted carrier frequency power to the total power of the digital block-pair for the all-digital configurations.

The ratio of the carrier frequency power to the total power of the digital block-pair may be adjusted using the power adjustment parameters L_p , L_{st} and L_s (as defined in Annex 1).

The cases (and models) and their related required C/N_0 (carrier power to noise spectral density ratio) as analysed for planning purposes are provided in Table 8 for the parameter-dependent adjustable settings. All the values are rounded towards the nearest 0.5 dB-Hz.

TABLE	8
	v

HD radio receiver required C/N_0 for various reception modes (adjustable settings)

Reco	eption mode	FX	МО	РО
Channel model sy	vmbol	FXWGN	UFGCS/RFGCS	FXWGN
Environment		Suburban/Urban	Suburban/Urban	Suburban/Urban
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)
MA1 – 10 kHz	Required <i>C</i> / <i>N</i> ₀ (dB–Hz) For receiving P1	$53 + L_{p}^{*}$	$53 + L_{p}^{*}$	53 + L _p *
MA1 – 30 kHz	Required <i>C</i> / <i>N</i> ₀ (dB–Hz) For receiving P1	$53 + L_{p}*$	53 + L _p *	53 + L _p *
MA1 – 30 kHz	Required C/N_0 (dB–Hz) For receiving P1 and P3	$50.5 + L_{st}^*$	$50.5 + L_{st}$	$50.5 + L_{st}$
MA3 – 10 kHz	Required <i>C</i> / <i>N</i> ₀ (dB–Hz) For receiving P1	$53.5 + L_{p}^{*}$	$53.5 + L_{p}*$	$53.5 + L_p*$
MA3 – 20 kHz	Required <i>C</i> / <i>N</i> ₀ (dB–Hz) For receiving P1	$53.5 + L_{p}^{*}$	$53.5 + L_{p}^{*}$	$53.5 + L_{p}^{*}$
MA3 – 20 kHz	Required C/N_0 (dB–Hz) For receiving P1 and P3	$53.5 + L_s*$	$53.5 + L_s*$	$53.5 + L_s*$

* Power adjustment parameter.

5.2 Noise level related audio protection minimum usable field strength (Legacy method)

The minimum usable field strength E_{min} for the HD Radio system, using legacy audio protection noise-level-based approach, is indicated in Table 9 through Table 12. All the values are rounded towards the nearest 0.5 dBµV/m.

It is noted that the minimum usable field strength is indicated for the carrier frequency (as a measurable reference). It employs the relevant carrier to digital block-pair power ratio (L_p , L_{st} and L_s , respectively).

NOTE – The value of L_p , L_{st} and L_s may vary from one configuration to another.

The reception environment and related antenna and noise considerations are further described in § 3.

HD radio receiver minimum usable carrier field strength for hybrid configuration primary bands reception based on noise level (adjustable settings)

]	Reception mode	FX	МО	РО
Channel model s	symbol	FXWGN	UFGCS/RFGCS	FXWGN
Environment		Suburban/Urban	Suburban/Urban	Suburban/Urban
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)
Indicated antenna noise @10 kHz BW (dBµV/m)		23.5	23.5	23.5
MA1 – 10 kHz	Minimum carrier field strength E_{min} (dB μ V/m) For receiving PL+PU	$36.5 + L_p$	36.5 + L _p	$36.5 + L_p$
MA1 – 30 kHz	Minimum carrier field strength E_{min} (dB μ V/m) For receiving PL+PU	36.5 + L _p	36.5 + L _p	36.5 + L _p

TABLE 10

HD radio receiver minimum usable carrier field strength for hybrid configuration secondary and tertiary bands reception based on noise level (adjustable settings)

	Reception mode	FX	МО	РО
Channel model	symbol	FXWGN	UFGCS/RFGCS	FXWGN
Environment		Suburban/Urban	Suburban/Urban	Suburban/ Urban
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)
Indicated antenn	Indicated antenna noise @10 kHz BW (dBµV/m)		23.5	23.5
MA1 – 30 kHz	Minimum carrier field strength E_{min} (dB μ V/m) For receiving SL+SU and TL+TU	$34 + L_{st}$	$34 + L_{st}$	$34 + L_{st}$

HD radio receiver minimum usable carrier field strength for all-digital configuration primary bands reception based on noise level (adjustable settings)

Reception mode		FX	МО	РО
Channel model symbol		FXWGN	UFGCS/ RFGCS	FXWGN
Environment		Suburban/Urban	Suburban/ Urban	Suburban/ Urban
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)
Indicated antenna noise @10 kHz BW (dBµV/m)		23.5	23.5	23.5
MA3 – 10kHz	Minimum carrier field strength E_{min} (dB μ V/m) For receiving PL+PU	36.5 + L _p	36.5 + L _p	36.5 + L _p
$\begin{array}{c} MA3 - \\ 20 \text{kHz} \end{array} \begin{array}{c} \text{Minimum carrier field strength} \\ E_{min} (\text{dB}\mu\text{V/m}) \\ \text{For receiving PL+PU} \end{array}$		36.5 + L _p	36.5 + L _p	36.5 + L _p

TABLE 12

HD radio receiver minimum usable carrier field strength for all-digital configuration secondary bands reception based on noise level (adjustable settings)

	Reception mode	FX	МО	РО	
Channel model symbol		FXWGN UFGCS/RFGC		FXWGN	
Environment		Suburban/Urban Suburban/ S Urban S		Suburban/Urban	
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)	
Indicated antenna noise @10 kHz BW (dBµV/m)		23.5	23.5	23.5	
MA3 – 20 kHz	IA3 - 0 kHzMinimum carrier field strength E_{min} (dB μ V/m) For receiving SL+SU		36.5 + L _s	36.5 + L _s	

5.3 Integrated receiver practice related minimum usable field strength

The minimum usable field strength E_{min} for the HD Radio system, using an integrated receiver practice-based approach, is indicated in Table 13 to Table 16. All the values are rounded towards the nearest 0.5 dBµV/m.

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It is noted that the minimum usable field strength is indicated for the carrier frequency (as a measurable reference). It employs the relevant carrier to digital block-pair power ratio (L_p , L_{st} and L_s , respectively).

NOTE – The value of L_p , L_{st} and L_s may vary from one configuration to another.

TABLE 13

HD radio receiver minimum usable carrier field strength for hybrid configuration primary bands reception based on integrated receiver practice (adjustable settings)

Reception mode		FX	МО	РО
Channel mode	l symbol	FXWGN	UFGCS/RFGCS	FXWGN
Environment		Suburban/Urban	Suburban/Urban	Suburban/Urban
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)
Antenna type		Air loop	Whip	Ferrite loop
Calculated receiver noise factor (dB)		85	64.5	91.5
Calculated antenna noise @10 kHz BW (dBµV/m)		29.5	9	36
Fading margin (dB)		0	3	0
Implementatio	n loss (dB)	3	3	4
MA1 - 10 kHz	Minimum carrier field strength E_{min} (dB μ V/m) For receiving PL+PU	45.5 + L _p	28 + L _p	53 + L _p
MA1 - 30 kHz	Minimum carrier field strength <i>E_{min}</i> (dBµV/m) For receiving PL+PU	45.5 + L _p	28 + L _p	53 + L _p

HD radio receiver minimum usable carrier field strength for hybrid configuration secondary bands reception based on integrated receiver practice (adjustable settings)

Reception mode		FX	МО	РО
Channel mode	l symbol	FXWGN	UFGCS/RFGCS	FXWGN
Environment		Suburban/Urban	Suburban/Urban	Suburban/Urban
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)
Antenna type		Air loop	Whip	Ferrite loop
Calculated receiver noise factor (dB)		85	64.5	91.5
Calculated antenna noise @10 kHz BW (dBµV/m)		29.5	9	36
Fading margin (dB)		0	3	0
Implementation loss (dB)		3	3	4
MA1 - 30 kHz	Minimum carrier field strength E_{min} (dB μ V/m) For receiving SL+SU and TL+TU	43 + L _{st}	$25.5 + L_{st}$	50.5 + L _{st}

TABLE 15

HD radio receiver minimum usable carrier field strength for all-digital configuration primary bands reception based on integrated receiver practice (adjustable settings)

Reception mode		FX	МО	РО
Channel mode	l symbol	FXWGN	UFGCS/RFGCS	FXWGN
Environment		Suburban/Urban	Suburban/Urban	Suburban/Urban
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)
Antenna type		Air loop	Whip	Ferrite loop
Calculated receiver noise factor (dB)		85	64.5	91.5
Calculated antenna noise @10 kHz BW (dBµV/m)		29.5	9	36
Fading margin (dB)		0	3	0
Implementation loss (dB)		3	3	4
MA3 - 10 kHz	Minimum carrier field strength E_{min} (dB μ V/m) For receiving PL+PU	45.5 + L _p	28 + L _p	49 + L _p
MA3 - 20 kHz	Minimum carrier field strength E_{min} (dB μ V/m) For receiving PL+PU	45.5 + L _p	28 + L _p	49 + L _p

Reception mode		FX	МО	РО	
Channel mode	l symbol	FXWGN	UFGCS/RFGCS	FXWGN	
Environment		Suburban/Urban	Suburban/Urban	Suburban/Urban	
Speed (km/h)		0 (static)	55, 100 (driving)	0 (quasi static)	
Antenna type		Air loop	Whip	Ferrite loop	
Calculated receiver noise factor (dB)		85	64.5	91.5	
Calculated antenna noise @10 kHz BW (dBµV/m)		29.5	9	36	
Fading margin	Fading margin (dB)		3	0	
Implementation loss (dB)		3	3	4	
MA3 - 20 kHz	MA3 - 20 kHz Minimum carrier field strength E_{min} (dB μ V/m) For receiving SL+SU		$28 + L_s$	49 + L _s	

HD radio receiver minimum usable carrier field strength for all-digital configuration secondary bands reception based on integrated receiver practice (adjustable settings)

6 **RF** protection ratios for HD Radio system (a realization of in-band on-channel) in the MF band

6.1 HD Radio system spectral configurations

The system can be configured to use multiple frequency blocks. Each frequency block occupies a nominal bandwidth of 5 kHz (actual bandwidth of approximately 4.8 kHz). Such spectral configurations are shown for hybrid signal composition in Fig. 1, and for all-digital signal composition in Fig. 2.

Ideally, it is desired to configure each matching block-pair at the same power level. However, the system supports setting the power level of each individual block. Therefore, for the purpose of defining the protection ratios each such configuration can be analysed by each block at a time.

FIGURE 5 HD Radio hybrid signal spectra – MA1 at 10 kHz used bandwidth digital signal spectra and emissions mask and normalized analogue PSD



HD Radio digital waveform spectral emissions limits for hybrid configuration - Mode MA1

Frequency offset relative to carrier	Level relative to uniform distribution of unmodulated carrier Rec. ITU-R SM.328-11, § 6.3.3 (dBc per 100 Hz)
9.4 to 15 kHz offset	-16.3
15 to 15.2 kHz offset	-17.5
15.2 to 15.8 kHz offset	$-28.5 - (\text{frequency offset in kHz} - 15.2) \cdot 43.3$
15.8 to 25 kHz offset	-54.5
25 kHz to 30.5 kHz offset	$-54.5 - (\text{frequency offset in kHz} - 25) \cdot 1.273$
30.5 kHz to 75 kHz offset	$-61.5 - (\text{frequency offset in kHz} - 30.5) \cdot 0.292$
> 75 kHz offset	-74.5

The spectra of one supported hybrid signal configuration, using 10 kHz bandwidth, is shown in Fig. 5. In that case, the secondary and tertiary bands are not present. Referring to Recommendation ITU-R SM.328, the emissions mask is shown for each block, and details are provided in Table 17. For protection and interference analysis, the contribution of each block may be calculated individually and then combined (if combination is still relevant, given the frequency-separated positioning). Additionally, the power level of the blocks may be set independently of each other, if considered necessary for mitigating potential interference in a specific case.



FIGURE 6 HD Radio hybrid signal spectra and digital signal emissions mask – Mode MA3 at 10 kHz used bandwidth

Frequency offset relative to carrier	Level relative to uniform distribution Rec. ITU-R SM.328-11, § 6.3.3
	(abc per 100 Hz)
0.3 kHz to 5.0 Hz offset	0
5.0 kHz to 7.0 kHz offset	- (frequency offset in kHz $- 5.0$) $\cdot 17.35$
7.0 to 10.4 kHz offset	$-34.7 - (\text{frequency offset in kHz} - 7.0) \cdot 2.06$
10.4 to 20.0 kHz offset	$-41.7 - (\text{frequency offset in kHz} - 10.4) \cdot 1.25$
20.0 to 30.0 kHz offset	$-53.7 - (\text{frequency offset in kHz} - 20.0) \cdot 0.60$
30.0 to 60.0 kHz offset	$-59.7 - (\text{frequency offset in kHz} - 30.0) \cdot 0.27$
> 60 kHz offset	-67.8

HD Radio digital waveform spectral emissions limits for all-digital configuration – Mode MA3 10kHz bandwidth

The spectra of one supported all-digital signal configuration using 10 kHz bandwidth is shown in Fig. 6. In that case, the secondary bands are not present. Referring to Recommendation ITU-R SM.328, the emissions mask is shown for the block-pair, and details are provided in Table 18. For protection and interference analysis, the contribution of the block-pair should be used, following by setting the power level of the block-pair accordingly. However, it is possible to calculate the contribution of each block individually and then combine the results. Then, the power level of the blocks may be set independently of each other, if considered necessary for mitigating potential interference in unique cases.



FIGURE 7

Frequency offset relative to carrier	Level relative to uniform distribution Rec. ITU-R SM.328-11, § 6.3.3 (dBc per 100 Hz)
0.3 kHz to 5.0 kHz offset	0
5.0 kHz to 5.9 kHz offset	$-$ (frequency offset in kHz $-$ 5.0) \cdot 16.67
5.9 kHz to 10.0 kHz offset	-15
10.0 to 11.2 kHz offset	$-15 - (\text{frequency offset in kHz} - 10.0) \cdot 23.08$
11.2 to 20.0 kHz offset	-42.7 - (frequency offset in kHz - 11.2) · 1.25
20.0 to 30.0 kHz offset	$-53.7 - (\text{frequency offset in kHz} - 20.0) \cdot 0.6$
30.0 to 60.0 kHz offset	$-59.7 - (\text{frequency offset in kHz} - 30) \cdot 0.27$
> 60 kHz offset	-67.8

HD Radio digital waveform spectral emissions limits for all-digital configuration – Mode MA3 20 kHz bandwidth

The spectra of higher bitrate supported all-digital signal configuration using 20 kHz bandwidth is shown in Fig. 7. In that case, the secondary bands are not present. Referring to Recommendation ITU-R SM.328, the emissions mask is shown for the block-pair, and details are provided in Table 19. For protection and interference analysis, the contribution of each block-pair (PL+PU and SL+SU respectively) should be used, following by setting the power level of each block-pair accordingly. However, it is possible to calculate the contribution of each block individually and then combine the results. Then, the power level of the blocks may be set independently of each other, if considered necessary for mitigating potential interference in unique cases.

6.2 **RF** protection levels

For calculating the protection ratio required for the analogue AM signal, preserving the performance of the audio frequency (thus the audio protection ratio) may be considered. Recommendation ITU-R BS.560 provides the required RF signal protection ratio, which is required for ensuring the audio signal protection ratio. For Region 2, the AF protection ratio and the employed related (un-corrected) RF protection ratio is 26 dB. For ITU Regions 1 and 3, an AF protection ratio of 30 dB, was adopted by the Regional Administrative LF/MF Broadcasting Conference for Regions 1 and 3 (Geneva, 1975). The same value is used for calculating the RF protection ratio, as the AF correction is less than 1 dB.

While the HD Radio system is initially associated with ITU Region 2 and its practiced protection ratios, the protection ratios have been also calculated and provided in the following Tables in respect to ITU Regions 1 and 3.

The relative RF protection ratio for AM interfered by AM follows Recommendation ITU-R BS.560 § 2, Table 1. The higher protection ratio demanding case of low audio compression (curve C) is used, thus ensuring sufficient protection for the highly compressed audio (curve D). The relative ratio is provided in Table 20.

Relative protection ratio for AM interfered by AM

			F _{undesired} – F _{desired} (kHz)							
Desired	Un-desired	-20	-18	-10	-9	0	+9	+10	+18	+20
AM	AM	-55.4	-53.3	-32	-25	0	-25	-32	-53.3	-55.4

6.2.1 Calculation methodology for interference involving analogue AM

Calculating the interference to analogue AM signals may require certain assumptions. A possible approach to calculating the interference to analogue AM signals may involve assumption regarding the parameters of a receiver filter. However, such assumption may be valid only for a given time and may not represent receiver improvements. HD Radio receivers, which handle simultaneously both analogue AM and digital signals, have employed various filters, thus suggesting that assuming a specific filter (for modelling receiver performance) may be inadequate.

An alternative approach is adopted by HD Radio system. It is based on a firmly defined reference broadcast waveforms for analogue AM and a long time established and field employed AM to AM interference paradigm. The approach examines the relatively added interference by the digital signal in comparison to a potentially existing (or hypothetically placed or previously existing but now removed) analogue AM signal. Employing the defined signals and familiar paradigm is assumed more reliable and sustainable for deriving the adjusted RF protection ratios.

Detailed and refined calculations of protection ratio and coloured noise modulated analogue AM spectra are already defined. For practical reason, including channel raster resolution, flow up Figures and analysis in Recommendation ITU-R BS.560 (Fig. 1) for protection requirements, Recommendation ITU-R SM.328 (Fig. 11) for spectra modelling, and Recommendation ITU-R BS.559 (Fig. 8) for objective analysis, are provided for frequency shifts (Δf) resolution of 1 kHz.



The HD Radio hybrid signal in modified mode MA1 consists of the original analogue signal ('host') and a digital signal block (or block-pair). The analogue signal spectra, generated by using coloured noise for modulation, as recommended in Recommendation ITU-R BS.559, and including both digital blocks (PL and PU) and their spectral mask are shown in Fig. 8, using resolution of 1 kHz. Since the

original analogue AM signal is present, the level of the digital signal PSD does not exceed -23 dBc. The level of each block can be individually reduced or set such that only one block is present.



The desired analogue AM signal along with interfering HD Radio hybrid signal consisting of AM and PU is shown in Fig. 9. The co-channel (shift of 0 kHz) hybrid signal is required to adhere to the AM protection ratio of 30 dB, referenced to hypothetical interfering analogue AM signal.

The digital block PU (of that interfering hybrid signal) is inherently located in the frequency band that otherwise would be interfered by a shifted analogue AM signal. Therefore, a hypothetical AM signal shifted by +9 kHz and set at the maximum allowed AM to AM protection level of 5dB, is shown for reference. The added interference by PU is the calculated contribution of PU spectra that exceeds the spectra of hypothetical (allowed) AM interference in that band. In the specific example in Fig. 9, it can be seen that PU interference does not exceed that interference of the hypothetical AM.



Similarly, when the undesired above HD Radio hybrid signal configuration is shifted by +10 kHz, the incremental interference (if exists) overlaps with a hypothetical analogue shifted further. Therefore, the added interference (if exists) is calculated for hypothetical AM signal at any applicable shift. As can be seen (or interpreted) from Figs 9 and 10, there seem to be no added interference from PU at any frequency shift > 0 Hz, for channel spacing in multiples of 9 kHz and 10 kHz.

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In the situation shown in Fig. 11, the undesired HD Radio hybrid signal configuration is shifted by -9 kHz, and the analogue component is set at the allowed level of -5 dBc. The incremental interference (caused by PU) overlaps with a hypothetical interfering analogue shifted by 0 Hz. The hypothetical interfering analogue signal is adjusted by 30 dB as required for protecting the desired signal. Yet, the digital block PU (or the entire hybrid signal) must be further reduced by approximately 21 dB (to approximately 12 dB below the level of the hypothetical interfering analogue) in order for the entire integrated PU power to not exceed the interference allowed for the hypothetical signal.

It is noted that the interference is calculated without assuming the additional filtering of a receiver filter. Any given receiver filter may further reduce the interference by 1 dB to 7 dB, thus allowing to adjust (relief) the protection requirements accordingly. For example, a narrow receiver filter with a bandwidth of 2.4 kHz at -3 dB and a slope of 36 dB/Octave may further filter the interference from PU by an amount of approximately 5 dB, thus requiring the reduction of PU level by approximately 7 dB (instead of the no-filter case), and setting it at a power level similar to that of the hypothetical interfering analogue shifted by 0 Hz (i.e. -30 dBc).

FIGURE 11 Desired AM signal interfered by HD Radio Hybrid signal analogue + PU (-9 kHz



In the situation shown in Fig. 12, the undesired HD Radio hybrid signal configuration is shifted by -20 kHz, and the analogue component is set at the allowed level of +25.4 dBc. The incremental interference (caused by PU) overlaps with a hypothetical interfering analogue shifted by -10 Hz. The hypothetical interfering analogue signal is adjusted by 30 dB as required for protecting the desired signal. Yet, the digital block PU (or the entire hybrid signal) must be further reduced by approximately 18 dB in order for the entire integrated PU power to not exceed the interference allowed for the hypothetical signal.

It is noted that the interference is calculated without assuming the additional filtering of a receiver filter. Any given receiver filter may further reduce the interference by 3 dB to 15 dB, thus allowing to adjust (relief) the protection requirements accordingly. For example, a narrow receiver filter with a bandwidth of 2.4 kHz at -3 dB and a slope of 36 dB/Octave may further filter the interference from PU by an amount of approximately 11 dB, thus requiring the reduction of PU level by approximately 7 dB (instead of the no-filter case), and setting it at a power level similar to that of the hypothetical interfering analogue shifted by -10 Hz (i.e. +2 dBc).



The desired analogue AM signal along with co-channel interfering HD Radio digital signal consisting of PL and PU is shown in Fig. 13. The digital signal is configured to mode MA3 at 10 kHz bandwidth. In that specific configuration, the total power of the modulated subcarriers is approximately 2.3 dB above the power of the included un-modulated carrier (at 0 Hz). Therefore, the actual resulting spectrum of the modulated subcarrier is equivalently lowered (in reference to 0 dBc) by 2 dB.

The co-channel (shift of 0 kHz) digital signal is required to adhere to the AM protection ratio of 30 dB, referenced to hypothetical interfering analogue AM signal.

The hypothetical interfering analogue signal is adjusted by 30 dB as required for protecting the desired signal. Yet, the digital signal has to be further reduced by approximately 6 dB (having the modulated subcarriers at approximately 8 dB below the level of the hypothetical interfering analogue) in order for the entire integrated digital signal power to not exceed the interference allowed for the hypothetical signal.

It is noted that the interference is calculated without assuming the additional filtering of a receiver filter. Any given receiver filter may further reduce the interference by 1 dB to 7 dB, thus allowing to adjust (relief) the protection requirements accordingly. For example, a narrow receiver filter with a bandwidth of 2.4 kHz at -3 dB and a slope of 36 dB/Octave may further filter the interference from PL + PU by an amount of approximately 2 dB, thus requiring the reduction of digital signal by only 4 dB (instead of the no-filter case), resulting in setting the modulated subcarriers at approximately 6 dB below the level of the hypothetical interfering analogue.



The desired analogue AM signal along with interfering HD Radio digital signal consisting of PL and PU, shifted by +9 kHz, is shown in Fig. 14. The digital signal resulting spectrum of the modulated subcarrier is equivalently lowered (in reference to 0 dBc) by 2 dB.

The hypothetical interfering analogue signal, shifted by +9 kHz, and set at the allowed level of -5 dBc as required for protecting the desired signal from such analogue AM. Yet, the digital signal has to be further reduced by approximately 9 dB (Having the modulated subcarriers at approximately 11 dB below the level of the hypothetical interfering analogue) in order for the entire integrated digital signal power to not exceed the interference allowed for the hypothetical signal. The adjustment consists approximately 6 dB in band excess power and approximately additional 3 dB difference between the hypothetical AM spectrum and the digital signal mask in the out-of-band range of -5 kHz to -7 kHz removed from the enter frequency of the digital interference.

It is noted that the interference is calculated without assuming the additional filtering of a receiver filter. Any given receiver filter may further reduce the interference by 2 dB to 12 dB, thus allowing to adjust (relief) the protection requirements accordingly. For example, a narrow receiver filter with a bandwidth of 2.4 kHz at -3 dB and a slope of 36 dB/Octave may further filter the interference from PL by an amount of approximately 8 dB, thus requiring the reduction of digital signal by only 1 dB (instead of the no-filter case), resulting in setting the modulated subcarriers at approximately 3 dB below the level of the hypothetical interfering analogue.

When the digital interfering signal and the hypothetical AM interference are shifted by +10 kHz and compared to the maximum allowed AM to AM interference at +10 kHz, similar relative results as for the shift by +9 kHz, may be obtained for the cases without and with assuming additional receiver filtering.



The desired analogue AM signal along with interfering HD Radio digital signal consisting of PL and PU, shifted by +20 kHz, is shown in Fig. 15.

The hypothetical interfering analogue signal, shifted by +20 kHz, is set at the allowed level of +25.4 dBc as required for protecting the desired signal from such analogue AM (having the modulated subcarriers at approximately 8 dB below the level of the hypothetical interfering analogue) in order for the entire integrated digital signal power to not exceed the interference allowed for the hypothetical signal.

It is noted that the interference is calculated without assuming the additional filtering of a receiver filter. Any given receiver filter may further reduce the interference by very little, as the excess interference is caused by the slow drop of the far out-of-band signal. For example, a narrow receiver filter with a bandwidth of 2.4 k Hz at -3 dB and a slope of 36 dB/Octave may further filter the interference by an amount of approximately 1 dB, resulting in setting the modulated subcarriers at approximately 7 dB below the level of the hypothetical interfering analogue.

When the digital interfering signal and the hypothetical AM interference are shifted by +18 kHz and compared to the maximum allowed AM to AM interference at +18 kHz, similar relative results as for the shift by +20 kHz, may be obtained for the cases without and with assuming additional receiver filtering.



The desired analogue AM signal along with co-channel interfering HD Radio digital signal consisting of SL, PL, PU and SU, is shown in Fig. 16. The digital signal is configured to mode MA3 at 20 kHz bandwidth. In that specific configuration, the total power of the modulated subcarriers is approximately 2.4 dB above the power of the included un-modulated carrier (at 0 Hz). Therefore, the actual resulting spectrum of the modulated subcarrier is equivalently lowered (in reference to 0 dBc) by approximately 2 dB.

The co-channel (shift of 0 kHz) digital signal is required to adhere to the AM protection ratio of 30 dB, referenced to hypothetical interfering analogue AM signal.

The hypothetical interfering analogue signal is adjusted by 30 dB as required for protecting the desired signal. Yet, the digital signal has to be further reduced by approximately 6 dB (Having the modulated subcarriers PL + PU at approximately 8 dB below the level of the hypothetical interfering analogue) in order for the entire integrated digital signal power to not exceed the interference allowed for the hypothetical signal.

It is noted that the interference is calculated without assuming the additional filtering of a receiver filter. Any given receiver filter may further reduce the interference by 1 dB to 7 dB, thus allowing to adjust (relief) the protection requirements accordingly. For example, a narrow receiver filter with a bandwidth of 2.4 kHz at -3 dB and a slope of 36 dB/Octave may further filter the interference from the digital signal (caused nearly solely by PL + PU) by an amount of approximately 2 dB, thus requiring the reduction of digital signal by only 4 dB (instead of the no-filter case), resulting in setting the modulated PL + PU subcarriers at approximately 6 dB below the level of the hypothetical interfering analogue.



The desired analogue AM signal along with interfering HD Radio digital signal consisting of PL and PU, shifted by +9 kHz, is shown in Fig. 17. The digital signal resulting spectrum of the modulated subcarrier is equivalently lowered (in reference to 0 dBc) by 2 dB.

The hypothetical interfering analogue signal, shifted by +9 kHz, and set at the allowed level of - 5 dBc as required for protecting the desired signal from such analogue AM. Yet, the digital signal has to be further reduced by approximately 14 dB (Having the modulated subcarriers PL + PU at approximately 16 dB below the level of the hypothetical interfering analogue) in order for the entire integrated digital signal power to not exceed the interference allowed for the hypothetical signal. The adjustment is required mostly due to the level of SL, which is perceived as co-channel. Residual interference is caused by the digital signal mask in the out-of-band range of -5 kHz to -5.9 kHz removed from the enter frequency of the digital interference.

It is noted that the interference is calculated without assuming the additional filtering of a receiver filter. Any given receiver filter may further reduce the interference very little, thus barely allowing to adjust (relief) the protection requirements. For example, a narrow receiver filter with a bandwidth of 2.4 kHz at -3 dB and a slope of 36 dB/Octave may further filter the interference from PL by an amount of approximately 8 dB, thus requiring the reduction of digital signal by only 1 dB (instead of the no-filter case), resulting in setting the modulated subcarriers at approximately 3 dB below the level of the hypothetical interfering analogue.

When the digital interfering signal and the hypothetical AM interference are shifted by +10 kHz and compared to the maximum allowed AM to AM interference at +10 kHz, the interference from SL may be reduced by up to 1 dB comparing to that for the shift by +9 kHz. Receiver filtering may not help with reducing the interference noticeably.



The desired analogue AM signal along with interfering HD Radio digital signal consisting of PL and PU, shifted by +20 kHz, is shown in Fig. 18. The digital signal resulting spectrum of the modulated subcarrier is equivalently lowered (in reference to 0 dBc) by 2 dB.

The hypothetical interfering analogue signal, shifted by +20 kHz, and set at the allowed level of +25.4 dBc as required for protecting the desired signal from such analogue AM. Yet, the digital signal has to be further reduced by approximately 14 dB (Having the modulated subcarriers PL + PU at approximately 16 dB below the level of the hypothetical interfering analogue) in order for the entire integrated digital signal power to not exceed the interference allowed for the hypothetical signal. The adjustment is required mostly due to the level of SL, which is perceived as an interference shifted by +10 kHz.

It is noted that the interference is calculated without assuming the additional filtering of a receiver filter. Any given receiver filter may further reduce some of the interference, thus allowing to adjust (relief) the protection requirements accordingly. For example, a narrow receiver filter with a bandwidth of 2.4 kHz at -3 dB and a slope of 36 dB/Octave may further filter the interference from the digital signal (caused nearly solely by SL) by far more than 9 dB. However, raising back the digital signal is limited to 9 dB, after which any excess interference is caused by the slow drop of the far out-of-band signal. It is then requiring the reduction of digital signal by only 5 dB (instead of the no-filter case), resulting in setting the modulated PL + PU subcarriers at approximately 7 dB below the level of the hypothetical interfering analogue.

When the digital interfering signal and the hypothetical AM interference are shifted by +18 kHz and compared to the maximum allowed AM to AM interference at +18 kHz, similar relative results as for the shift by +20 kHz, with additional adjustment by 3 dB (the relative interference added by SL in the range of +8 kHz to +10 kHz), may be obtained for the cases without and with assuming additional receiver filtering.

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Desired	ed Un-Desired	$\mathbf{F}_{undesired} - \mathbf{F}_{desired}$ [kHz]								
Desireu		-20	-18	-10	-9	0	+9	+10	+18	+20
AM	AM	-55.4	-53.3	-32	-25	0	-25	-32	-53.3	-55.4
AM	MA1: PU	-37	-30	-4	-4	0	-25	-32	-53.3	-55.4
AM	MA1: PL	-55.4	-53.3	-32	-25	0	-4	-4	-30	-37
AM	MA3: 10kHz	-49	-47	-23	-16	6	-16	-23	-47	-49
AM	MA3: 20kHz	-41	-36	-12	-11	6	-11	-12	-36	-41

Relative protection ratio⁽¹⁾ for AM interfered by with HD Radio waveform

TABLE 21

⁽¹⁾ Relative protection values are calculated based on signals spectral characteristics, before considering additional filtering by any chosen receiver filter.

TABLE 22

Relative protection ratio⁽¹⁾ for HD Radio digital components of hybrid waveform interfered with by digital components of hybrid waveform

Destruct		$\mathbf{F}_{undesired} - \mathbf{F}_{desired}$ [kHz]				
Desirea	Un-Desired	-20	-10	0	+10	+20
AM	AM	-55.4	-32	0	-32	-55.4
Hybrid mode MA1: PL+PU	Hybrid mode MA1: TL+SL+PL+PU+SU+TU	<-75 ⁽²⁾	-44.5	-22.8	-44.5	<-75 ⁽²⁾
Hybrid mode MA1: TL+SL+ SU+TU	Hybrid mode MA1: TL+SL+PL+PU+SU+TU	-74	-23.2	-19	-23.2	-74
Hybrid mode MA1: PL+PU	All-Digital mode MA3: SL+PL+PU+SU	<-75 ⁽²⁾	-44.2	-28.2	-44.2	<-75 ⁽²⁾
Hybrid mode MA1: TL+SL+ SU+TU	All-Digital mode MA3: SL+PL+PU+SU	-74	-23	-28.5	-23	-74
All-Digital mode MA3: PL+PU	All-Digital mode MA3: SL+PL+PU+SU	<-75 ⁽²⁾	-59	-18	-59	<-75 ⁽²⁾
All-Digital mode MA3: SL +SU	All-Digital mode MA3: SL+PL+PU+SU	<-75 ⁽²⁾	-59	-18	-59	<-75 ⁽²⁾

⁽¹⁾ Relative protection values are calculated based on signals spectral characteristics, before considering additional filtering by any chosen receiver filter. Calculations are in reference to the protection requirements for analogue AM.

⁽²⁾ Results are calculated but are unlikely to be experienced in actuality due to the high range.

Annex 1

Background for calculating minimum useful field strength requirements for HD Radio system

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

Background for calculating the actual noise factor at the receiver input

Receiver sensitivity, being the minimum required signal field strength at the receiver antenna (E) is expressed as a function of the required pre-detection SNR (or C/N_0). For a given signal field strength E (μ V/m) impinging upon the antenna, the C/N_0 exhibited at the receiver input 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 N₀.

For a short monopole antenna of length *h* relative to wavelength λ (*h* << λ) (over a 'sufficient' ground plane), the indicated relationship (Recommendation ITU-R P.372) between the noise field strength and the antenna noise factor is given by:

$$E_n = F_a + 20 \cdot \log(f_{MH_z}) + 10 \cdot \log(b_{H_z}) - 95.5 \quad dB\mu V/m$$
(18)

And for a reference point of f = 1 MHz; b = 10 kHz:

$$E_n = F_a - 55.5 \text{ dBuV/m} \tag{19}$$

However, the indicated noise field is at the antenna. It is then transformed to noise voltage at the receiver input. The transformation is done by the receiver antenna circuit that is represented by the antenna factor (AF) (as resulting from the antenna effective length $h_e(f)$, and the transfer function $H_a(f)$). The transformation can then be expressed by the antenna factor (AF) and by the actual noise factor at the receiver input.

$$E_{nrcv} = V_{nrcv} - AF = F_{arcv} - 55.5 \text{ dB}\mu\text{V/m}$$
(20)

where equation (20) is referenced at the receiver input.

The actual noise factor at the receiver input:

$$F_{arcv} = 55.5 + V_{nrcv} - AF_{dB} \tag{21}$$

The actual noise factor can be calculated for specific cases where the receiver antenna circuit is defined.

For reference only, three typical receiver antennas were chosen as indicated in § 3. Then, the HD Radio broadcasting-specific integrated method has been used for calculating the actual receiver noise factor. The results are indicated in Table 5.

Determining the minimum usable field strength using ITU noise related data

For each system configuration and for each reception mode, the applicable C/N_0 is defined.

The minimum usable field strength based on SNR and ITU related noise field E_n :

$$E_{\min}\left(dBu\right) = SNR + E_n \tag{22}$$

Using the conversion definitions as provided in Annex 1 (related to analogue signal bandwidth of 10 kHz), the minimum usable field strength is:

$$E_{\min}(dBu) = C / N_0 - L_x - 40 + E_n$$
(23)

where L_x is the relevant power ratios (L_p , L_s , L_{st}) as indicated in § 4.

Determining the minimum usable field strength using receiver practice integrated method

The integrated method considers the actual receiver input noise factor (and noise field strength), specific margins related to the reception modes, and implementation losses.

Using the general format in equation (22), in addition to the factors indicated for this specific method, the expression for calculating minimum usable field strength is:

$$E_{\min}(dBu) = C / No - L_x - 40 + E_{nrcv} + L_f + L_{im}$$
(24)

where:

 L_x : relevant power ratios (L_p , L_s , L_{st}) as indicated in § 4

- L_f : fading margin as applicable to the specific reception mode
- L_{im} : implementation loss as applicable to the specific receiver for the reception mode.

The reception environment and related antenna and noise considerations are further described in § 3.

Annex 2

Channel models employed for deriving useful field strength requirements for HD Radio system

The channel models included in this section may apply to the reception modes, as follows:

- FXWGN applies to reception modes FX and PO
- UFGCS and RFGCS apply to reception mode MO
- Lightning model applies to all reception modes.

TABLE 23

Fixed reception under white Gaussian noise (FXWGN) channel model

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

The fixed reception model consists of a single path, without any additional impairments, as indicated in Table 23.

To create reference signal strength variability profiles for mobile reception, in addition to theoretical analysis, practical validation approach was taken including the use of recorded signal reception levels along several routes. The locations that were considered suitable for the purpose of analysis are indicated in Tables 24 and 25.

The data includes instantaneous (short term) signal strength variations of up to 60 dB.

Additionally, the recorded data conforms to the following:

- 1 Co-channel interference >> 30 dB D/U
- 2 Adjacent signal interference at \pm 10 kHz >> 30 dB D/U
- 3 Adjacent signal interference at \pm 20 kHz >> 40 dB D/U

Urban slow ground conductive structures (UFGCS) reference channel model

Definition	Location	Recording frequency (kHz)	Doppler frequency (Hz)	
Railroad overpass	N39°:05:45.4, W76°:50:55.4 Bowie Rd, Laurel, MD	900		
Two lane road overpass	N39°:09:25, W76°:49:18 Guilford Rd., Columbia, MD	900		
Overhead power lines	N39°:07:34, W76°:49:23 US Route 1, Laurel, MD	900	0.043 - 0.079 (reflects	
Pedestrian walkway overpass Metal frame	N39:16.474/W84:28.893 Chester Road near Princeton schools. Northernmost of two walkways	1 660	~55 km/h)	
Overhead highway sign spanning entire road	N39:08.244/W84:32.122 Hopple St. East to I-75 North on-ramp	1 660		

TABLE 25

Rural fast ground conductive structures (RFGCS) Reference channel model

Definition	Location	Recording frequency (kHz)	Doppler frequency (Hz)
Two lane metal support road overpass	N39:09:14.8 / W76:50:15.4 I-95 S, Laurel, MD	900	
Overhead metal highway sign spanning entire highway Metal support at both ends	N39:08:43.4 / W76:50:42.5 I-95 N, Laurel, MD	900	0.079 - 0.13 (reflects ~100 km/h)
Railroad overpass	N39:10.835 / W84:29.123 I-75 Southbound, @1 mile north of Paddock Rd. exit	1 660	
Pedestrian walkway overpass Concrete frame	N39:11.962 / W84:28.199 I-75 Southbound, south of the Lockland split	1 660	
Pedestrian walkway overpass Concrete frame	N39:08.808 / W84:32.309 I-75 Northbound, south of the I-74 split	1 660	

Definition	Location	Recording frequency (kHz)	Doppler frequency (Hz)
Overhead power lines	N39:11.342 / W84:28.893 I-75 Southbound, south of Paddock Rd. exit	1 660	
Overhead power lines	N39:09.699 / W84:30.748 I-75 Northbound, south of Mitchell Ave. exit	1 660	

TABLE 25 (end)

The lightning model, as provided in Fig. 19 and Table 26, simulates the operation in the presence of impulsive noise due to lightning. The frequency of the interferer is non-harmonically related to the desired channel frequency, F_{in} . The sine wave is pulsed on and off with a pulse duration representative of typical lightning strikes.



FIGURE 19 Diagram of lightning impulse noise generator

TABLE 26

AM lightning noise parameters

Test case	Description
Pulse width / repetition frequency	Case 1: 20 µs / 83 Hz
	Case 2: 200 µs / 9 Hz
Pulse rise and decay time	-3 to $+4$ ns
Sine wave interferer level into receiver	0 dBm
Sine wave interferer frequency	3 (<i>F</i> _{in}) / 7

Annex 3

Conversion of C/N₀ to SNR for HD Radio signals

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-spectral-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 AM system analysis, the carrier-to-noise-spectral-density ratio C/N_0 is being used. The analogue carrier power *C* is an easily measurable reference, both in analysis and in field evaluation.

IBOC AM conversion of C/N₀ **to digital CNR or SNR example**

In order to convert C/N_0 to SNR, the ratio of carrier power to digital band power C/C_d is used.

For example, in system configuration mode MA1-10 kHz that has a single block-pair and employs 10 kHz bandwidth, with power ratio $L_p = (C/C_d)_{dB}$.

$$SNR_{dB} \equiv (Cd/N)_{dB} = Cd_{dB} - N_{dB} = C - L_p - N_{dB}$$
$$N_{dB} = N_{0dB} + 10 \cdot \log(10 \text{ kHz}) = N_{0dB} + 40 \text{ dB}$$
(25)

Then

$$SNR_{dB} \equiv (C/N_0)_{dB} - L_p - 40 \text{ dB}$$
 (26)

where:

 C_d : total digital power in a 10 kHz bandwidth

 N_0 : noise spectral density in dB-Hz.

Annex 4

Reference documents

- [1] Recommendation ITU-R BS.1514-2: Systems for digital sound broadcasting in the broadcasting bands below 30 MHz
- [2] Recommendation ITU-R P.368-9: Ground-wave propagation curves for frequencies between 10 kHz and 30 MHz
- [3] Recommendation ITU-R P.1321-3: Propagation factors affecting system using digital modulation techniques at LF and MF
- [4] Recommendation ITU-R P.1147-4: Prediction of sky-wave field strength at frequencies between about 150 kHz and 1700 kHz
- [5] Nicholas DeMinco, "Medium Frequency Propagation Prediction Techniques and Antenna Modeling for Intelligent Transportation System (ITS) Broadcast Applications", NTIA Report 99-368
- [6] Recommendation ITU-R P.372-10: Radio noise
- [7] Report ITU-R SM.2055: Radio noise measurements
- [8] Recommendation ITU-R BS.703: Characteristics of AM sound broadcasting reference receivers for planning purposes

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- [9] Recommendation ITU-R BS.415-2: Minimum performance specifications for low-cost soundbroadcasting receivers
- [10] Recommendation ITU-R BS.560-4: Radio-frequency protection ratios in LF, MF and HF broadcasting
- [11] U.S.A FCC Title 47, Part 73, Subpart A: AM Broadcast Stations
- [12] U.S. National Radio System Committee NRSC-5-C: In-Band/On-Channel Digital Radio Broadcasting Standard
- [13] iBiquity Digital Corporation. HD Radio Air Interface Design Description Layer 1 AM. Document Number SY_IDD_1012s
- [14] U.S.A. FCC MM Docket No. 99-325, 17 FCC RCD 19990: Digital Audio Broadcasting System and Impact on the Terrestrial Radio Broadcast Service, First Report and Order. October 10, 2002
- [15] S. López, D. de la Vega, I. Angulo, D. Guerra, P. Angueira, A. Arrinda, J. L. Ordiales, "A Comparative Study of Field Strength Prediction Methods in Medium Wave Band", IEEE Electronic Letters, volume 44, issue 22, pp. 1286-1288, October 2008
- [16] D. de la Vega, S. López, U. Gil, D. Guerra, P. Angueira, A. Arrinda, J. L. Ordiales, "Irregular Terrain Attenuation in the Medium Frequency Band: Planning for Digital Radio Systems", IEEE Transactions on Antenna and Propagation, volume 56, issue 8, pp. 2770-2775, August 2008
- [17] U. Gil, I. Pena, D. Guerra, D. de la Vega, P. Angueira, J. L. Ordiales, "Statistical Characterization of Medium Wave Spatial Variability Due to Urban Factors", IEEE Transactions on Antenna and Propagation, volume 59, issue 9, pp. 3498-3500, September 2011
- [18] David H. Layer, Alan Lane, Russ Mundschenk, E. Glynn Walden, Danis Wallace, Tom Kink, "WCBN All-digital AM IBOC Field Test Project", NRSC, January 2013
- [19] Cesidio Bianchi, Antonio Meloni, "Natural and Man-Made Terrestrial Electromagnetic Noise: An Outlook", Annals of Geophysics, Vol. 50, N. 3, June 2007
- [20] Iratxe Landa, Amaia Arrinda, Igor Fernández, Pablo Angueira, "Indoor Radio Noise Long-Term Measurements in Medium Wave band in buildings of city areas in the north of Spain", IEEE Antennas and Propagation Letters, Vol. 10, pp. 17-20, January 2011
- [21] Gorka Prieto, Manuel Velez, Amaia Arrinda, Unai Gil, David Guerra, David de la Vega, "External Noise Measurements in the Medium Wave Band", IEEE Transactions on Broadcasting, Vol. 53, Issue 2, pp. 553-559, June 2007
- [22] iBiquity Digital Corporation. HD Radio AM Transmission System Specifications. Document Number SY_SSS_1082s.