



Report ITU-R BT.2209
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**Calculation model for SFN reception
and reference receiver characteristics
of ISDB-T system**

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Summary

This Report provides detailed considerations on receiver characteristics under single frequency network (SFN) conditions for ISDB-T system. It introduces new technical parameters that dominate receiver performances, in addition to the conventional planning parameters. The new parameters are amplitude proportional noise (APN), FFT window setting margin and interpolation filter characteristics used for reference carrier recovery. Using these parameters, the overall receiver characteristics can be expressed by a single parameter called guard interval mask characteristics, which is useful in estimating whether or not the signal is received correctly.

Furthermore, the Report gives a reference receiver characteristic that would be applied in frequency planning and/or network design of ISDB-T based broadcasting systems. The calculation method for SFN reception and the reference receiver characteristics have been established in ARIB TR-B14, which is successfully applied in planning and designing of broadcasting networks in Japan.

It is shown that SFN does not work unconditionally, but works well only when the reception signals are kept under certain conditions in terms of reception voltages, DURs, delays between main and SFN signals and so on.

Chapter I – SFN with delays less than guard interval duration

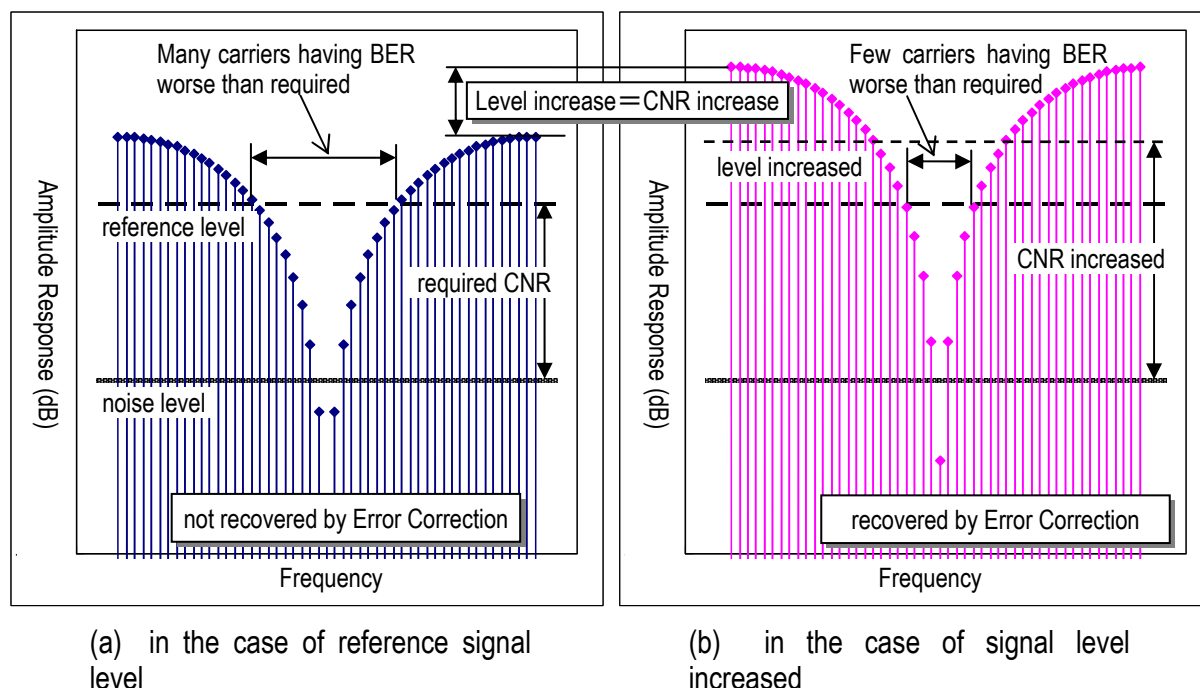
First we will derive the condition that gives single frequency network (SFN) failure when a single SFN wave exists. Then, we will discuss about the conditions when multiple SFN waves exist. Also we will give some considerations on the receiver characteristics that are necessary to estimate the area of failure. We call SFN with delays less than guard interval duration as “inner-GI SFN” in short.

1 In the case of a single SFN wave

The received signal exhibits ripples in frequency response when the desired signal is received with SFN waves. In this case, the bit error rates (BER) of the OFDM carriers positioned at peaks in frequency response becomes better, because the input signal levels are high for those carriers. On the other hand, the BER of the carriers positioned at dips in frequency response become worse because the input levels are low. We can estimate the occurrence of SFN failure by calculating the BERs for every carrier and summing up them to check whether or not the total BER is worse than the required value.

Figure 1 shows an example of frequency response of received signal. Figure 1a) is the case where the desired signal is just at the level that gives the required carrier-to-noise ratios (CNR). In this example, we assume the total BER being worse than the required value, as there are many carriers of which BER is worse than the reference value. If we increase the levels of both desired and SFN signals, the number of carriers having worse BER is decreased, and then the signal is correctly received, as shown in Fig. 1b). The SFN failure takes place depending not only on the desired to undesired ratios (DUR) but also on the levels of the received signal itself.

FIGURE 1
Example of received signal



1.1 Mathematical equations used in this text

The relationship between BER and CNR are to be following:

for QPSK

$$BER = \frac{1}{2} \operatorname{Erfc} \left(\sqrt{\frac{1}{2} \frac{C_p}{N_p}} \right) \quad \text{and} \quad \frac{C_a}{N_a} = \sqrt{\frac{C_p}{N_p}} = \sqrt{2} \cdot \operatorname{Erfc}^{-1}(2 \cdot BER) \quad (1)$$

for 16-QAM

$$BER = \frac{3}{8} \operatorname{Erfc} \left(\sqrt{\frac{1}{10} \frac{C_p}{N_p}} \right) \quad \text{and} \quad \frac{C_a}{N_a} = \sqrt{\frac{C_p}{N_p}} = \sqrt{10} \cdot \operatorname{Erfc}^{-1} \left(\frac{8}{3} \cdot BER \right) \quad (2)$$

for 64-QAM

$$BER = \frac{7}{24} \operatorname{Erfc} \left(\sqrt{\frac{1}{42} \frac{C_p}{N_p}} \right) \quad \text{and} \quad \frac{C_a}{N_a} = \sqrt{\frac{C_p}{N_p}} = \sqrt{42} \cdot \operatorname{Erfc}^{-1} \left(\frac{24}{7} \cdot BER \right) \quad (3)$$

where:

C_p : average power of signal

C_a : r.m.s. amplitude of signal

N_p : noise power

N_a : r.m.s. amplitude of noise

and $\operatorname{Erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-t^2) dt$

The relationship between the *Erfc* above and *Ndist* (normal distribution function) generally used in mathematics are as follows:

$$\begin{aligned}
 Ndist(x) &= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^x \exp(-t^2/2) dt \\
 Erfc(x) &= \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-t^2) dt \\
 &= \frac{2}{\sqrt{\pi}} \int_{\sqrt{2}x}^{\infty} \exp(-u^2/2) \frac{du}{\sqrt{2}} = 2 \frac{1}{\sqrt{2\pi}} \int_{\sqrt{2}x}^{\infty} \exp(-u^2/2) du \\
 &= 2 \cdot Ndist(-\sqrt{2}x)
 \end{aligned} \tag{4}$$

where:

$$u: \quad \sqrt{2} \, t$$

The relationship between the inverse functions of the above are:

by using:

$$\begin{aligned}
 \frac{P}{2} &= Erfc(x) = 2 \cdot Ndist(-\sqrt{2}x) \\
 \frac{P}{2} &= Ndist(-\sqrt{2}x) \Rightarrow x = \frac{-1}{\sqrt{2}} Ndist^{-1}\left(\frac{P}{2}\right) \\
 \therefore Erfc^{-1}(P) &= \frac{-1}{\sqrt{2}} Ndist^{-1}\left(\frac{P}{2}\right)
 \end{aligned} \tag{5}$$

1.2 Increase in the required CNR

In the case of a single SFN wave, the frequency response of the received signal is given by equation (6).

$$F_a(\omega) = \sqrt{1 + U_a^2 + 2U_a \cdot \cos(\omega \cdot \tau)} \tag{6}$$

where:

- U_a : amplitude of SFN wave relative to desired wave
- τ : delay of SFN signal.

Figure 2 shows examples of increase in the required CNR when an SFN wave exists. The horizontal axis of the graphs denotes the input power of the SFN wave relative to the desired signal, that is, the inverse figures of DUR. The vertical axis denotes the increase in the required CNR. The actual values of CNR necessary for correct reception are obtained by adding these increases to the reference CNR such as 20 dB for 64-QAM-FEC3/4, 22.5 dB for 64-QAM-FEC7/8, and so on. The curves in Fig. 2 are obtained by calculating the CNR that gives BER of 8.5×10^{-3} for FEC3/4 or 1.1×10^{-3} for FEC7/8 against a number of SFN waves of which amplitude and delay are given randomly. The relationships given by these curves are called “CNR Increase Functions” in this document.

Since CNR Increase Function cannot be expressed by simple mathematical formula, we introduce approximated function for it, as below:

$$\begin{aligned}
 CN_{up}(UdB) &= \alpha \cdot \exp \left[-|\beta \cdot UdB|^\gamma \right] & (UdB \leq 0) \\
 &= \alpha \cdot \exp \left[-|\beta \cdot UdB|^\gamma \right] - UdB + A \cdot UdB & (UdB > 0)
 \end{aligned} \tag{7}$$

where:

U_{dB} : denotes the power of SFN wave expressed (dB)

$CN_{up}(U_{dB})$: denotes the increase in the required CNR expressed (dB)

The values of the coefficients, α , β and γ are given in Table 1. The value for A in equation (7) should be zero in usual cases.

FIGURE 2

Example of increase in the required CNR

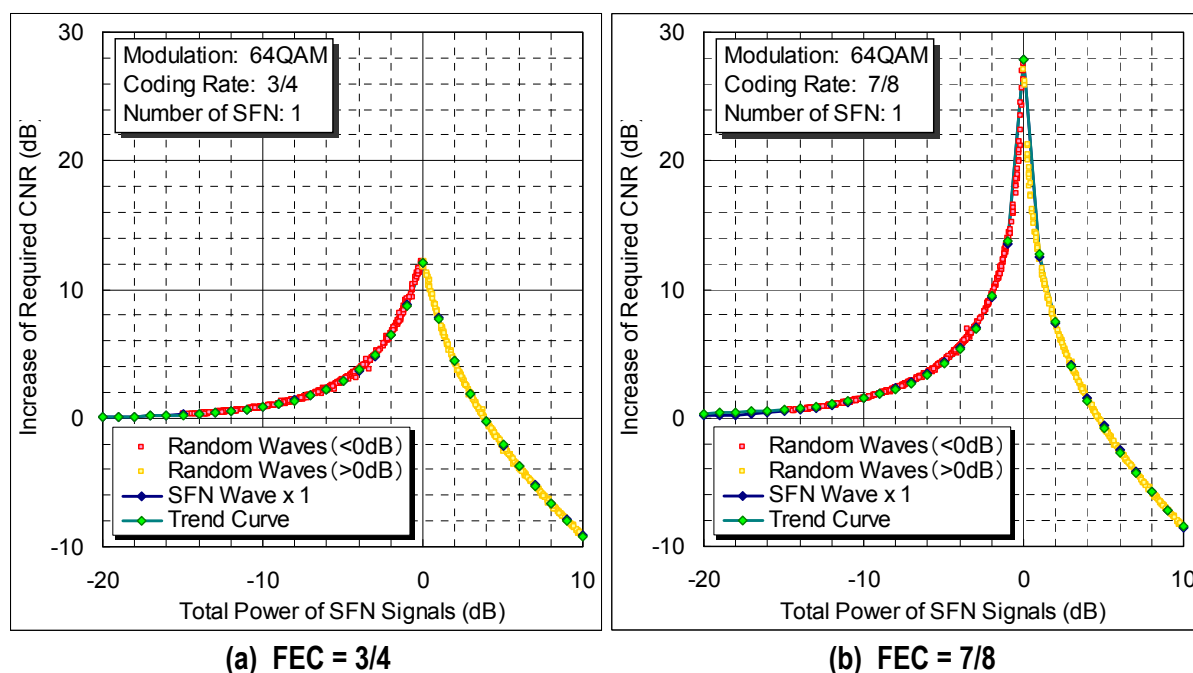


TABLE 1

Coefficient for CNR increase function

Coefficient	Modulation	FEC:7/8	FEC:5/6	FEC:3/4	FEC:2/3	FEC:1/2
α	64-QAM	27.749	20.257	12.090	8.1386	3.8797
	16-QAM	29.800	22.163	13.874	9.8342	5.4002
	QPSK	32.255	24.378	15.953	11.827	7.2391
β	64-QAM	0.5592	0.4117	0.2953	0.2527	0.2074
	16-QAM	0.6074	0.4453	0.3171	0.2702	0.2251
	QPSK	0.6702	0.4876	0.3450	0.2922	0.2437
γ	64-QAM	1.0662	0.7253	0.9096	1.0341	1.2100
	16-QAM	0.5954	0.6936	0.8616	0.9776	1.1378
	QPSK	0.5710	0.6608	0.8115	0.9172	1.0662

The value of α corresponds to the maximum increase in the required CNR, which takes place at $\text{DUR} = 0$ dB. A large difference is found in the maximum CNR increase between FEC 3/4 7/8, comparing to 2-3 dB in the case without SFN waves. This difference must be noted in the design of broadcasting networks, in other words, FEC of 7/8 could not be applied in the actual world where SFN is more or less used.

1.3 Noise characteristics in receivers

The noise that affects the reception performance can be summarized in two categories; one is the noise of which amplitude is independent of the input signal, such as thermal noise, and the other is the noise of which amplitude increases/decreases according to the input signal level. The former is called “fixed noise” and the latter “amplitude proportional noise” (APN) in this text.

Fixed noise consists of thermal noise, man-made noise, noise figure of receivers, and so on. An example of link budget reported by the National Council on Information and Telecommunication in Japan applies thermal noise of 300 K, man-made noise of 700 K, and noise figure of 3 dB. The value of fixed noise is estimated to be 8.5 dB(μV) (@75 Ω) in this case.

Amplitude proportional noise is mainly determined by the receiver characteristics, such as the quantization noise of A/D conversion, clipping noise, phase jitter of local oscillator.

The words “fixed” and “amplitude proportion” come from the features of noise when expressed equivalently at the receiver input terminal.

1.3.1 Clipping noise

Since the amplitude distribution of OFDM signal exhibits a normal distribution, an enormous dynamic range is required for the receiver signal processing to treat without distortions. Normal receivers clip the signals exceeding a certain level, and generate clipping noise in some extent.

Figure 3 explains the affect of clipping. The clipped waveform is equivalent to the input waveform with adding the signal components that exceed the clipping level in the opposite polarity. The component that exceeds the clipping level has a pulse waveform, as shown in the Figure.

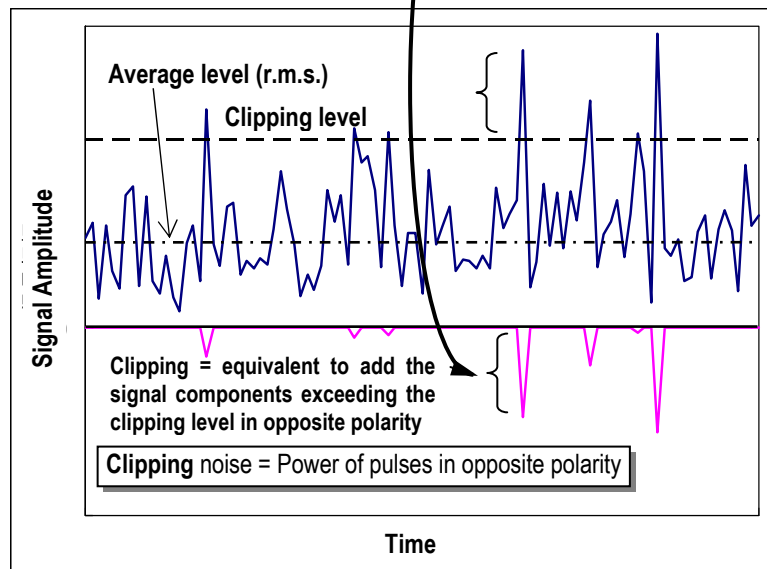
The probability that the OFDM signal takes a level of x is written by $\text{Gauss}(x/S_{rms})$, where S_{rms} denotes the *r.m.s.* amplitude of the signal, and $\text{Gauss}(*)$ the probability density function of a normal distribution. The amplitude of the pulse component that exceeds the clipping level is written by $(x - CL)$, where CL denotes the clipping level.

Using the above, we can estimate the power of the pulses or clipping noise as below:

$$NP_{clip} = \int_{CL/S_{rms}}^{\infty} (x - CL)^2 \cdot \text{Gauss}(x/S_{rms}) dx \quad (8)$$

The spectrum of clipping noise can be regarded as flat noise, because the intervals of these pulses are considerably large and isolated pulse has flat spectrum.

FIGURE 3
Clipping noise



1.3.2 Quantization noise of A/D conversion

It is assumed for normal receivers that the clipping level is set equal to the full scale of the A/D converter. Then, the quantization noise is given by the well-known equation (9).

$$\begin{aligned}
 NP_{adc} &= LSB^2/12 \\
 &= (CL \cdot 2^{-N})^2/12 = CL^2 \cdot 2^{-2N}/12
 \end{aligned}
 \tag{9}$$

where:

LSB : denotes the amplitude of the least significant bit

N : denotes the bit-length of A/D converter.

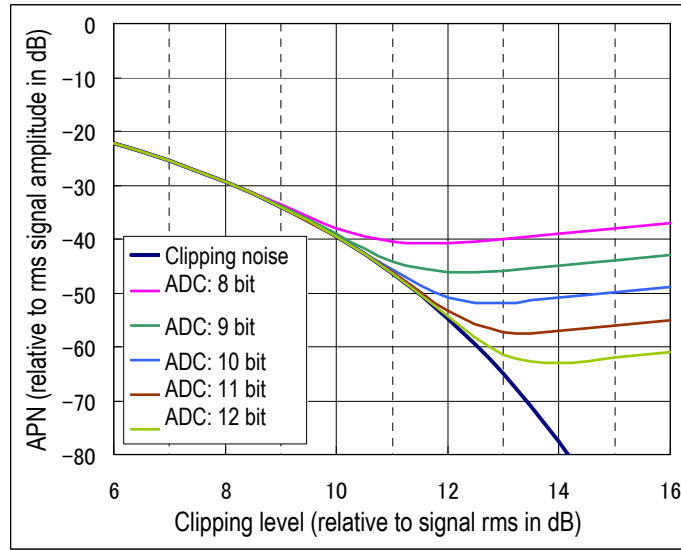
The noise power given by equations (8) and (9) is in proportion to square of clipping level, that is, the amplitude of the noise is in proportion to the clipping level. As the receivers usually adjust the signal amplitude by AGC to a certain level corresponding to the clipping level, we can regard these noises to be in proportion to the input signal level.

Figure 4 shows examples of amplitude proportional noise. It is seen from the figure that the clipping level should be set at approximately 4 times (+12 dB) of the *r.m.s.* signal amplitude and that the optimum clipping level depends on the bit-length of A/D conversion.

Figure 4

FIGURE 4

Amplitude proportional noise



1.3.3 Other amplitude proportional noises

There are a lot of amplitude proportional noise sources other than described above, such as phase jitter of PLL, computational errors, and so on. In addition, transmitted signals include APN such as inter-modulation components generated in the power amplifiers, noises included in the reception signal (in the case of relay stations with broadcasting wave relay), etc. We can treat these transmitter noises to be equivalently generated in the receiver, and we will express the APN including all noise sources in a single value relative to the *r.m.s.* signal amplitude.

1.4 Conditions that gives SFN failure

Now we will express the factors that are used in the digital reception estimation. They are:

$$\begin{aligned}
 CN &= CN_0 \times CN_{up}(U_{rms}/D_{rms}) \\
 NP &= NP_{fix} + NP_{amp}(S_{rms}) \\
 S_{rms} &= \sqrt{D_{rms}^2 + U_{rms}^2}
 \end{aligned} \tag{10}$$

where:

- CN : required CNR when SFN wave exists
- CN_0 : required CNR without SFN waves
- $CN_{up}(*)$: CNR increase function defined by equation (7)
- U_{rms} : *r.m.s.* amplitude of SFN wave
- D_{rms} : *r.m.s.* amplitude of desired wave
- S_{rms} : *r.m.s.* amplitude of the input wave composed of the desired and SFN waves
- NP : sum of fixed noise and amplitude proportional noise
- NP_{fix} : noise power of fixed noise
- $NP_{amp}(*)$: noise power of amplitude proportional noise expressed as a function.