

RECOMMENDATION ITU-R SM.853-1*

NECESSARY BANDWIDTH

(1992-1997)

Scope

This Recommendation provides the necessary bandwidth formulae.

Keywords

Necessary bandwidth, Frequency modulation, digital modulation, channel deviation, bandwidth formulae

The ITU Radiocommunication Assembly,

considering

- a) that the concept of “necessary bandwidth” defined in No. 146 (1.152) of the Radio Regulations, is useful for specifying the spectral properties of a given emission, or class of emission, in the simplest possible manner;
- b) that with regard to the efficient use of the radio-frequency (RF) spectrum, necessary bandwidths for individual classes of emission must be known, that in some cases the formulae listed in Recommendation ITU-R SM.1138 can only be used as a guide and that the necessary bandwidth for certain classes of emissions is to be evaluated corresponding to a specified transmission standard and required quality;
- c) that changes in technology have resulted in additions and variations in the modulations used for radiocommunication;
- d) that the numerical parameters used in the necessary bandwidth formulae may change with time due to changes in signal characteristics (e.g. average talker level),

recommends

that the necessary bandwidth formulae (contained in Recommendation ITU-R SM.1138) be supplemented with the following formulae.

1 Multi-channel frequency division multiplex – frequency modulation (FDM-FM) emissions

To account for changes in average talker level, which may occur over time, the formula for the necessary bandwidth B_n of multi-channel FDM emission is:

$$B_n = 2M + 2 \left[d \times 3.76 \times \text{antilog} \left(\frac{X + Y \log N_c}{20} \right) \right] K$$

where:

M : maximum modulating frequency (Hz)

d : per-channel deviation

N_c : number of circuits in the multiplexed message load

K : unity

$X = -2$ to $+2.6$ for $12 \leq N_c < 60$ and for $Y = 2$

$X = -5.6$ to -1.0 for $60 \leq N_c < 240$ and for $Y = 4$

$X = -19.6$ to -15.0 for $N_c \geq 240$ and for $Y = 10$.

The term enclosed in brackets is the peak deviation, D . The numerator ($X + Y \log N_c$) of the fraction represents the average power of the composite signal delivered to the modulator input of the transmitter.

* Radiocommunication Study Group 1 made editorial amendments to this Recommendation in the years 2018 and 2019 in accordance with Resolution ITU-R 1.

The basis for this formula is contained in § 1, Annex 1. In particular, Annex 1 shows how to determine the appropriate value for the variable X in the formula.

2 Unmodulated pulse emissions

The necessary bandwidth for unmodulated pulses with either a trapezoidal or rectangular pulse shape is given in Table 1.

TABLE 1
Unmodulated pulse emissions

Description of emission	Necessary bandwidth		Designation of emission
	Formula	Sample calculation	
Unmodulated pulse emission	Case 1: $B_n = \frac{1.79}{\sqrt{t \cdot t_r}} \text{ Hz}$ at points 20 dB below the peak envelope value of the spectrum of a trapezoidal pulse	$t = 3 \times 10^{-6} \text{ s}$ $t_r = 0.06675 \times 10^{-6} \text{ s}$ Bandwidth: $4 \times 10^6 \text{ Hz}$	4M00P0N
	Case 2: $B_n = 1.27 \sqrt{\frac{\frac{1}{t_r} + \frac{1}{t_f}}{t}}$ at points 20 dB below the peak envelope value of the spectrum of an unsymmetrical trapezoidal pulse	$t = 3 \times 10^{-6} \text{ s}$ $t_r = 0.06675 \times 10^{-6} \text{ s}$ $t_f = 0.167 \times 10^{-6} \text{ s}$ Bandwidth: $3.36 \times 10^6 \text{ Hz}$	3M36P0N
	Case 3: $B_n = \frac{6.36}{t} \text{ Hz}$ at points 20 dB below the peak envelope value of the spectrum of a rectangular (ideal) pulse	$t = 1.41 \times 10^{-6} \text{ s}$ $B_n = 4.5 \times 10^6 \text{ Hz}$	4M50P0N

Annex 2 contains the method used for determining the necessary bandwidth of the unmodulated pulses.

3 Digital modulation

The necessary bandwidth and example K values for several digital modulations are given in Table 2.

Annex 3 contains the methods used for determining the necessary bandwidths for digital modulation.

TABLE 2

Digital modulation

Modulation and conditions	Necessary bandwidth formula	Example K value	Percentage fractional power containment bandwidth ⁽¹⁾
2-PSK (unfiltered) $S = 2$ (computed)	$B_n = \frac{2 RK}{\log_2 S}$	10.28 2.0	99 95
2-PSK (filtered, BER = 1×10^{-3}) $S = 2$ (computed)	$B_n = \frac{2 RK}{\log_2 S}$	1.0 ⁽²⁾ 0.75 ⁽³⁾	100 100
MSK (unfiltered) $S = 2$ (computed) $D = 0.25 R$	$B_n = \frac{R}{\log_2 S} + 2 DK$	0.36 3.52	99 99.9
Gaussian filtered MSK (GMSK) 3 dB premodulation Gaussian filter bandwidth = $0.25 R$ $S = 2$ (computed) $D = 0.25 R$	$B_n = \frac{R}{\log_2 S} + 2 DK$	-0.28 0.18	99 99.9
Digital FM (Continuous phase FSK) rectangular pulses $S = 2$ (computed) $D = 0.35 R$	$B_n = \frac{R}{\log_2 S} + 2 DK$	0.89	99
m -QAM Microwave digital $S = 2^n$ ($n \geq 2$) Roll-off = 0 to 1 50% splitted Tx/Rx optimally filtered (computed) ^{(4), (5)}	$B_n = \frac{2 RK}{\log_2 S}$	See Fig. 1	See Fig. 1

BER: binary error ratio.

FSK: frequency shifting key.

MSK: minimum shifting key.

PSK: phase shift keying.

QAM: quadrature amplitude modulation.

(1) Recommendation ITU-R F.1191 foresees that for digitally modulated systems in the fixed service the necessary bandwidth should be defined for a percentage fractional power containment equal to 99%.

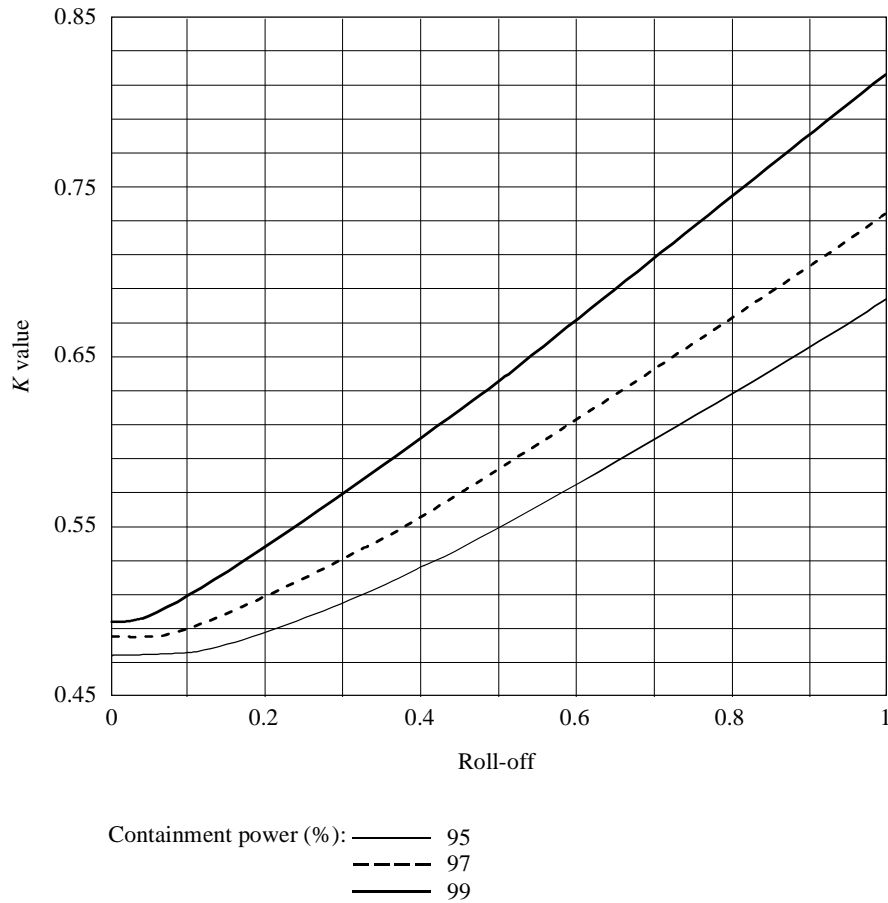
(2) For this case $E_b/N_0 = 7.5$ dB.

(3) For this case $E_b/N_0 = 9.3$ dB.

(4) Practical filtering may give slight difference in the K value versus containment computed relationship.

(5) 4- and 8- QAM formats coincide with filtered 4- and 8- PSK formats.

FIGURE 1
 K value versus roll-off for m -QAM modulation formats
 Parameters: power containment factor



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ANNEX 1

FDM-FM necessary bandwidth calculations**1 Multi-channel FDM-FM emissions**

Recommendation ITU-R SM.1138 “Determination of necessary bandwidths including examples for their calculation and associated examples for the designation of emissions” includes under its Annex 1, Table III-B, the necessary factors for use in computing peak frequency deviation of multi-channel FDM-FM emissions. Peak frequency deviation is a critical factor in Carson’s rule, $B_n = 2M + 2DK$, used to calculate necessary bandwidth for frequency spectrum allocation purposes. Table III-B is reproduced as Table 3.

The factors 2.6, -1 and -15 in the Table are the average power (dBm0 (see Note 1)) values that were found in a standard, commercial telephone, public switched network circuit. The values were, in fact, based upon measurements of “talker volume” conducted in 1960 that were previously agreed to in the ex-CCIR and eventually at the World Administrative Radio Conference (Geneva, 1979) as applicable, for the purposes of necessary bandwidth calculation.

NOTE 1 – “dBm0” refers to the power (dB) relative to 1 mW referred to a point of zero relative transmission level.

TABLE 3

Multi-channel FDM-FM emissions

MULTIPLYING FACTORS FOR USE IN COMPUTING D , PEAK FREQUENCY DEVIATION, IN FDM-FM MULTI-CHANNEL EMISSIONS

For FDM-FM systems the necessary bandwidth is:

$$B_n = 2M + 2DK$$

The value of D , or peak frequency deviation, in these formulae for B_n is calculated by multiplying the r.m.s. value of per-channel deviation by the appropriate "Multiplying factor" shown below.

In the case where a continuity pilot of frequency f_p exists above the maximum modulation frequency M , the general formula becomes:

$$B_n = 2f_p + 2DK$$

In the case where the modulation index of the main carrier produced by the pilot is less than 0.25, and the r.m.s. frequency deviation of the main carrier produced by the pilot is less than or equal to 70% of the r.m.s. value of per-channel deviation, the general formula becomes either

$$B_n = 2f_p \quad \text{or} \quad B_n = 2M + 2DK$$

whichever is greater.

	Multiplying factor ⁽¹⁾
Number of telephone channels, N_c	(Peak factor) \times antilog $\left[\frac{\text{Value in dB above modulation reference level}}{20} \right]$
$3 < N_c < 12$	$4.47 \times$ antilog $\left[\frac{\text{Value in dB specified by the equipment manufacturer or station licensee, subject to administration approval}}{20} \right]$
$12 \leq N_c < 60$	$3.76 \times$ antilog $\left[\frac{2.6 + 2 \log N_c}{20} \right]$
$60 \leq N_c < 240$	$3.76 \times$ antilog $\left[\frac{-1 + 4 \log N_c}{20} \right]$
$N_c \geq 240$	$3.76 \times$ antilog $\left[\frac{-15 + 10 \log N_c}{20} \right]$

⁽¹⁾ In the above chart, the multipliers 3.76 and 4.47 correspond to peak factors of 11.5 dB and 13.0 dB, respectively.

In 1975 and 1976, further measurements of speech signal power were made in the same circuits and networks, using similar methodology, so as to allow direct comparison of results to the earlier work. The later measurements have been under study, both in industry and government, since that time, finally leading to modifications to typical domestic applications in the public switched telephone networks.

To summarize the 1975-1976 study, which included the reasons why differences from the earlier study occurred, it was found that substantial changes have aggregated over time to produce an average decrease in actual average talker power level of approximately 4.6 dB. The changes have tended to increase the uniformity of service in the switched public networks from the viewpoint of speech volumes. These include a decrease in the proportion of toll grade battery systems, loss plan improvements, upgraded telephone sets, and an increase in direct trunking. Direct distance dialling has become normal practice with new loop and trunk design techniques. Furthermore, advanced digital data acquisition technology facilitated the measurement in 1975-1976 of speech signal power with greater precision than was possible in 1960 when volume unit meters were used for that survey. Standard deviation of all measurement between the 1960 and 1975-1976 surveys, was reduced by an average of about one third, from 7 to 4.6 volume units. A multi-stage statistical sampling scheme (near-end and far-end) of talker power measurements on more than 10 000 calls, originating from approximately 2 500 loops, was used. Average conversational signal power (averaged over the entire observation interval), and a new measure of speech level known as equivalent peak level (EPL) were the measures used to characterize talker signals. Loop d.c. current, class of service, switch type, and call destination were recorded as part of the 1975-1976 study.

NOTE 2 – Volume unit is one way of measuring speech level with a power-level indicator calibrated in terms of dB for a steady sine-wave voltage, with 1 mW in 600 Ω taken as a reference. The response of the indicator is not frequency weighted. Volume unit readings are averages achieved by a particular set of meter ballistic (mechanical) characteristics.

The later study indicated that with (1975 and 1976) public switched network systems, there was little dependence of speech signal power on call destination or originating class of service (residence, business, local, toll, and combined). Small differences are explained for the most part by loop characteristics. There is little, if any, variation in speech signal power attributed by study conclusions to psychological factors such as call distance or perception of received volume. The average values measured indicate that the switched telecommunication network in 1975-1976 was essentially transparent to customers in the sense that talker signal power was not found sensitive to call distance, local or toll call classification, or other factors that are outside local loop circumstances. In summary, it is believed that the later measurements of telephone “talker level” indicate the same, normal speech levels of the population when not using the telephone. It is concluded that little or no further change in representative talker level is expected in the future on the switched public telephone network where the measurements were taken. Consequently, this fact should be taken into account in an examination of the necessary bandwidth formulae for FDM-FM systems when telephone speech comprises a significant part of the total FDM-FM circuit.

In the B_n formula as shown in Table 3, the three factors 2.6, -1 and -15 are components of the multiplying factor used to determine D , or peak frequency deviation. Practical consequences of a reduction in “talker power” on the telephone circuit feeding an FDM-FM radio circuit is less peak deviation. There are three independent parameters that determine the peak deviation of the FM signal, all of which are constrained by the design of the system so as to limit the maximum value of each so that D does not exceed a predetermined value (in FDM-FM systems). Those variables are:

- r.m.s. value of per-channel deviation,
- average power in a message channel,
- number of total channels in the multiplexed message load.

If the average power of speech signals can be reduced, as indicated in the 1975-1976 study, a trade-off would be possible with the two other parameters. This could be achieved by:

- increasing the number of channels in the same frequency bandwidth,
- increasing spectrum efficiency by reducing the bandwidth for the same number of channels,
- a combination of the two methods.

For example, in systems using 4 kHz voice grade message channels, it would be possible to vary the ratio of data to voice traffic. A user could choose to remain within a specified RF bandwidth and then select an average message channel power level which could be used to make a trade-off between an increase in the number of message channels against their individual frequency deviation. For a given ratio of data traffic to voice traffic, a user might consider that a too large increase in the number of 4 kHz message channels would reduce the per channel deviation to the point where signal quality would become degraded. However, an average message channel power level could be chosen which keeps

within the specified RF bandwidth and which can permit some increase in the number of message channels while still allowing a proportional increase in the individual channel frequency deviations. By this method, instead of using all the available spectrum to maximize the number of message channels, it would be possible to obtain an increase in the value of the per-channel deviation which would provide an improvement of the signal-to-noise ratio and a probable reduction of BER of the data traffic.

A microwave system can therefore be designed for which the parameter for the average message power level is chosen between the level used in the current equations and one 4.6 dB lower. There are valid reasons for changing (i.e. increasing) the other available parameters in the system when the average message power level (talker power) is decreased. However, a decision to carry out the change is appropriate for the carriers (or governments) concerned to make, taking account of the advantages and disadvantages of the possible trade-offs.

The important point here is recognition of the changed average “talker power” level. To take account of the decrease in average “talker power” by 4.6 dB in speech telephone circuits, typically the 2.6, –1 and –15 values are replaced by the variable X which can then range between limits comprised of the present values, and corresponding values that are 4.6 dB lower, depending upon the total number of circuits in the FDM-FM system, and the composition of the system itself.

Thus, the necessary bandwidth, B_n is:

$$B_n = 2M + 2 \left[d \times 3.76 \times \text{antilog} \left(\frac{X + Y \log N_c}{20} \right) \right] K$$

where:

M : maximum modulating frequency (Hz)

d : per-channel deviation

N_c : number of circuits in the multiplexed message load

K : unity

$X = -2$ to $+2.6$ for $12 \leq N_c < 60$ and for $Y = 2$

$X = -5.6$ to -1.0 for $60 \leq N_c < 240$ and for $Y = 4$

$X = -19.6$ to -15.0 for $N_c \geq 240$ and for $Y = 10$.

The term enclosed in brackets is the peak deviation, D . The numerator ($X + Y \log N_c$) of the fraction represents the average power of the composite signal delivered to the modulator input of the transmitter. The value of 3.76, as noted in Table 3, corresponds to a peak factor of 11.5 dB.

To correctly select a value for X in the formula for B_n , it is helpful to summarize applicable conditions under which it is used in an FDM-FM system. Final choice within the 4.6 dB range may be empirical. It is clear from the study details compiled that average “talker power levels” of –2, –5.6 and –19.6 dBm0 should replace the corresponding numbers for $N_c \geq 12$ in the B_n formulation with an FDM-FM system that is used to provide trunk connections for modern commercial public telephone circuits where most of the FDM-FM channels are used for speech.

In smaller, private, or older FDM-FM systems, particularly those with $N_c < 12$ or those containing data (non voice) in most of the channels, the original values, as shown in Table 3, nominally apply. Typical multi-channel data circuits operate at power levels from –13 to –15 dBm0. Therefore, the composite loading limit will be determined by using the value $X = -13$ to –15 for systems with a large percentage of data circuits for $N \geq 240$. Individual channel signalling, as opposed to common channel signalling, is an indication that the –15 dBm0 level is applicable (systems with $N_c \geq 240$).

The choice over the range 4.6 dB of signal power level is, as stated above, largely one of experience. The RF band itself is unrelated to choice of “talker power” parameters. It has been noted that, as an example of practical application of the newer parameters, as many as 1 800 telephone channels could be operated in the same terrestrial fixed point-to-point microwave radio-frequency bandwidth now designated for only 1 500 circuits, a significant development in improved spectrum efficiency.

ANNEX 2

Unmodulated pulse necessary bandwidth calculations

The necessary bandwidth for the common cases of unmodulated pulses with either a trapezoidal or rectangular pulse shape is specified. A value of 20 dB below the peak of the theoretical envelope of the pulse spectrum is the criteria used to establish the necessary bandwidth for unmodulated pulses. The values for the envelope of the pulse spectrum of the unmodulated pulses were determined using simple calculation techniques.

Table 1 lists the calculated necessary bandwidths for unmodulated pulses. In Case 1 (trapezoidal pulse) the pulse width, t , is the time between 50% amplitude points and t_r (rise time) is the time between 10% and 90% amplitude points. The fall time, t_f , is equal to the rise time t_r . In Case 2 the rise time t_r does not necessarily equal the fall time t_f . The fall time is the time between the 90% and 10% amplitude points. In Case 3 (rectangular pulse), t is the pulse width.

ANNEX 3

Digital modulation necessary bandwidth calculations

The formulae for the necessary bandwidths of digital data modulations (Recommendation ITU-R SM.1138) include a factor K which accounts for trade-offs which are made in designing a system. Trade-off decisions usually involve system power, bandwidth, and performance (BER). For example, by utilizing higher levels of modulation, digital line-of-sight systems trade power for bandwidth. The higher level digital modulations, such as 16-QAM, 64-QAM and 256-QAM, for a given amount of spectra can transfer more bits/s than the lower levels of modulation but require more power (i.e. higher carrier-to-noise). Conversely, in satellite systems where on-board power is limited, spectrum is often traded for power and the lower level modulations are utilized. Digital signals often require significant filtering to achieve adjacent channel protection requirements.

The filtering of the digital signals may take place as premodulation filtering of the baseband transmitter signal or at one or more other points within the transmitter or receiver. The compensation for the addition of this filtering is to increase the system C/N . The numerical values of the K factor depend upon the amount and shape of the filter selectivity characteristic. Filter characteristics are designed on a case-by-case basis. Thus, it is not practical or advantageous to include in the necessary bandwidth formulae single numerical values for K .

Table 2 shows some example values of K for several digital modulations. The K values are either for computed or measured spectra. Table 2 includes the necessary bandwidth formulae used, the K value for other parameters such as power, E_b/N_0 , and BER. The formula for the necessary bandwidth (B_n) of digital FM is from Recommendation ITU-R SM.1138. R is the bit rate, S is the number of signalling states, and D is the frequency deviation. The formula for the necessary bandwidth of PSK modulation is based on the principle that this bandwidth should be some multiple of the symbol rate.

The MSK, GMSK and digital FM modulations are examples of a class of modulations which are of constant amplitude and continuous phase. These continuous phase signals can be viewed as using simultaneously phase and frequency modulation. Either of the necessary bandwidth formulae (frequency or phase) might be used for this class of modulation. Since the signals are typified by a modulation index ($2D/R$), the FSK formula for necessary bandwidth was used for these signals in Table 2. Also, for QAM modulation, the PSK necessary bandwidth formula is used. The rationale is that the m -QAM signals are made up of a statistical sum of $m/2$ 2-PSK signals with different signal amplitudes, bit-rate of ($R/\log_2 m$) and with the same filtering.