# Annex J

# Guidance for Determination of Necessary Bandwidth

## J.1 INTRODUCTION

This Annex provides guidance for determining the necessary bandwidth of federal radiocommunication systems. Necessary bandwidth forms part of the emission designator used for frequency management purposes and is used as a parameter in spectrum standards, frequency assignments, spectrum certification, etc., throughout this Manual. The other portion of the emission designator, emission classification symbols, is defined in Paragraph 9.8.2.16 of this Manual. Necessary bandwidth in this Manual is defined as follows:

"*Necessary Bandwidth*: For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions."

## J.2 GENERAL

1. Except for radars, the necessary bandwidth may be determined by one of the following methods with the order of preference shown:
   a. Use of the appropriate formula from Section J.3 or Table A in this Annex.
   b. Computation in accordance with the latest versions of Recommendations ITU-R SM.328, SM.853 or SM.1138.
   c. Measurements of specialized modulations not covered by a. or b. above.
   d. Use of the best available technical information from other sources.
2. For radars, the necessary bandwidth shall be determined at a point that is 20 dB below the peak envelope value of the spectrum ($B_{20dB}$) by one of the following with the order of preference shown:
   a. Computation in accordance with the radar formulas from Section J.3 or Table A in this Annex.
   b. Results of actual measurements.
   c. Use of the best available technical information from other sources.

## J.3 DERIVATIONS

1. It is recognized that the determination of necessary bandwidth based on the above definition can sometimes be imprecise, especially since the "quality required" is often unavailable or vaguely defined. For analog modulation types, the necessary bandwidth is generally based on rules-of-thumb, such as Carson's Rule (described later), that have been in use since the early days of radio. For digital modulations, the necessary bandwidth is generally based on a more precise measure of bandwidth – the theoretical 99% occupied bandwidth.[1] As described above, the necessary bandwidth for radars and other pulsed systems is based on the theoretical $B_{20dB}$ bandwidth.

2. The discussion below provides the general methods and equations for determining necessary bandwidth followed by a list of symbols used and Table A containing a series of examples.

### J.3.1 ANALOG AMPLITUDE MODULATION

1. For analog Amplitude Modulation (AM) systems, the necessary bandwidth ($B_n$) is calculated as:

$B_n = KM$ *Reference Eq. J-1*

where K is a factor determined by the specific AM format and practical filtering constraints or established technical standards. M is the maximum modulation frequency. Typical K values for analog AM formats are provided below.[2]

[1] See Section 5.1.5 for the desired relationship of measured occupied bandwidth to necessary bandwidth.
[2] "Spectra and Bandwidth of Emissions" Recommendation ITU-R SM.328-11, 2006, Geneva - http://www.itu.int/pub/R-REC

a. Single sideband, suppressed carrier (SSB-SC) $K < 1$, *Reference Eq. J-2*
b. Single sideband, reduced carrier (SSB-RC) $K = 1$, *Reference Eq.* J-3
c. Single sideband, full carrier (SSB-FC) $K = 1$, *Reference Eq.* J-4
d. Vestigial sideband (VSB) $1 < K < 2$, *Reference Eq.* J-5
e. Double sideband (DSB) $K = 2$, *Reference Eq.* J-6
f. Independent sideband (ISB) (see below).

2. For SSB-SC, an alternative equation is normally used as follows:

$B_n = M - M_l$ (where $M_l$ is the lowest modulation frequency) *Reference Eq.* J-7

3. For VSB, the necessary bandwidth may also be expressed as:

$B_n = M + M_{res}$ (where $M_{res}$ is the width of the residual sideband) *Reference Eq.* J-8

4. For ISB, the individual channels may be arranged in a DSB format, i.e., on both sides of the carrier or in an SSB format with all channels on one side of the carrier. For these ISB cases, $B_n$ can be expressed as:

$B_n = M_{sum}$ (where $M_{sum}$ is the sum of the M for each channel) *Reference Eq. J-9*

for DSB, SSB-FC, and SSB-RC formats and for SSB-SC formats as:

$B_n = M_{sum} - M_l$ *Reference Eq. J-10*

5. For analog AM systems that use one or more subcarriers located above the baseband (including subcarriers that are angle modulated), the maximum modulation frequency is given by:

$M = C_{max} + 0.5B_{sc}$ *Reference Eq. J-11*

where $C_{max}$ is the highest frequency subcarrier and $B_{sc}$ is the bandwidth of the highest frequency subcarrier. By combining equations J-6 and J-11, the necessary bandwidth for double sideband analog AM with subcarriers, would then be:

$B_n = 2C_{max} + B_{sc}$ *Reference Eq. J-12*

Depending on the type of subcarrier modulation, the $B_{sc}$ term can be determined using equations defined herein. For example, if the highest frequency subcarrier is an unmodulated tone, equation J-12 reduces to simply:

$B_n = 2C_{max}$ *Reference Eq.* J-13

If the highest frequency subcarrier is frequency modulated, then (see subsection C. below):

$B_n = 2C_{max} + 2M + 2KD$ (where D is the peak frequency deviation) *Reference Eq. J-14*

The necessary bandwidth for analog SSB systems with subcarriers is determined in a similar manner.

6. Typical values for M include:

| | |
|---|---|
| M = 2.7 to 3.1 kHz | Commercial quality voice |
| M = 4 to 10 kHz | Broadcast quality voice & music |
| M = 4.2 MHz | Standard definition broadcast video |

## J.3.2 ANALOG FREQUENCY MODULATION

1. The basis of the necessary bandwidth of analog Frequency Modulation (FM) systems is the long-established Carson's Rule as follows:[3]

$B_n = 2M + 2KD$ (where D is the peak frequency deviation) *Reference Eq. J-15*

2. In its fundamental form, Carson's rule uses a fixed value of K = 1, but there may be instances where a different value, higher or lower, is appropriate based on measurements. For analog FM systems using one or more modulated or unmodulated subcarriers above the baseband, combining equations J.11 and J.15 yields:

$B_n = 2C_{max} + 2M + 2KD$ *Reference Eq. J-16*

3. In some cases where a variety of subcarriers is used, established standards may specify only that the composite M including the baseband, subcarriers, and all modulation products be limited to a specific value.[4] In this case the composite M is used to compute equation J-15.

4. Analog FM equipment using frequency division multiplex/FM (FDM/FM) techniques have been largely displaced by digital radios. Reference can be made to Recommendation ITU-R SM.853 for necessary bandwidth calculation methods for FDM/FM systems.[5] Values for M and D are often stated in terms of a Modulation Index (MI) where

$$MI = \frac{D}{M} \text{ and } 0.25 \leq MI \leq 5 \text{ (typically)}$$

5. Typical values for M include:

| | |
|---|---|
| M = 2.7 to 3.1 kHz | Commercial quality voice |
| M = up to 15 kHz | Broadcast quality high-fidelity voice and music |
| M = 24 kHz to 4028 kHz | Frequency division multiplex (6 to 960 voice channels) |
| M = 4.2 MHz | Standard definition video links |

## J.3.3 ANALOG PHASE MODULATION

Analog Phase Modulation (PM) is rarely used because of the more complex receiving hardware required. No examples of analog PM are included herein. If needed, an equivalent Carson's Rule for analog PM can be defined as:

$B_n = 2(h + 1)M$ (where h is the phase modulation index) *Reference Eq. J-17*

## J.3.4 PULSE CODE MODULATION/PM

The next several sections contain K-factors for Pulse Code Modulation (PCM)/PM unfiltered and baseband filtered, with and without subcarriers.

The next subsections show the K-factors for unfiltered PCM/PM without subcarriers, as well as a selective set of unfiltered PCM/PM with subcarrier, and a selective set of filtered PCM/PM. It is recommended that the unfiltered PCM/PM results be also used as upper bounds on filtered PCM/PM with similar settings. Note the K-factors are equal to $BW_{95\%}/R$, where R is the input data rate, and $BW_{95\%}$ is the Two-Sided 95% power containment bandwidth. The input data rate R could include all source and channel encoding bits, such as error coding.

**<u>K-factors for Unfiltered PCM/PM:</u>**

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[3] "Notes on the Theory of Modulation", Proceedings of the Institute of Radio Engineers, volume 10, issue 1, February 1922, pages 57–64.
[4] See for example 47 CFR 73.44 and 47 CFR 73.317 for commercial AM and FM broadcast station standards.
[5] "Necessary Bandwidth", Recommendation ITU-R SM.853-1, 1997, Geneva - http://www.itu.int/pub/R-REC

Tables 1-3) show the K-factors for unfiltered PCM/PM with NRZ, and Bi-Phi (or Manchester), with and without subcarriers (sinewave, and squarewave). The cases with subcarrier (Table 2 and Table 3) are limited and as such engineering judgment should be made on settings that differ from those listed (example choose the settings that are closest to the given subcarrier system, or averaging between two settings).

Note that the unfiltered cases are proposed for use not only for unfiltered PCM/PM, but also as upper bounds for filtered PCM/PM, when none of the selective filtered cases shown in the next subsection apply.

**Table 1: K-factors for PCM/PM Unfiltered without subcarrier**

| **Modulation Index** | **K-factor** | |
|---|---|---|
| | **PCM/PM NRZ** | **PCM/PM Bi-Phi** |
| 0.2 | 2x0.1 | 2x0.5 |
| 0.3 | 2x0.2 | 2x0.8 |
| 0.4 | 2x0.4 | 2x1.0 |
| 0.5 | 2x0.5 | 2x1.2 |
| 0.6 | 2x0.6 | 2x1.5 |
| 0.7 | 2x0.7 | 2x2.8 |
| 0.8 | 2x1.1 | 2x3.1 |
| 0.9 | 2x1.4 | 2x3.3 |
| 1 | 2x1.5 | 2x4.7 |
| 1.1 | 2x1.6 | 2x4.9 |
| 1.2 | 2x1.7 | 2x5.1 |
| 1.3 | 2x1.8 | 2x5.3 |
| 1.4 | 2x2.1 | 2x5.4 |
| 1.5 | 2x2.2 | 2x6.3 |
| $\pi/2$ | 2x2.2 | 2x6.4 |

**Table 2: K-factors for PCM/PM Unfiltered with Squarewave Subcarrier**

| **Modulation Index (m)** | **K-factor** | | |
|---|---|---|---|
| | **Subcarrier frequency (Fs) over data rate (R) ratio=($F_s$/R)=3** | **Subcarrier frequency (Fs) over data rate (R) ratio=($F_s$/R)=9** | **Subcarrier frequency (Fs) over data rate (R) ratio=($F_s$/R)=15** |
| 0.4 | 2x4.8 | 2x11.9 | 2x16.7 |
| 1.2 | 2x23.8 | 2x61.9 | 2x104.8 |

**Table 3: K-factors for PCM/PM Unfiltered with Sinewave Subcarrier**

| **Modulation Index (m)** | **K-factor** | | |
|---|---|---|---|
| | **Subcarrier frequency (Fs) over data rate (R) ratio=($F_s$/R)=3** | **Subcarrier frequency (Fs) over data rate (R) ratio=($F_s$/R)=9** | **Subcarrier frequency (Fs) over data rate (R) ratio=($F_s$/R)=15** |
| 0.4 | 2x3.3 | 2x9.2 | 2x15.0 |
| 0.8 | 2x4.2 | 2x10.0 | 2x16.7 |
| 1.2 | 2x4.2 | 2x10.0 | 2x16.7 |
| 1.4 | 2x4.2 | 2x10.0 | 2x16.7 |

**K-factors for Filtered PCM/PM without subcarrier**

The K-factors for a few baseband filtered PCM/PM settings are shown below (Table 4 and Table 5), which can be used when applicable. Only the PCM/PM without subcarrier is shown since the cases with subcarrier are less common, especially for filtered PCM/PM. When a setting approximately matches one of those listed in the tables below, the corresponding K-factors should be used, otherwise the upper bound limits given by the unfiltered results discussed in the previous section can be utilized. Furthermore, it is recommended to utilize simulation tools when available to estimate the required bandwidth and K-factors for other settings, while noting that filtered values should never exceed the upper bounds provided by the unfiltered cases. The simulation results may vary depending on the included models (example power amplifiers, nonlinearities, input data asymmetry and imbalance, and other nonlinear effects), and hence additional margins can be added accordingly.

The next two tables show the K-factors values for a selective set of filtered PCM/PM. The K-factors are equal to $BW_{95\%}/R$ where R is the input data rate, which could include all source and channel encoding bits, such as error coding. The tables show results for filtered PCM/PM with NRZ, and Bi-Phi (or Manchester).

**Table 4: K-factors for PCM/PM NRZ with Filtering and without Subcarrier**

| Modulation Index (m) | Filter Type | Filter Characteristics | K-factor |
|---|---|---|---|
| 1.2 | Square Root Raised Cosine | 2000 tap; roll off factor=1 | 2x0.6 |
| 1.2 | Butterworth | 3 pole; Bandwidth Symbol Time Product (BTs)=2 | 2x1.1 |
| 1.2 | Bessel | 3 pole; Bandwidth Symbol Time Product (BTs)=2 | 2x1.3 |
| π/2 | Square Root Raised Cosine | 2000 tap; roll off factor=1 | 2x1.0 |
| π/2 | Butterworth | 3 pole; Bandwidth Symbol Time Product (BTs)=2 | 2x2.0 |
| π/2 | Bessel | 3 pole; Bandwidth Symbol Time Product (BTs)=2 | 2x1.8 |

**Table 5: K-factors for PCM/PM Bi-Phi with Filtering and without Subcarrier**

| Modulation Index (m) | Filter Type | Filter Characteristics | K-factor |
|---|---|---|---|
| 1.2 | Square Root Raised Cosine | 2000 tap; roll off factor=1 | 2x2.0 |
| 1.2 | Butterworth | 3 pole; Bandwidth Symbol Time Product (BTs)=2 | 2x3.0 |
| 1.2 | Bessel | 3 pole; Bandwidth Symbol Time Product (BTs)=2 | 2x3.0 |
| π/2 | Square Root Raised Cosine | 2000 tap; roll off factor=1 | 2x2.6 |
| π/2 | Butterworth | 3 pole; Bandwidth Symbol Time Product (BTs)=2 | 2x4.0 |
| π/2 | Bessel | 3 pole; Bandwidth Symbol Time Product (BTs)=2 | 2x4.0 |

## J.3.5 DIGITAL FM

1. Digital FM is generally a form of frequency shift keying (FSK) modulation. For the necessary bandwidth of digital FM systems, a form of Carson's Rule is again used with the first term replaced by its digital equivalent as follows:[6]

$B_n = R/\mathrm{Log}_2 S + 2KD$ *Reference Eq. J-18*

[6] "Necessary Bandwidth", Recommendation ITU-R SM.853-1, 1997, Geneva - http://www.itu.int/pub/R-REC

where R is the transmitted RF bit rate and S is the number of equivalent non-redundant signaling states. The value for K depends on the modulation format and specific filtering, but a value of 0.89 to 1.2 is often used based on the theoretical 99% occupied bandwidth. In some cases where the modulation index and filtering are standardized, the $B_n$ can be expressed simply as:[7]

$B_n = KR/Log_2S$ J-19 or $B_n = KR$ *Reference Eq. J-20*

2. Minimum shift keying (MSK), Gaussian-filtered MSK (GMSK), and Continuous Phase FSK (CPFSK) are popular forms of FSK that are defined by a bandwidth·time ($B_{3dB}T$) product.[8] Using equation J.20, Recommendation ITU-R SM.328 defines the K factor for several values of $B_{3dB}T$ given below based on the theoretical 99% occupied bandwidth.

| Modulation | D | $B_{3dB}T$ | K |
|---|---|---|---|
| CPFSK (unfiltered) | .35R (typical) | ∞ | 1.62 |
| MSK (unfiltered) | .25R | ∞ | 1.28 |
| GMSK | .25R | 1.0 | ≈1.15 |
| GMSK | .25R | 0.5 | 1.03 |
| GMSK | .25R | 0.3 | .91 |
| GMSK | .25R | 0.25 | .86 |
| GMSK | .25R | 0.15 | .70 |

Caution should be exercised to define R as the transmitted RF data rate with all data, overhead, redundancy, and error-correction bits included rather than the data rate available to the end user, which can be significantly lower. Also caution should be used in applying the factor D since often in the literature the modulation index for FSK systems may be stated in terms of the total deviation which is twice the peak deviation (D) used herein. Examples are provided later in Table A.

3. For telegraphy systems using FSK, the information rate is normally expressed in bauds (B) with the necessary bandwidth given by:

$B_n = B + 2KD$ *Reference Eq. J-21*

where K is typically 1.1 to 1.2.[9]

## J.3.6 DIGITAL AMPLITUDE SHIFT KEYING, PHASE SHIFT KEYING, AND QUADRATURE AMPLITUDE MODULATION

1.The necessary bandwidth for Amplitude Shift Keying (ASK), Phase Shift Keying (PSK), and Quadrature Amplitude Modulation (QAM) are all computed in the same manner as:[10]

$B_n = 2KR/Log_2S$ *Reference Eq. J-22*

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[7] "Spectra and Bandwidth of Emissions", ITU-R SM.328-11, 2006, Geneva - http://www.itu.int/pub/R-REC
[8] Where $B_{3dB}$ is the filter 3 dB bandwidth and T is the symbol length
[9] Determination of necessary bandwidths including examples for their calculation and associated examples for the designation of emissions, Rec. ITU-R SM.1138-2, Geneva, October 2008 - http://www.itu.int/pub/R-REC
[10] Recommendation ITU-R SM.853-1, Necessary Bandwidth, 1997 - http://www.itu.int/pub/R-REC

Values for K depend primarily on the nature of the baseband filtering employed in the transmitter. One common form of filtering is root raised cosine (RRC) that is defined by a rolloff factor (α) with a value between 0 and 1.

Figure 1, taken from Recommendation ITU-R SM.853, gives computed K values as a function of the rolloff factor for use with Equation J.22 for QAM systems using RRC filtering. Figure 1 may also be a useful guide for ASK and PSK modulation types as well. Note that in the special case where vestigial sideband techniques are used with ASK, PSK, or QAM, the K value could approach ½ of the value given by Figure 1. In some cases where the modulation index and filtering are standardized, the necessary bandwidth can be expressed simply as:

$B_n = KR$ *Reference Eq. J-23*

As described above, caution should be exercised to define R as the transmitted RF value with all data, overhead, redundancy, and error-correction bits included.

### Figure 1 K Value Versus Roll off for QAM Modulation

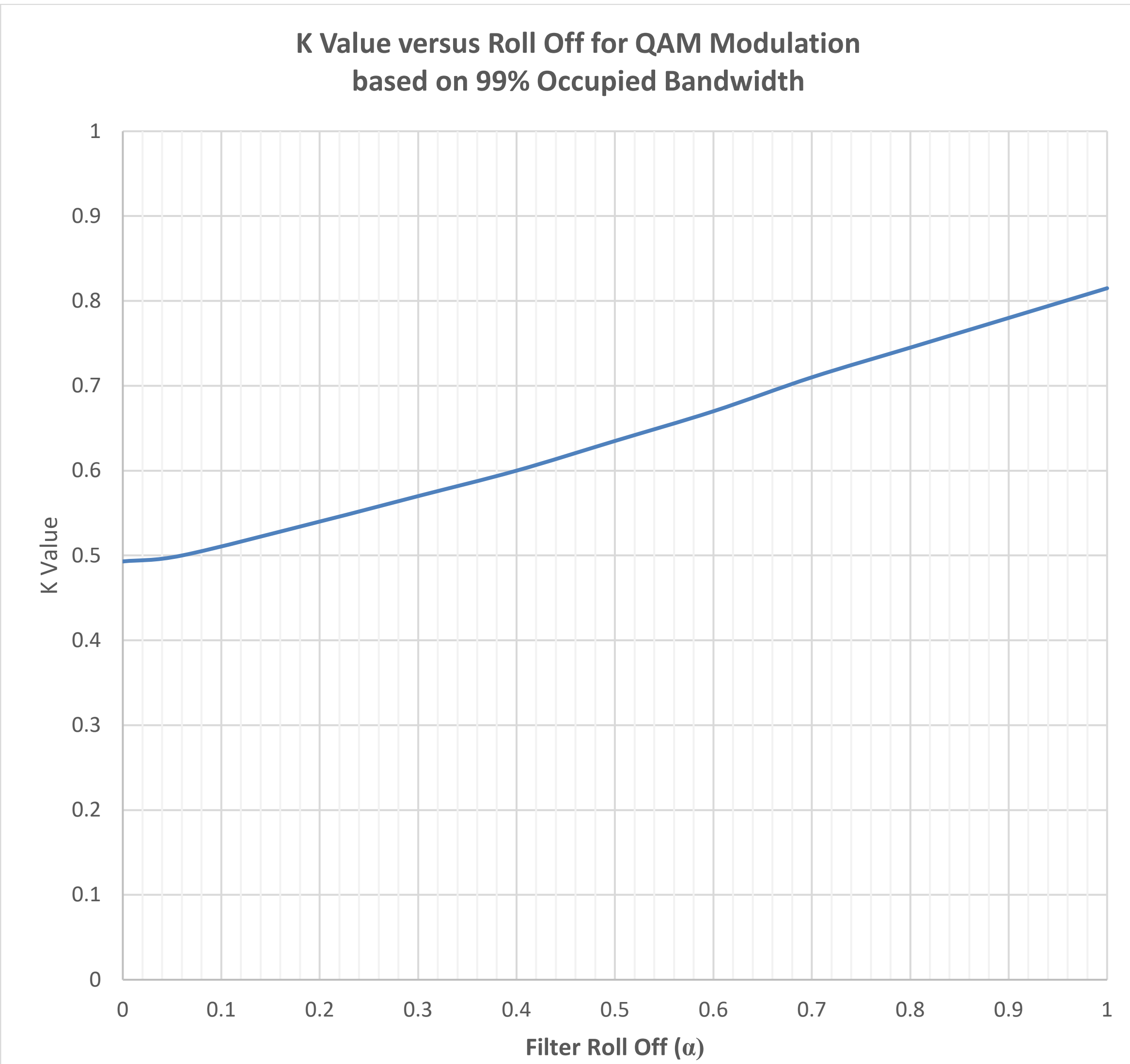


Figure 1

2. For the special case of telegraphy using manual ASK techniques (Morse code), the necessary bandwidth is defined by:

$B_n = KB$ *Reference Eq. J-24*

where K is 5 for fading circuits and 3 for non-fading circuits.

## J.3.7 RADAR SYSTEMS AND PULSE MODULATION

1. Five types of radar systems are in common use: unmodulated continuous wave (CW), frequency modulated CW (FM/CW), unmodulated pulse, phase-coded pulse, and frequency modulated pulse. For federal radar systems, agreed upon methodologies for calculating necessary bandwidth have been established as shown below:

| Radar Type | $B_n$ | Reference Eq. |
|---|---|---|
| CW[11] | 0 Hz | J-25 |
| FM/CW | $2B_{FM/CW}$ | J-26 |
| Unmodulated pulsed[12,13] | $MIN\left\{\frac{1.79}{\sqrt{t_r t}}, \frac{6.36}{t}\right\}$ | J-27 |
| Phase-coded pulsed[12,13, 14] | $MIN\left\{\frac{1.79}{\sqrt{t_r t}}, \frac{6.36}{t}\right\}$ | J-28 |
| Frequency modulated pulsed [12] | $\left\{\frac{1.79}{\sqrt{t_r t}} + 2B_c\right\}$ | J-29 |

where $B_C$ = Bandwidth of the frequency deviation for FM modulated pulsed radars (the total frequency shift during the pulse duration) in MHz.

$B_{FM/CW}$ = Bandwidth of the frequency deviation (peak difference between instantaneous frequency of the modulated wave and the carrier frequency for FM/CW radar systems).

t = Emitted pulse duration in µsec at 50% amplitude (voltage) points. The 100% amplitude is the nominal peak level of the pulse.

$t_r$ = Emitted pulse rise time in µsec from the 10% to the 90% amplitude points on the leading edge.

2. For non-radar pulse systems, a universally accepted methodology has not been identified. For unmodulated pulse systems, Recommendation ITU-R SM.1138 lists:

$B_n = 2K/t$ *Reference Eq. J-30*

But this recommendation states "K depends upon the ratio of pulse duration to pulse rise time. Its value usually falls between 1 and 10 and in many cases it does not need to exceed 6." For purposes herein, equations J-27 through J-29 may be used for non-radar pulse systems.

## J.3.8 MULTIPLE CARRIER MODULATION

Many modern communication systems employ multiple carrier modulation. These take several forms including orthogonal frequency division multiplex (OFDM), coded OFDM (COFDM) and orthogonal frequency division multiple access (OFDMA). Each of these types use a large number of closely spaced orthogonal subcarriers to carry data with each subcarrier modulated using conventional techniques such as PSK or QAM. For federal multiple carrier systems with $N_s > 16$ , the following approximation has been used to calculate necessary bandwidth:

$B_n = (N_s + 16.25)C_s$ *Reference Eq. J-31*

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[11] The emission of a CW transmitter will not be zero due to noise and other considerations. However, designating zero as the necessary bandwidth is a valid method for identifying such equipment.

[12] For frequency hopping systems the necessary bandwidth is the instantaneous one of an individual channel.

[13] MIN means the minimum of the two indicated terms.

[14] For phase coded pulse signals the pulse width and rise times are those associated with a single sub-pulse or chip. If the rise time of a single sub-pulse is not available, assume it is 40% of the time to switch from one phase or sub-pulse to the next.

where $N_s$ is the number of active subcarriers and $C_s$ is the spacing between subcarriers.[15]

It is noted that many commercial systems using multiple carrier modulation specify the bandwidth as simply:[16]

$$B_n = N_s C_s \qquad \textit{Reference Eq. J-32}$$

As an exception to the above, some multiple carrier systems, such as hybrid systems discussed below, do not have a contiguous series of carriers in which case equation J-12 may be used.

## J.3.9 SPREAD SPECTRUM MODULATION

Spread spectrum systems can be defined in several ways but normally take the form of either direct sequence spread spectrum (DSSS) or frequency-hopping spread spectrum (FHSS). In both cases the signal is intentionally spread over a much wider bandwidth than the baseband information bandwidth. For DSSS (also called CDMA, see below), binary PSK (BPSK) is typically used as the spreading technique and the necessary bandwidth can be calculated using methods described earlier for PSK. As noted earlier for frequency hopping systems, such as FHSS (also called FHMA, see below), the necessary bandwidth is normally the instantaneous bandwidth of an individual channel. However, it should be noted that the necessary bandwidth of some federal frequency hopping systems has been historically defined using the full hopping bandwidth as:

$$B_n = B_h + B_{ch} \qquad \textit{Reference Eq. J-33}$$

where $B_h$ is the total frequency hopping bandwidth and $B_{ch}$ is the individual channel bandwidth.

## J.3.10 MULTIPLE ACCESS SYSTEMS

Multiple access techniques are not modulation methods per se but are often included as part of the overall modulation description of a system. There are a large number of multiple access methods including: frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), orthogonal frequency division multiple access (OFDMA), spatial division multiple access (SDMA), frequency hopping multiple access (FHMA), and carrier sense multiple access (CSMA). The necessary bandwidth for systems using CDMA, OFDMA, and FHMA techniques has been discussed earlier. For systems using TDMA, SDMA, FDMA, or CSMA techniques, the necessary bandwidth is generally calculated based on the modulation used by an individual user using techniques described earlier.

## J.3.11 HYBRID SYSTEMS

In some cases, two signals can be overlaid within the same channel called composite or hybrid modulations. This is the case for the U.S. digital AM and FM commercial broadcast standards known as in-band on-channel (IBOC). IBOC refers to the method of transmitting a digital radio broadcast signal in the same channel as the AM or FM station's analog signal. The transmission of the digital signal using COFDM methods occupies the sidebands above and below the analog signal and transmitted at a lower power level. For these broadcast stations, the composite emission is limited by regulations to the existing analog spectral emission mask and, as a result, the necessary bandwidth is considered to be the same as the original analog signal.

## J.3.12 ULTRAWIDEBAND SYSTEMS

Ultrawideband (UWB) systems are authorized under provisions of Sections 7.8, 7.9, 8.3.31, or 10.11 of this Manual. The bandwidth of UWB systems is defined as the frequency band bounded by the points that are 10 dB below the highest radiated emission, as based on the complete transmission system including the antenna. These

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[15] In some cases, certain subcarriers are not active (do not carry data or pilot tones) to provide guardbands. Only the number of active subcarriers is used in these equations.

[16] Determination of necessary bandwidths including examples for their calculation and associated examples for the designation of emissions, Rec. ITU-R SM.1138-2, Geneva, October 2008 - http://www.itu.int/pub/R-REC

systems are typically pulse or impulse modulated but may include other forms. There are no defined methodologies for calculating the UWB necessary bandwidth, which is usually defined by measurements. Section K.3.6 describes emission limitations applicable to these systems.

## J.3.13 OTHER FACTORS

Guardbands are not normally included as part of the necessary bandwidth of a system, although they are occasionally included especially in commercial systems. For example, a 4G-LTE signal specified as 10 MHz typically has an actual necessary bandwidth of 9 MHz. Also since most of the equations described above include certain approximations, it is sometimes misleading or false precision to specify a calculated necessary bandwidth result to three or four significant digits. Consequently, rounding of calculated results to two significant digits or even one significant digit is sometimes used.

## J.4 SYMBOLS

As appropriate, Table A shall be used for calculation of necessary bandwidth. The following symbols are used in this table:

$B_{3dB}$ = 3 dB filter bandwidth

B = Digital symbol rate for telegraphy (i.e. baud)

$B_c$ = Bandwidth of the frequency deviation for FM modulated pulsed radars (the total frequency shift during the pulse duration) in MHz.

$B_{ch}$ = Bandwidth of an individual channel (frequency hopping system)

$B_{FM/CW}$ = Bandwidth of the frequency deviation (peak difference between instantaneous frequency of the modulated wave and the carrier frequency for FM/CW radar systems).

$B_h$ = Total frequency hopping bandwidth

$B_n$ = Necessary bandwidth

$B_{sc}$ = Bandwidth of the highest frequency subcarrier.

$BW_{95\%}$ = The 95% power containment two sided bandwith

$C_{max}$ = Highest frequency subcarrier or furthest removed from the carrier frequency.

$C_s$ = Separation in frequency between adjacent sub-carriers or carriers of a multi-carrier modulation.

D = Peak deviation, i.e., half the difference between the maximum and minimum values of the instantaneous frequency.

$F_s$ = The frequency (Hz) for a PCM/PM modulation subcarrier

K = An overall numerical factor which varies according to the emission and which depends upon the allowable signal distortion.

M = Maximum modulation frequency

MI = Modulation index

$M_l$ = Lowest modulation frequency

$M_{res}$ = Width of the residual sideband in a vestigial sideband system.

$M_{sum}$ = Sum of the M for each channel in a multichannel system.

$N_c$ = Number of baseband channels in radio systems employing multichannel multiplexing.

$N_s$ = Number of sub-carriers

R = Total bit rate, which includes data, encoding, and any other overhead bits.

S = Number of equivalent non-redundant signaling states.

t = Emitted pulse duration in µsec at 50% amplitude (voltage) points. The 100% amplitude is the nominal peak level of the pulse.

$t_f$ = Emitted pulse fall time in µsec from the 90% to the 10% amplitude points on the trailing edge.

$t_r$ = Emitted pulse rise time in µsec from the 10% to the 90% amplitude points on the leading edge.

## J.5 EXAMPLES

Table A below, provides a list of common modulations used by federal agencies and specific examples of necessary bandwidth calculations for each type. The modulations are ordered by radio service for ease of use. Because of continued expansion of sharing of frequency bands by both federal and non-federal users, some common non-federal examples are included for illustrative purposes. While it is impractical herein to address all modern forms of digital modulation, the expanded list of digital examples includes many common forms.

**TABLE A: Example Necessary Bandwidth Calculations**

| Type of Service/ Description of Emission | Formula/ Reference Equation | Type of Signal/ Sample Calculation | Emission Designator |
|---|---|---|---|
| **BROADCASTING SERVICE** | | | |
| **HF Sound Broadcasting** Analog AM (DSB) | $B_n = 2M$ J-1/J-6 | Single channel voice and music $M = 4.5$ kHz; $B_n = 9$ kHz | 9K00A3E |
| **HF Sound Broadcasting** Analog AM (SSB-SC) | $B_n = M - M_l$ J-7 | Single channel voice and music $M = 4.5$ kHz; $M_l = 150$ Hz $B_n = 4.35$ kHz | 4K35J3E |
| **HF Sound Broadcasting** Analog AM (SSB-RC) | $B_n = M$ J-1/J-3 | Single channel voice and music $M = 4.5$ kHz; $B_n = 4.5$ kHz | 4K50R3E |
| **HF Sound Broadcasting** Digital COFDM | $B_n = C_sN_s$ J-32 | Digital Radio Mondiale standard BPSK to 64 QAM channel modulation $C_s = 41.66$ Hz; $N_s = 228$ $B_n = 9.5$ kHz | 9K50W1E[17] |
| **AM Sound Broadcasting** Analog AM (DSB) | $B_n = 2M$ J-1/J-6 | Speech and music (U.S. standard) $M = 10$ kHz; $B_n = 20$ kHz | 20K0A3E |
| **AM Sound Broadcasting** IBOC hybrid analog AM (DSB) plus Digital OFDM (U.S. digital AM broadcast standard) | $B_n = 2M$ (analog) J-1/J-6 | Analog speech and music $M = 8$ kHz; $B_n = 16$ kHz | 20K0X9W[18] (hybrid system) |
| | $B_n = 2C_{max} + B_{sc}$ (digital) $B_{sc} \approx C_s$ J-12 | Digital voice, music & data $C_s = 181.7$ Hz; $N_s = 50$; $C_{max} = 14.717$ kHz $B_{sc} = 181.7$ Hz $B_n \approx 30$ kHz | |
| **FM Sound Broadcasting** Analog FM monaural | $B_n = 2M + 2KD$ $K = 1$ (typical) J-15 | High fidelity voice & music $M = 15$ kHz; $D = 75$ kHz $B_n = 180$ kHz | 180KF3E |
| **FM Sound Broadcasting** Analog FM stereophonic with multiplexed subcarriers | $B_n = 2M + 2KD$ $K = 1$ (typical) J-15 | High fidelity voice, music & data Composite $M = 100$ kHz; $D = 75$ kHz $B_n = 350$ kHz | 240KF9W[19] |
| **FM Sound Broadcasting** IBOC hybrid mode analog FM plus digital OFDM (U.S. digital FM broadcast standard) | $B_n = 2M + 2KD$ (Analog) $K = 1$ (typical) J-15 | High fidelity voice, music & data Composite $M = 100$ kHz; $D = 75$ kHz $B_n = 350$ kHz | 240KF9W[19] (hybrid system) |
| | $B_n = 2C_{max} + B_{sc}$ (Digital) $B_{sc} \approx C_s$ J-12 | Digital voice, music & data $C_s = 363.4$ Hz; $N_s = 382$; $C_{max} = 198.4$ kHz; $B_{sc} = 363.4$ Hz $B_n \approx 400$ kHz | |

[17] See 47 CFR 73.758. Other combinations of $C_s$ and $N_s$ are also possible.
[18] Compliance with requirements of 47 CFR 73.44 is deemed by the FCC to show the occupied bandwidth to be 20 kHz or less. Other analog and digital parameters also possible. See http://www.nrscstandards.org/SG/NRSC-5-D.pdf .
[19] Compliance with requirements of 47 CFR 73.317 is deemed by the FCC to show the occupied bandwidth to be 240 kHz or less. Other analog and digital parameters also possible. See http://www.nrscstandards.org/SG/NRSC-5-D.pdf.

| Type of Service/ Description of Emission | Formula/ Reference Equation | Type of Signal/ Sample Calculation | Emission Designator |
|---|---|---|---|
| **Television Broadcasting (Analog)**<br>Video AM - VSB | $B_n = M + M_{res}$ (video)<br>J-8 | Standard definition video<br>$M = 4.2$ MHz; $M_{res} = 0.75$ MHz<br>$B_n = 4.95$ MHz (5.75 MHz w/guardbands) | 5M75C3F<br>250KF8E[20]<br>combined in a 6 MHz channel |
| Audio FM – stereo plus multiplex subcarriers<br>(U.S. NTSC analog TV standard) | $B_n = 2M + 2KD$ (audio)<br>$K = 1$ (typically)<br>J-15 | Stereo voice and music<br>Composite $M = 120$ kHz; $D = 75$ kHz<br>$B_n = 390$ kHz | |
| **Television Broadcasting (Digital)**<br>8ASK, vestigial sideband (8VSB)<br>Rate 0.6 FEC<br>Filter rolloff = 0.115 | $B_n = 2KR/\log_2 S$<br>$K \approx 0.278$<br>J-22 | U.S. HDTV Standard<br>Multiplexed video, audio, data<br>$R = 32.28$ Mbps (19.39 Mbps to user)<br>$S = 8$ $B_n = 6$ MHz | 6M00C7W |
| **FIXED AND MOBILE SERVICES (Telegraphy)** | | | |
| **Manual Telegraphy**<br>On-off keying (OOK) of carrier | $B_n = KB$<br>$K = 5$ (typical) J-24 | Manual Morse code[21]<br>WPM = 25; $B = 20$ Hz $B_n = 100$ Hz | 100HA1A |
| **Manual Telegraphy**<br>On-off keying (OOK) of subcarrier | $B_n = 2C_{max} + KB$<br>$K = 5$ (typical)<br>J-12/J-24 | Manual Morse code<br>WPM = 25; $B = 20$ Hz; $C_{max} = 1$ kHz<br>$B_n = 2.1$kHz | 2K10A2A |
| **Direct Printing Telegraphy**[22]<br>FSK on a subcarrier with SSB suppressed carrier | $B_n = B + 2KD$<br>$K = 1.2$ (typical)<br>J-21 | Telegraph data<br>$B = 100$ Hz; $D = 85$ Hz $B_n = 304$ Hz | 304HJ2B |
| **Direct Printing Telegraphy**<br>Two frequency FSK (2FSK) | $B_n = B + 2KD$<br>$K = 1.2$ (typical) J-21 | Telegraph data<br>$B = 100$ Hz; $D = 85$ Hz $B_n = 304$ Hz | 304HF1B |
| **Direct Printing Telegraphy**<br>Four-frequency FSK (4FSK) with synchronized duplex channels | $B_n = B + 2KD$<br>$K = 1.1$ (typical)<br>J-21 | Telegraph data<br>$B = 100$ Hz; $D = 600$ Hz $B_n = 1.42$ kHz | 1K42F7B |
| **FIXED AND MOBILE SERVICES (Telemetry & Telecommand)**[23] | | | |
| **PCM/FM**<br>Filtered non-return to zero pulse code modulation/FM<br>$D = 0.35R$; premodulation filter bandwidth = 0.7R | $B_n = 1.16R$<br>J-20 | Single channel data<br>$R = 5$ Mbps; $D = 1.75$ MHz<br>$B_n = 5.8$ MHz | 5M80F1D |

[20] Compliance with requirements of 47 CFR 73.682 is deemed by the FCC to show the occupied bandwidth to be 250 kHz or less.
[21] For manual telegraphy, the Baud rate is typically 0.8 times the words per minute.
[22] See Recommendation ITU-R M.476-5 - http://www.itu.int/pub/R-REC
[23] The necessary bandwidths given here for telemetry and telecommand systems are based on the 99% occupied as defined in Telemetry Standards, IRIG 106-15, Appendix A, July 2015. It is recognized that this IRIG source also defines somewhat wider necessary bandwidth values for purposes of frequency scheduling.

| Type of Service/ Description of Emission | Formula/ Reference Equation | Type of Signal/ Sample Calculation | Emission Designator |
|---|---|---|---|
| **QPSK**<br>Constant envelop offset QPSK (OQPSK); Feher's patented QPSK (FQPSK-B, FQPSK-JR); shaped offset QPSK (SOQPSK-TG) | $B_n = 0.78R$<br>J-23 | Single channel data<br>R = 5 Mbps; $B_n = 3.9$ MHz | 3M90G1D |
| **ARTM CPM**<br>Advanced range telemetry continuous phase modulation MI = 4/16 and 5/16 on alternating symbols | $B_n = 0.56R$<br>J-23 | Single channel data<br>R = 5 Mbps, S = 4<br>$B_n = 2.8$ MHz | 2M80G1D |
| **FIXED AND MOBILE SERVICES (Telephony)** | | | |
| **Analog AM DSB**<br>Single channel voice | $B_n = 2M$<br>J-1/J-6 | Commercial grade voice<br>M = 3 kHz $B_n = 6$ kHz | 6K00A3E |
| **Analog AM ISB**<br>Two equal-size DSB voice channels | $B_n = M_{sum}$<br>J-9 | Commercial grade voice<br>2 channels; M = 3 kHz; $M_{sum} = 6$ kHz<br>$B_n = 6$ kHz | 6K00B8E |
| **Analog AM SSB**<br>Full or reduced carrier voice | $B_n = M$<br>J-1/J-3 | Commercial grade voice<br>M = 3 kHz $B_n = 3$ kHz | 3K00H3E |
| **Analog AM ISB**<br>Suppressed carrier, two or more channel voice | $B_n = M_{sum} - M_l$<br>J-10 | Commercial grade voice<br>2 channels; M = 3 kHz; $M_{sum} = 6$ kHz<br>$M_l = 250$ Hz $B_n = 5.75$ kHz | 5K75J8E |
| **Analog AM SSB**<br>Suppressed carrier, single channel voice | $B_n = M - M_l$<br>J-7 | Maritime mobile HF voice<br>M = 2.7 kHz; $M_l = 350$ Hz<br>$B_n = 2.35$ kHz | 2K80J3E[24] |
| **Analog FM**<br>Narrowband voice | $B_n = 2M + 2KD$<br>K = 1 (typical) J-15 | Commercial grade voice<br>M = 3 kHz, D = 2.5 kHz $B_n = 11$ kHz | 11K0F3E |
| **Analog FM**<br>Wideband voice | $B_n = 2M + 2KD$<br>K = 1 (typical)<br>J-15 | Commercial grade voice<br>M = 3 kHz, D = 5 kHz $B_n = 16$ kHz | 16K0F3E |
| **FDM/FM**<br>Analog frequency division multiplex/FM radio relay | $B_n = 2M + 2KD$<br>K = 1 (typical)<br>J-15 | 960 multiplexed voice channels<br>M = 4028 kHz; D = 4140 kHz<br>$B_n = 16.4$ MHz | 16M4F8E |

[24] Voice passband and necessary bandwidth defined by Recommendation ITU-R M.1173 - http://www.itu.int/pub/R-REC

| Type of Service/<br>Description of Emission | Formula/<br>Reference Equation | Type of Signal/<br>Sample Calculation | Emission Designator |
|---|---|---|---|
| **C4FM**<br>Compatible four level FSK voice<br>Rate ½ rate FEC<br>(APCO Project 25 Phase 1) | $B_n = R/Log_2S + 2KD$<br>$K \approx 0.92$<br><br>J-18 | Commercial grade voice and/or data<br>R = 9.6 kbps<br>S = 4; D = 1.8 kHz<br>$B_n$ = 8.1 kHz | 8K10F1W |
| **CQPSK**<br>Quadrature phase shift keying<br>(APCO Project 25 Phase 2) | $B_n = 2KR/Log_2S$<br>K ≈ 0.5 to 0.8 (typical, depending on filter roll-off factor)<br>J-22 | voice channel<br>R = 12 kbps<br>S = 4<br>$B_n$ = 5.76 kHz | 5K76G1E |
| **H-DQPSK**<br>Harmonized DQPSK (downlink)<br>RRC filter rolloff = 1<br>(APCO Project 25 Phase 2) | $B_n= 2KR/Log_2S$<br>$K \approx 0.817$<br><br>J-22 | Commercial grade voice and/or data<br>R = 12 kbps; S = 4; $B_n$ = 9.8 kHz | 9K80G1W[25] |
| **H-CPM**<br>Two slot TDMA (uplink)<br>Harmonized continuous phase modulation – a form of QPSK<br>(APCO Project 25 Phase 2) | $B_n = 2KR/Log_2S$<br>$K \approx 0.675$<br><br>J-22 | Commercial grade voice and/or data<br>R = 12 kbps; S = 4<br><br>$B_n$ = 8.1 kHz | 8K10G1W[26] |
| **FIXED AND MOBILE SERVICES (Video Links)** | | | |
| **Analog FM Video**<br>Single channel wideband video | $B_n = 2M + 2KD$<br>K = 1 (typical) J-15 | Standard definition video<br>M = 4.2 MHz; D = 4 MHz; $B_n$ = 16.4 MHz | 16M4F3C |
| **Analog FM Video**<br>Single channel reduced bandwidth video | $B_n = 2M + 2KD$<br>K = 1 (typical)<br>J-15 | Standard definition video<br>M = 4.2 MHz; D = 1.7 MHz;<br>$B_n$ = 12 MHz | 12M0F3C |
| **Digital Video Link**<br>GMSK modulation with H.264 video compression; ½ Rate FEC<br>D = 0.25R; Filter bandwidth = R | $B_n= KR/Log_2S$<br>$K \approx 1.2$<br><br>J-20 | Digital Data Link (Video Mode)<br>R = 11 Mbps (5.5 Mbps to user); S = 2<br>$B_n$ = 13.2 MHz | 13M2F1F |
| **FIXED AND MOBILE SERVICES (Data)**[27] | | | |
| **Binary FSK (BFSK or 2FSK)**<br>$0.5R \leq D \leq 10R$ | $B_n = R/Log_2S + 2KD$<br>K = 1.2 (typical)<br>J-18 | Single channel data<br>R = 1 Mbps; D = 750 kHz; S = 2<br>$B_n$ = 2.8 MHz | 2M80F1D |
| **Multilevel FSK (MFSK)** | $B_n = R/Log_2S + 2KD$<br>K = 0.89 (typical)<br>J-18 | 4 level FSK<br>R = 10 Mbps; D = 2 MHz; S = 4<br>$B_n$ = 8.56 MHz | 8M56F1D |

[25] In some references, this emission designator is referred to as 9K80F1E or 9K80D7W.
[26] In some references, this emission designator is referred to as 8K10F9W or 8K10DXW
[27] All data rates shown are gross RF data rate including all data, overhead, redundancy, and error-correction bits

| Type of Service/ Description of Emission | Formula/ Reference Equation | Type of Signal/ Sample Calculation | Emission Designator |
|---|---|---|---|
| **CPFSK**<br>Coherent phase FSK<br>Unfiltered D = 0.35R | $B_n$ = KR<br>K = 1.63 (typical)<br>J-20 | 2 level coherent phase FSK<br>R = 5 Mbps<br>$B_n$ = 8.15 MHz | 8M15F1D |
| **MSK**<br>Minimum shift keying unfiltered<br>D = 0.25R | $B_n$ = KR<br>K = 1.28<br>J-20 | 2 level coherent phase FSK<br>R = 2 Mbps; $B_n$ = 2.56 MHz | 2M56F1D |
| **GMSK**<br>Gaussian MSK D = 0.25R<br>Filter $B_{3dB}T$ = 0.5 | $B_n$ = KR<br>K = 1.03<br>J-20 | 2 level Gaussian coherent phase FSK<br>R = 10 Mbps; $B_n$ = 10.3 MHz | 10M3F1D |
| **GMSK**<br>Gaussian MSK D = 0.25R<br>Filter $B_{3dB}T$ = 0.25 | $B_n$ = KR<br>K = 0.86<br>J-20 | Maritime Automatic Identification System (AIS)<br>R = 9.6 kbps; $B_n$ = 8.3 kHz | 8K30F1D |
| **GMSK**<br>Gaussian MSK D = 0.25R<br>Filter $B_{3dB}T$ = 0.5<br>Frequency hopping | $B_n$ =KR + $B_h$<br>K = 1.03<br>J-20/J-33 | Bluetooth (IEEE 802.15.1 v1.2)<br>$B_h$ = 79 MHz; R = 1 Mbps;<br>$B_n \approx$ 80 MHz | 80M0F1D |
| **PSK**[28]<br>Binary phase shift keying (BPSK)<br>Unfiltered | $B_n$ = 2KR/$Log_2S$<br>K ≈ 1 (for 95% occupied bandwidth) J-22 | Data<br>R = 10 Mbps; S = 2<br>$B_n$ = 20 MHz | 20M0G1D |
| **M-PSK**<br>M-ary phase shift keying<br>Symbol $M=2^n$, n=1,2,3… | $B_n$ = 2KR/$Log_2S$<br>K ≈ 0.6 to 0.8 (typical, depending on filter roll-off factor)<br>J-22 | 4 PSK<br>R = 10 Mbps; S = 4; k = 0.7<br>$B_n$ = 7.0 MHz | 7M00G1D |
| **BPSK TDMA**<br>Fixed frequency Mode | $B_n$ = 2KR/$Log_2S$<br>K ≈ 0.9<br>J-22 | DoD Link 16<br>t = 6.4 us; R = 5 Mbps; S =2<br>$B_n$ = 9.0 MHz | 9M00Q1D |
| **BPSK TDMA**<br>Frequency hopping Mode | $B_n$ =2KR/$Log_2S$ + $B_h$<br>K ≈ 0.9<br>J-22/J-33 | DoD Link 16<br>t = 6.4 us; R = 5 Mbps; S = 2<br>$B_h$ = 237 MHz $B_n$ = 246 MHz | 237MQ1D[29] |
| **M-QAM**<br>Quadrature amplitude modulation<br>$M=2^n$, n = 1,2,3… | $B_n$ = 2KR/$Log_2S$<br>K ≈ 0.6 to 0.8 (typical, depending on filter roll-off factor)<br>J-22 | 64QAM<br>R = 135 Mbps, S = 64, K = 0.65<br>$B_n$ = 29.3 MHz | 29M3D1D |

[28] Included for illustrative purposes only; all practical systems employ some form of baseband filtering.
[29] The Link 16 necessary bandwidth in the frequency hopping mode has historically been stated in terms of the total hopping bandwidth.

| Type of Service/ Description of Emission | Formula/ Reference Equation | Type of Signal/ Sample Calculation | Emission Designator |
|---|---|---|---|
| **M-Trellis-Coded Modulation**<br>$M=2^n$, n = 1,2,3… | $B_n = 2KR/Log_2S$<br>K ≈ 0.6 to 0.8 (typical, depending on filter roll-off factor)<br>J-22 | 128TCM<br>R = 155.5 Mbps, K = 0.65<br>S = 128 $B_n = 28.9$ MHz | 28M9D7W |
| **Multicarrier Modulation**<br>Orthogonal frequency division multiplexing (OFDM)<br>Federal system | $B_n = (N_s + 16.25)C_s$<br>$N_s > 16$<br>J-31 | Data<br>$N_s = 48$ active subcarriers; $C_s = 250$ kHz<br>16 QAM channel modulation<br>$B_n = 16.1$ MHz | 16M1D1D |
| **Multicarrier Modulation**<br>OFDM (20 MHz channel)<br>Voice, data, video<br>Commercial system | $B_n = N_sC_s$<br>J-32 | WiFi (IEEE 802.11ac standard)<br>$N_s = 56$ active subcarriers; $C_s = 312.5$ kHz<br>BPSK through 256QAM carrier modulation<br>$B_n = 17.5$ MHz | 17M5D7W |
| **Multicarrier Modulation**<br>OFDM voice, data, video<br>Commercial system | $B_n = N_sC_s$<br>J-32 | 4G-LTE downlink (3GPP Release 10)<br>BPSK through 64QAM mod.; $C_s = 15$ kHz<br>10 MHz chan. $N_s = 600$<br>$B_n = 9.0$ MHz | 9M00D7W |
| **RADIODETERMINATION AND METEOROLOGICAL AID SERVICES**[30] | | | |
| **CW Radar**[31] | $B_n = 0$ J-25 | CW Doppler radar | 0H00N0N |
| **FM/CW Radar** | $B_n = 2B_{FM/CW}$<br>J-26 | Linear swept FM<br>$B_{FM/CW} = 100$ MHz; $B_n = 200$ MHz | 200MF3N |
| **Unmodulated Pulse Radar** | $B_n$ = Min [1.79/SQRT($t_r$t),6.36/t]<br>J-27 | Non-trapezoidal shaped pulses[32]<br>t = 1 usec; $t_r = 0.2$ usec; $t_f = 0.15$ usec<br>$B_n = 4.62$ MHz | 4M62P0N |

30 Certain navigation system parameters were drawn from "Spectrum Management Regulations and Procedures Manual," Federal Aviation Administration, 17 Nov 2005

31 The emission of a CW transmitter will not be zero due to noise and other considerations. However, designating zero as the necessary bandwidth is a valid method for identifying such equipment.

32 For non-trapezoidal shaped pulses, use the smaller of $t_r$ and $t_f$ in the equation in place of $t_r$

| Type of Service/ Description of Emission | Formula/ Reference Equation | Type of Signal/ Sample Calculation | Emission Designator |
|---|---|---|---|
| **FM Chirp Pulse Radar** | $B_n = \frac{1.79}{\sqrt{t_r * t}} + 2B_c$<br>Starting on January 1, 2020, when the following conditions are met (for linear and non-linear chirps),<br>is:<br>$B_n = 1.44 * \left[B_C + Ln(B_C * t)^{0.35} * Min(B_{Rise}, B_{Fall}, B_{Rise\_Fall}) + \frac{Max(B_{Rise}, B_{Fall}, B_{Rise\_Fall})}{(B_c * t)^{1.5}}\right]$<br>Where:<br>$B_{Rise} = \frac{1}{\sqrt{t_r * t}}$<br>$B_{Fall} = \frac{1}{\sqrt{t_f * t}}$<br>$B_{Rise\_Fall} = \frac{1}{\sqrt[3]{t * t_r * t_f}}$<br>Else<br>$B_n = \frac{1.79}{\sqrt{t_r * t}} + 2B_c$<br>J-29 | Trapezoidal shaped pulses<br>t = 25 usec; $t_r$ = 0.15 usec; $t_f$ =0.15 usec<br>$B_c$ = 3 MHz $B_n$ = 6.92MHz | 6M92Q3N |
| **Phase-coded Pulse Radar** | $B_n$ = Min [1.79/SQRT($t_r$t),6.36/t]<br>J-28 | Trapezoidal shaped pulses<br>chip t = 0.5 usec; chip $t_r$ = 0.02 usec;<br>chip $t_f$ =0.02 usec $B_c$ = 12.7 MHz | 12M7Q1N |

| Type of Service/ Description of Emission | Formula/ Reference Equation | Type of Signal/ Sample Calculation | Emission Designator |
|---|---|---|---|
| **VHF Omnidirectional Range (VOR)**<br>Analog DSB AM with subcarriers | $B_n = 2C_{max} + 2M + 2KD$<br>K = 1 (Typical)<br>J-14 | Carrier DSB modulated by:<br>1) 30 Hz subcarrier<br>2) 9960 Hz subcarrier with 30 Hz FM tone; D = 480 Hz<br>3) 3 kHz voice channel<br>4) keyed 1020 Hz subcarrier<br>$C_{max}$ = 9960 Hz; M = 30 Hz; D = 480 Hz<br>$B_n$ = 20.9 kHz | 20K90A2A (without voice)<br>20K9A9W (voice) |
| **Marker Beacon**<br>AM-DSB Tone modulated | $B_n = 2C_{max}$<br>J-13 | Carrier modulated by:[33]<br>400 Hz tone (Outer marker) $B_n$ = 800 Hz<br>1.3 kHz tone (Mid marker) $B_n$ = 2.6 kHz<br>3 kHz tone (Inner marker) $B_n$ = 6 kHz | 800HA2A<br>2K60A2A<br>6K00A2A |
| **DME**<br>Distance Measuring Equipment Interrogator & transponder | $B_n$ = Min [1.79/SQRT($t_r$t),6.36/t]<br>J-27 | Sequence of position modulated pulses<br>t = 3.5 us; $t_r$ = 2.5 us; $t_f$ = 2.5 us<br>$B_n$ = 605 kHz (typ. rounded to 650 kHz) | 650K00M1A<br>605K00M1A |
| **TACAN**<br>Tactical Air Navigation System | $B_n$ = Min [1.79/SQRT($t_r$t),6.36/t]<br>J-27 | Sequence of position modulated pulses<br>t = 3.5 us; $t_r$ = 2.5 us; $t_f$ = 2.5 us<br>$B_n$ = 605 kHz (typ. rounded to 650 kHz) | 650K00V1A |
| **IFF**<br>Identification Friend or Foe Transponder<br>Pulse position modulation | $B_n$ = Min [1.79/SQRT($t_r$t),6.36/t]<br>J-27 | IFF Mode 4 response<br>Sequence of position modulated pulses<br>t ≈ .5 us; $t_r$ = .065 us; $t_f$ = .08 us<br>$B_n$ ≈ 10 MHz | 10M0M1D |
| **ATCRBS**<br>Air Traffic Control Radar Beacon System Interrogator | $B_n$ = Min [1.79/SQRT($t_r$t),6.36/t]<br>J-27 | Sequence of position modulated pulses<br>t = 0.8 us; $t_r$ = 0.05 to 0.1 us;<br>$t_f$ = 0.05 to 0.2 us<br>$B_n$ ≈ 6.3 MHz (typ. rounded to 6 MHz) | 6M00M1D |
| **Mode S**<br>Interrogator | $B_n$ = Min [1.79/SQRT($t_r$t),6.36/t]<br>J-28 | Sequence of position modulated pulses some of which are biphase modulated<br>chip t = 0.25 us; chip $t_r$ ≈ 0.028 us<br>$B_n$ ≈ 21.5 MHz | 21M5V1D |
| **ILS Localizer**<br>Instrument Landing System AM-DSB | $B_n = 2C_{max}$<br>J-13 | Carrier modulated by:[30]<br>1. 90 Hz tone<br>2. 150 Hz tone<br>3. 1020 Hz tone<br>$B_n$ = 2.04kHz | 2K04A1A<br>10K04A9W<br>8K00A9W |

[33] Although one or more tones may periodically be modulated with low speed Morse code identification or other low speed data, it is considered inconsequential to the overall bandwidth.

| Type of Service/ Description of Emission | Formula/ Reference Equation | Type of Signal/ Sample Calculation | Emission Designator |
|---|---|---|---|
| **GBAS**<br>Ground Based Augmentation System | [TBD] | Phase modulated by two or more channel transmitting data.<br>$B_n \approx 14$ kHz | 14K00G7D |
| **GBTS**<br>Ground Based Transceiver Service | [TBD] | Frequency modulated by single channel transmitting data<br>$B_n \approx 1.73$ MHz<br>$B_n \approx 1.30$ MHz | 1M73F1D<br>(978MHz)<br>1M30F1D<br>(1090 MHz) |
| **Glide Slope** | [TBD] | Single channel with Amplitude modulated Double-sideband<br>$B_n \approx 8.30$ kHz<br>$B_n \approx 300$ Hz | 8K30A1N<br>(Capture effect & Endfire)<br>300H00A1N<br>(normal/traditional GS) |
| **Non-directional beacon (NDB)**<br>AM-DSB tone modulated | $B_n = 2C_{max}$<br>J-13 | Carrier modulated by a 1.02 kHz tone[30]<br>$B_n = 2.04$ kHz<br>$B_n = 6.00$ kHz | 2K04A2A<br>(single carrier)<br>6K00A3E<br>(w/voice and weather information) |
| **SPACE SERVICES** | | | |
| **CW** | $B_n = 0$ J-25 | Unmodulated downlink satellite beacon | N0N |
| **Tone modulated CW** | $B_n = 2*M$<br>J-1/J-6 | Tone modulated satellite beacon<br>M = 1 MHz | 2M00A3N |
| **GPS**<br>Global Positioning System<br>DSSS with BPSK spreading | $B_n = 2KR/Log_2S$<br>$K \approx 1.17$<br>J-22 | R = 10.23 Mbps; S = 2<br>$B_n = 24$ MHz | 24M0G1D |
| **QPSK** | $B_n = 2KR/Log_2S$<br>$K \approx 0.6$ to 0.8 (typical, depending on filter roll-off factor) | Data Link<br>R = 312 kBps; S = 4; k = 0.65<br>$B_n = 203$ kHz | 203KG1D |

**(Last Page in Annex J)**