# FT8 Modulation and Decoding - A Dive into SNR interpretation  N6MW 12/20/20

In the ham world FT8 has been strongly embraced by operators because it allows some elementary exchange at rather low signal levels. Some ops think, with some merit, that this may be the end of ham radio as we know it.

However the technical understanding of this mode in the community is sometimes lacking.  This note is an attempt to clarify the matter using some language from more conventional digital communication evaluation while determining an estimate for FT8 communications capability based on broader perspective as might be provided from the communications engineering community.

**First the (slightly simplied) basic elements of FT8.**

FT8 uses a version of 8-ary FSK (Frequency Shift Keying) modulation called GFSK.  The G means the pulses are Gaussian shaped in the time domain, rather than more squared off, to limit the spectral spread.  Still for analysis purposes, this is essentially a mildly improved version of 8-ary FSK.  So the transmission consists of a sequence of tones on one of 8 possible frequencies. Each pulse tone has the same amplitude.  The tone locations in frequency are spaced at 6.25 Hz so the total occupied bandwidth within which the tones fall is 50 Hz.

The duration of each tone is 1/6.25 seconds which is 0.16 seconds.  This duration and tone spacing provides "orthogonal" tones that minimize the spectral overlap of the tones to improve detection. Each tone corresponds to a "symbol" which consists of 3 bits, of which there are of course 8 possible conbinations. The actual transmitted symbols can be called "channel" symbols as opposed to information symbols. The difference between these is due to error correction coding plus the use of extra bits to allow Cyclic Redundancy Check (CRC), or checksum.

Each message consists of 74 user message information bits plus 3 bits for message type plus 14 bits for CRC use for a total of 91 uncoded information bits.  The error correction than adds 83 bits to provide forward error correction (FEC) with a code rate (input bits/output bits) of 91/174.  So there are 91 (74+3+14) information bits and 174 (73+3+14+83) is the total number of resulting coded channel bits transmitted each 15 sec message interval. This FEC is a low density parity check (LDPC) block code. So each message interval consists or 174/3 = 58 channel symbols so 58 tones are transmitted distributed over the 8 frequencies.  At 0.16 seconds per tone, the total channel message time is 58 X 0.16= 9.28 seconds during each 15 second segment.  The total transmission time is 12.6 seconds which includes synchronization elements, ramp up and ramp down times.

The signal to noise ratio for ham digital signaling has now come to be reported and displayed in software as Received Signal Power divided by the effective Received Noise Power in a 2500 Hz bandwidth. This measure is now commonly used in the amateur world software for most digital modes. This may be regarded by some, especially communications experts, as potentially confusing since the bandwidths of most signals are far from 2500 Hz.  The usual reasoning for this being that SSB typically uses 2500 Hz bandwidth, and the WSJT software normally uses a receiver set to SSB mode.

The reported SNR for WSJT for FT8 and FT4 [2] takes Noise by an estimation across a received 2500 Hz bandwidth using the lowest 10% of the spectral amplitudes, so usually other users will not contribute.  However for other JT modes the noise may be found from the "empty" tone frequencies in the target signal.  Then the raw noise power estimate from the WSJT processing in a part of the spectrum is increased to the equivalent value it would be in 2500 Hz if the noise power density was the same across the remainder of that spectrum. The Signal power is taken as the nominal average received power in individual tones bandwidth of the target coded signal. For clarity let's call the WSJT reported signal to noise value SNR2500, which is the ratio of the carrier received power to the nominal minimum background noise power in a 2500 Hz bandwidth, normally with no other users.

This 2500 Hz selection is really arbitrary aside from allowing direct comparison with SSB for which some say ~ +10 is the communications threshold. Beyond that, the value of SNR2500 does provide a nominal measure of the <u>relative</u> received carrier power for different signals in the current spectrum. For a given WSJT mode, the value of SNR2500 may provide some indiction of the prospects of decoding but the minimum SNR250 requirements for decoding for the different modes are different. For example, as discussed later, for AWGN and no fading, FT8 is -20.8 and FT4 is -17.5.

The decoding of the tone sequence is controlled by a detection method that effectively looks for a tone within a 6.25 Hz band around the potential tone frequencies. So the true Noise effective bandwidth, that which dictates performance, is 6.25 Hz rather than 2500 Hz. This is a factor of 400, or 26 dB. To get the ratio of Signal Power in a channel symbol divided by the Noise power in the 6.25 Hz bandwidth one could add that 26 dB to the reported SNR2500 to get a more conventional measure of the channel SNR.

Franke, Somerville and Taylor [1] (FST) indicate that the WSJT FT8 decoder using its best full array of decoding techniques can decode a message error free under additive white gaussian noise (AWGN) conditions with no fading or multipath for an SNR2500 of -20.8 dB. This is for laboratory simulations where there are no other users are in the portion of the 2500 Hz band contributing to the noise estimate. For a spectrum largely filled by other users, the noise estimate used for WSJT reporting may be larger due to contributions from other users, thus making the reported SNR2500 smaller (more negative in dB) than the quoted limiting -20.8 dB value. On the other hand, if you put a narrow filter across a signal in the 2500 Hz band on receive, effectively removing many other users and other noise outside the signal bandwidth, it is possible to get a huge increase in the reported SNR2500 since the noise will now be estimated from the portion of the spectrum that is filtered out. However this increase appears to have no practical meaning or utility.

So the -20.8 dB limiting value of SNR2500 corresponds to a more conventional channel symbol SNR of 26-20.8 = 5.2 dB which is the Signal power in a tone divided by the Noise power from the noise power density, often called No, so No*6.25 Hz is that noise power in the tone bandwidth. The reader should be aware that in the literature a common signal to noise measure is C/No where C is the carrier power. This is not the same as the SNR measures used in this note although for a signal bandwidth, BW, in Hertz, the channel SNR is C/No/BW.

**Now for some heavier lifting.**

First note that the CRC use effectively means that nearly no decoded message will be displayed unless it is perfect [3]. This is not typically done for communication systems since potentially useful information would be discarded. Evaluation of communication performance for various modulations codes and power levels is conventionally expressed as the BER (<u>information</u> Bit Error Rate) versus the energy in an information (not channel) bit divided the noise power density (per Hertz) No, or Eb/No (often pronounced "ebb-know" by the pros, without grinning). Information theory (you can look up Shannon) places limits on what's possible for information flow rate for a propagation channel in terms of Eb/No. Note that Eb/No is dimensionless and typically provided in dB - it is the gold standard.

So for FT8 modulation, Ebinfo = Eschannel/3 *174/91. Here the FEC "code rate" is 91/174 or ~ 1/2 for this LDPC code. Here Eschannel is the energy in a coded (channel) symbol. Energy is received signal power times the transmitted tone length in seconds.

The limiting channel symbol SNR for success from the prior FT8 discussion (5.2 dB) could be called Eschannel/No and the corresponding Eb/No limit would be 5.2 +10log(1/3*174/91) = 3.2 dB, which includes the benefits of the coding, all processing, CRC and message structure restrictions. So IF there were no coding or other unique processing as used for FT8, the conventional textbook result for raw 8-FSK information BER for AWGN would be ~ 4*10^-2 at this Eb/No (see Figure 1).

Without analyzing and knowing the full details of the constrained messages, coding, decoding methods, decision processing, parity checking and synchronization it is hard to determine what would be the result for FT8 protocols, which only output messages that are nearly certain to be correct. Significant improvement over raw 8-FSK BER is certainly expected, say, 4dB Eb/No improvement (over the 3.2 dB Eb/No limit from before) would get a BER of ~ 10^-4. Exactly what BER level is needed to get mostly perfect FT8 messages to allow reliable output is not clear so the value or improvement over raw 8FSK, in the example just given of 4 dB is just informed speculation. If the BER needed to be 10^-5 for reliable decoding, then the coding/processing improvement would need to be 6 dB. However note that FST Figure 7 indicates that small increases in SNR can quickly improve Probability of Decode near the limiting SNR.

The following Figure 1 plot is the BER for no FEC code in AWGN for three FSK modulation formats. Note that this is for non-coherent detection. In different literature other detection methods provide somewhat different values. (https://www.researchgate.net/publication/343099200_BER_Performance_of_M-ary_FSK_Modulation_over_AWGN_and_Rayleigh_Fading_Channels/link/5f16c45145851515ef3beb30/download).

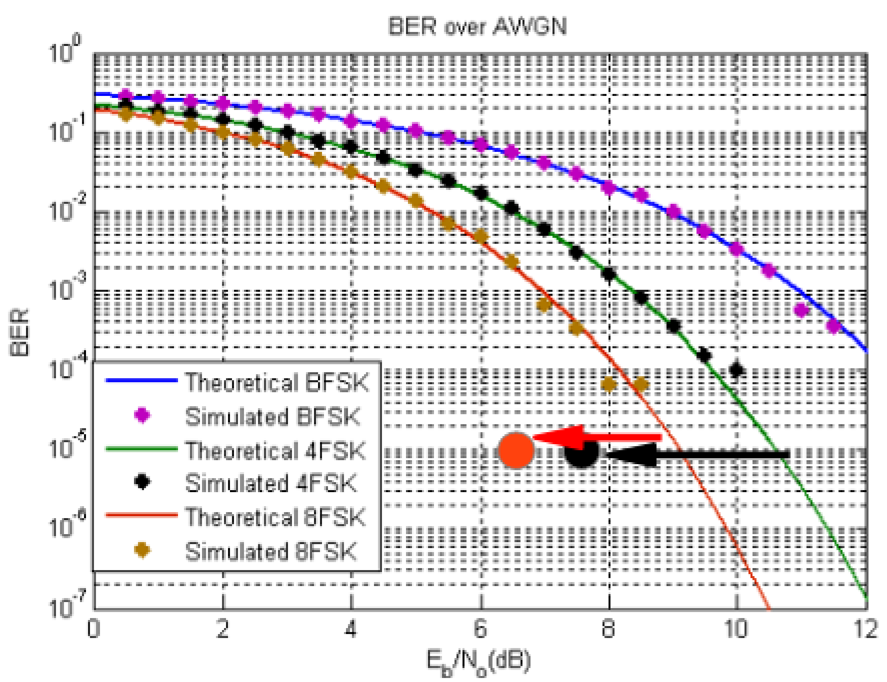


Figure 1. BFSK, 4- and 8-ary FSK BER for AWGN. Arrows and dots indicate benefits from rate 1/2 convolutional coding with soft decision Viterbi decoding just as examples for 4- and 8-ary FSK.

It is known (information from an undisclosed but solid expert), **for example**, that for a rate 1/2 convolutional code, Viterbi soft decision decoding for AWGN using 8FSK, a channel Eb/No of 4 dB (giving an uncoded BER of 4.8*10^-2) input leads to an output BER of 10^-5 with an information Eb/No of 6.4 dB - which is 2.7 dB better than without coding (9.1 vs 6.4) to get that BER of 10^-5. This code benefit value is shown as a large red dot for 8FSK and arrow in the plot above. The black dot and arrow is the same but for 4FSK - note that the benefit for 4FSK is a bit bigger.
Under fading channel signal conditions required Eb/No will be higher for that BER. Although the coding benefits are better against fading, the Eb/No needed is still larger than for AWGN.

For general interest, below in Figure 2 is an **example** of coding and hard vs soft decision decoding methods for AWGN only, **however it is not for FT4/8 but BPSK so it just provides the general character of the effects.** (https://www.unilim.fr/pages_perso/vahid/codage/Convolution.pdf - note the significant effect of decoding schemes soft vs hard decisions for this case.

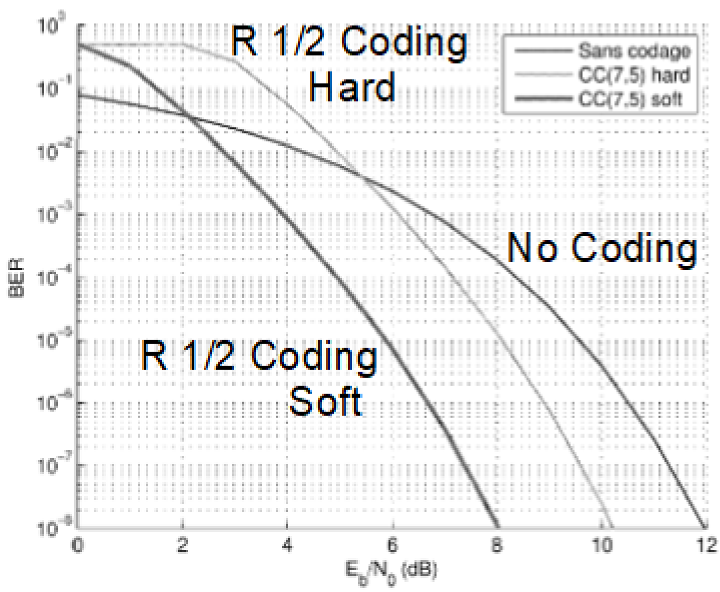


Figure 2. BPSK (**not BFSK**) BER for no coding, and Rate 1/2 convolutional coding with soft and hard decision processing example.

Again, the two plot examples above are **NOT from FT8** but they are representative of the character of the effects.

**And the corresponding FT4 story**

FT4 uses 4-FSK with Gaussian pulse shaping, so there are not 8 but 4 tones.
Each tone is now 2 symbols but with same 174 channel bits and 91 information bits as FT8. The same FEC coding is used at code rate ~1/2, but now 87 symbols per transmisson are needed.

The per symbol transmission time is 0.16 sec for FT8 but 0.048 sec for FT4. The bandwidth of a tone is 20.8 Hz (1/ 0.048) which is equal to the FT4 orthogonal tone spacing.

So the total FT4 symbol transmisson time is 4.176 sec and sync plus ramp up/down makes the full transmission time per segment to less than 6 sec, the length of the FT4 segment. For FT4 the decoding limit under AWGN, but not with other users, is said to be –17.5 dB SNR2500.

The total occupied bandwidth is 4X20.8 = 83.2 Hz.
So the effective noise bandwidth for one tone of FT4 is reduced from the conventionally reported 2500 Hz to 20.8 Hz that is, oddly, 20.8 dB.
So the -17.5 dB limiting value of SNR2500 for FT4 corresponds to a more conventional channel symbol SNR of 20.8 -17.5 = 3.3 dB which is the Signal power in a tone (2 bits) divided by the Noise power of No*20.8 Hz, the noise power in the tone bandwidth.

Expressing in terms of Eb, Ebinfo = Eschannel/2 *174/91 Code Rate ~ 1/2, low density parity check (LDPC) block code.

The limiting symbol channel SNR from above (3.3 dB) might the called Eschannel/No so information Eb/No limit would be 3.3 +10log(1/2*174/91) = 3.1 dB that is nearly the same as FT8 (3.2 dB). FST says "Overall, block detection and the hybrid decoder offer 2.2 and 1.2 dB of sensitivity improvement over the baseline case for FT4 and FT8, respectively" so FT4 gains about 1 dB in AWGN relative to FT8. This provides 4FSK an additional coding/processing advantage that, to some degree, makes up for the nearly 2 dB advantage of 8FSK seen in Figure 1. That benefit difference is similar to the Black and Red arrow differences in Figure 1, although for a different coding/decoding scheme.

**Concluding Thoughts**

On the whole, FT8 (and FT4) do conform pretty closely to more academic performance evaluations of M-ary FSK. The implementation of FT8 takes advantage of some additional features allowing an somewhat more effective mode than standard coded 8FSK compared to FT8 at approximately the same code redundancy. It is difficult to make a more precise statement because of the differences in coding and decoding methods and lack of knowledge of what information bit error rate, BER, is required to achieve near perfect decoding from CRC use. At an Eb/No of 3.2 dB, the success threshold for FT8, the coding and all other FT8 processing contibutions need to provide an additional 4+ dB benefit to get a BER of 10^-4 or 6- dB to get BER of 10^-5, either of which would be impressive although 6 dB seems a lot.
The Shannon maximum throughput, bits/second, for a noisy channel with bandwidth BW is BW*log2(1+S/N) where S and N are the signal and noise powers in that BW. For the limiting S/N (tone power/noise power, not in dB in the formula) in that BW of 6.25 Hz, a 5.2 dB SNR allows a bit rate of ~ 13 bits/sec. For FT8 the information bit rate is 91 bits/12.6 seconds or 7 bits/sec. So this is remarkably close to the Shannon limit.
Finally again note that the SNR2500 measure of SNR certainly is unconventional in the professional world, although it has become accepted in the ham world. However it is really just a relative measure of the received signal in a tone compared with the arbitrary BW of 2500 Hz of noise in the current propagation channel. Therefore the use for it depends on the signaling protocol being used. In particular, it is normally compared with the nominal minimum SNR2500 required for successful communications with that protocol. For FT8 that is -20.8 dB. For other protocols including FT4, JT65 and JT9, the minimum SNR2500 required ranges over more than 10 dB for just AWGN although SNR2500 is measured the same way for all modes. This range of minimum SNR2500 values depends on the details of the protocols in non-obvious ways. Furthermore for real world conditions the actual required SNR2500 depends on fading characteristics and rates as well as doppler due to ionospheric variations with time - all of which further depend on the protocols due to different timing and bandwidths.

[1] The FT4 and FT8 Communication Protocols
https://www.physics.princeton.edu/pulsar/K1JT/FT4_FT8_QEX.pdf
[2] private communication
[3] If Enable AP is used, it is possible that questionable decodes can occur but the displayed results for these cases are flagged with a "?."