BANDWIDTH EFFICIENCY AND BER PERFORMANCE OF ENHANCED AND FEC CODED FQPSK

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ABSTRACT

Bit error rate (BER) and bandwidth efficiency of several variations of enhanced Feher patented quadrature phase shift keying (FQPSK) [1] are described. An enhanced FQPSK increases the channel packing density of that of the IRIG 106-00 standardized FQPSK-B by approximately 50% in adjacent channel interference (ACI) environment. As the bandwidth efficiency of FQPSK-B DOUBLES (2×) that of pulse code modulation/Frequency modulation (PCM/FM) [5], the enhanced FQPSK, with a simpler transceiver than FQPSK-B, has a channel packing density of TRIPLE (3×) that of PCM/FM. One of the other enhanced FQPSK prototypes has an end to end system loss of only 0.4 dB at BER=1×10^{-3} and 0.5 dB at BER=1×10^{-4} from ideal linearly amplified QPSK theory. The enhanced FQPSK has a simple architecture, thus is inexpensive and has small size, for ultra high bit rate implementation.

With low redundancy forward error correction (FEC) coding which expands the spectrum by approximately 10%, further improvement of about 3-4.5dB E_b/N_o is attained with NLA FQPSK-B and enhanced FQPSK at BER=1×10^{-5}.

KEY WORDS

Enhanced Feher patented Quadrature Phase Shift Keying (FQPSK), forward error correction (FEC), modulation, bit error rate (BER), bandwidth efficiency

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[*] Significant parts of this material are based on the author's reports and remain the property of the authors.

INTRODUCTION

FQPSK-B [2]-[6] has been demonstrated by AIAA, DoD, NASA, and international CCSDS's multi-year studies to be the most spectral and power efficient systems when non-linearly amplified. In January 2000, FQPSK-B was specified as the modulation method used by Telemetry IRIG standard 106-00 [8].

FQPSK-B provides high power efficiency. The 99.99% and -60 dBc bandwidths of filtered FQPSK-B are approximately one half of the corresponding bandwidths of optimized PCM/FM when the signal is non-linearly amplified; the E_b/N_o requirement for a BER of 1×10^{-5} for non-optimized FQPSK-B is approximately 12 dB, approximately the same as limiter detected PCM/FM [5]. Compared with GMSK, FQPSK-B spectral efficiency advantage is 25% to 100% if non-linearly amplified and 100% to 300% if linearly amplified; the BER robustness of FQPSK-B is 1-2 dB better than GMSK in BER = 10^{-2} to 10^{-4} range; and FQPSK-B is much simpler to implement, has smaller size, lower DC power requirement, and considerably lower cost [7].

The FQPSK technique introduced in [3] and [4] (or SQAM) used a double-interval raised-cosine pulse superposed with an amplitude weighted single-interval raised cosine pulse as its baseband signal. It has superb BER versus E_b/N_o performance, only 0.5 dB worse than linear BPSK-QPSK theory [5]. But compared to FQPSK-B, it is less bandwidth efficient. Enhanced FQPSK modifies its transmitter and receiver to achieve better bandwidth efficiency while maintaining outstanding BER performance.

PERFORMANCES OF ENHANCED FQPSK MODEM IN AN AWGN CHANNEL

The performances of enhanced FQPSK in an additive white Gaussian noise channel is evaluated by computer simulation. In all cases, non-linear amplifier (NLA) is used.

Bit Error Rate of Enhanced FQPSK

The computer simulated bit error rate (BER) for enhanced FQPSK and the measured BER performance of FQPSK-B and PCM/FM for a 1Mb/s signal and 1 MHz IF filter bandwidths [5] is shown in Figure 1. Compared with measured BER of FQPSK-B and PCM/FM, a BER of 1×10^{-5} can be achieved at an E_b/N_o of 1 to 1.5 dB lower with enhanced FQPSK. In the measurement of BER, the FQPSK-B signal was differentially encoded to solve the phase ambiguity of 0, 90, 180, or 270 degrees offset from the transmitter's reference phase, and the demodulator of FQPSK-B was an non-optimized modified QPSK demodulator; the PCM/FM was limiter detected. Figure 2 shows the BER performance of enhanced FQPSK (variation L2), FQPSK-B with Viterbi receiver and simplified FQPSK-B with Viterbi receiver (both by Marvin Simon and Ysun-Yee Yan of JPL) [9][12].

Power Spectral Density of Enhanced FQPSK

Figure 3 shows the power spectral density of enhanced FQPSK (variation L1 and L2), FQPSK-B, and GMSK NLA systems. Enhanced FQPSK has similar PSD performance as that of FQPSK-B, which has approximately twice the bandwidth efficiency than that of the optimized PCM/FM [5]. Enhanced FQPSK uses a simple first order low pass filter and is suitable for ultra high bit rate implementation.

Adjacent Channel Interference of Enhanced FQPSK

The integrated adjacent channel interference (ACI) performance (with specific receiver filter) [10] of enhanced FQPSK family, FQPSK-B, and standardized GMSK (with transmitter low pass filter bandwidth BT_b = 0.3) NLA systems is shown in Figure 4. Enhanced FQPSK has the simplest transmitter filter (first order) among all. As for the receiver, the receiver bandpass filter of enhanced FQPSK uses two cascaded 4th order filter; for GMSK, 4th order Gaussian bandpass filters with B_iT_b = 0.6 is used. Enhanced FQPSK shows about 50% better channel packing density, based on the ACI criteria [10], than FQPSK-B, or triple (3×) that of PCM/FM.

Performances of Different Variations of Enhanced FQPSK

There is a trade off between good bandwidth efficiency and BER performance. An advantage of enhanced FQPSK is that it can achieve among the best BER performance if the bandwidth requirement is a second consideration, or achieve high bandwidth efficiency if higher BER is tolerable. Therefore, enhanced FQPSK can suit various applications that have different bit error rate and bandwidth efficiency requirements.

PERFORMANCES OF FEC CODED FQPSK

To achieve better BER performance, low redundancy FEC can be applied to FQPSK systems. The computer simulated Reed-Solomon coded FQPSK-B with NASA standard RS(255,223) code and RS(255,239) code show significant improvement of BER performances, as shown in Figure 5, 6, 7, and 8, as well as Table 1. We can see that the rate of the increase of coding gain becomes smaller as coding redundancy increases, and that at lower bit error rate, small amount of redundancy achieves significant coding gain.

CONCLUSION

This paper presented a bandwidth efficient and BER robust enhanced FQPSK suitable for ultra high bit rate, as well as FEC coded FQPSK and enhanced FQPSK. Enhanced FQPSK can achieve a BER of 1×10^{-4} at an E_b/N_o of 0.5 dB within the linear theory of QPSK and 1 dB lower than PCM/FM and FQPSK-B. It can achieve a channel packing density in adjacent channel interference environment of approximately three times of that of PCM/FM and two times of that of GMSK. The enhanced FQPSK has simple transmitter and receiver, so the implementation will be much easier and less expensive than GMSK. Different variations of enhanced FQPSK provide a tradeoff between its outstanding bandwidth efficiency and BER performance, therefor it suits various applications that has different bandwidth efficiency and BER requirements. With low redundancy FEC coding, further improvement of about 3-4.5 dB Eb/No is attained with NLA FQPSK-B and enhanced FQPSK at BER=1×10^{-5}.

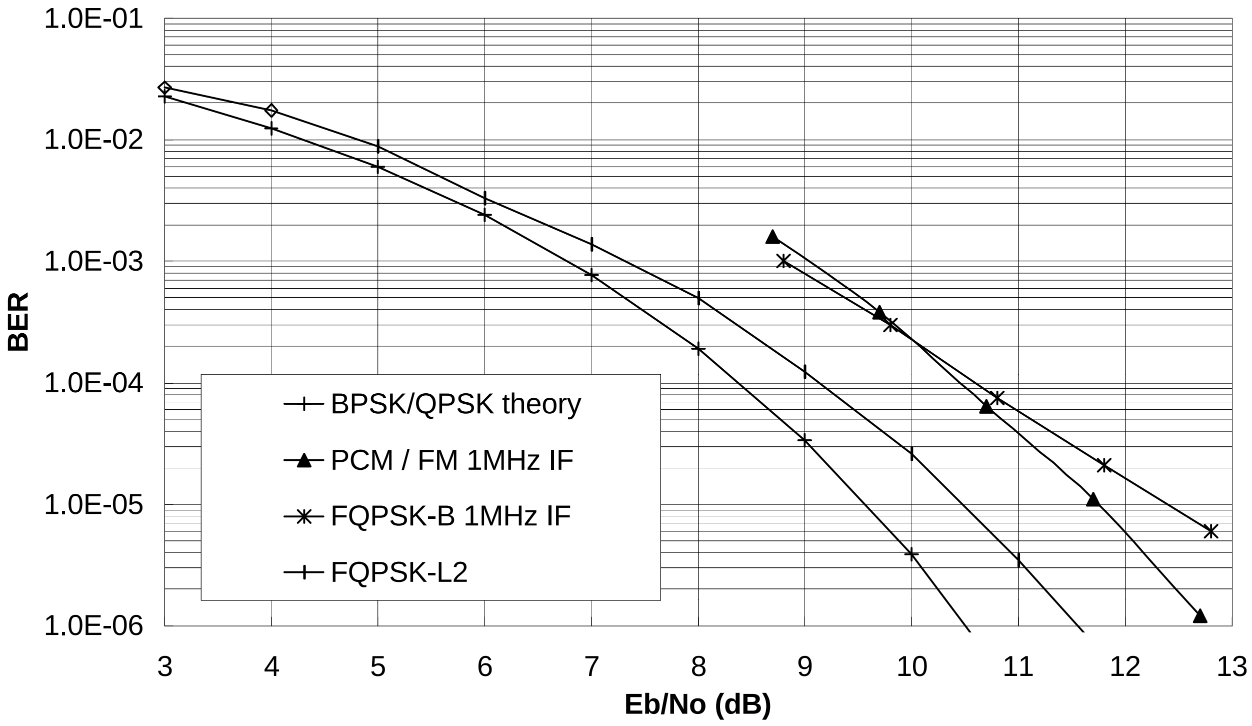

Figure 1. BER for enhanced FQPSK (variation L2), and 1Mb/s FQPSK-B and PCM/FM. The BER performance of FQPSK-B and PCM/FM was measured for a 1Mb/s signal and 1 MHz IF filter bandwidth. The demodulator of FQPSK-B was an non-optimized modified QPSK demodulator; the PCM/FM was limiter detected.

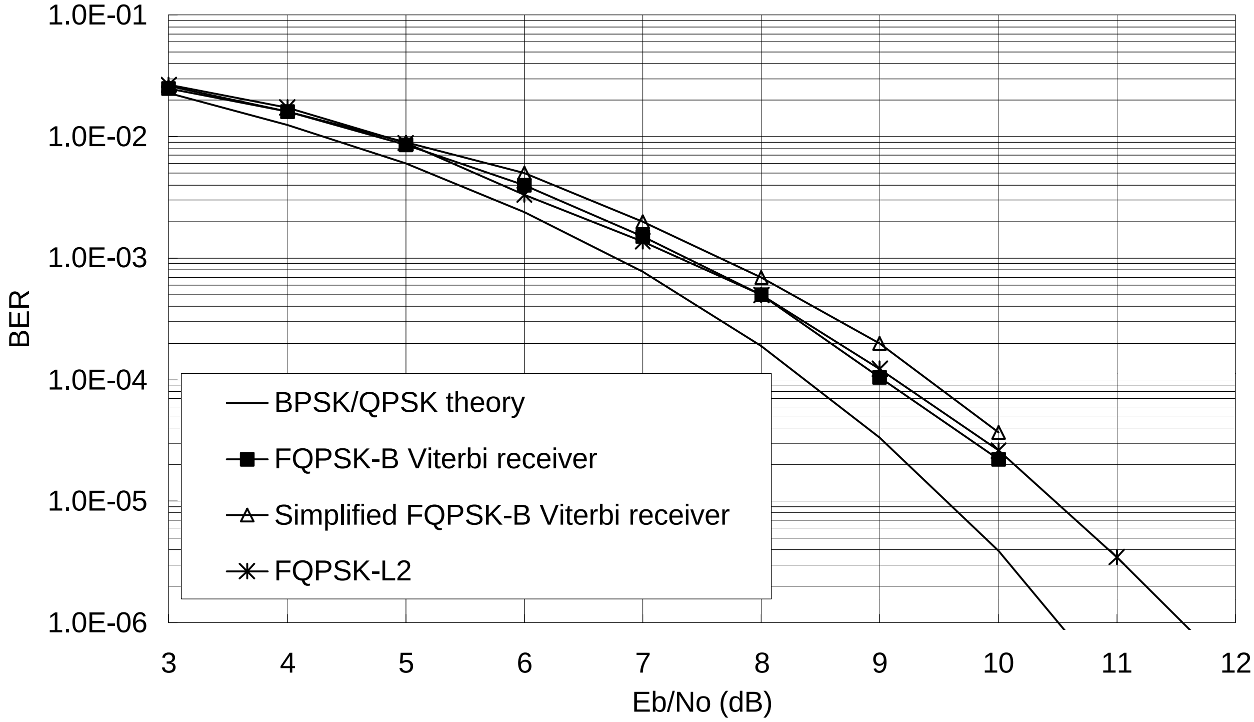

Figure 2. BER performance of enhanced FQPSK (variation L2), FQPSK-B with Viterbi receiver, and simplified FQPSK-B with Viterbi receiver [12] (both by Marvin Simon and Ysun-Yee Yan of JPL) in NLA mode. Note enhanced FQPSK has simpler transmitter, and uses simple threshold detector.

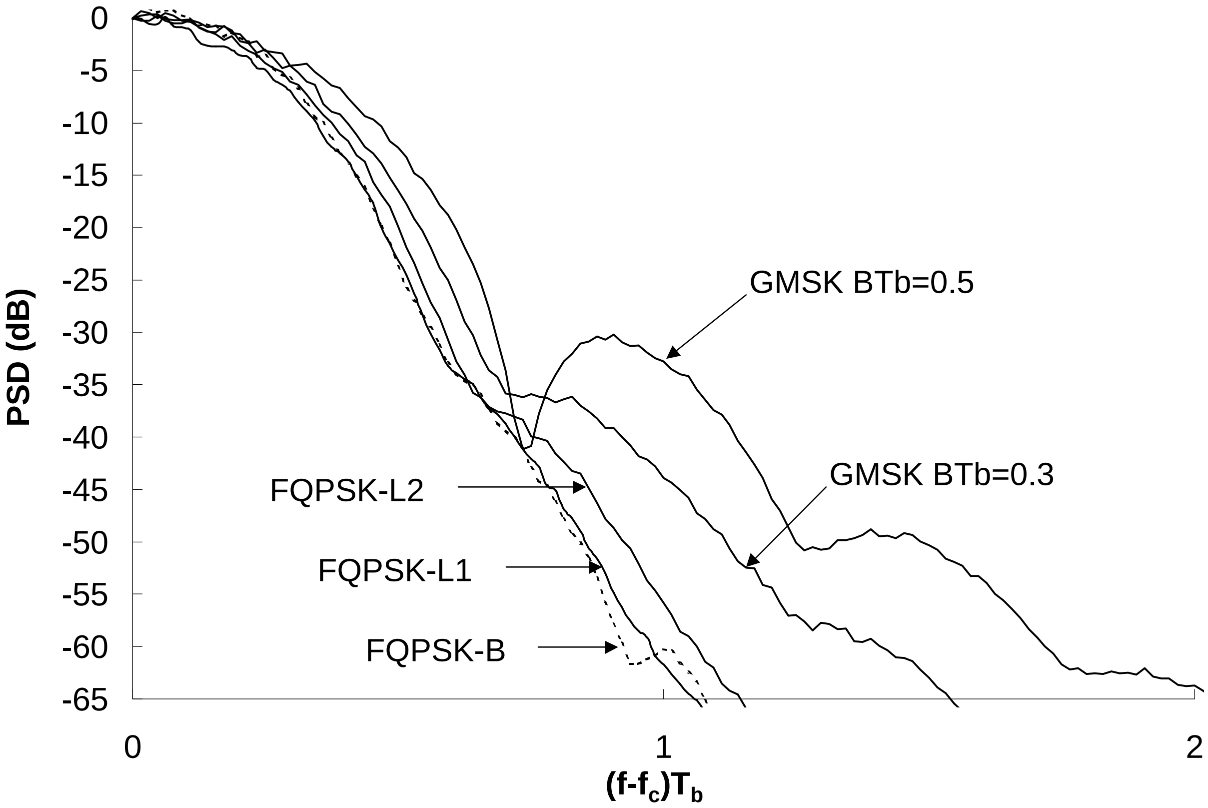

Figure 3. Computer simulated power spectral density of enhanced FQPSK (variation L1 and L2), FQPSK-B, and GMSK NLA systems. FQPSK-L1 has virtually the same BER performance as that of FQPSK-B, while the BER performance of FQPSK-L2 is better, as indicated in Figure 1. GMSK transmitter filter bandwidths $BT_b = 0.3$ and 0.5, while enhanced FQPSK uses simple first order filter and thus is suitable for ultra-high bit rate implementation.

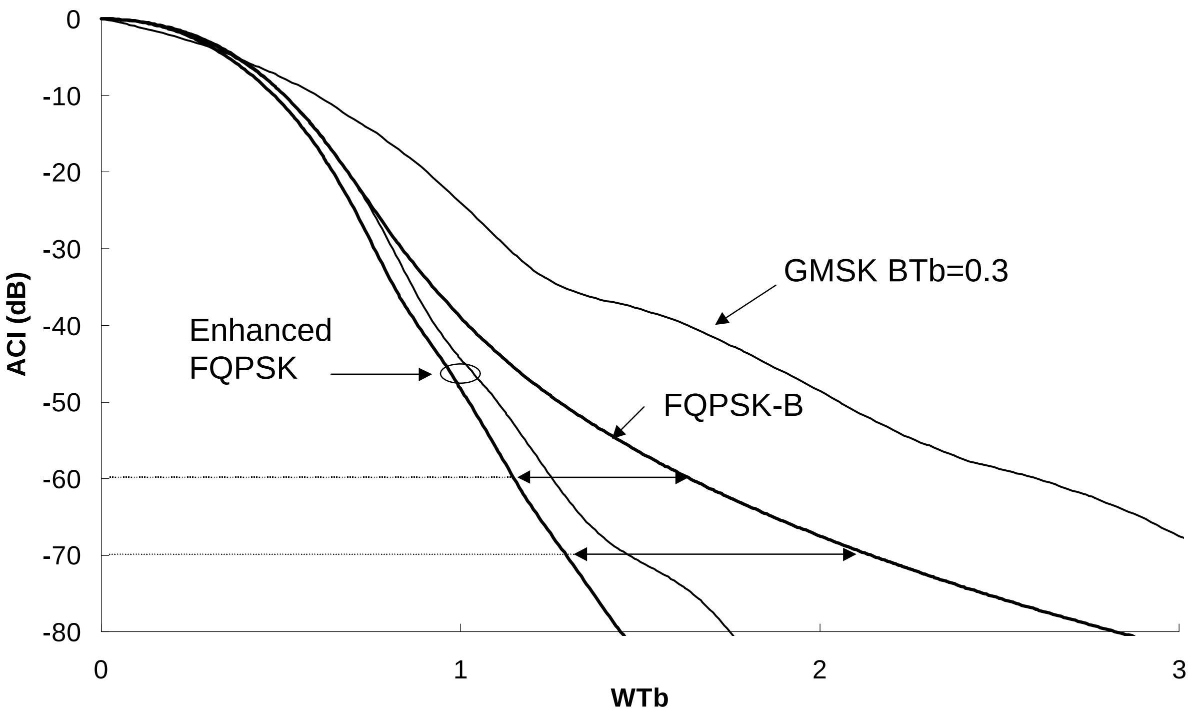

Figure 4. Adjacent channel interference performances of the enhanced FQPSK (variation L1 and L2, from the left curve to the right, respectively), FQPSK-B, and GMSK NLA systems. GMSK receiver used 4th order Gaussian bandpass filter with B_iT_b = 0.6 and transmitter filter bandwidths BT_b=0.3, while enhanced FQPSK uses much simpler receiver. At ACI = -60 dB and -70 dB, the channel packing density of the enhanced FQPSK is 45% and 68% higher than that of FQPSK-B, respectively.

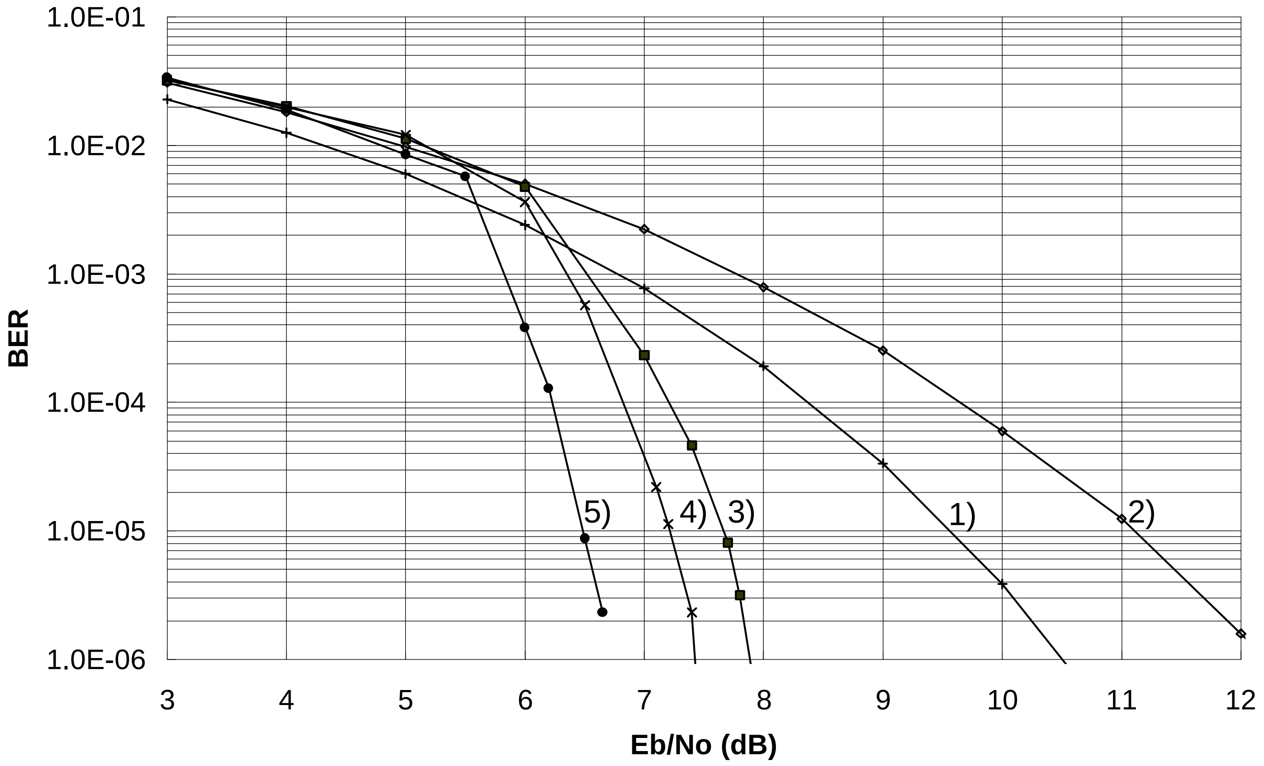

Figure 5. FQPSK-B with Reed-Solomon codes in NLA mode: 1) BPSK/QPSK theory, 2) FQPSK-B, 3) FQPSK-B with RS(255,239,8) code, 4) FQPSK-B with RS(255,235,10) code, 5) FQPSK-B with RS(255,235,16) code.

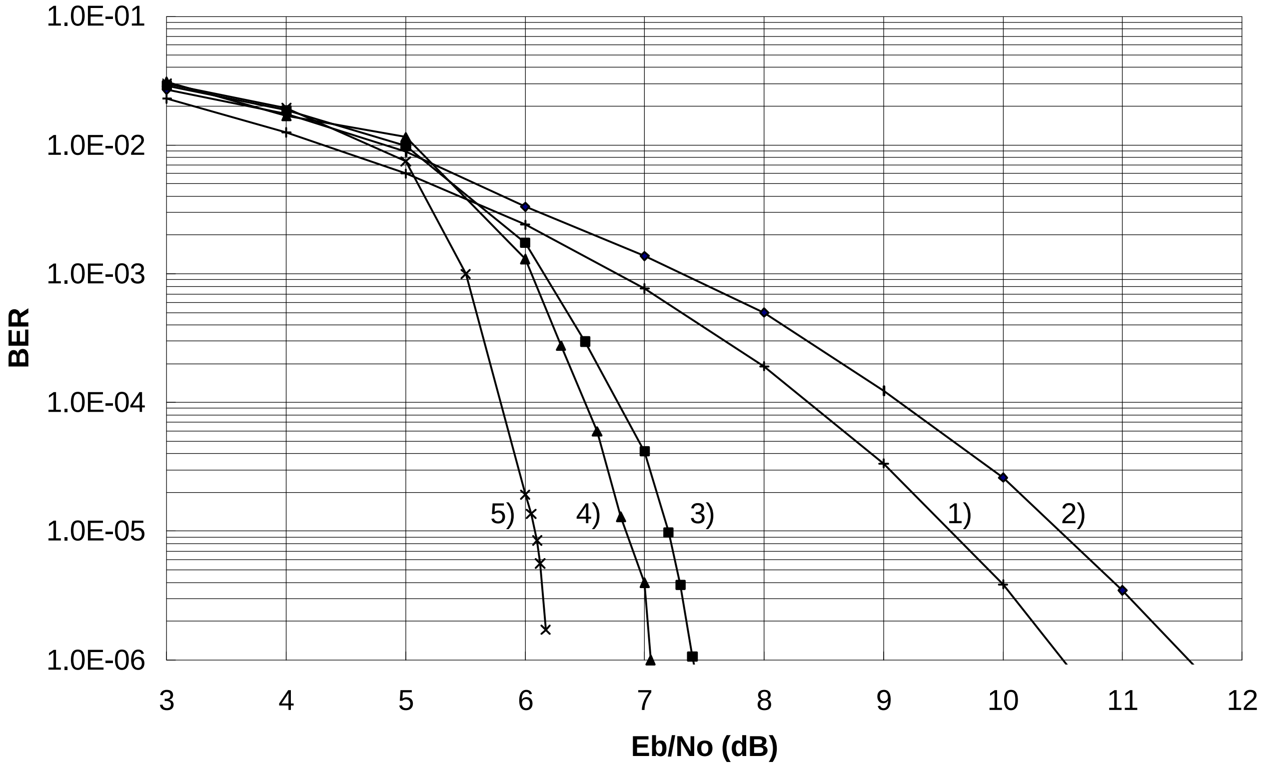

Figure 6. Enhanced FQPSK (variation L2) with Reed-Solomon codes in NLA mode: 1) QPSK linear theory, 2) enhanced FQPSK, 3) enhanced FQPSK with RS(255,239,8) code, 4) enhanced FQPSK with RS(255,235,10) code, 5) enhanced FQPSK with RS(255,235,16) code.

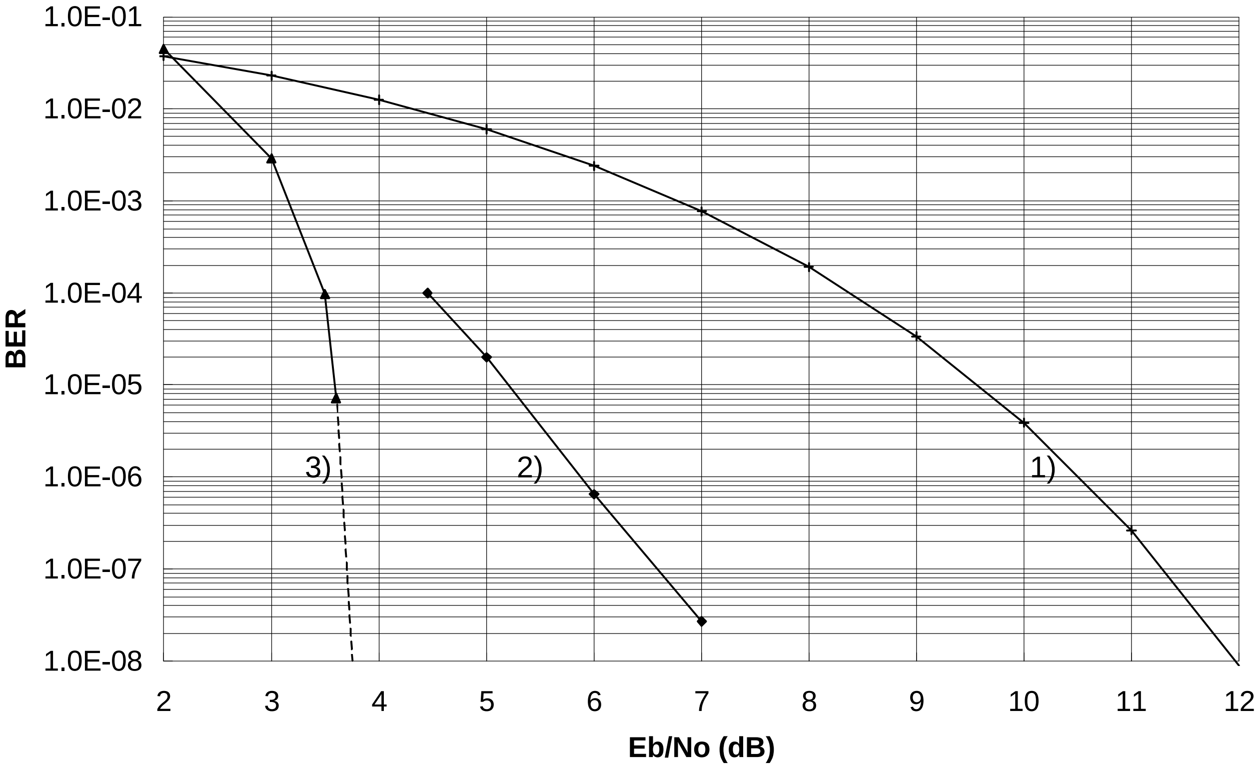

Figure 7. BER performance of FQPSK-B with 50% redundancy. 1) QPSK linear theory. 2) measured FQPSK with 1/2 convolutional code L band BW 2.7 MHz [11]. 3) the solid line is simulated FQPSK-B with RS(255, 128) code; the dashed line is anticipated BER performance.

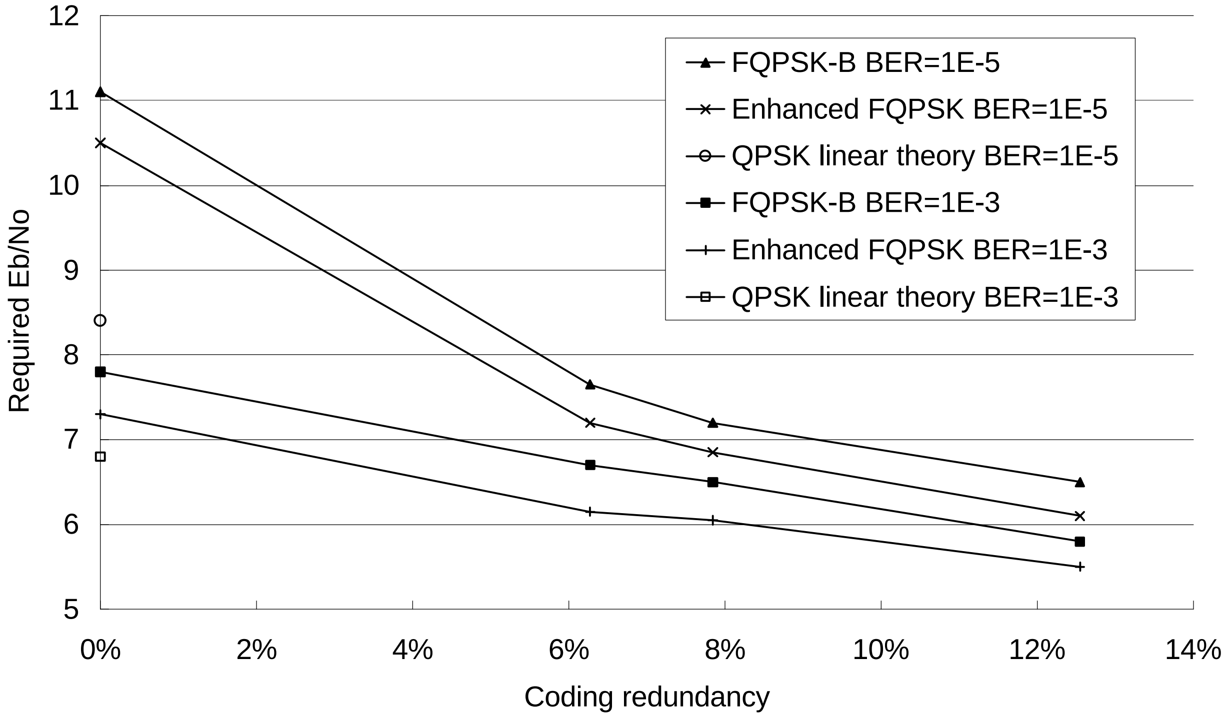

Figure 8. Required Eb/No at BER=1E-5 vs. coding redundancy for FQPSK-B and enhanced FQPSK (variation L2). The FEC codes used are RS(255,239), RS(255,235), RS(255,223).

Reed-Solomon code	Coding gain (dB) at BER=1E-3		Coding gain (dB) at BER=1E-5	
	FQPSK-B	Enhanced FQPSK	FQPSK-B	Enhanced FQPSK
RS (255, 239)	1.1	1.15	3.5	3.3
RS (255, 235)	1.3	1.25	3.9	3.7
RS (255, 223)	2	1.8	4.6	4.4

Table 1. Coding gain of Reed-Solomon coded FQPSK-B and Enhanced FQPSK.

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