FQPSK VERSUS PCM/FM FOR AERONAUTICAL TELEMETRY APPLICATIONS; SPECTRAL OCCUPANCY AND BIT ERROR PROBABILITY COMPARISONS

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ABSTRACT

The aeronautical telemetry community is investigating alternative modulation methods to the commonly used non-return-to-zero (NRZ) pulse code modulation (PCM)/frequency modulation (FM). This paper outlines the important characteristics being investigated. Measured data comparing the spectral occupancy and bit error probability (BEP) performance of PCM/FM with that of a prototype constant envelope Feher's quadrature phase shift keying (FQPSK) modulator and demodulator will also be presented. Measured results in several radio frequency bands demonstrate that the 99.99% and -60 dBc bandwidths of filtered FQPSK are only approximately one-half of the corresponding bandwidths of optimized PCM/FM even when the signal is non-linearly amplified. The signal energy per bit to noise power spectral density (E_b/N_0) required for a BEP of 1×10^{-5} for non-optimized FQPSK was approximately 12 dB which is approximately the same as limiter discriminator detected PCM/FM.

KEY WORDS

Modulation, Feher's quadrature phase shift keying, non-linear amplification, spectral occupancy, radio frequency power and bandwidth efficiency

INTRODUCTION

Telemetry data rates are increasing rapidly while the total amount of available spectrum has decreased slowly. Higher bit rates occupy more spectra and result in decreased link margin. Radio frequency spectra and link margin are both in limited supply. Therefore, the aeronautical telemetry community is investigating alternative modulation methods to the commonly-used PCM/FM[1,2,3]. This study will focus on modulation methods that will allow us to pack more users/data into our available spectrum. Some of the characteristics of interest for aeronautical telemetry applications include:

Bandwidth (99% and -25 dBm) and required pre-transmission filtering
BEP vs. E_b/N_0; 10^{-5} BEP or better is a common requirement
Effect of non-linearities in transmitter and/or receiver (phase and amplitude)
Adjacent channel interference, general interference performance
Performance during multipath fading (frequency selective and flat)
Recovery from multipath fading (frequency selective and flat)
Data coding (level or differential)
Effect of link dropouts (including reacquisition)
Compatibility with existing equipment including tracking antennas, receivers, diversity combiners, etc.
Power conversion efficiency (DC to RF)
Cost, volume

In this paper we highlight the bandwidth efficiency and BEP performance of FQPSK and PCM/FM in an additive white Gaussian noise (AWGN) environment with non-linear amplification. Non-linear amplifiers provide higher DC to RF power conversion efficiency and lower cost for the same RF output power than linear amplifiers. Spectrally efficient systems are required for efficient use of the RF spectrum. The spectral efficiency of the newest generation of commercially available wireless systems is in the 1 b/s/Hz to 1.6 b/s/Hz range. Availability of integrated circuits and radio subsystems is also an important requirement.

FQPSK is a family of modulation methods which have good BEP versus E_b/N_0 performance and which maintain good spectral control even when non-linearly amplified. FQPSK is compatible with offset QPSK, minimum shift keying (MSK), and Gaussian MSK (GMSK). References 4 through 9 describe various members of the FQPSK family. In this paper, we describe the spectral and BEP performance of two members of this family designated as FQPSK-B[5,7] and FQPSK-S[5,7]. The "-B" is one of the more spectrally efficient members while the "-S" has among the best BEP vs E_b/N_0 performance. The FQPSK technology has been used in a variety of US military and commercial applications.

Future investigations will include other types of offset QPSK modulation including GMSK, M-ary higher state systems such as 16-quadrature amplitude modulation (QAM), 64-QAM, and also orthogonal modulation and other recent modem/radio inventions. The explosive growth of commercial wireless digital communications technology will be leveraged to the maximum extent possible.

TEST RESULTS

The measurement test setup is shown in figure 1. The RF spectral plots and BEP curves were measured in the Telemetry Laboratory at the NAWCWPNS, Point Mugu, CA. A telemetry receiver which is used at many ranges, the Microdyne model 1200MRA, was used in the BEP tests to demonstrate the compatibility with existing telemetry equipment. The intermediate frequency (IF) output of the receiver was connected to the prototype demodulator.

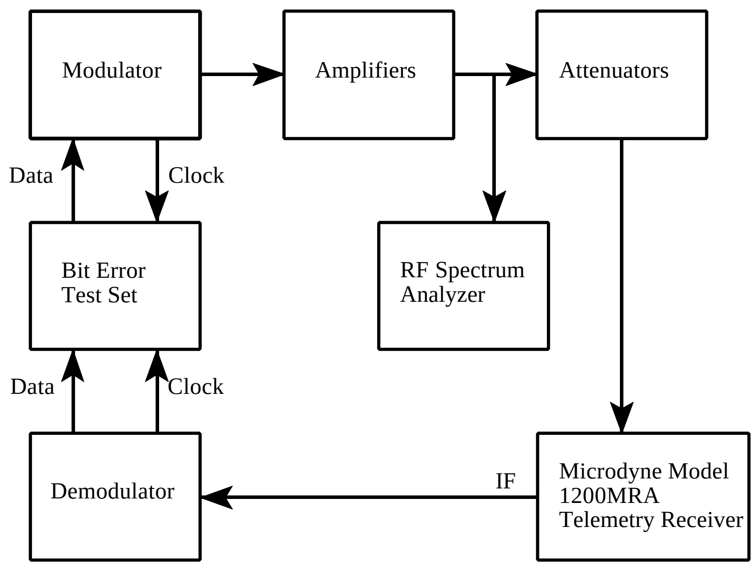

Figure 1. Block diagram of test setup.

The constellation (sometimes called vector) diagram of FQPSK-B is shown in figure 2. The amplitudes of I and Q are cross-correlated to maintain a nearly constant signal envelope. Because the signal envelope is nearly constant, it is not surprising that the spectral regrowth is minimal when the FQPSK-B signal is applied to a saturating (class C) amplifier, also referred to as a non-linear amplifier (NLA).

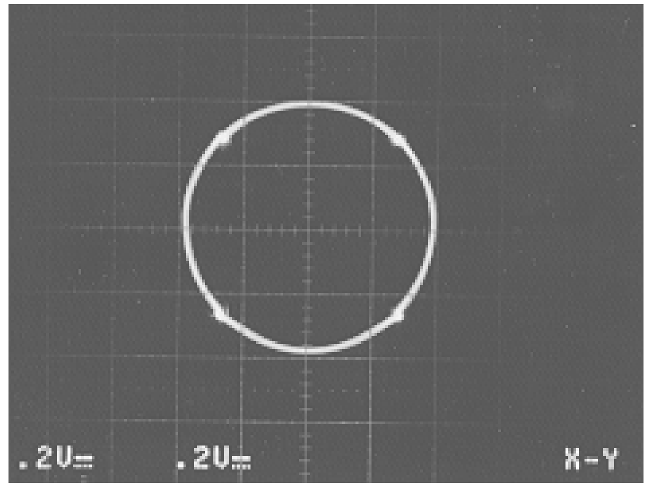

Figure 2. Q vs I for FQPSK-B.

Measured RF spectra for 1 Mb/s filtered FQPSK-B and PCM/FM signals at the output of a saturated amplifier are shown if figure 3. Similar results were achieved with other amplifiers and other FQPSK modulators. The PCM/FM peak deviation is 0.35 times the bit rate and the premodulation filter bandwidth is 0.7 times the bit rate (references 1 and 3 show these that values provide the optimum combination of BEP and spectral efficiency). Various measured bandwidths for the data in figure 3 are presented in a normalized form in table 1. The 99% power bandwidth of filtered PCM/FM is approximately 50% wider than the 99% power bandwidth of FQPSK-B. The 99.9%, 99.99%, and −60 dBc bandwidths of filtered PCM/FM are 80% to 100% wider than the corresponding bandwidths of FQPSK-B.

Bandwidth	PCM/FM	FQPSK-B
99%	1.16	0.78
99.9%	1.98	0.98
99.99%	2.4	1.33
-60 dBc	3.15	1.78
-65 dBc	3.22	2.03

Table 1. Normalized bandwidths with non-linear amplification (bit rate = 1).

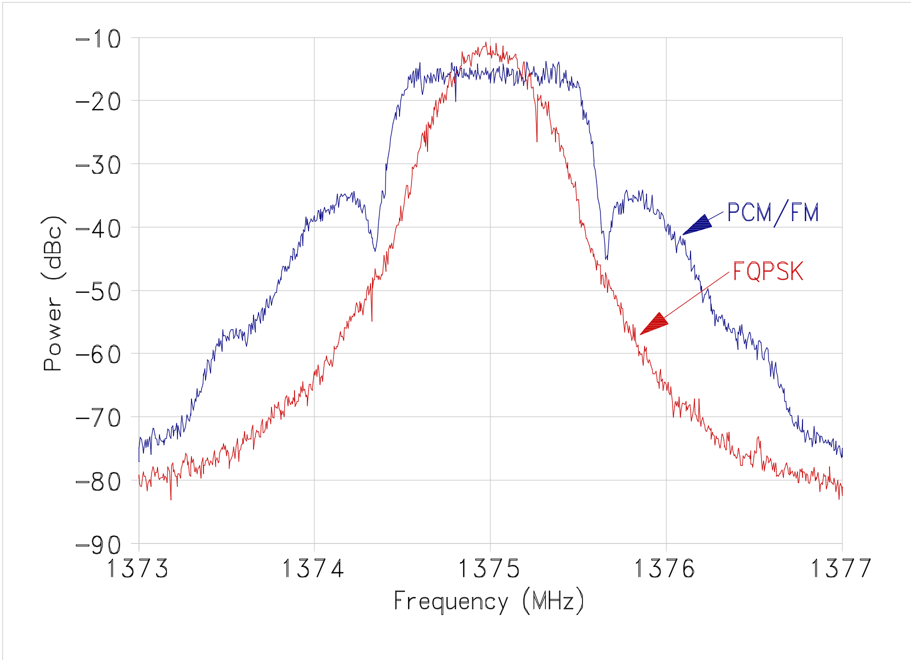

Figure 3. RF Spectra for 1 Mb/s filtered FQPSK-B and PCM/FM (non-linear amplifier).

BEP performance, as a function of received or available Carrier-to-Noise (C/N), is one of the most fundamental and important radio communication system requirements. In order to normalize the C/N, noise bandwidth (B_w) and bit rate (f_b) the following equation

$$\mathbf{E_b/N_0 = C/N \bullet B_w/f_b}$$

has been used in performance studies and measurements.

The **BEP=f(E_b/N_o)** relationship has to be optimized, i.e., minimized, for robust performance. If a radio receiver/demodulator attains a low BEP with the lowest possible C/N or corresponding E_b/N_0 then the range/distance and quality of the telemetry receiver is optimized. Figure 4 presents the results of computer simulations of linearly amplified BPSK/QPSK systems and non-linearly amplified FQPSK and GMSK systems. This computer simulation shows that the theoretical BEP performance of FQPSK-S is only 0.5 dB worse than linear BPSK/QPSK theory. The figure also shows that the theoretical BEP of GMSK (BT_b=0.25) is approximately 1.5 dB worse than linear BPSK/QPSK theory. Several NLA models including class-C, fully saturated class-AB, and hard limited NLAs were simulated and led to essentially the same spectral and BEP performance. Several simulation tools including MATLAB, Signal Processing Workstation (SPW), and University of California, Davis developed software packages gave virtually the same results.

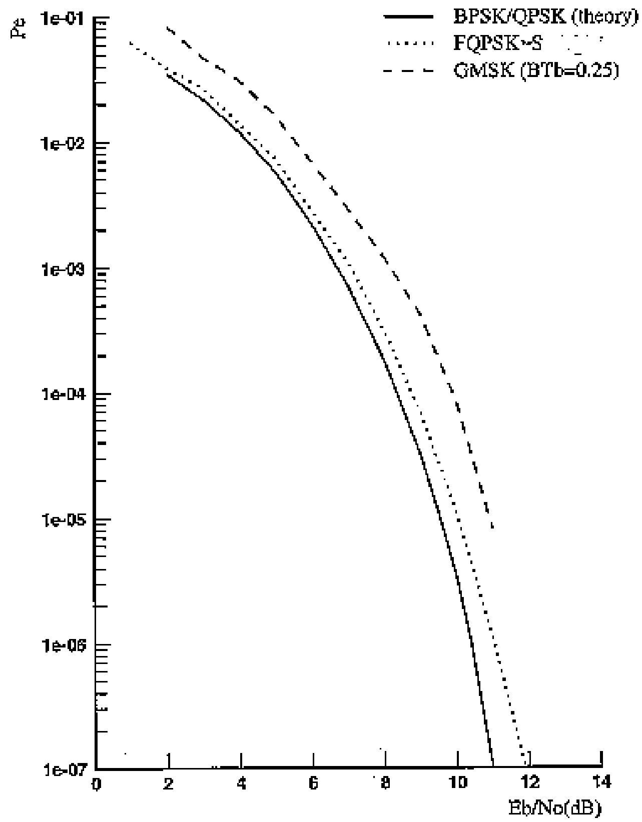

Figure 4. Computer simulation of linearly amplified BPSK/QPSK (ideal theory) and non-linearly amplified FQPSK and GMSK in an AWGN environment. Note that FQPSK-S is within 0.5 dB of ideal linearly amplified uncoded QPSK performance. The optimized GMSK system requires a higher E_b/N_0.

The measured BEP versus E_b/N_o is presented in figure 5 for a 1 Mb/s signal, 1 and 1.5 MHz IF filter bandwidths, and PCM/FM and FQPSK-B modulations. A Microdyne model 1200MRA receiver was used in these tests. The FQPSK modulator was programmed to a center frequency of 250 MHz and connected to the receiver through amplifiers and attenuators (see figure 1). The FQPSK demodulator was programmed to a center frequency of 20 MHz and was connected to the linear IF output of the receiver. The FQPSK signal was differentially encoded to solve the polarity ambiguity problem that occurs because the reconstructed reference phase used for demodulation can be 0, 90, 180 or 270 degrees offset from the transmitter's reference phase. The prototype hardware FQPSK demodulator used in these experiments was a modified QPSK demodulator and because of resource and time limitations has not been optimized for FQPSK. Computer simulations presented in figure 4 show that a BEP of 1×10^{-5} can be achieved at an E_b/N_o approximately 1.5 dB lower than the measured performance in figure 5 (note also that figure 4 showed simulated FQPSK-S and figure 5 presents the performance of FQPSK-B). The measured BEP performance of FQPSK-B with either the 1 or 1.5 MHz IF filter bandwidths was a few tenths of a dB worse than that of PCM/FM with an IF filter bandwidth of 1 MHz at a BEP of 1×10^{-5} and better than the BEP performance of PCM/FM with a 1.5 MHz IF filter bandwidth.

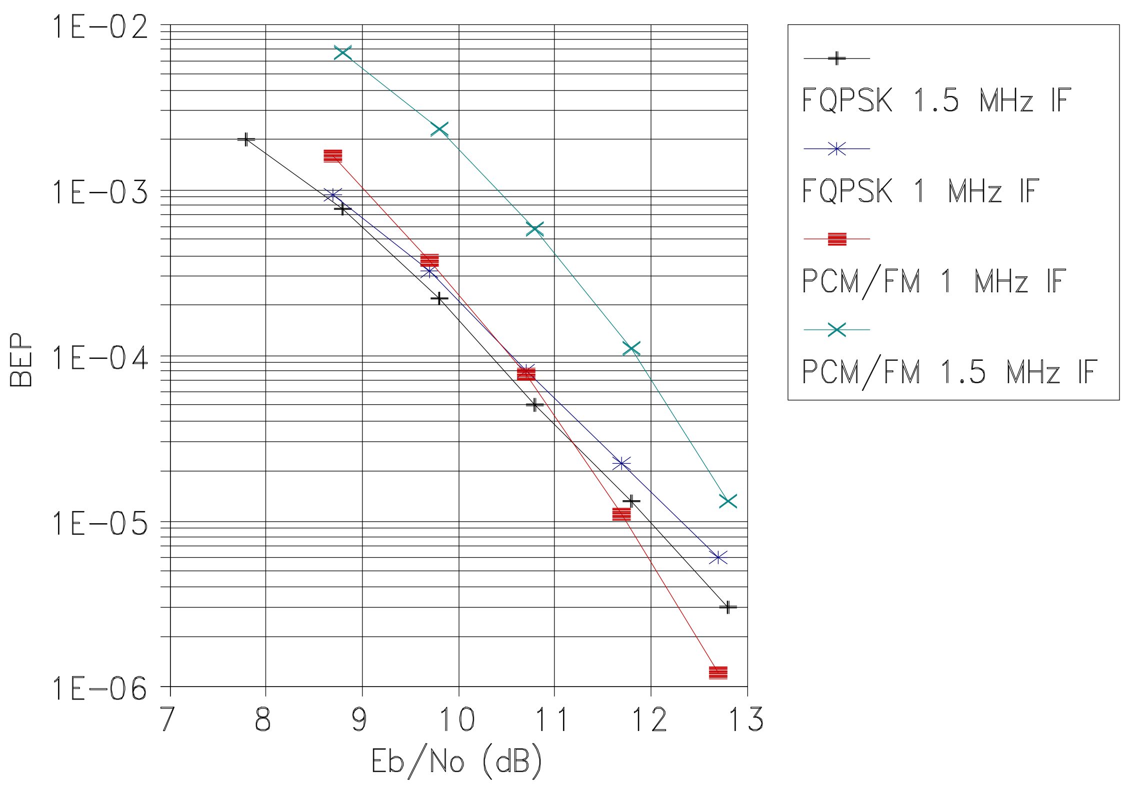

Figure 5. BEP for 1 Mb/s FQPSK-B and PCM/FM (note the FQPSK demodulator was not optimized).

CONCLUSIONS

1. The 99.99% and -60 dBc bandwidths of filtered FQPSK-B are only approximately one-half of the corresponding bandwidths of optimized PCM/FM even when the signal is non-linearly amplified.

2. The E_b/N_o required for a BEP of 1×10^{-5} for non-optimized FQPSK-B was approximately 12 dB which is approximately the same as limiter discriminator detected PCM/FM.

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