FQPSK-O: An Improved Performance Constant Envelope Modulation Scheme for OQPSK

Tong-Fu Lee and Shih-Ho Wang
Dept. of Electrical and Computer Engineering
University of California
Davis, California 95616

Chia-Liang Liu
Computer and Communication Research Laboratories
Industrial Technology Research Institute
Taiwan, ROC

ABSTRACT

A new constant envelope modulation scheme for OQPSK, called FQPSK-O, is presented. This modulation technique is an extension of the Feher Quadrature Shift Keying (FQPSK) patented technologies, see Ref[l]. This scheme uses cubic spline interpolation to generate very smooth baseband waveforms in order to increase the spectral and power efficiency. Being a constant envelope modulation, FQPSK-O can operate with class C power amplifier without spectrum regrowth. We achieve a more compact spectrum with comparable bit error rate performance. For example, the spectrum of FQPSK-O is 25% narrower than that of GMSK with BT_b=0.3 and FQPSK-1 with hardlimiter [2] at -40 dB attenuation point. For coherent demodulation under AWGN channel, FQPSK-O has almost the same BER performance as FQPSK-1 with hardlimiter. Both of them are better than GMSK with BT_b=0.3 for BER < 10^{-4}. In Rayleigh fading channel, FQPSK-O outperforms GMSK with BT_b=0.3 by 2 dB. FQPSK-O is an excellent scheme for wireless and satellite communications which require high spectral and power efficiency.

KEY WORDS

Modulation, FQPSK Feher’s quadrature phase shift keying, OQPSK, non-linear amplification, and bandwidth efficiency.

1. Introduction

Constant envelope modulation techniques such as MSK, GMSK, and digital FM can be non-linearly amplified without spectral regeneration. This is particularly important for portable phones where battery power supply is limited. Modulation techniques can improve the efficiency of wireless system significantly, with impact on cost, size, power and spectral efficiency, data transmission, throughput speed, and capacity. The proper combination of modulation and RF amplification technologies can further improve the power and spectral efficiency of communication system.

OQPSK has been widely used for digital modulation. For example, GMSK with BT_b=0.3 has been adopted by GSM standard. GMSK with coherent demodulator can be viewed as an OQPSK-type of signal [2]. FQPSK is another well-known OQPSK-type modulation with good spectral and power efficiency. In this paper, we compare the performance of FQPSK-O with that of GMSK with BT_b=0.3 and FQPSK-1 in detail. Further information on this subject can be found in [5].

An architecture and algorithm for constant envelope modulation with good spectral and power efficiency, named FQPSK-O, is presented. Being a constant envelope modulation, FQPSK-O can operate with class C power amplifier without spectrum regrowth. A compact spectrum is achieved by applying the cubic spline interpolation to generate OQPSK-type signals.

In section 2, the transmitter architecture is described. The block diagram and phase mapping algorithm are discussed. We compare the phase trellis and I/Q channel baseband waveforms of FQPSK- I and FQPSK-O. The power spectrum of FQPSK-O is obtained by simulation and hardware experiment.

In section 3, the BER performance is obtained by simulation. It shows that FQPSK-O is more power efficient than that of GMSK with BT_b=0.3 for BER < 10^{-4} in AWGN channel. In Rayleigh fading environment, FQPSK-O outperforms GMSK with BT_b=0.3 by 2 dB.

We conclude in section 4 that the spectral and power efficient FQPSK-O is an excellent scheme for wireless and satellite communications.

2. Transmitter

2.1 Simulation model

The architecture of the FQPSK-O modulation is shown in Fig. 1. The input binary data bits with duration T_b are mapped into four possible phase angles. This phase mapping algorithm is the same as that of OQPSK. Therefore, FQPSK-O is compatible with the existing OQPSK coherent demodulators. In each symbol duration, two phase values are generated. This sequence of phase values θ_k are interpolated to achieve smooth phase transitions. The number of the interpolated values per symbol is choosen large enough, in order to have an acceptably small aliasing error and thus simplify the low-pass filter design. The sine and the cosine values of the interpolated phase θ_{ki} are obtained by table lookup, where θ_{ki} is the *i*-th interpolated phase value of the *k*-th symbol. These are the In–phase and Quadrature (I/Q) baseband signals, which are used to modulate the carrier. By summing these two modulated signals, we have a constant envelope signal which can be non-linearly amplified without spectral regeneration.

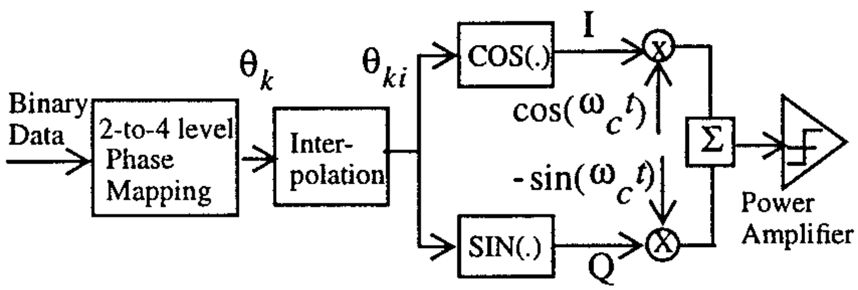


Fig.1 Block diagram of the transmitter of FQPSK-O system.

In this paper, we use cubic spline interpolation [3]. Other interpolation methods such as linear interpolation, cubic interpolation, cubic smoothing spline, and spline with tension [4] have also been considered in [5].

In the actual implemetation of the transmitter, $I_{ki} = COS(\theta_{ki})$ and $Q_{ki} = \sin(\theta_{ki})$ are converted to analog signals and then fed to low pass filters to remove higher frequency components. The analog I/Q baseband signals are modulated with the carrier, added together and amplified. Due to its constant envelope, FQPSK-O can be amplified with fully non-linear (saturated, C-class or hard-limited) power amplifier without spectral regrowth. Since we are using cubic spline interpolation, the phase is defined by a third-order polynomial of time within each symbol duration. By taking the derivative of the phase with respect to time, we obtain the frequency as a second-order polynomial of time. Hence, we could implement FQPSK-O as a frequency modulation using a voltage-controlled oscillator.

In the simulation, we use baseband equivalent model. The I/Q baseband signals are passed through the channel model. The receiver BPF is replaced by its equivalent LPF.

The I/Q channel eye diagram and phase trellis are plotted in Fig.2. The corresponding diagram for FQPSK-1 with hard-limiter [2] are plotted in the right column of Fig.2 for comparison. Note that the waveforms of FQPSK-O have more variations than that of FQPSK-1. As a result, the side-lobe of the FQPSK-O spectrum is narrower than that of FQPSK-1 and GMSK with BT_b=0.3 (Fig.3). The PSD of FQPSK-O has the same main-lobe as that of FQPSK- I with hardlimiter till -27 dB attenuation. After -27 dB point, the PSD of FQPSK-O is better than that of FQPSK- 1 with hardlimiter where it starts to regrow. Moreover, the PSD of FQPSK-O is better than that of GMSK with BTb=0.3 till –70 dB attenuation. For example, FQPSK-O is 25% better than GMSK with BTb=0.3 and FQPSK-1 with hardlimiter at -40 dB attenuation point.

The ratio of out-of-band power to total power are plotted in Fig.4. The horizontal axis of Fig.4 is the channel spacing normalized by bit rate. Based on the definition of the 99% in-band-power, FQPSK-O has a spectral efficiency of 1.3 b/s/Hz, while GMSK with BT_b=0.3 has a spectral efficiency of 1.1 b/s/Hz.

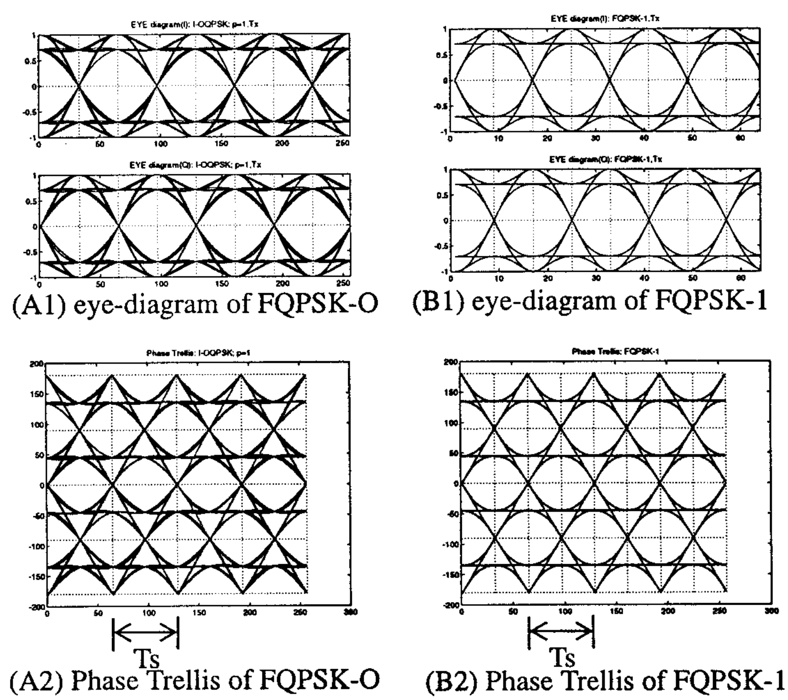
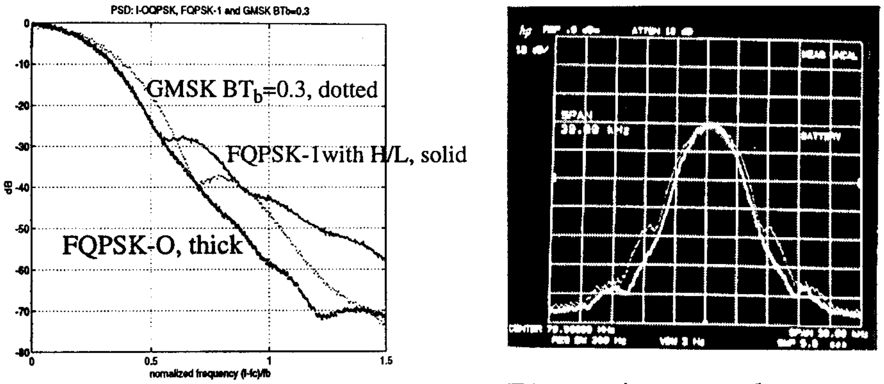


Fig.2 I/Q channel eye diagram and phase trellis: (A) FQPSK-O (B) FQPSK-1 with hardlimiter



(A) simulation results

(B) experiment results:
upper trace: GMSK BT$_b$=0.3
lower trace: FQPSK-O
spectrum analyzer:
vertical: 10 dB/div
horizontal: 3K Hz/div
(span=30K Hz)
sweep time= 5 sec
center freq. (f_c) = 70M Hz
input data rate: 7.27 K b/s

Fig.3 PSD of FQPSK-0, FQPSK- I with hardlimiter and GMSK BTb=0.3.

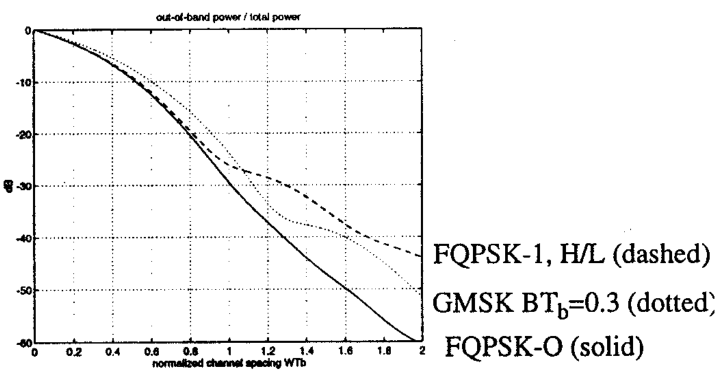


Fig.4 Out-of-B and Power vs. Normalized Channel Spacing plot.

3. BER performance

The BER performance of the coherent demodulation of FQPSK-O, FQPSK-1 and GMSK with BT_b=0.3 in AWGN channel are obtained by computer simulations as shown in Fig.5. The receiver BPF for FQPSK-O is a Butterworth 4th order filter with B_iT_b=0.55. For GMSK with BT_b=0.3 and FQPSK-1, a Butterworth 4th order BPF with BiT_b=0.6 is employed. Fig. 6 shows the eye diagram for the receiver.

Note that the eye openings are asymmetrical due to the non-constant group delay of the receiver BPR FQPSK-O is about 0.2 dB worse than FQPSK-1 with hardlimiter. Both FQPSK-O and FQPSK-1 outperform GMSK with BTb=0.3 for $E_b/N_o < 10^{-}4$. Similar results of comparing FQPSK-1 and GMSK are given in [6].

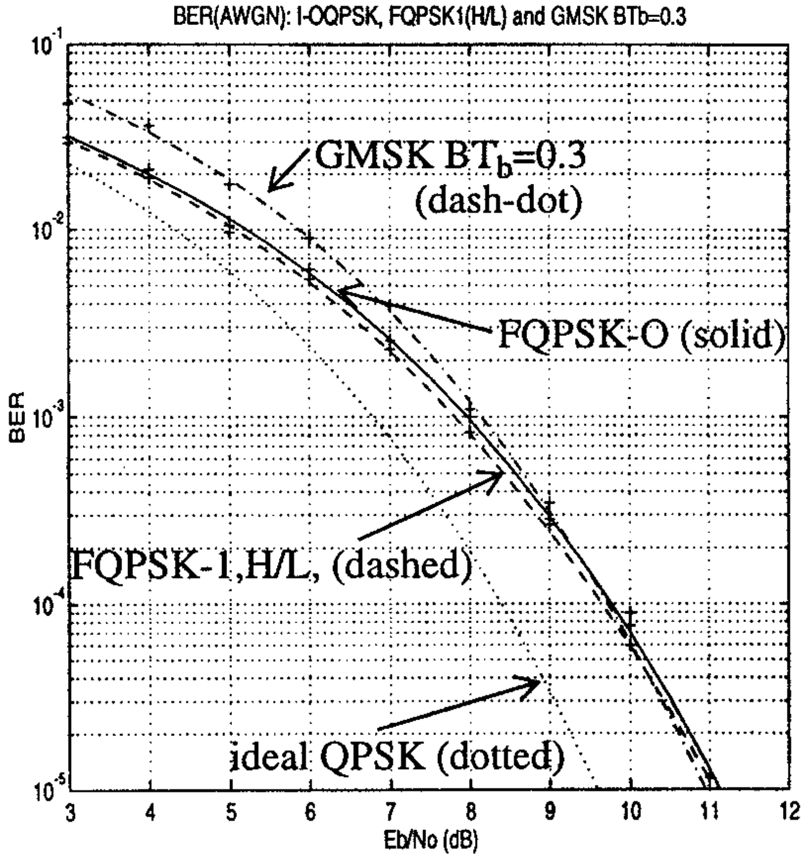


Fig.5 BER performance of coherent demodulation of FQPSK-O, FQPSK-1 (hardlimiter), GMSK with BT_b=0.3 and ideal QPSK with AWGN.

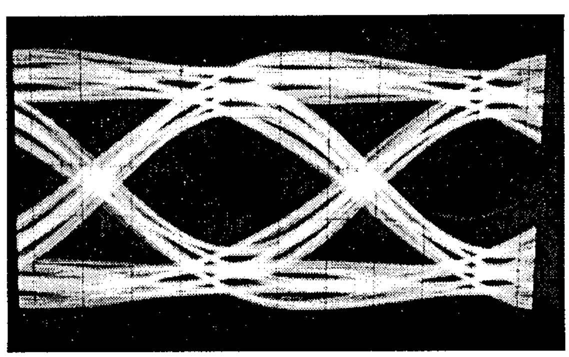


Fig.6 Eye diagram of the coherently demodulated FQPSK-O signals. Only in-phase channel is shown. The bit rate is 7.27k b/s. The receiver LPF is a Butterworth 4th order LPF with cut-off frequency at 2.0k Hz, which corresponds to a normalized IF bandwidth of B_iT_b=0.55.

The BER performance of the coherent detection of FQPSK-O in slow Rayleigh fading channel is depicted in Fig.7. Here, we assume perfect Carrier Recovery (CR) and Symbol Time Recovery (STR). To obtain this result, we use the same set of receiver BPF as in the AWGN case. The normalized Doppler frequency is $f_D T_b = 1.65 \times 10^{-3}$, that corresponds to a 40 Hz Doppler and a data rate of 24.3K b/s. A Butterworth 4th order receiver BPF with BiTb=0.55 is employed for FQPSK-O. Ideal Gaussian BPF with BiTb=0.6 is used for GMSK with BTb=0.3. Comparing with coherent detection of GMSK with BT_b=0.3, FQPSK-O is 2 dB better under the same BER requirements.

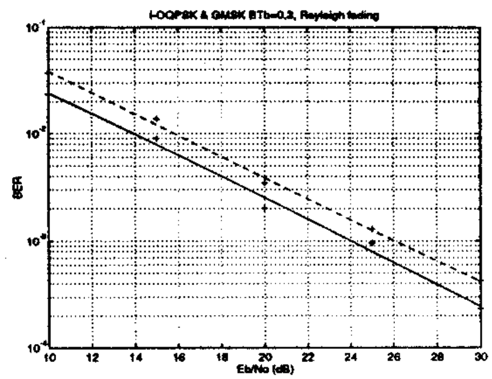


Fig.7 BER performance of FQPSK-O and GMSK with BTb=0.3 as a function of E_b/N_o in Rayleigh fading channel. FQPSK-O outperforms GMSK by 2 dB.

4. Conclusion

A new modulation scheme for OQPSK using cubic spline interpolation is presented. It increases the spectral and power efficiency. Being a constant envelope modulation, FQPSK-O can be operated with class C power amplifier without spectrum regrowth. FQPSK-O has a narrower spectrum than that of GMSK with BTb=0.3 till 70 dB attenuation. Especially, it has 20% - 30% better spectral efficieny than that of GMSK with BTb=0.3 from 40 dB to 70 dB attenuation. FQPSK-O is more power efficient than that of GMSK BT_b=0.3 for BER < 10^{-4} in AWGN channel. In Rayleigh fading, FQPSK-O outperforms GMSK BTb=0.3 by 2 dB. Thus, FQPSK-O is an excellent scheme for wireless and satellite communications which require high spectral and power efficiency.

5. Acknowledgments

This research has been supported by the State of California under MICRO grant #96–192 and the Air Force under grant AFOSR-F49620-98-1-0097.

6. References

[1] K. Feher et a;: US Patents 4,567,602;4,339,724;4,44,565;5,491,457;5,784,402 and Canadian Patents: 1,211,517;1,130,871;1,265,851 and post-patent improvements, including Digicom's proprietary 'know-how' and other US and international patent pending/in applications-in-process. These have been licensed on an equal-opportunity, non discriminatory fair market value basis for "dual-use"commercial and military FQPSK-GMSK use, developments and other use and applications to large, medium size and small corporations and organizations in the USA and Internationally by Digicom, Inc. For FQPSK consortium, FQPSK-GMSK licensing and technology transfer information write to: FQPSK Consortium-Digicom, Inc., 44685 Country Club Drive; El Macero, CA 95618; USA; Tel.530-753-0738; Fax 530-753-1788.

[2] K. Feher, *Wireless Digital Communications: Modulation and Spread-Spectrum Applications*, Prentice Hall, 1995

[3] C. de Boor, *A Practical Guide to Splines*, Applied Mathematical Science, Vol. 27. Springer-Verlag, 1978

[4] A. K. Cline, "Scalar- and Planar- Valued Curve Fitting Using Splines Under Tension", *Communications of the A CM*, Apr. 1974, Vol. 17, No. 4

[5] T. F. Lee, "Spectral and Power Efficient Modulation Schemes for Digital Communications", Ph.D. dissertation, University of California, Davis, 1997.

[6] P. S. K. Leung and K. Feher, "A Superior Modulation Technique for Mobile and Personal Communications", IEEE Trans. on Broadcasting, Vol. 39, No.2, pp.288-294, June 1993.