Continuous Phase Modulation of Spectrally Efficient FQPSK Signals

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***Abstract*—A continuous phase modulation (CPM) implementation alternative of a recently standardized class of Feher-patented quadrature phase-shift keying (FQPSK-B) modulation is proposed. It is based on the fact that FQPSK-B signal has quasi-constant amplitude and continuous phase characteristics, allowing CPM interpretation. Based on this, we derive the *modulation index*, *premodulation filter* and *alternating change monitor differential encoder* for the CPM generated FQPSK-B signal to be fully compatible with original I/Q-modulated one. It is shown that the power spectral density and the bit error rate performance of CPM generated FQPSK-B signal are almost the same as those of I/Q modulated FQPSK-B signal.**

I. Introduction

During last few decades, there have been extensive research efforts for BER and bandwidth trade-off. QPSK-family such as QPSK, OQPSK, and π/4 QPSK are certainly among the most popular BER-bandwidth optimized modulation techniques in relatively high noisy channel such as mobile personal communication network. The signal amplitude of these, however, is not constant, leading to poorer power efficiency compared with continuous phase modulation (CPM)-derived system such as FSK, which has constant amplitude modulation (CAM) characteristics. It is well known that CAM signal is very immune to nonlinear distortion, resulting in higher power efficiency. Recently, therefore, there has been great interest in both BER and bandwidth efficient system having CAM characteristics. FQPSK modulation, which was originally proposed in 1983 [1], with later introduction of specific Butterworth low pass filter (LPF), i.e., FQPSK-B [2], is certainly one of the promising modulation methods satisfying above requirements. Not only it is bandwidth-efficient, but has quasi-CAM characteristics with BER performance approaching QPSK limit, being suitable for power efficient system. It is worth noticing that these merits are important especially in telemetry system, where both power and spectrum efficiency is preferred over other requirements. Multiyear studies by the US Department of Defense (DoD), NASA, AIAA, and the Consultative Committee for Space Data Systems (CCSDS) confirmed that FQPSK-B is one of the most spectrally efficient modulated signals with robust (smallest degradation from ideal theory) bit error rate (BER) performance in Non-Linear Amplification (NLA, saturation mode operation of high power amplifier)-RF power efficient systems.

However, since FQPSK-B modulation has been proposed, I/Q modulation scheme has been used for transmitter implementation. In this paper, we present the continuous phase modulation method for FQPSK-B signal. Based on the observation that FQPSK-B signal has quasi-constant amplitude and continuous phase characteristics, we first show that FQPSK-B can be interpreted as a kind of CPM. There are two merits in CPM generation. Firstly, it allows higher data bandwidth using much simpler circuits with much lower power consumption. I/Q-based signal synthesis is much more complex and difficult to achieve the signal match between I and Q signal paths because of various gain and phase mismatches in the local oscillators, LPF and mixers, and so forth. This is especially true for quasi-CAM system such as FQPSK-B, where I/Q signals should precisely be synthesized to satisfy CAM characteristics as much as possible. This calls for I/Q signal synthesis using digital signal processing, which limits the data bandwidth and power consumption budget appreciably. Secondly, most of the existing systems already in service in telemetry ones are based on CPM such as FSK.

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Therefore they are generated by FM type modulation using voltage controlled oscillator (VCO), for example. Thus, if FQPSK-B signal can be generated by FM type modulation, it can be easily incorporated into existing system without having to change the RF hardware, which is especially advantageous for satellite telemetry system.

In next section, we interpret FQPSK-B signal as a kind of CPM. For the CPM representation of FQPSK-B signal, the modulation index and premodulation filter must be specified. They are presented in Section III. And, the *alternating change monitor differential encoder* (ACMDE) is proposed. The CPM of FQPSK-B requires ACMDE to produce the same phase behavior with I/Q modulation of FQPSK-B. In Section IV, power spectral density (PSD) and BER performance of the proposed continuous phase modulated FQPSK-B signal are evaluated and compared with those of conventional I/Q modulated FQPSK-B signal. Finally, Section V presents the conclusion.

II. CPM INTERPRETATION OF FQPSK-B MODULATION

FQPSK-B modulation is a kind of inter-symbol interference (ISI) and jitter-free OQPSK modulation schemes, which is composed of cross correlator and LPF [1-3]. The cross correlation is done to obtain quasi-CAM characteristics. In this regards, this is very similar to the shaped OQPSK (SOQPSK) [4,5], where I/Q-envelope signals are shaped such that the magnitude of the modulated signal be constant. In [5], it is pointed out that CPM characteristics of SOQPSK allow us to generate it using CPM. But there is no systematic approach on modulating function.

In order to derive the CPM characteristics of FQPSK-B signals, it is necessary to look at the relationship between transmitted data and transient phase behavior. It is summarized as follows. Firstly, three consecutive binary data, i.e., two consecutive Q bits with I bit in between, and vice versa, determines one out of 8 allowed phase values at the middle symbol time given by $\phi(nT_b)=k\cdot(\pi/4)$, $k=0,\ldots,7$. Secondly, four consecutive binary data determine two phase values at $t=nT_b$ and $t=(n+1)T_b$, and *single-phase transition* between them. FQPSK-B signal can have only one out of *5* single-phase transition values, which are given as $\pm\pi/2, \pm\pi/4 \, and \, 0$. Thirdly, five consecutive binary data determines *two-phase transitions*, i.e., two consecutive single-phase transitions. It is worth noticing that the number of the allowed two-phase transitions is 15 which is much less than 25 that is obtained from the random combination with 5 allowed single-phase transitions. It means that FQPSK-B modulation has memory [6].

III. CPM GENERATION OF FQPSK-B SIGNAL

Since the largest magnitude of phase transition of FQPSK-B signal during T_b is $\pi/2$, it can be generated using FM with a modulation index h of 0.5.

Note that, to generate CPM-based FQPSK-B signal using FM, the premodulation filter should be determined such that it approximates the original signal as closely as possible. In other to derive the premodulation filter of CPM-based FQPSK-B signal, let us first look at the instantaneous frequency of FQPSK-B signal. Here the instantaneous frequency is calculated from the derivative of the phase which is approximately derived from arctangent of basic I, Q envelope functions defined in original FQPSK-B signal [2].

Let us start to look at the instantaneous frequency of basic FQPSK-KF signal shown in Fig. 1. Note that FQPSK-B is a low pass filtered version of FQPSK-KF (See [3] for more detail). In Fig. 1, we also show that of EFQPSK, which was proposed by Simon et al. and used the waveform $\sin(\pi t/2T_b)-\left(1-1/\sqrt{2}\right)\cdot\sin^2(\pi t/2T_b)$ instead of $1/\sqrt{2}\cdot\sin(\pi t/2T_b), 0\le t\le T_b$ in the FQPSK-KF waveforms [6]. Note here that EFQPSK has much smoother transition. This is expected because it was introduced to remove the discontinuity of first order derivative of the envelope function in the FQPSK-KF signal. But its second order derivative is still not continuous. Because of the large discontinuity, neither FQPSK-KF nor EFQPSK is not easy to reproduce using CPM. Much smoother frequency change is preferable for CPM generation. In this paper, we propose another smoother signal called FQPSK-E^2, which uses the waveform $\sin(\pi t/2T_b)-\left(1-1/\sqrt{2}\right)\cdot\sin^3(\pi t/2T_b)$ instead of $1/\sqrt{2}\cdot\sin(\pi t/2T_b), 0\le t\le T_b$ in the FQPSK-KF waveforms.

FQPSK-E^2 guarantees the continuity up to the second order derivative of instantaneous frequency, implying that the power spectrum of CPM of FQPSK-E^2 is more compact than the FQPSK-KF and EFQPSK. Based on FQPSK-E^2 signal, we can easily derive the premodulation filter $w(t)$ for the CPM of FQPSK-B from the phase change and instantaneous frequency, which is presented in (1) and shown in Fig. 1.

$$w(t)=\begin{cases} 1/4T_b\cdot sin\left(\pi/2T_b\left(t+3/2\cdot T_b\right)\right)\cdot\left\{1+\left(3/\sqrt{2}-5/2\right)\cdot cos^2\left(\pi/2T_b\left(t+3/2T_b\right)\right)\right. \\ \left.+\left(2-7/2\sqrt{2}\right)\cdot cos^4\left(\pi/2T_b\left(t+3/2\cdot T_b\right)\right)+\left(3-2\sqrt{2}\right)/2\sqrt{2}\cdot cos^6\left(\pi/2T_b\left(t+3/2T_b\right)\right)\right\} & ,-3/2T_b<t\le -1/2T_b \\ 1/4T_b & ,-1/2T_b<t\le 1/2T_b \\ 1/4T_b\cdot cos\left(\pi/2T_b\left(t-1/2T_b\right)\right)\cdot\left\{1+\left(3/\sqrt{2}-5/2\right)\cdot sin^2\left(\pi/2T_b\left(t-1/2T_b\right)\right)\right. \\ \left.+\left(2-7/2\sqrt{2}\right)\cdot sin^4\left(\pi/2T_b\left(t-1/2T_b\right)\right)+\left(3-2\sqrt{2}\right)/2\sqrt{2}\cdot sin^6\left(\pi/2T_b\left(t-1/2T_b\right)\right)\right\} & ,1/2T_b<t<3/2T_b \\ 0 & ,elsewhere \end{cases} \quad (1)$$

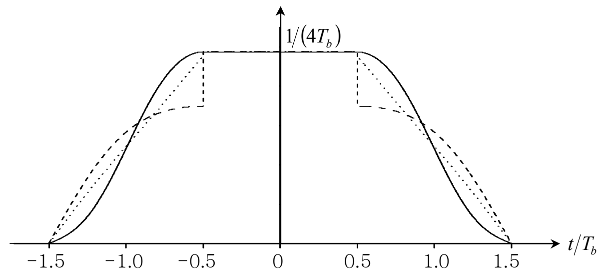

Fig. 1. Instantaneous frequency of FQPSK MODEM family. FQPSK-KF (dashed line), EFQPSK (dotted line) and FQPSK-E^2 (solid line).

Note, however, the power spectrum of FQPSK-E^2 signal is a little broader than that of FQPSK-B signal. To be fairly compared with I/Q modulated FQPSK-B signal which does not require RF band pass filter, we are proposing to use of the premodulation filter $g(t)$ for the CPM of FQPSK-B composed of cascading $w(t)$ and the raised cosine filter $n(t)$ with the roll-off factor of 1.0 and –6dB bandwidth of $0.44/T_b$. Note that this specific function satisfies the all the phase transition requirement described in this paper with very compact power spectrum.

The final premodulation filter $g(t)$ is then written as

$$g(t) = w(t) * n(t) = \int_{-\infty}^{\infty} w(\tau) \cdot n(t-\tau) d\tau, \qquad (2)$$

where $w(t)$ is given in (1). And, $n(t)$ is written as

$$n(t) = \frac{\sin(0.88\pi t/T_b)}{(0.88\pi t/T_b)} \cdot \frac{\cos(0.88\pi t/T_b)}{1 - 4 \cdot (0.88 t/T_b)^2}.$$

It is well known that some kind of decoder is necessary to make CPM generated OQPSK signals, such as MSK and GMSK, to have identical data sequence as that from I/Q-based modulated ones [7]. In addition, new differential encoding scheme was proposed, which eliminated the de Buda's differential decoder, leading BER performance improvement by two times over uncoded data [8]. However, it is complex to implement. So, we propose a differential encoder, called *alternating change monitor differential encoder* (*ACMDE*), based on the Ho's differential encoding mechanism and the phase behavior of I/Q-modulated and continuous phase modulated FQPSK-B signal, which is written as

$$\begin{aligned} v_n &= v_{n-1} \oplus \overline{q_n \oplus q_{n+2}}, \qquad n = 1,2,\cdots \\ v_0 &= q_0 \oplus q_1 \end{aligned} \qquad (3)$$

Here q denotes the input data and v denotes the *ACMDE* output data, i.e., the premodulation filter input data. ⊕ means modulo-2 addition. Note further that the continuous phase modulated FQPSK-B signal has the same phase transition behavior with the I/Q-modulated FQPSK-B signal using ACMDE, as it should be.

IV. BER AND SPECTRUM COMPARISON USING ANALYTIC CALCULATION AND COMPUTER SIMULATION

The numerically calculated power spectral density (PSD) of CPM of FQPSK-B is shown and compared with other signals in Fig. 2. It shows that continuous phase modulated FQPSK-B signals has almost the same PSD with I/Q modulated FQPSK-B signal. Note further that the PSD of this is very comparable to SOQPSK-A.

Since the CPM of FQPSK-B is partial response binary CPM with h=1/2, the BER analysis method introduced by Aulin, Sundberg and Svensson [9] can be used for BER analysis of coherent symbol-by-symbol detection. Since ACMDE is used in the transmitter of CPM of FQPSK-B, the bit error probability is equal to the phase node error probability, i.e., (28) and (30) in [9]. Fig. 3 shows the BER performance of CPM of FQPSK-B with coherent symbol-by-symbol detection in the AWGN channels. Both analytic and simulation results give the BER performance of 10^{-4} of the CPM of FQPSK-B at an E_b/N_0 of 10.2dB. It suffers only 0.3dB degradation at BER of 10^{-4} from the performance of I/Q-modulation of FQPSK-B, which is due to the fact that the eye opening of the continuous phase modulated FQPSK-B signal is about 7% smaller than that of the I/Q modulated FQPSK-B signal. However, it has 0.8dB and 0.5dB better performance at BER of 10^{-4} than the SOQPSK-A and SOQPSK-B, respectively.

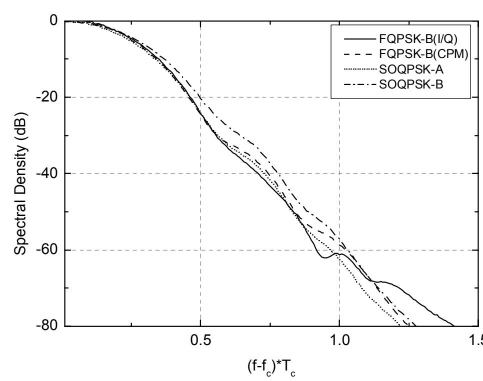

Fig. 2. PSD of the continuous phase modulated FQPSK-B signal in NLA environment. I/Q-modulation of FQPSK-B (solid line), CPM of FQPSK-B (dashed line), SOQPSK-A (short dotted line), and SOQPSK-B (dash-dotted line).

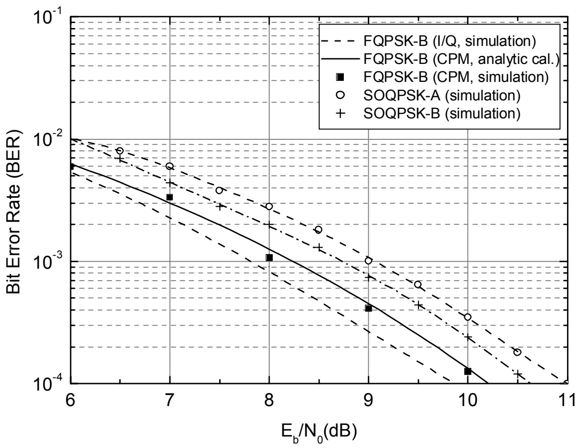

Fig. 3. BER performance of CPM of FQPSK-B with coherent symbol-by-symbol detection in the AWGN channels. I/Q-modulation of FQPSK-B (simulation, dashed line), CPM of FQPSK-B (solid line: theory, solid square: simulation), SOQPSK-A (simulation, open circle), and SOQPSK-B (simulation cross).

V. CONCLUSIONS

In this paper, continuous phase modulation method for FQPSK-B has been proposed. The CPM characteristics of FQPSK-B signal have been derived from the quasi-constant amplitude and continuous phase characteristics of FQPSK-B signal. Based on this, we derived the modulation index and premodulation filter. A new simple differential encoder, called *alternating change monitor differential encoder* (ACMDE), has been proposed, which not only produces the same phase behavior with I/Q-modulated FQPSK-B signal, but also allows direct symbol-by-symbol detection without any special decoding scheme inherent in all CPM schemes. Simulation results and analytical calculation have shown that the PSD and BER performance are almost same with the conventional I/Q-modulation of FQPSK-B.

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