NON-COHERENTLY DETECTED FQPSK: RAPID SYNCHRONIZATION AND COMPATIBILITY WITH PCM/FM RECEIVERS[#]

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ABSTRACT

A new class of non-coherent detection techniques for recently standardized Feher patented quadrature phase-shift keying (FQPSK) systems is proposed and studied by computer aided design/simulations and also verified by experimental hardware measurements.

The theoretical concepts of the described non-coherent techniques are based on an interpretation of the instantaneous frequency deviation or phase transition characteristics of FQPSK-B modulated signal at the front end of the receiver. These are accomplished either by Limiter-Discriminator (LD) or by Limiter-Discriminator followed by Integrate-and-Dump (LD I&D) methods. It is shown that significant BER performance improvements can be obtained by increasing the received signal's observation time over multiple symbols as well as by adopting trellis-demodulation. For example, our simulation results show that a BER=10^{-4} can be obtained for an E_b/N_0=12.7 dB.

KEYWORDS

Feher patented QPSK or FQPSK, Non-coherent detection, Multiple symbol observation, Viterbi detection, Maximum likelihood sequence detection.

[#] Significant parts of the material in this publication are based on Park's Thesis and Feher et al. patents [1] and on other material which remains property of the authors.

I. INTRODUCTION

Multiyear studies by the US Department of Defense (DoD), NASA, AIAA, and the International Committee Consultative on Space Data Systems (CCSDS) confirmed that FQPSK technologies [1-7] offer the most spectrally efficient and robust (smallest degradation from ideal theory) BER performance of NLA-RF power efficient systems.

For coherent FQPSK-B detection, an E_b/N_0=9.8dB is required for a BER=10^{-4} if simplest symbol-by-symbol detection is used. For FQPSK-B with trellis decoding using Viterbi algorithm, for BER=10^{-4}, reduced E_b/N_0=9.1dB is required [8]. These NLA requirements of FQPSK-B are 1.4dB and 0.7dB worse than that of ideal theoretical QPSK operated in a linear amplified system, respectively [5], [8]. However, since phase noise caused by oscillators and frequency synthesizers, and relatively large Doppler spread [2], [9] may degrade the performance of relatively low bit rate coherent demodulators and may increase the synchronization time, non-coherent detection is preferable for certain mobile applications [10].

In this paper, eight non-coherent detection techniques for FQPSK-B signal are proposed and their BER performance in a Gaussian channel is compared using a simulation study as well as hardware evaluation. In the next section, Section II, we summarize the analysis of non-linearly amplified FQPSK-B modulation with non-coherent detection. In Section III, eight non-coherent detection techniques for FQPSK-B signal are presented. Section IV contains simulation results, hardware measurements and discussion. Finally, Section V presents the conclusion.

II. FQPSK-B MODULATION ANALYSIS FOR NON-COHERENT DETECTION PROPOSAL

In the FQPSK-B modulator, the amplitude parameter *A* of the cross correlator is chosen to $1/\sqrt{2}$ for the modulated signal to have quasi-constant envelope. This quasi-constant amplitude characteristic of FQPSK-B signal allows us to interpret it as a continuous phase modulation (CPM) [11]-[13]. The interpretation of the FQPSK signals as a non-quadrature CPM [11]-[13] allows us to detect FQPSK-B modulated signal non-coherently by differential decoding of the I and Q channel data, separately.

Observations 1 and 2 of References [11]-[13], allow us to use limiter-discriminator (LD) detection scheme for non-coherent detection with the instantaneous frequency deviation characteristic. And the observation 3 allows us to use differential detection of phase change or limiter-discriminator followed by integrate-and-dump (LD I&D) detection schemes for non-coherent detection with the characteristic phase transition at T_b interval.

III. NON-COHERENT DETECTION TECHNIQUES FOR FQPSK-B SIGNALS

FQPSK-B signal can be detected symbol-by-symbol using LD detection (*Method 1*). Both observations 1 and 2 in References [11]-[13] allow us to detect FQPSK-B signal using 3-level frequency discrimination, i.e., $+\Delta f, 0, \text{and} -\Delta f$.

In addition, differential decoders in respective I and Q channel data are required for non-coherent detection techniques for FQPSK-B signals. Differential decoding has a problem of error propagation. Thus, a special encoding scheme called *quadrature differential encoding* (QDE) is proposed to solve this problem. This is to encode differentially for the I, Q channel data separately. It is represented in (1).

$$y_{2n} = y_{2(n-1)} \oplus x_{2n}, \qquad (1)$$
$$y_{2n+1} = y_{2n-1} \oplus x_{2n+1}.$$

Here x is the NRZ input data and y is the QDE output and ⊕ means modulo-2 addition. The IRIG 106-00 standardized FQPSK-B specifies also the use of a differential encoder [7]. This is somewhat different from QDE. However, QDE is equivalent to cascaded *pre-coding differential encoder* (PDE) and differential encoder in the IRIG 106-00 standard, as shown in . PDE is represented in (2).

$$y_{n+1} = y_n \oplus \overline{x_n} \qquad (2)$$

Here $\overline{x}$ is the inversion of NRZ input data and y is the PDE output and ⊕ means modulo-2 addition.

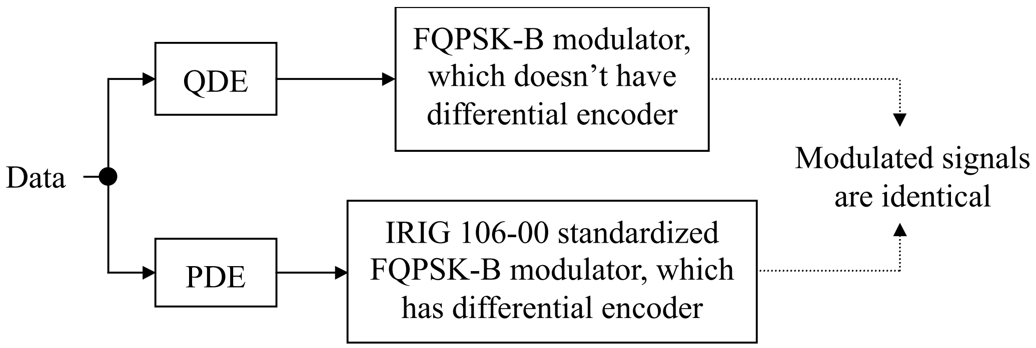

Fig. 1. Relationship between QDE, PDE and differential encoder, which is defined in IRIG 106-00 standard [7].

Note that if QDE is employed, then very simple receiver structure can be obtained, as shown in Fig. 2, which also gives better BER performance.

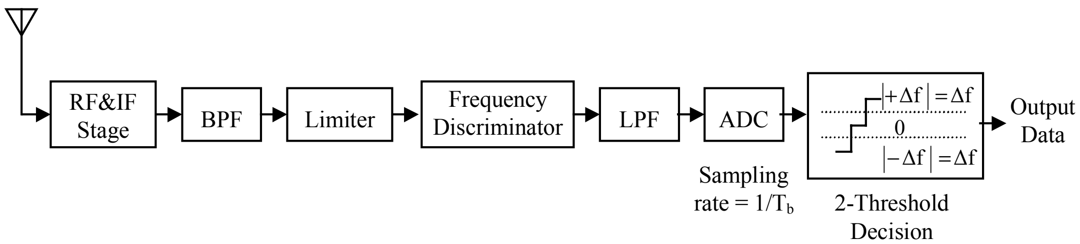

Fig. 2. Receiver structure based on LD followed by symbol-by-symbol detection for QDE FQPSK-B signal.

Also, it is noticed that only certain combinations of phase changes of FQPSK-B modulated signals are allowed, i.e., FQPSK signal has memory. In this case, it is well known that the detection based on multiple symbol observation performs better than symbol-by-symbol detection [14], [15].

As described in References [1] and [11]-[13], N+3 data sequence is required to get an instantaneous frequency deviation vector that is composed of "N" instantaneous frequency deviation components. This means that many of the input vectors in L-space are mapped into the identical vector in m-space. As the symbol observation interval increases, the ratio, m/M, of number of the allowed instantaneous frequency deviation vector to the total number of random combinations of symbol-by-symbol data (3 level in our case of Section II) reduces significantly. This means that the correction ability for the erroneous LD output value improves significantly.

Three detection techniques with multiple symbol observation are studied in our work, i.e., multiple symbol observation and middle bit decision (*Method 2*), multiple symbol observation and majority voting (*Method 3*), and maximum likelihood sequence detection (MLSD) [16] with multiple symbol observation (*Method 4*).

Also, it is well known that integrate-and-dump (I&D) detection can give better BER performance than simple sampling based one [17]. Thus, we expect better BER from integrate-and-dump of LD output signals, which is nothing but the phase transition. In the Reference [11], it is shown that when differentially encoded bit 0 is transmitted, the absolute value of the sum of two-phase transition values between $t=(n-1)T_b$ and $t=(n+1)T_b$ interval is less than or equal to $\pi/4$, and it is larger than $\pi/4$ when 1 is transmitted. Thus transmitted data can be detected on a symbol-by-symbol basis from the observation of the total phase transition in $2T_b$ period. It is the LD I&D followed by symbol-by-symbol decision, i.e., *Method 5*.

Likewise in LD based detection techniques, the multiple phase transition observation method can improve the performance of LD I&D detection. There are also 3 methods, multiple phase transition observation and middle bit decision (*Method 6*), multiple phase transition observation and majority voting (*Method 7*), and MLSD with multiple phase transition observation (*Method 8*).

IV. SIMULATION RESULTS, HARDWARE MEASURMENTS AND DISCUSSION

To show the bit error rate (BER) performance of the proposed non-coherent detection techniques, MATLAB simulation is performed using baseband equivalent model [18]. The receiver BPF, which is implemented with equivalent LPF in the MATLAB, is the phase equalized 4th order Butterworth filter, $BT_b = 0.5$. The LPF of LD output signals is raised cosine filter with roll-off factor = 0.5 and –6dB bandwidth = $0.42*1/T_b$. Hard limiter is assumed to approximate the non-linear amplifier in the transmitter. And, ideal symbol synchronization is assumed.

Fig. 3 presents the BER performance of the various detection techniques with LD scheme. The number of observed symbols is chosen at N=5. The LD followed by symbol-by-symbol decision scheme suffers as large as 9.5dB degradation at $BER=10^{-4}$ from the best symbol-by-symbol coherent detection [5]. But this degradation decreases significantly as we increase the observation time. Middle bit decision, majority voting, and MLSD based on 5-

symbol observation leads to 5.3dB, 4.6dB, 3.8dB degradation at BER=10^{-4} compared with best symbol-by-symbol coherent detection of FQPSK-B performance.

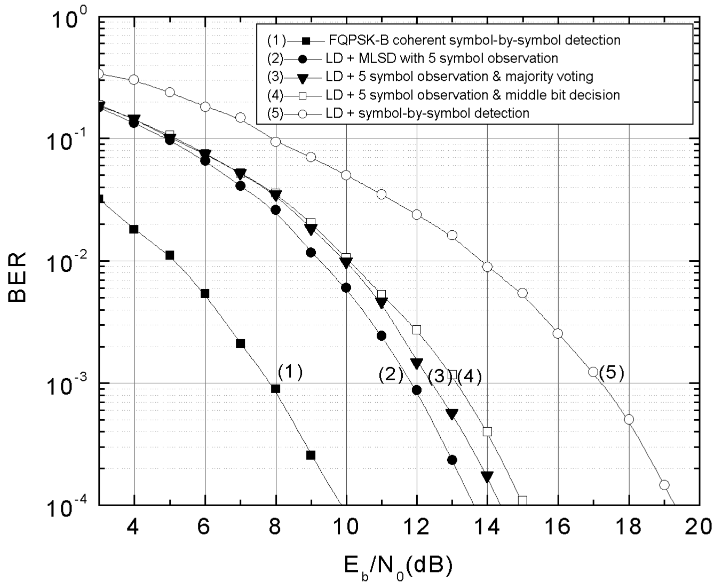

Fig. 3. BER performance of LD-based non-coherent detection techniques.

Fig. 4 shows the BER performance comparison of different symbol observation intervals with LD followed by multiple symbol observation and middle bit decision scheme. It is shown that the performance is increased as the symbol observation interval increases, as shown in Section III.

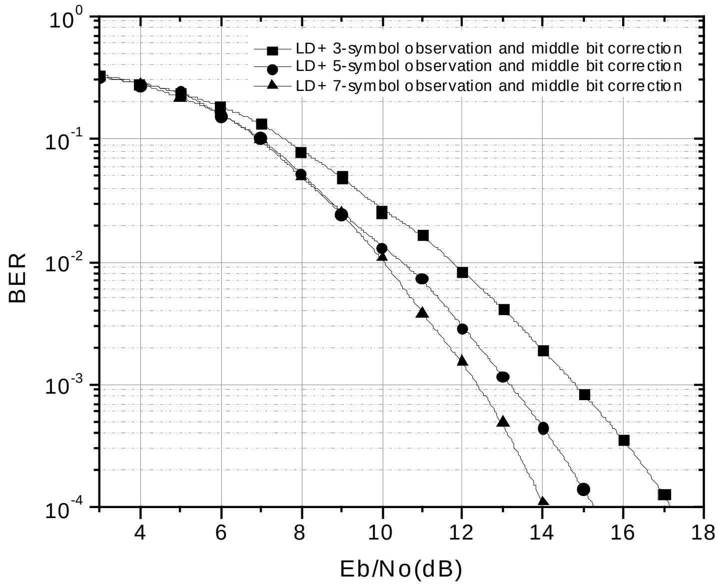

Fig. 4. BER performance of LD followed by multiple symbol observation and middle bit decision with various symbol observation intervals.

Fig. 5 represents the BER performance of the various detection techniques with LD I&D scheme. The number of observed symbols is chosen at N=5. The LD I&D followed by symbol-by-symbol decision scheme suffers 8.6dB degradation at BER=10^{-4} from the best symbol-by-symbol coherent detection of FQPSK-B performance. But this degradation decreases significantly as we increase the observation time. Middle bit decision, majority voting, MLSD based on 5-symbol observation leads to 5.6dB, 4.7dB, 2.9dB degradation at BER=10^{-4} compared with best symbol-by-symbol coherent detection of FQPSK-B performance.

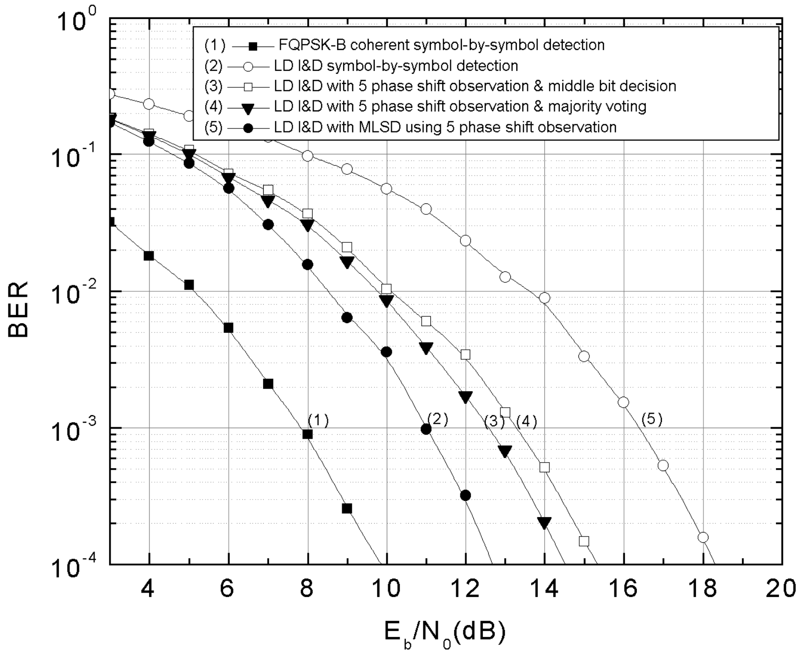

Fig. 5. BER performance of LD I&D-based non-coherent detection techniques.

However, simulation results are not optimized.

To measure the non-coherent detector output of FQPSK-B signal, the simple non-coherent detector is implemented, which is presented in Fig. 6. In the experimental system, the data rate is 1 Mb/s, the carrier frequency of transmitted signal is 70 MHz, the delay time for the non-coherent detection is about 35nsec, i.e., about 1/30 of bit period, and the -3dB bandwidth of Butterworth LPF is 420kHz.

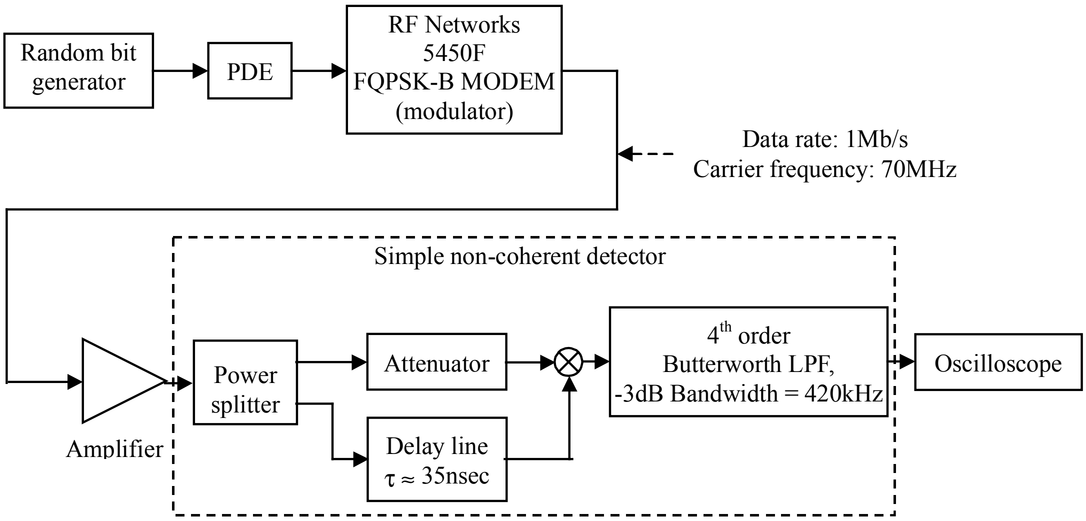

Fig. 6. Implemented non-coherent detector block diagram for non-coherent detector output measurement.

The implemented non-coherent detector is an approximate model of the limiter-discriminator detector with small delay time, i.e., $\tau \approx$ 35nsec $\approx 1/30^*T_b$. The measured time patterns of detector output are compared with the computer-generated patterns as shown in Fig. 7. It is noticed that the measured and generated time patterns are similar to each other.

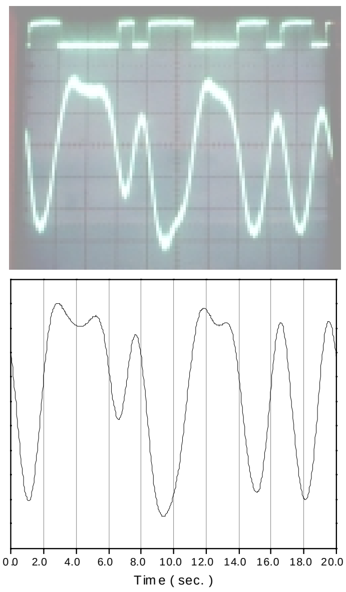

Fig. 7. Measured time patterns (upper) and computer-generated time patterns (lower) of non-coherent detector output. In the measured photos, the horizontal scale is 2μsec/div, upper signal is transmitted NRZ data and lower signal is non-coherent detector output. And, the data rate is 1Mb/s, the carrier frequency of transmitted signal is 70MHz, and -3dB bandwidth of post frequency discrimination LPF is 420kHz.

V. CONCLUSIONS

Based on the CPM based interpretation, we have proposed eight non-coherent detection techniques for FQPSK-B. It is shown that the BER performance of the LD and LD I&D-based non-coherent detection techniques improves significantly using the inherent memory in the FQPSK-B modulated signal phase, i.e., multiple symbol observation followed by middle bit decision, majority voting, and MLSD.

Simulation results show that LD followed by MLSD with 5-symbol observation performs BER=10^{-4} at E_b/N_0 =13.6dB. In addition, LD I&D, followed by MLSD with 5 phase transition observation, performs BER=10^{-4} at E_b/N_0 as low as 12.7dB. These non-coherent receivers suffer 3.8dB, 2.9dB degradation at BER=10^{-4} from the best symbol-by-symbol coherent detection of FQPSK-B performance, respectively.

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