Transmission Performance of Half-Symbol-Rate-Carrier Offset QPSK Modulation in Band-limited Channels

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***Abstract*—**This paper examines the BER performance of the recently proposed half-symbol-rate-carrier (HSRC) offset quadrature phase-shift-keying (OQPSK) receiver for high-speed data communication. A modified demodulation technique using a bit-time period signal integration, the bit-error-rate (BER) performance of the HSRC-OQPSK signal improves more than 4dB compared to that of a demodulation technique using a symbol-time period integration. This paper also examines the BER performance of modified demodulation with various band-limited channels modeled using low-pass filters, and the three different data-rate systems are simulated and compared with the performance of the system using the conventional demodulation technique.

***Index Terms*—**half-symbol-rate-carrier, phase-shift-keying, BER, band-limited channel, high-speed data communications.

I. INTRODUCTION

The demand for high-speed data communication over low-cost bandwidth-limited channels such as a printed wiring board (PWB) has rapidly increased. Recently, half-symbol-rate-carrier (HSRC)-offset quadrature phase-shift-keying (QPSK) modulation based on QPSK modulation has been proposed and demonstrated its feasibility of increasing data-rate in wire-line communications [1]. The modulation technique uses two orthogonal half-symbol-rate-carrier signals to construct quadrature modulations and reduces the transmitted signal bandwidth by 25% compared to non-return-to-zero (NRZ) signal which is widely used in high-speed communications [1]. However, the bit-error-rate (BER) performance of the modulation is degraded due to the low energy modulated signal [2].

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This paper introduces a practical model for evaluating the bit-error-rate (BER) performance of the HSRC-OQPSK, which provides a more feasible BER result of the HSRC-OQPSK modulation. In order to estimate the channel effect to the BER performances of the modified demodulation, the behavior of band-limited channels modeled using one-pole low-pass filters and the results are compared to that of NRZ signaling.

In addition, the BER performances of the modified demodulation of the HSRC-OQPSK with various data-rate systems are simulated.

II. HSRC-OQPSK SIGNALING

[1] introduced the HSRC-OQPSK modulation to reduce the bandwidth of the transmitted signal through the wire-line channel for the high-speed data communications, Fig. 1 shows the HSRC-OQPSK modulation scheme and the theoretical time domain waveforms, respectively [1].

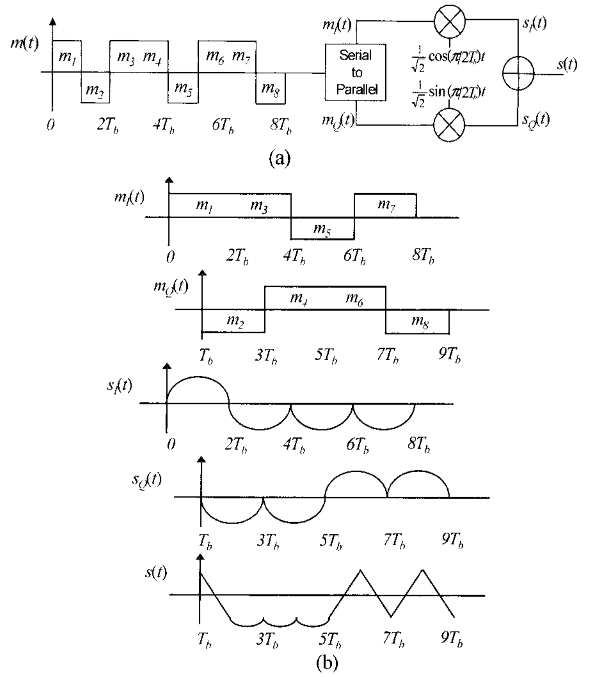

Fig. 1 HSRC-OQPSK (a) modulation scheme (b) time-domain waveforms

III. MODIFIED HSRC-OQPSK DEMODULATION

Generally, a demodulation with a matched filter offers maximum BER performance to the PSK modulation [3]. A matched filter at the receiver integrates the received signal over the symbol period. However, the HSRC-OQPSK modulation cannot provide the maximum BER performance with this matched filter scheme due to the violation of the orthogonality of the modulated signal [2].

This section investigates a demodulation scheme which offers the more reasonable performance of a HSRC-OQPSK demodulator for the high-speed data communication. Fig. 2 shows conceptual demodulation architecture of the HSRC-OQPSK receiver. Flip-flops are used for I/Q demodulators for each I/Q channel because it is very difficult to realize an analog integrator for the demodulation at such a high frequency range (GHz). The input buffer amplifies the incoming signal followed by I and Q channel mixers. I and Q channel mixers demodulate the received signal using the quarter data-rate carrier signals. The Flip-flops are followed by I/Q mixers which determine the retimed data of I and Q channels. The receiver architecture using a carrier recovery loop based on the Costas loop has been also introduced in [4].

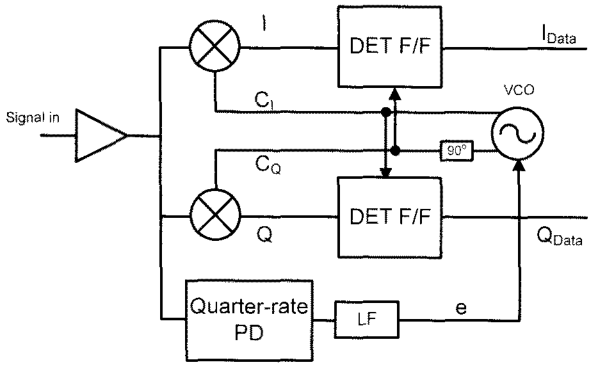

Fig. 2 A conceptual demodulation architecture for the HSRC-OQPSK receiver.

The BER performance of the HSRC-OQPSK modulation has been analyzed with a matched filter scheme in detail, and the result shows the more than 7dB BER degradation compared to that of NRZ modulation [2]. However, this is not an optimal result because the demodulation with a matched filter scheme does not offer the best BER performance due to the loss of orthogonality of the modulated signal. As shown in Fig 3, the negative values of the demodulated signal at the periods of the first and the last half bit make the signal energy lower, thus the BER performance of the receiver is degraded. Therefore, it is necessary to select the partial period out of the 2bit-time period to maximize the BER performance, which represents the more realistic model of the HSRC-OQPSK receiver using flip-flops to describe the actual behavior of fetching data at the center of the symbol period.

Fig. 3 (a) shows the incoming modulated signal at the receiver and the carrier signal, C_I or C_Q. The symbols' energies are analyzed in [2]. The BER performance of the HSRC-OQPSK is different from that of the conventional OQPSK, due to the existence of three different symbol energies – namely, $E_{s,t}$, $E_{s,f}$, $E_{s,p}$, which are caused by a violation of the orthogonality of carrier signals [2]. Since data are changed every 1-bit time in the HSRC-OQPSK modulation, the orthogonality of the carrier signal is no longer valid over the period of $[0, T_b]$. The signal's energy that are represented as $E_{s,t}$, $E_{s,f}$, $E_{s,p}$ correspond to the signals whose periods are T_b~$3T_b$, $3T_b$~$5T_b$, $5T_b$~$7T_b$ in Fig. 1(b), respectively. The peak signal ($E_{s,p}$) has the lowest symbol energy which mainly determines the BER performance of the HSRC-OQPSK receiver [2].

In the demodulation process, the incoming signal is mixed with a carrier signal at the receiver, and the mixed signal's peak signal ($E_{s,p}$) is at node I, as shown in Fig 3(a). The first half and the last half's bit time of the demodulated signal shown in Fig. 3(b), has negative values. Therefore, the integrated signal of the demodulated signal over the period of $2T_b$ has lower value than that of the signal over the period of $0.5T_b$~$1.5T_b$.

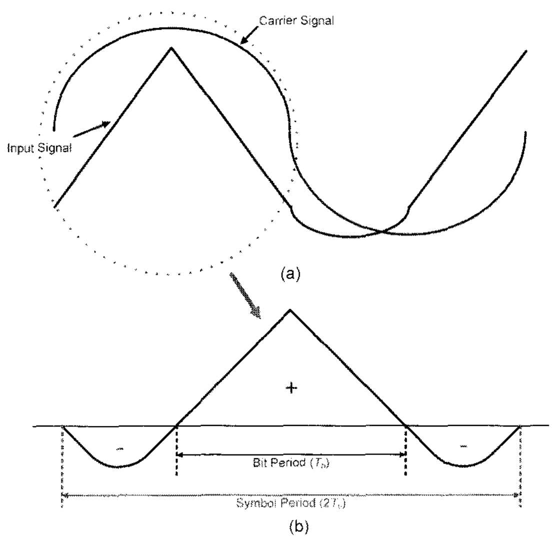

Fig. 3 The demodulated signal (a) demodulation process of I (or Q) channel (b) demodulated peak signal ($E_{s,p}$) of the HSRC-OQPSK

The signal energy over the time period of $T_b/2 \sim 3T_b/2$ is calculated as (1).

$$E'_{s,p} = 2\cdot\sqrt{2}A_c^2\int_{\frac{T_b}{2}}^{T_b}\cos\left(\frac{\pi t}{2T_b}+\frac{\pi}{4}\right)\cdot\sin\left(\frac{\pi t}{2T_b}\right)dt = \frac{1}{2}\cdot E_{s,t} \quad (1)$$

Since the BER performance of the HSRC-OQPSK modulation is mainly determined by the lowest energy symbol($E_{s,p}$) [3], the BER performance with the symbol energies of (1) can be represented as (2) approximately.

$$P_e \approx \frac{1}{4}\cdot Q\left(\left(\frac{1}{2}\right)\sqrt{\frac{2E_b}{N_0}}\right) \quad (2)$$

Fig. 4 shows the theoretical BER performance using (2) and simulated BER performance. From the simulation results, the difference of the BER performances between the theoretical PAM-2 (NRZ) and the HSRC-OQPSK is approximately 4dB, which means the modified demodulation scheme improves the BER performance by approximately 4dB compared to that of the matched filter scheme.

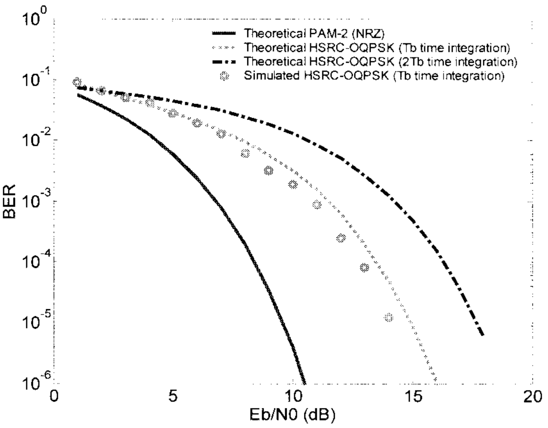

Fig. 4 Comparison of the BER performances between the matched filter scheme ($2T_b$ integration) and the modified scheme ($1T_b$ integration).

IV. BER PERFORMANCE

This section examines the BER performances for various band-limited channels and data-rate systems. In order to simulate the BER performance in various band-limited channels such as a copper wire, band-limited channels modeled with simple low-pass filters represented in (3) are used for the simulation. The modeled band-limited channels have the channel losses of 0.5dB/GHz, 0.75dB/GHz, and 1dB/GHz respectively. The transfer functions are given (3) and Fig. 5 shows the frequency responses of (3).

$$H(s) = \begin{cases} \dfrac{4\cdot 10^{10}}{s+4\cdot 10^{10}} & \text{- 0.5dB/GHz} \\ \dfrac{3\cdot 10^{10}}{s+3\cdot 10^{10}} & \text{- 0.75dB/GHz} \\ \dfrac{2\cdot 10^{10}}{s+2\cdot 10^{10}} & \text{- 1.0dB/GHz} \end{cases} \quad (3)$$

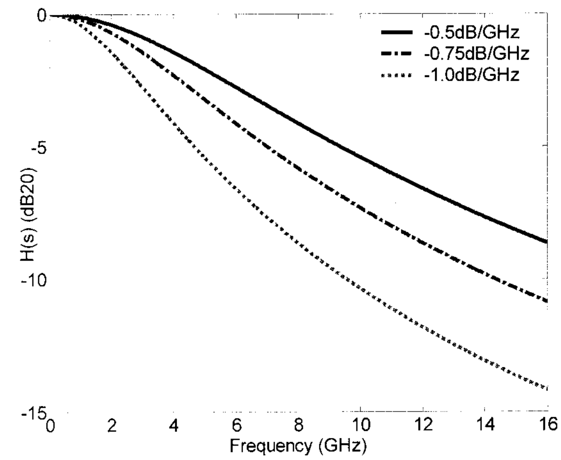

Fig. 5 Frequency responses of the band-limited channel modeled with one-pole low-pass filters.

Fig. 6 shows the simulated BER performances of the HSRC-OQPSK modulation and the NRZ modulation using a channel which has a loss of 0.75dB/GHz. In the previous section, the theoretical BER performance of the modified demodulation scheme has been analyzed. The difference between the BER performances of the NRZ and the HSRC-OQPSK modulations are approximately 4dB.

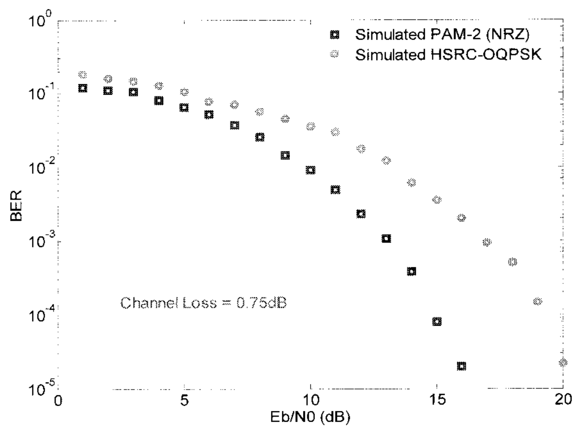

Fig. 6 Comparison of simulated BER performance of the PAM-2 (NRZ) and HSRC-OQPSK modulation with band-limited channel.

The signals lose their energy of 4dB by the band-limited channel. However, the simulation result shows that the theoretical analysis is still valid in a band-limited channel as shown in Fig.6. Moreover, the difference between the BER performance of the NRZ and the HSRC-OQPSK modulations are reduced by 0.5dB approximately, which means the HSRC-OQPSK modulation is more effective than the NRZ modulation in a band-limited channel. Because the HSRC-OQPSK has the same spectrum of minimum shift-keying (MSK), we can expect that the HSRC-OQPSK modulation has better performance in band-limited channels such as the MSK modulation [5].

Fig. 7 shows that the simulated results of the 10Gbps HSRC-OQPSK receiver of $2T_b$ integration and modified $1T_b$ integration demodulation with two band-limited channels modeled in (3). For the simulation, the two of -0.5dB/GHz, -0.75dB/GHz band-limited channels are used for both the modified demodulation scheme ($1T_b$ integration) and the matched filter scheme ($2T_b$ integration). As expected from the theoretical analysis, approximately more than 4dB less signal energy is required to get the same BER performance of that of the demodulation scheme using the symbol-period ($2T_b$) integration. Moreover, the improvement of the BER performance of the modified demodulation scheme is more effective in the band-limited channel from the simulation result.

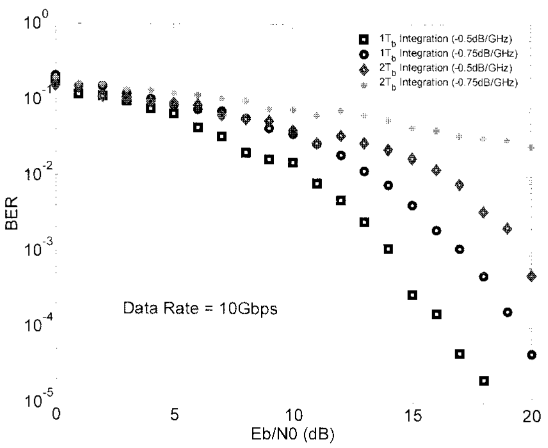

Fig. 7 The Comparison of the BER performances between the modified demodulation of $1T_b$ and $2T_b$ integration schemes using the band-limited channels modeled with one-pole low-pass filters.

Fig. 8 shows the BER performance of the HSRC-OQPSK receiver with various data-rates; 5Gbps, 10Gbps, and 15Gbps. The channel loss of 0.75dB/GHz is used for the simulation. From the frequency response of the band-limited channel shown in Fig. 5, the higher data-rate signal loses more signal energy than the lower data-rate signal in the band-limited channel. As expected, the required signal to noise ratio per bit (E_b/N_0) to achieve the same BER performance is proportional to the data-rate due to the greater energy loss.

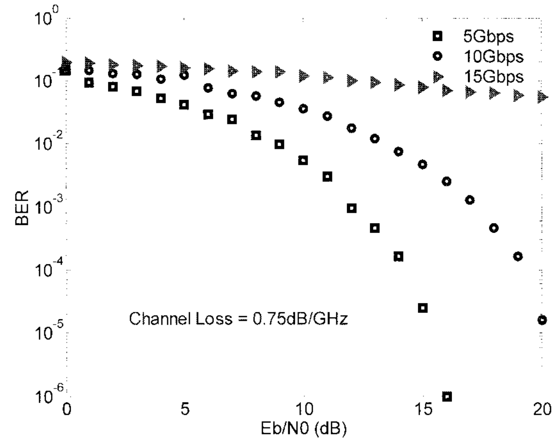

Fig. 8 Frequency responses of the band-limited channel modeled with a one-pole low-pass filter.

V. CONCLUSIONS

A modified demodulation method for HSRC-OQPSK signal which is recently proposed for the high data-rate communication over the wire-line is examined in this paper. A modified demodulation uses a bit-period (T_b) instead of a symbol-period ($2T_b$) for the integration of the demodulated signal. From the simulation results, more than 4dB of the BER performance has been improved compared to that of the demodulation method using a symbol-period ($2T_b$) integration as expected from the theoretical analysis. 4dB difference of the BER performance between the HSRC-QOPSK with modified demodulation and PAM-2 is well matched with a theoretical one.

This paper also investigated the BER performance with various data-rate transmission systems and compared with those of the conventional ones. The results show that the modified demodulation scheme can also be effective in the various data-rate systems.

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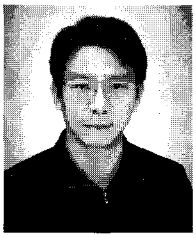

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