A Hybrid DQPSK-MPPM Technique for High Sensitivity Optical Communication Systems

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***Abstract*—A new class of advanced optical modulation formats, which has a better performance than traditional ones and is suitable for high sensitivity transmission, is proposed. This technique is based on combinations of both MPPM and DQPSK modulation techniques.**

I. Introduction

One of the most important issues to many optical communications systems is the receiver sensitivity. Indeed, when increasing the receiver sensitivity, less number of signal photons per bit can be transmitted to achieve a given bit-error rate (BER) [1]. One of the preeminent modulation schemes for increasing the receiver sensitivities in optical communications systems is direct-detection differential quadrature phase shift keying (DD-DQPSK) [2]. DQPSK is one of the most popular receivers for multilevel phase-modulated optical communications systems and is more bandwidth efficient than differential binary phase shift keying (DBPSK) but with the price of increased complexity. DD-DQPSK can be demodulated using an optical delay demodulator so that it avoids the need of an optical local oscillator [2]. Of course using DD-DQPSK significantly simplifies the receiver implementation. In this paper we propose a hybrid differential quadrature phase shift keying-multipulse pulse-position modulation (DQPSK-MPPM) technique assuming optical amplifier-noise limited systems in an attempt to increase further the receiver sensitivity of optical communications systems. The key idea here is to use DQPSK on top of an energy efficient modulation scheme, e.g., MPPM, in order to gain the advantages of both schemes. It turned out that the proposed system would enhance the performance of traditional DBPSK, DQPSK, and MPPM techniques.

II. Hybrid DQPSK-MPPM System Model

Our proposed hybrid DQPSK-MPPM transmitter is shown in Fig. 1. The transmitter sends data symbols within time frames. Each time frame has a duration T and is composed of M disjoint slots. Optical pulses (each of pulsewidth $\tau = T/M$) are signaled within n slots of each time frame. A block

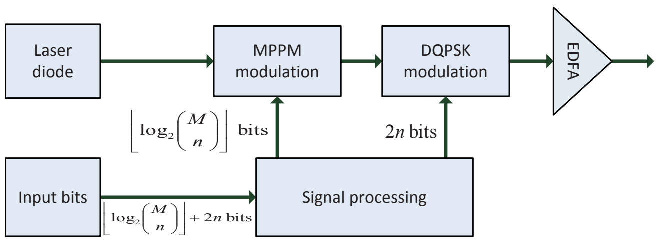

Fig. 1: Block diagram of the hybrid DQPSK-MPPM transmitter.

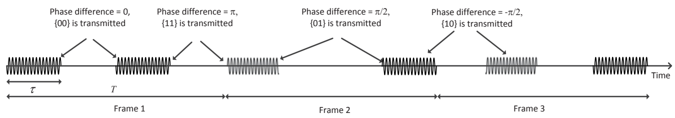

Fig. 2: An example of the transmitted signal of a hybrid DQPSK-MPPM scheme with $M = 4$ and $n = 2$.

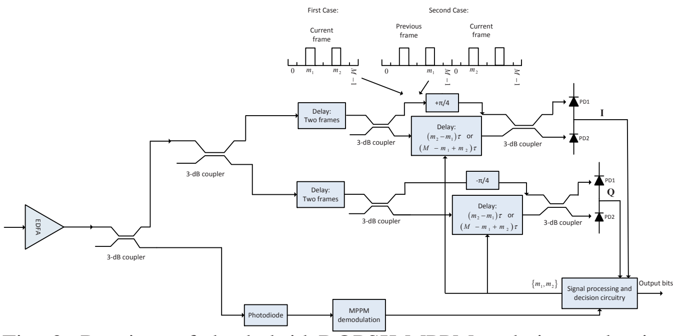

Fig. 3: Receiver of the hybrid DQPSK-MPPM technique adopting DQPSK optical delay detection.

of $\left\lfloor \log_2 \binom{M}{n} \right\rfloor + 2n$ bits are transmitted each time frame as follows. The first $\left\lfloor \log_2 \binom{M}{n} \right\rfloor$ bits are encoded using MPPM scheme. These bits would identify the positions of the n pulses within the frame. Each MPPM optical pulse is then DQPSK modulated using an additional two bits. That is, compared with traditional DQPSK, instead of transmitting a consecutive stream of DQPSK pulses (each with a relatively low power), we transmit less number of high-power DQPSK pulses. The positions of these pulses within the frames are identified using more data bits. An example of the transmitted signal of a hybrid DQPSK-MPPM scheme with $M = 4$ and $n = 2$ is shown in Fig. 2.

At the receiver side, the received signal is first split into two branches using a 3-dB coupler, Fig. 3. The lower branch is composed of a traditional direct-detection MPPM receiver in order to identify the positions of the received n pulses within the frame. In the upper branch, the DQPSK data is directly detected.

In the upper branch, the DD-DQPSK demodulation needs the received optical signal to be split through two asymmetric interferometers with phase difference of $\pi/2$ [2]. As shown in the figure, the received optical signal is further divided into two parts, one part is variably delayed depending on the positions of the previous and current signal slots being compared. If the previous and current signal slots being compared exist in the same frame, the delay is $(m_2 - m_1)\tau$, where $m_1 \in \{0, 1, \ldots, M-2\}$ and $m_2 \in \{m_1 + 1, m_1 + 2, \ldots, M-1\}$

are the positions of the previous and current signal slots, respectively. On the other hand, if the previous and current signal slots being compared exist in different frames, the delay is $(M - m_1 + m_2)\tau$, where $m_1, m_2 \in \{0, 1, \ldots, M-1\}$. The output of DQPSK receiver depends on the phase difference between any two neighboring pulses and is used by the decision circuit to determine the DQPSK bits. It should be noticed that the delay by two time frames in the upper branch is to guarantee the availability of information about both m_1 and m_2 from the lower branch. As seen from Fig. 3, the BER of the hybrid system depends on both current and previous frames. We obtain an upper bound of the BER of the proposed hybrid DQPSK-MPPM technique by considering the worst case scenario. That is, we assume that all the n positions are incorrectly decoded whenever an MPPM frame is incorrectly detected. This upper bound can be written as [3]:

$$\begin{aligned}\mathrm{BER}_{Hybrid} \le \frac{1}{N+2n}\Bigg[&\mathrm{SER}_{MPPM}\left(\frac{N2^N}{2(2^N-1)}+n\right)\\ &+(1-\mathrm{SER}_{MPPM})\,\mathrm{SER}_{MPPM}\,(1-2\,\mathrm{BER}_{DQPSK})\\ &+(1-\mathrm{SER}_{MPPM})\,2n\,\mathrm{BER}_{DQPSK}\Bigg].\end{aligned} \tag{1}$$

where SER_{MPPM} is the symbol-error rates (SER) of MPPM data, BER_{DQPSK} is the BER of DQPSK data bits on top of the current MPPM frame, and $N = \left\lfloor \log_2 \binom{M}{n} \right\rfloor$. The SER_{MPPM} is given by [4] with slight modifications. Also, BER_{DQPSK} can be found in [2].

III. Numerical Results

In Figs. 4 and 5 we plot the BER versus average received optical power for both hybrid DQPSK-MPPM and traditional systems. All systems under comparisons are assumed to have same transmission data rate (R_b) and bandwidth except for traditional DQPSK system (comparison with traditional DQPSK system cannot be made under same R_b and bandwidth simultaneously), we assume that traditional DQPSK system has same R_b but half the bandwidth of other systems under comparison. It can be seen from both figures that the performance of the hybrid system improves as M increases. Indeed the energy efficiency of the system improves by increasing M. Also it can be seen that the proposed DQPSK-MPPM system performs better than corresponding traditional DBPSK, DQPSK and MPPM systems. Specifically from Fig. 4, for the proposed DQPSK-MPPM system with $M = 20$ and $n = 4$, there is an improvement of about 2.4 dB at $\mathrm{BER} = 10^{-9}$ when compared to the polarized DBPSK system. And there is an improvement of about 1.5 dB at $\mathrm{BER} = 10^{-9}$ for hybrid DQPSK-MPPM system (of $M = 36$ and $n = 3$) when compared with traditional MPPM system (of $M = 36$ and $n = 5$). The reason behind this improvement is because hybrid system has higher peak power per slot as compared to corresponding traditional systems under the aforementioned constraints.

IV. Conclusion

A hybrid DQPSK-MPPM modulation technique has been proposed for high sensitivity optical communications systems.

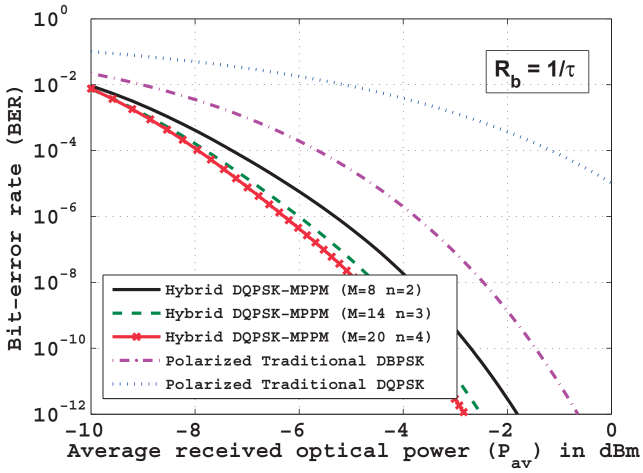

Fig. 4: Average bit-error rate versus average received optical power for proposed DQPSK-MPPM systems, traditional DBPSK, and traditional DQPSK systems with $\sigma_n^2 = 1.6 \times 10^{-5} A^2$.

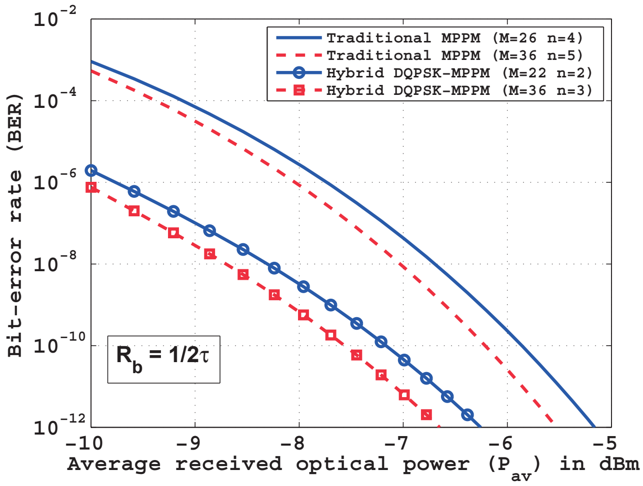

Fig. 5: Average bit-error rate versus average received optical power for both hybrid DQPSK-MPPM and traditional MPPM systems with $\sigma_n^2 = 1.6 \times 10^{-5} A^2$.

A simple detection mechanism, based on direct-detection DQPSK receivers, has been proposed and studied. Our results reveal that the proposed technique is more power efficient than traditional ones and has an improved BER and receiver sensitivity.

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