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Hybrid direct-detection differential phase shift keying-multipulse pulse position modulation techniques for optical communication systems

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ABSTRACT

In this paper, a hybrid differential phase shift keying-multipulse pulse position modulation (DPSK–MPPM) technique is proposed in order to enhance the receiver sensitivity of optical communication systems. Both binary and quadrature formats are adopted in the proposed systems. Direct-detection DPSK schemes that are based on an asymmetric Mach–Zehnder interferometer with a novel ultrafast discrete delay unit are presented to simplify the receiver implementation. Expressions for the bit-error rate (BER) of the proposed hybrid modulation techniques are derived taking into account the effect of the optical amplifier noise. Under the constraints of the same transmitted data rate, bandwidth, and average received optical signal-to-noise ratio, the BER performances of the proposed schemes are then evaluated numerically and compared with that of traditional differential binary phase shift keying (DBPSK), differential quadrature phase shift keying (DQPSK), and MPPM schemes and with that of recent hybrid schemes. Furthermore, a comparison between the proposed systems and the traditional ones is held in terms of the bandwidth-utilization efficiency. Our results reveal that the proposed hybrid schemes are more energy-efficient and have higher receiver sensitivity compared with the traditional ones while improving the bandwidth-utilization efficiency. The proposed DPSK–MPPM system is ready to accommodate adjustable (or variable) bit rates, by virtue of the programmable delay integrated to the receiver system.

1. Introduction

The sensitivity of the receiver is one of the most important issues for many optical communication systems. Higher receiver sensitivity implies less number of transmitted signal photons per bit at the same bit-error rate (BER) [1]. Among the preeminent modulation schemes of optical communication systems featuring high receiver sensitivities are differential binary phase shift keying (DBPSK) and differential quadrature phase shift keying (DQPSK) [2]. On the other hand, DQPSK is one of the most popular receivers for multilevel phase-modulated optical communication systems and is more bandwidth efficient than DBPSK. Optical differential phase shift keying (DPSK) signals can be directly detected using an asymmetric Mach–Zehnder interferometer. This simplifies the receiver implementation and avoid the need for optical local oscillators and microwave carrier recovery circuits.

Recently, several ideas for optical hybrid-modulation systems have been suggested so as to enhance the sensitivity of the receiver. Liu et al. presented a combination of m-ary pulse position modulation (PPM) or m-ary frequency-shift keying (FSK) with additional polarization and/or phase modulation [1,3]. The first experimental realization was then carried out in [4] of hybrid polarization-multiplexed-2PPM-quadrature phase-shift keying (PM-2PPM-QPSK) modulation for long-haul transmission at a data rate of 42.8 Gbit/s. As a good step to improve the performance of both traditional binary phase shift keying (BPSK) and multipulse pulse position modulation (MPPM) techniques in optical fiber communications, Selmy et al. proposed hybrid BPSK–modified MPPM, which surpasses the traditional BPSK and MPPM techniques [5]. A hybrid orthogonal frequency-division multiplexing-pulse-position modulation (OFDM-PPM) technique was then proposed in [6] for free-space optical communications (FSO). Furthermore, Shi et al. proposed a hybrid polarization-division-multiplexed quadrature phase-shift keying-MPPM (PDM-QPSK-MPPM) for FSO [7].

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In an attempt to increase further the receiver sensitivity of optical communication systems, in this paper, we propose hybrid differential phase shift keying-multipulse pulse position modulation (DPSK–MPPM) techniques. The key idea here is to use the sensitivity- and spectrally- efficient DPSK scheme along with an energy-efficient modulation scheme, such as MPPM [8], in order to integrate the advantages of both schemes. We study the implementation and evaluate the performance of both DBPSK and DQPSK formats. This is the first time that a hybrid modulation scheme for optical communication systems is based on direct-detection DPSK (DD-DPSK). This significantly simplifies the receiver implementation as there is no longer need for optical local oscillators or microwave carrier recovery circuits.

To evaluate the performance of the proposed modulation techniques, we derive expressions for the achieved bit-error rate (BER), under the assumption of optical amplifier-noise limited systems (which is realistic for long-haul optical fiber communication systems [2]). In addition, we compare the performance of the proposed modulation techniques to that of traditional DBPSK, DQPSK, and MPPM techniques. Different design parameters such as BER and bandwidth-utilization efficiency, are addressed in our comparisons, under the same conditions of data rate, bandwidth, and average received optical signal-to-noise ratio.

The rest of the paper is organized as follows. The system description and receiver model are presented in Section 2. Section 3 is devoted for the derivation of a BER expression for the proposed hybrid systems. Optical amplifier-noise limited systems are assumed during our derivation. In Section 4, we compare the performance of the proposed hybrid systems to that of traditional systems, under the same conditions of transmission data rate, bandwidth, and average received optical signal-to-noise ratio. Also, we compare the performance of our systems to some of similar hybrid systems in the literature. Finally, our conclusions are given in Section 5.

2. Hybrid DPSK–MPPM system model

In this section we describe the proposed hybrid DPSK–MPPM system model, including both the transmitter and the receiver. In addition, we give an example of the transmitted hybrid signal.

2.1. Transmitter side and signal example

Our proposed hybrid 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. Coherent optical pulses (each of pulsewidth $\tau = T/M$) are signalled within n slots of each time frame. A block of $\left\lfloor \log_2\binom{M}{n} \right\rfloor + p$ bits are transmitted each time frame, where

$$p = \begin{cases} n & \text{for DBPSK}, \\ 2n & \text{for DQPSK}. \end{cases} \quad (1)$$

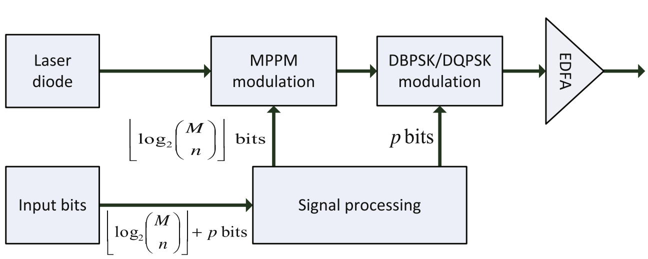

Fig. 1. Block diagram of the hybrid transmitter.

The first $N = \lfloor \log_2\binom{M}{n} \rfloor$ bits are encoded using the MPPM scheme. These bits would identify the positions of the n pulses within the frame. Each MPPM optical pulse is then DBPSK or DQPSK modulated using an additional q bits, where $q=1$ in the case of DBPSK and $q=2$ in the case of DQPSK. That is, compared with traditional DPSK, instead of transmitting a consecutive stream of DPSK pulses (each with a relatively low power), we transmit less number of higher power DPSK pulses. The positions of these pulses within the frames are identified using more data bits. An example of the transmitted signal of a hybrid DBPSK–MPPM scheme with $M=4$ and $n=2$ is shown in Fig. 2.

2.2. Receiver side

Figs. 3 and 4 show the receiver sides of both DBPSK–MPPM and DQPSK–MPPM techniques, respectively. The received signal is first split into two branches using a 3-dB coupler. 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 DPSK data is directly detected.

The DD-DBPSK receiver is implemented using the asymmetric Mach–Zehnder interferometer with balanced detection [2]. As shown in Fig. 3, the received optical signal is further splitted into two portions with one portion subject to programmable discrete delay based on the positions of the previous and current signal slots being compared. In Section 2.2.1, we present a novel ultrafast delay unit (see the schematic diagram in Fig. 5) capable of applying discrete optical delays at switching speeds up to 40–50 Gb/s (as fast as symbol rates) [9,10]. 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 $m_1, m_2 \in \{0, 1, \ldots, M-1\}$ are the positions of the previous and current signal slots, respectively. It should be noticed that the signal processing and decision circuitry set the value of the binary control for the ultrafast discrete delay unit depending on the value of the required delay.

It is worth mentioning that the output of DBPSK receiver depends on the phase difference between any two neighboring pulses and is used by the decision circuit to determine the DBPSK bit. 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.

It should be noticed that the demodulation of DD-DQPSK, as shown in Fig. 4, is done in a similar way to DD-DBPSK except for

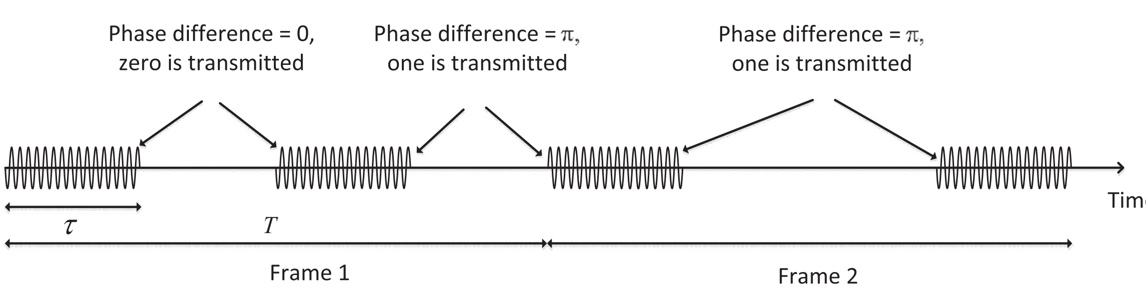

Fig. 2. An example of the transmitted signal of a hybrid DBPSK–MPPM scheme with $M=4$ and $n=2$. The phase differences due to DBPSK modulation are also shown.

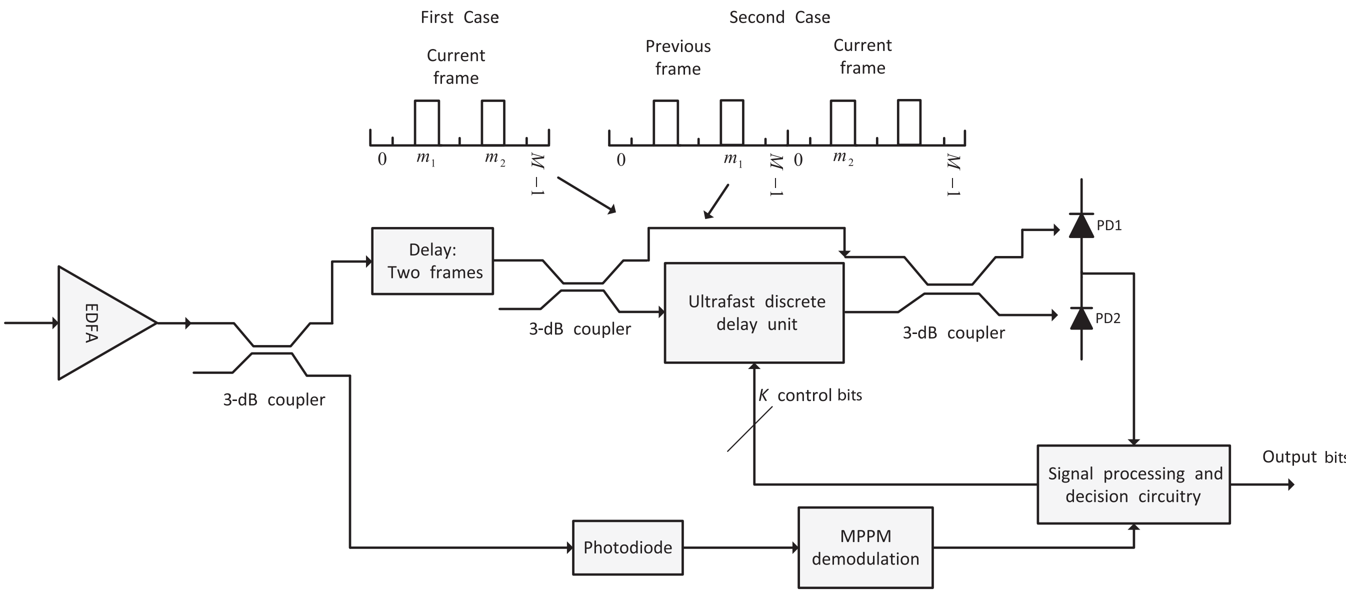

Fig. 3. Receiver of the hybrid DBPSK–MPPM technique adopting asymmetric Mach–Zehnder interferometer.

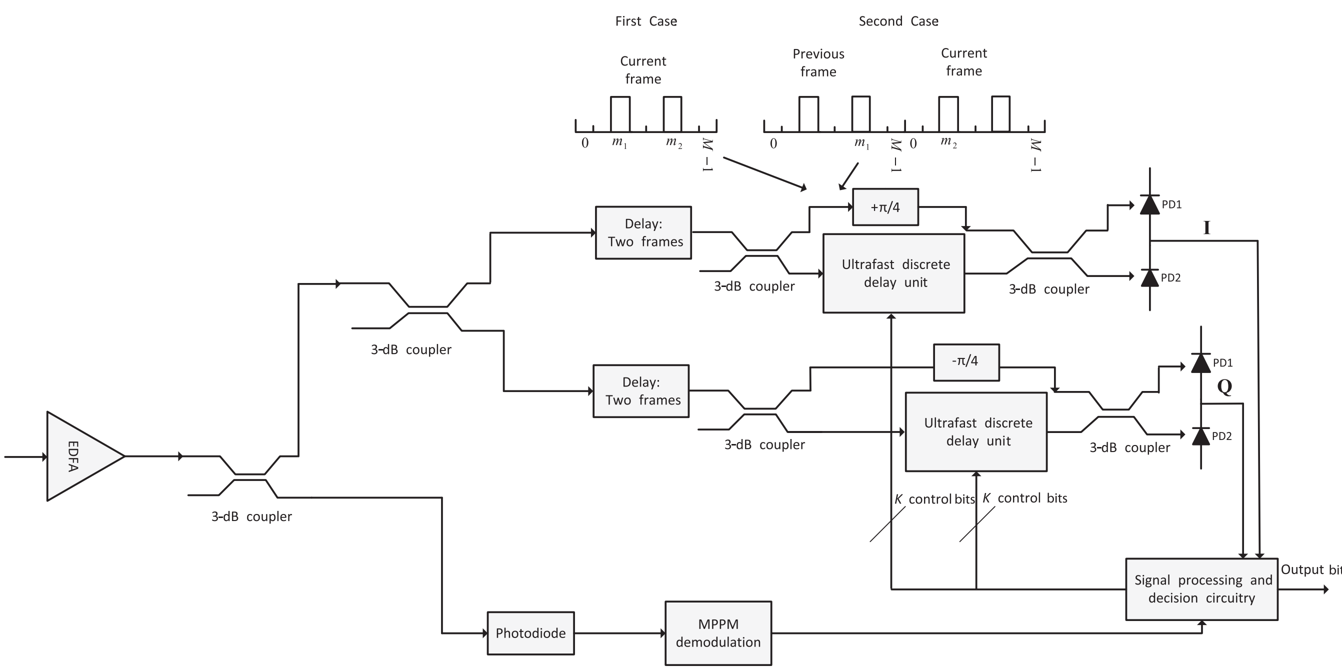

Fig. 4. Receiver of the hybrid DQPSK–MPPM technique adopting asymmetric Mach–Zehnder interferometer.

that DD-DQPSK demodulation needs the received optical signal to be split through two asymmetric interferometers with phase difference of $\pi/2$.

2.2.1. Phase- and polarization-preserving ultrafast discrete delay unit

In this subsection, we present a novel ultrafast discrete delay unit capable of preserving the state of polarization (SOP) and the phase of the input pulse. Consider a linearly polarized optical pulse fed into an electro-optic (EO) modulator whose two operational states; either to leave the SOP unchanged or to flip it to the orthogonal state [11]. The EO modulator is followed by a highly birefringent polarization-maintaining single-mode (PMSM) fiber of length L oriented such that its slow and fast axes are precisely aligned with the two possible SOPs emerging from the EO modulator. It is well known that, by virtue of its highly asymmetric structure or refractive-index [12], PMSM fiber allows guiding two principal SOP of monochromatic light at strict timing and phase relations without significant distortion. This feature highlights the merit of the PMSM fiber as a precise optical delay line preserving the phase information. Therefore, this simple apparatus can switch between two possible delay times; either $\tau_s = L/v_g^{slow}$ corresponding to the group velocity of the slow axis v_g^{slow}, or $\tau_f = L/v_g^{fast}$ corresponding to the group velocity of the fast axis v_g^{fast}, based on the binary control of the EO modulator (set by the signal processing and decision circuitry as shown in Figs. 3 and 4).

Now consider a series of K of such delay stage with each one equipped with PMSM fiber segment of length R-multiples of that of the preceding one (see the schematic diagram in Fig. 5). The fast and slow axes of all fiber segments and the EO modulators are aligned together, so that the manipulation of the SOP along the cascaded stages can assign the delay time of the emerging optical pulse to be one of the 2^K choices $\{\tau_f \sum_{i=0}^{K-1} R^i;\ \tau_s + \tau_f \sum_{i=1}^{K-1} R^i;\ R\tau_s + \tau_f(1 + \sum_{i=2}^{K-1} R^i);$

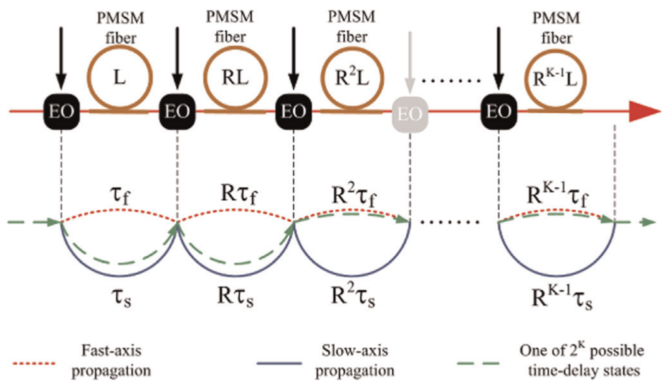

Fig. 5. Schematic diagram for K stages of the proposed ultrafast discrete delay unit. At a stage i, an input pulse is delayed based on the setting of the EO modulator either by $R^i\tau_f$ (fast-axis propagation) or by $R^i\tau_s$ (slow-axis propagation). The K binary inputs of the EO modulators therefore program the delay system to one of 2^K time-delay states.

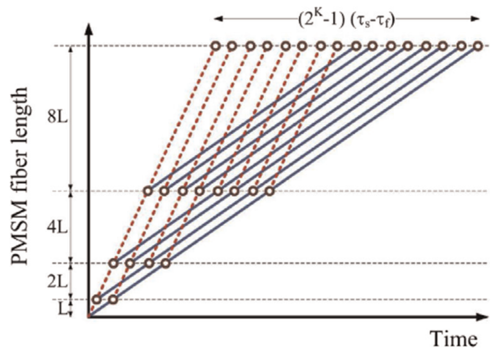

Fig. 6. Timing diagram for propagation through 1-, 2-, 3-, and 4-stages PMSM fibers when $R=2$. The red-dashed lines denote the fast-axis propagation and the blue-solid lines denote slow-axis propagation. The slope of the red-dashed and the blue-solid lines are the group velocities for fast-axis and slow-axis propagations, respectively. Notice the exponential increase of the number of possible delay steps with the number of sequential stages.

$(1+R)\tau_s+\tau_f\sum_{i=2}^{K-1}R^i$; $R^2\tau_s+\tau_f(1+R+\sum_{i=3}^{K-1}R^i)$; …; $\tau_s\sum_{i=0}^{K-1}R^i\}$. For an optical pulse, input to the system at time t_0, it can be then positioned at 2^K different time instants, where the first time instant is at $t_0+\tau_f\sum_{i=0}^{K-1}R^i$.

In general, this train of time instants is separated either by fixed time interval $(\tau_s-\tau_f)$ or by variable intervals which are functions of the parameter R. However, a fixed time interval $(\tau_s-\tau_f)$ can be realized between all delay times under the condition $R=2$, as depicted in Fig. 6. This condition can be interpreted in analogy to the binary numbering system as there are only two possible operational states per stage.

An advantage with the proposed discrete delay system is the relatively short optical fiber required to realize optical delays, compared with other methods utilizing the wavelength tuning and chromatic dispersion [13]. To clarify this point, let us elaborate a quantitative example. To make an optical pulse span of 1.5 ns delay interval at steps of 0.1 ns, if a PMSM fiber with differential group delay about 29.3 ps/m near the wavelength 1550 nm [14] is used, a 51.19 m total fiber length is required along a number of 4 stages with the fiber length of the first stage about 3.41 m. The short fiber length serves the delay system by limiting the pulse broadening effects caused by dispersion. Hence, there is no need for pre- and post-compensators used to recover the pulse width in other delay control systems utilizing much longer optical fibers [13].

Another advantage is the capability of the system to manipulate high-rates of optical pulses. Because each stage can switch between two operational states independent from the neighboring stages, different optical pulses can be simultaneously handled while sequentially propagating along the system. Therefore, the rate of the proposed system is determined, in principle, by the switching rate of the used EO modulators. Fortunately, current technologies offer a plethora of ultrafast EO modulators. For example, recent advances of GaAs-, silicon-, and photonic-crystal-based EO modulator can reach data rates up to 40–50 Gbit/s [9,10,15].

One more advantage is that the optical pulse emerging from PMSM fiber has a well defined polarization and phase with respect to the input. It is easy thereby to compensate for the polarization and phase changes using two additional EO modulators. This feature is essential for time division schemes that require extracting the phase information in a subsequent measurement system (like the scheme presented in this paper). It worth mentioning that by integrating this tunable optical delay unit to the receiver system, the proposed DPSK–MPPM system is ready to operate at adjustable (or variable) data rates.

3. Bit error rate analysis of proposed hybrid modulation techniques in optical amplifier-noise limited channels

In this section we develop an expression for the BER of the proposed hybrid modulation techniques. In our analysis, we assume optical amplifier-noise limited systems. As seen from Figs. 3 and 4, 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 modulation techniques 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

$$\begin{aligned}\mathrm{BER}_{Hybrid} \le \frac{1}{N+p}\Bigg[& N\,\mathrm{BER}_{MPPM}^{current} + \frac{p}{2}\mathrm{SER}_{MPPM}^{current} \\ &+ \left(1-\mathrm{SER}_{MPPM}^{current}\right)\mathrm{SER}_{MPPM}^{previous}\left(\frac{q}{2}+(p-q)\mathrm{BER}_{DPSK}\right) \\ &+\left(1-\mathrm{SER}_{MPPM}^{current}\right)\left(1-\mathrm{SER}_{MPPM}^{previous}\right)p\,\mathrm{BER}_{DPSK}\Bigg],\end{aligned} \quad (2)$$

where $\mathrm{SER}_{MPPM}^{current}$ and $\mathrm{SER}_{MPPM}^{previous}$ are the symbol-error rates (SERs) of MPPM data in both current and previous frames, respectively, $\mathrm{BER}_{MPPM}^{current}$ is the bit-error rate (BER) of MPPM data in current frame, and BER_{DPSK} is the bit-error rate (BER) of DBPSK or DQPSK data bits on top of the current MPPM frame. The MPPM BER is given by [16]

$$\mathrm{BER}_{MPPM} \le \frac{1}{2}\frac{2^N}{2^N-1}\mathrm{SER}_{MPPM} \quad (3)$$

It should be noticed that in the case of incorrect detection of the current MPPM frame, the DPSK data bits on top of current MPPM frame will be decoded incorrectly with probability 1/2 but in the case of incorrect detection of the previous MPPM frame with correct detection of current MPPM frame, only the first q DPSK data bits on top of current MPPM frame will be decoded incorrectly with probability 1/2. Noticing that $\mathrm{SER}_{MPPM}^{current} = \mathrm{SER}_{MPPM}^{previous} \stackrel{def}{=} \mathrm{SER}_{MPPM}$, the last inequality can be simplified to

$$\begin{aligned}\mathrm{BER}_{Hybrid} \le \frac{1}{N+p}\Bigg[& N\,\mathrm{BER}_{MPPM} + \frac{p}{2}\mathrm{SER}_{MPPM} \\ &+ \left(1-\mathrm{SER}_{MPPM}\right)\mathrm{SER}_{MPPM}\left(\frac{q}{2}-q\,\mathrm{BER}_{DPSK}\right) \\ &+\left(1-\mathrm{SER}_{MPPM}\right)p\,\mathrm{BER}_{DPSK}\Bigg],\end{aligned} \quad (4)$$

To confirm that the last upper bound is tight, we obtain a lower bound of the BER of the proposed modulation techniques by considering the best case scenario. That is, we assume that only the last position of the

n positions is incorrectly decoded whenever a current MPPM frame is incorrectly detected and incorrect detection of the previous MPPM frame does not affect the first q DPSK data bits on top of current MPPM frame. This lower bound can be written as

$$\mathrm{BER}_{Hybrid} \geq \frac{1}{N+p}\left[N\,\mathrm{BER}_{MPPM} + \frac{q}{2}\mathrm{SER}_{MPPM} + (1-\mathrm{SER}_{MPPM})p\,\mathrm{BER}_{DPSK}\right], \tag{5}$$

where SER_{MPPM} is given by [17] with slight modifications:

$$\mathrm{SER}_{MPPM} = \sum_{l=1}^{M-n}\sum_{m=1}^{n}\int_0^\infty \binom{n}{m}\binom{M-n}{l} p_1\left(\frac{P_{min}}{\sigma_n^2}\right)^m \times \left(1 - P_1\left(\frac{P_{min}}{\sigma_n^2}\right)\right)^{n-m} P_0\left(\frac{P_{min}}{\sigma_n^2}\right)^{M-n-l} \times \left[\left(1 - P_0\left(\frac{P_{min}}{\sigma_n^2}\right)\right)^l + p_0\left(\frac{P_{min}}{\sigma_n^2}\right)^l\left(1 - \frac{1}{\binom{l+m}{m}}\right)\right]\frac{dP_{min}}{\sigma_n^2}, \tag{6}$$

where P_{min} denotes the minimum power in symbol signal slots and σ_n^2 is the variance per dimension of complex zero-mean white Gaussian noise in each polarization. $p_1(\cdot)$ denotes the probability-density function (pdf) of the power in a signal slot, which follows a noncentral chi-squared χ^2 distribution with noncentrality parameter $A^2 = MP_{av}/n$, where P_{av} denotes the average received optical power. Similarly, $p_0(\cdot)$ denotes the pdf of the power in a non-signal slot, which follows a χ^2 distribution. In addition, $P_0(\cdot)$ and $P_1(\cdot)$ denote the corresponding cumulative distributions to p_0 and p_1, respectively. For any $P_{min} \geq 0$, $p_1(\cdot)$ and $p_0(\cdot)$ are given by

$$p_1\left(\frac{P_{min}}{\sigma_n^2}\right) = \frac{1}{2}\left(\frac{P_{min}}{A^2}\right)^{k/4-1/2} e^{-(P_{min}+A^2)/2\sigma_n^2} I_{k/2-1}\left(\sqrt{P_{min}}\frac{A}{\sigma_n^2}\right)$$
$$p_0\left(\frac{P_{min}}{\sigma_n^2}\right) = \frac{\left(\frac{P_{min}}{\sigma_n^2}\right)^{k/2-1} e^{-P_{min}/2\sigma_n^2}}{2^{k/2}\Gamma(k/2)}, \tag{7}$$

respectively, where $I_c(\cdot)$ is the cth order modified Bessel function of the first kind, and k is the number of degrees of freedom, where $k=4$ in a non-polarized receiver and $k=2$ in a polarized receiver. Next, BER_{DPSK} can be found in [2] with slight modifications. For the case of DBPSK, we have

$$\mathrm{BER}_{DBPSK} = \begin{cases} \frac{1}{2}e^{\left[-\left(\frac{M}{n}\right)\frac{P_{av}}{2\sigma_n^2}\right]} & \text{for a polarized receiver,} \\ \frac{1}{2}e^{\left[-\left(\frac{M}{n}\right)\frac{P_{av}}{2\sigma_n^2}\right]}\left[1 + \left(\frac{M}{n}\right)\frac{P_{av}}{8\sigma_n^2}\right] & \text{for a non-polarized receiver.} \end{cases} \tag{8}$$

It is worth citing here the BER of traditional DBPSK [2]:

$$\mathrm{BER}_{DBPSK}^{traditional} = \begin{cases} \frac{1}{2}e^{-P_{av}/2\sigma_n^2} & \text{for a polarized receiver,} \\ \frac{1}{2}e^{-P_{av}/2\sigma_n^2}\left(1 + \frac{P_{av}}{8\sigma_n^2}\right) & \text{for a non-polarized receiver.} \end{cases} \tag{9}$$

While, for the case of DQPSK, we have [2]

$$\mathrm{BER}_{DQPSK} = \begin{cases} Q(a,b) - \frac{1}{2}e^{-(a^2+b^2)/2}I_0(ab) & \text{for a polarized receiver,} \\ Q(a,b) - \frac{1}{2}e^{-(a^2+b^2)/2}I_0(ab) + \frac{I_1(ab)}{8}e^{-(a^2+b^2)/2}\left(\frac{b}{a} - \frac{a}{b}\right) & \text{for a non-polarized receiver,} \end{cases} \tag{10}$$

where $Q(\cdot,\cdot)$ is the Marcum Q function,

$$a = \begin{cases} \sqrt{\frac{P_{av}M}{2n\sigma_n^2}\left(1 - \sqrt{1/2}\right)} & \text{for hybrid receiver,} \\ \sqrt{\frac{P_{av}}{2\sigma_n^2}\left(1 - \sqrt{1/2}\right)} & \text{for traditional receiver,} \end{cases} \tag{11}$$

and

$$b = \begin{cases} \sqrt{\frac{P_{av}M}{2n\sigma_n^2}\left(1 + \sqrt{1/2}\right)} & \text{for hybrid receiver,} \\ \sqrt{\frac{P_{av}}{2\sigma_n^2}\left(1 + \sqrt{1/2}\right)} & \text{for traditional receiver.} \end{cases} \tag{12}$$

4. Numerical results

In this section we compare between the performance of polarized systems adopting the proposed hybrid modulation techniques and that adopting traditional DBPSK, DQPSK, and MPPM techniques. Our comparisons are made under the same average received optical signal-to-noise ratio for both the proposed and the traditional systems. The average received optical signal-to-noise ratio ($OSNR_{av}$) is given by [2]

$$OSNR_{av} = \begin{cases} \frac{P_{av}}{2\sigma_n^2} = \frac{P_{av}}{S_{n_s}B_o} & \text{for a polarized receiver,} \\ \frac{P_{av}}{4\sigma_n^2} = \frac{P_{av}}{2S_{n_s}B_o} & \text{for a non-polarized receiver,} \end{cases} \tag{13}$$

where S_{n_s} is the spectral density of the received spontaneous emission per polarization and B_o is the optical bandwidth of the received optical filter. In addition, all systems under comparisons are assumed to have the same transmission data rate R_b. Furthermore, we assume that all systems have the same receiver bandwidth, except for traditional DQPSK systems (because the comparison with traditional DQPSK systems cannot be made under the same R_b and receiver bandwidth simultaneously). Thus, we assume that traditional DQPSK system has the same R_b but half the receiver bandwidth of other systems under comparison. This might lead to different frame parameters (n and M) in order to be able to satisfy these conditions:

$$R_b = \begin{cases} \frac{1}{\tau} & \text{for traditional DBPSK and DQPSK,} \\ \frac{\lfloor \log_2\binom{M}{n} \rfloor}{M\tau} & \text{for traditional MPPM system,} \\ \frac{\lfloor \log_2\binom{M}{n} \rfloor + p}{M\tau} & \text{for proposed hybrid systems,} \end{cases} \tag{14}$$

where the pulsewidth τ is held fixed to keep the above constraint on the receiver bandwidth.

To verify that the upper bound is tight, we plot both the lower and the upper bounds for the proposed DBPSK–MPPM system in Fig. 7 where $M=22$ and $n=6$. One can notice that the lower and the upper bounds are very close to each other. This emphasizes that the upper bound is tight to the exact BER expression. Therefore, all the following results are obtained using the BER upper bound expression in Eq. (4).

In Figs. 7 and 8 we plot the bit-error rates (BERs) of proposed hybrid DPSK–MPPM and traditional DPSK systems versus average received optical signal-to-noise ratio. Of course n should be increased by increasing M in order to keep the constraint on transmission rate

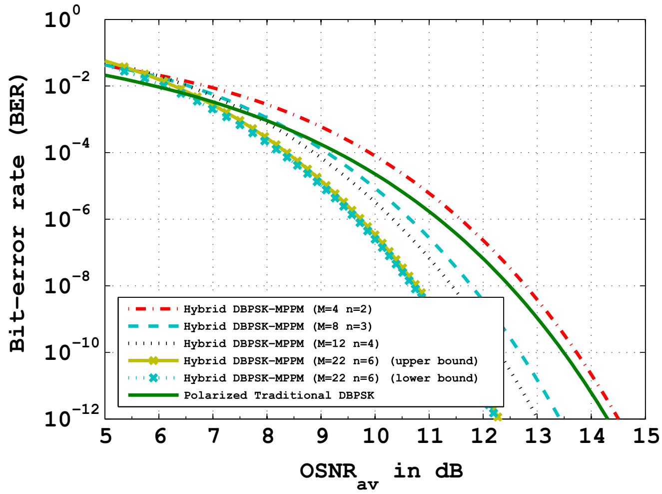

Fig. 7. Average bit-error rate versus average received optical signal-to-noise ratio for both proposed DBPSK–MPPM and traditional DBPSK systems.

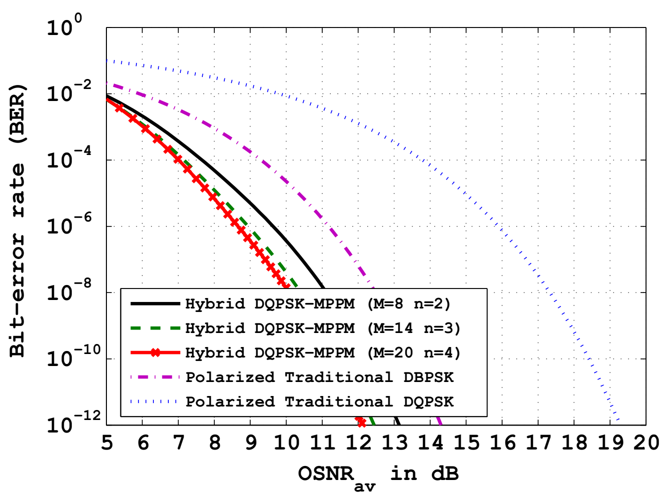

Fig. 8. Average bit-error rate versus average received optical signal-to-noise ratio for proposed DQPSK–MPPM system, traditional DBPSK, and traditional DQPSK systems.

fixed. It can be seen from the figures that the performance of the hybrid systems improves as M increases. Indeed, the energy efficiency of the systems improves by increasing M.

Also, it can be seen that the proposed systems perform better than the corresponding traditional DBPSK systems. Specifically from Fig. 7, for the proposed DBPSK–MPPM system with $M=22$ and $n=6$, there is an improvement of about 1.8 dB at BER = 10^{-9} when compared to polarized DBPSK system. Also it can be seen from Fig. 8 that for the proposed DQPSK–MPPM system with $M=20$ and $n=4$, there is an improvement of about 2.4 dB at BER = 10^{-9} when compared to the polarized DBPSK system.

The reason behind this improvement can be explained as follows. In the case of transmitting the same data rate at the same bandwidth and average received optical signal-to-noise ratio, hybrid systems have higher peak power per slot as compared to corresponding traditional DBPSK systems. This leads to a higher signal-to-noise ratio and improved BER. It should also be noticed from Fig. 8 that the proposed DQPSK–MPPM system outperforms traditional DQPSK system but under the condition that traditional DQPSK system receiver bandwidth is half the receiver bandwidth of proposed DQPSK–MPPM system.

Although traditional DBPSK system outperforms traditional DQPSK system [2], on the contrary it can be seen from Figs. 7 and 8 that the proposed DQPSK–MPPM system performs better than the proposed DBPSK–MPPM system. Specifically we notice that there is an improvement of about 1.6 dB at BER = 10^{-3} for the proposed DQPSK–MPPM system (of $M=8$ and $n=2$) when compared with DBPSK–MPPM system (of $M=8$ and $n=3$). The reason behind this improvement is because hybrid DQPSK–MPPM system has higher peak power per slot as compared to corresponding DBPSK–MPPM system in the case of transmitting the same data rate at the same bandwidth and average received optical signal-to-noise ratio. But this improvement is reduced to 0.5 dB at BER = 10^{-9} when increasing the average received optical signal-to-noise ratio. The reason behind this improvement reduction is because the influence of noise is reduced by increasing average received optical signal-to-noise ratio until a certain point. After this point, the situation reverses and becomes similar to traditional systems; DBPSK–MPPM system performs better than DQPSK–MPPM system.

Fig. 9 shows the receiver sensitivity improvement of the proposed systems over traditional DBPSK system at BER = 10^{-9} as a function of M, in the case of transmitting the same data rate at the same bandwidth. For all the values of M, the proposed systems surpass the traditional DBPSK system. Clearly, the improvement increases gradually with increasing M, until reaching its saturation at $M=18$ for proposed DBPSK–MPPM system and $M=20$ for proposed DQPSK–MPPM system.

In Figs. 10 and 11, we plot the bit-error rates of proposed hybrid and traditional MPPM systems versus average received optical signal-to-noise ratio. It can be seen from the figures that, under the above conditions, the hybrid systems perform better than corresponding traditional MPPM systems. Specifically, from Fig. 10 we notice that there is an improvement of about 2.2 dB at BER = 10^{-9} for hybrid DBPSK–MPPM system (of $M=16$ and $n=3$) when compared with traditional MPPM system (of $M=16$ and $n=5$). From Fig. 11, we notice that there is an improvement of about 1.5 dB at BER = 10^{-9} for hybrid DQPSK–MPPM system (of $M=36$ and $n=3$) when compared with traditional MPPM system (of $M=36$ and $n=5$). Again, the aforementioned improvements in the receiver sensitivity when transmitting the same data rate at the same bandwidth and average received optical signal-to-noise ratio is because the hybrid systems have a higher peak power per slot when compared to traditional MPPM system.

It is worth noticing that our proposed systems outperform traditional systems at BER = 10^{-3}, where the forward-error correction (FEC) schemes are commonly used. Specifically from Fig. 7, for the proposed DBPSK–MPPM system with $M=22$ and $n=6$, there is an

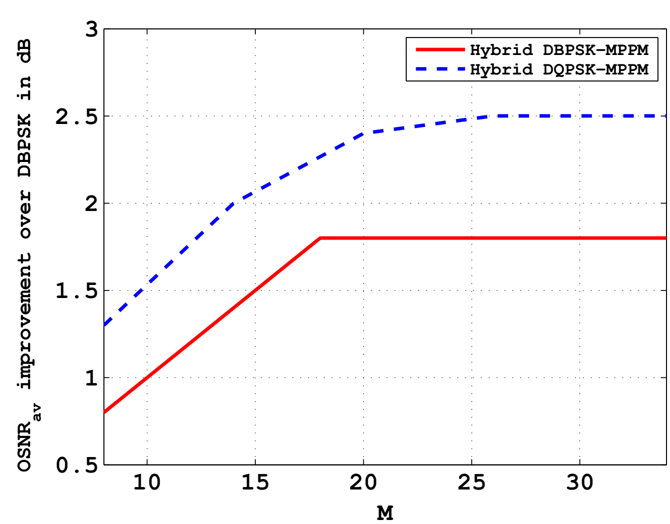

Fig. 9. Proposed systems receiver sensitivity improvement over a traditional DBPSK system at BER = 10^{-9}.

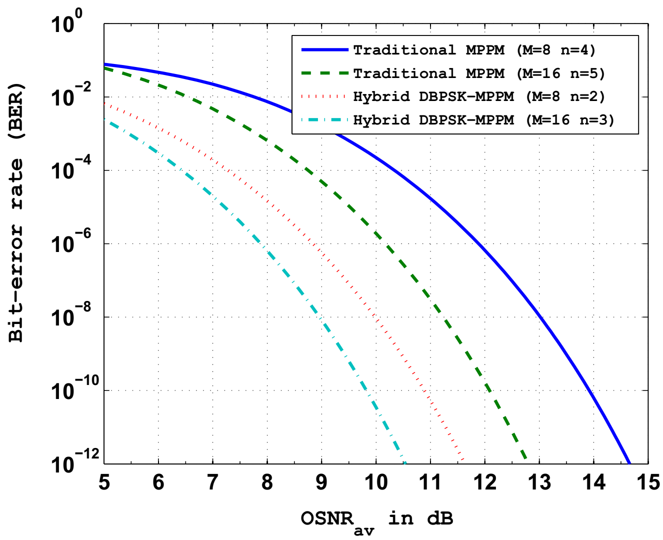

Fig. 10. Average bit-error rate versus average received optical signal-to-noise ratio for both hybrid DBPSK–MPPM and traditional MPPM systems.

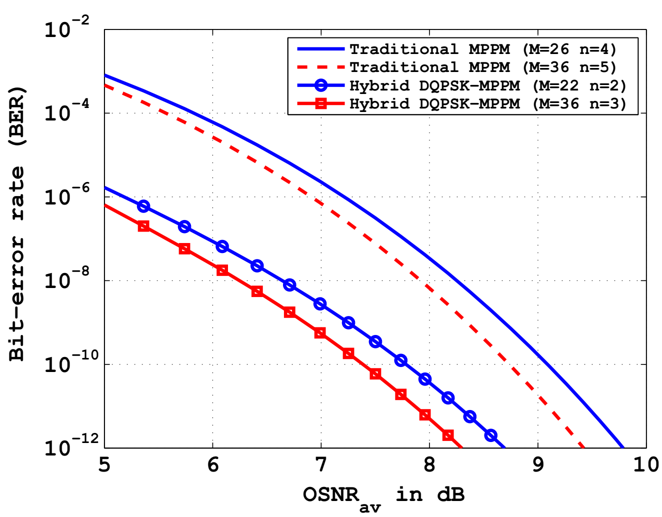

Fig. 11. Average bit-error rate versus average received optical signal-to-noise ratio for both hybrid DQPSK–MPPM and traditional MPPM systems.

improvement of about 0.5 dB at $\text{BER} = 10^{-3}$ when compared to the polarized DBPSK system. This improvement increases to about 1 dB at $\text{BER} = 10^{-4}$. Also it can be seen from Fig. 8 that for the proposed DQPSK–MPPM system with $M=20$ and $n=4$, there is an improvement of about 1.9 dB at $\text{BER} = 10^{-3}$ when compared to the polarized DBPSK system. Although our proposed systems surpass traditional systems at FEC limit, our proposed systems perform very well at $\text{BER} = 10^{-9}$ without the need of FEC schemes as seen from Figs. 7, 8, 10, and 11. Clearly, without implementing FEC schemes, the proposed systems could achieve the required BER.

It should be mentioned that although the proposed hybrid systems increase the peak power per slot, this increase would not result in crossing the threshold of nonlinear effects in optical fibers. Specifically, from Figs. 7 and 10, for the proposed DBPSK–MPPM systems with $M=22$ and $n=6$ and with $M=16$ and $n=3$, the peak power levels are 1.9 dBm and 1.8 dBm, respectively at $\text{BER} = 10^{-9}$. That is, stimulated Brillouin scattering (SBS) threshold of 2 dBm, which is the dominant nonlinear process, is not reached by these peak power levels [18]. Practically, the SBS threshold can reach higher power values (between 5 and 10 dBm) by core size variations along the fiber and other inhomogeneities. As a result, the proposed system would not suffer from the nonlinear effects.

Another key performance indicator is the bandwidth-utilization efficiency (BWUE). It can be defined as

$$BWUE = \begin{cases} \dfrac{\left\lfloor \log_2\binom{M}{n} \right\rfloor + p}{M} & \text{for proposed hybrid systems,} \\ \dfrac{\left\lfloor \log_2\binom{M}{n} \right\rfloor}{M} & \text{for traditional MPPM system.} \end{cases} \quad (15)$$

In addition to sensitivity improvement over the traditional systems, the proposed systems would improve the bandwidth-utilization efficiency by carrying more bits in the same transmission time duration. In Fig. 12, we plot bandwidth-utilization efficiency versus $\log_2 M$ under a fixed value of $n=4$ for the proposed and traditional MPPM systems. Clearly, increasing M results in a gradual decrease of bandwidth-utilization efficiency until reaching its saturation at large values of M. Also, in Fig. 13 we plot bandwidth-utilization efficiency versus n

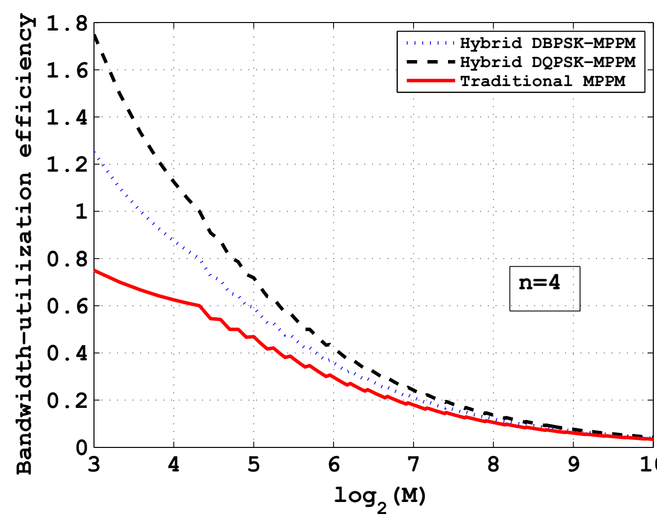

Fig. 12. Bandwidth-utilization efficiency as a function of $\log_2 M$.

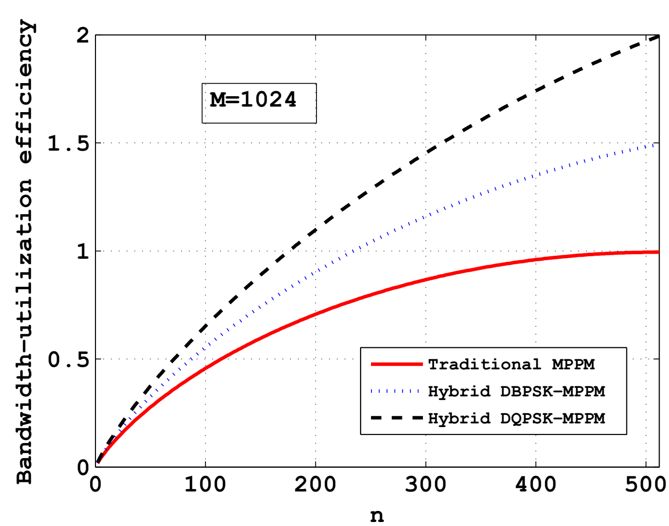

Fig. 13. Bandwidth-utilization efficiency as a function of n.

under a fixed value of $M=1024$ for the proposed and traditional MPPM systems. On the contrary, increasing n would result in a gradual increase of bandwidth-utilization efficiency.

It should be noticed from Figs. 12 and 13 that the proposed systems further enhance the bandwidth-utilization efficiency of traditional DBPSK ($BWUE_{DBPSK}=100\%$) under certain values of M and n and further enhance the bandwidth-utilization efficiency of MPPM systems for all values of M and n. In order to reach the value of bandwidth-utilization efficiency of traditional DQPSK systems ($BWUE_{DQPSK}=200\%$), hybrid DQPSK–MPPM systems need to use large values of M and n. That is, traditional DQPSK system is more bandwidth efficient than hybrid DQPSK–MPPM system. However, the receiver of the latter is more sensitive than traditional DQPSK receiver.

Finally, we compare the performance of non-polarized proposed DBPSK–MPPM system with that of the hybrid polarization-division-multiplexed quadrature phase-shift keying-m-ary pulse-position modulation (PQ–mPPM) system [1,3] and with that of the hybrid BPSK–modified MPPM system [5]. The comparison is made under the same data rate for fixed bandwidth and received optical signal-to-noise ratio.

Practically, the optical bandwidth in typical measurements is equal to $B_{ref}=12.5$ GHz, corresponding to 0.1 nm at 1550 nm carrier wavelength [2,19,20]. That is, a traditional optical signal-to-noise ratio $OSNR_{ref}$ is defined as

$$OSNR_{ref}=\frac{P_{av}}{2S_{n_s}B_{ref}} \tag{16}$$

To convert the signal-to-noise ratio per bit (SNR_b) used in [1,3] to $OSNR_{ref}$, the following relation is used [19,20]

$$OSNR_{ref}=\frac{R_b}{2B_{ref}}SNR_b, \tag{17}$$

where R_b is the signal bit rate. In order to make a fair comparison with the results in [1,3], the optical bandwidth of the received optical filter B_o is set equal to the signal bit rate $R_b=2.5$ Gb/s, same value used in [1,3].

In Fig. 14 we plot the BER versus $OSNR_{ref}$ for the proposed and PQ–mPPM systems. Although the PQ–16PPM system has higher peak power than the proposed systems, it can be seen from Fig. 14 that the proposed systems nearly have the same performance as the PQ–16PPM system at the FEC limit of $BER=10^{-3}$, however the proposed systems perform better than the corresponding PQ–16PPM system at $BER=10^{-9}$. Specifically, for the proposed DBPSK–MPPM system with $M=8$ and $n=1$, there is an improvement of about 1.7 dB at $BER=10^{-9}$ when compared to the PQ–16PPM system. The reason behind this improvement is that the DD-DBPSK receiver, which is used in the proposed system, surpasses the polarization-multiplexed QPSK receiver, which is used in the PQ–mPPM system [2,20]. Clearly, without implementing FEC schemes, the proposed systems would achieve the required BER. Furthermore, our proposed systems are more bandwidth efficient than PQ–mPPM system. It is worth mentioning that the proposed DBPSK–MPPM system with $M=8$ and $n=1$ has nearly the same performance as the proposed DBPSK–MPPM systems with $M=16$ and $n=2$ and with $M=18$ and $n=2$ because all of these systems have nearly the same peak power.

In Fig. 15, we plot the BER versus $OSNR_{av}$ for the proposed and hybrid BPSK–modified MPPM systems [5]. It can be seen from the figure that there is a little improvement of about 0.7 dB at $BER=10^{-9}$ of the hybrid BPSK–modified MPPM system over the corresponding proposed DBPSK–MPPM system. The higher peak power is not the reason for this improvement (as both systems have the same peak power) but because coherent BPSK receiver, which is used in the BPSK–modified MPPM system, gives slightly better performance than DD-DBPSK receiver, used in the proposed system. Furthermore, the proposed DBPSK–MPPM system has the same bandwidth-utilization efficiency as that of the BPSK–modified MPPM system. However, the BPSK–modified MPPM system is less bandwidth efficient than that of the proposed DQPSK–MPPM system.

Not to mention that the receivers of the proposed systems are simpler than those of the BPSK–modified MPPM and PQ–mPPM receivers as the former are based on direct-detection technologies. However, a limitation that may be seen with the proposed DPSK–MPPM receiver is the need for a fast tunable time delay, which increases the complexity and cost of the demodulation process relative to the traditional direct-detection DPSK receivers. While this statement may be accurate for the fixed-rate DPSK receiver, the structure of variable-rate DPSK receiver cannot also dispense with a programmable time-delay unit to accommodate different kinds of data traffic [21] (yet in such a case ultrafast switching of the time delay is not a requirement).

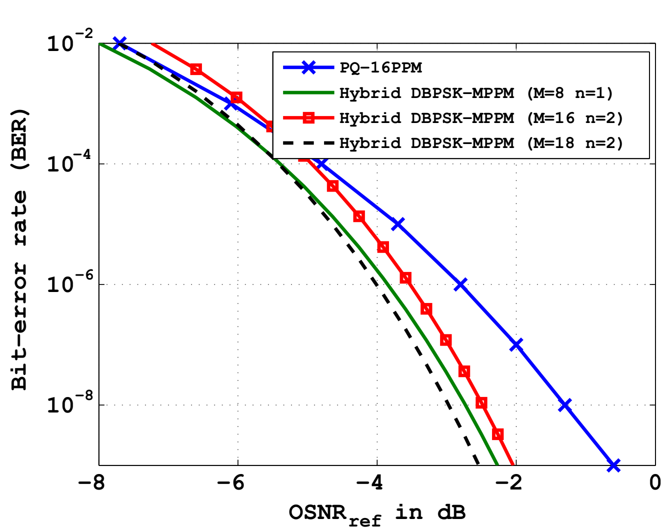

Fig. 14. Average bit-error rate versus $OSNR_{ref}$ for both hybrid DBPSK–MPPM and PQ–16PPM systems.

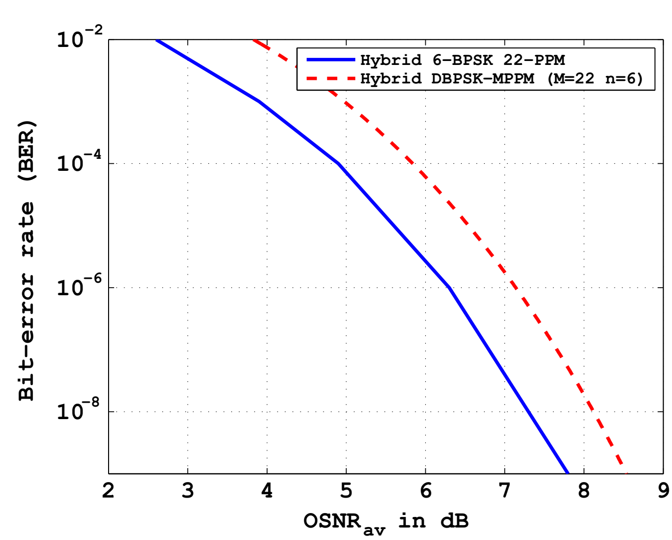

Fig. 15. Average bit-error rate versus average OSNR for both hybrid DBPSK–MPPM and BPSK–modified MPPM systems.

5. Conclusions

Hybrid DPSK–MPPM techniques have been proposed for optical communication systems in order to increase the receiver sensitivity. Simple detection mechanisms, based on direct-detection DPSK receivers with a novel ultrafast discrete delay unit, have been proposed and studied. The bit error rates of the proposed systems have been derived and compared numerically to that of corresponding systems adopting traditional DPSK, and MPPM techniques. In our derivation, the effect of optical amplifier noise has been taken into account. The comparisons have been performed under the constraints of the same transmitted data rates, bandwidth, and average received optical signal-to-noise ratio. In addition, the bandwidth-utilization efficiencies for the proposed and the traditional systems are studied. It turned out that the proposed modulation techniques are more power efficient than traditional ones and have improved BERs and receiver sensitivities and still improve the bandwidth-utilization efficiencies.

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