Hybrid BPSK-modified MPPM: A Scheme for Enhancing Optical MPPM in Optical Fiber Communications

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Abstract— **A hybrid binary phase shift keying-modified multipulse pulse-position modulation (hybrid BPSK-modified MPPM) scheme is proposed as a new modulation technique to improve both the symbol-error rate performance and bandwidth utilization efficiency of conventional optical multi-pulse pulse position modulation (MPPM) scheme in optical fiber communication systems. Whereas in conventional MPPM scheme, unmodulated pulses are transmitted in every signal block, BPSK modulated pulses is transmitted in the proposed hybrid scheme. That is, the information is encoded in both the positions and phases of the transmitted pulses. The transmission characteristics, transmitter and receiver structures, bandwidth utilization, and optimum decoding for the proposed scheme are presented in this paper. Several performance measures are derived and compared to those of conventional MPPM schemes, adopting both coherent and direct detection receivers, under the same data transmission rates. Our results reveal that, at same average power levels, the proposed hybrid BPSK-modified MPPM scheme achieves much lower levels of symbol-error rates compared to those of ordinary MPPM schemes. Furthermore, in terms of bandwidth-utilization efficiency, the proposed hybrid modulation scheme achieves much higher efficiencies than that of ordinary MPPM schemes.**

Keywords— *Optical modulation; BPSK; MPPM.*

I. INTRODUCTION

Pulse-position modulation technique represents an important modulation category for both optical fiber and free space optical communications systems. One important format of this category is multi-pulse pulse-position modulation (MPPM) scheme, which has been proposed to enhance the bandwidth utilization efficiency of ordinary single-pulse pulse-position modulation (PPM) scheme [1], [2]. Both PPM and MPPM have been used extensively with intensity modulation/direct detection (IM/DD) systems. However, for better receiver sensitivity, coherent detection has been recently proposed (including both homodyne and heterodyne detections) to demodulate such schemes [3], [4]. For shot noise limited systems, the sensitivity of heterodyne detection receivers is better by 3 dB than that of direct detection receivers. In order to further enhance the performance of pulse-position modulation techniques, hybrid modulations can be used. One direction of such hybrid modulations is to combine both phase and pulse-position modulation schemes in order to exploit the advantages of both of them. The main advantage of using phase modulation is to increase bandwidth utilization efficiency of the hybrid scheme. By combing phase modulation with pulse-position modulation, the average transmitted power will be reduced further, leading to both high bandwidth utilization efficiency and reasonable receiver sensitivity. The idea of hybrid phase and pulse-position modulations for optical communications has been recently proposed in many literatures. Both classical and quantum receivers for hybrid BPSK-2PPM scheme have been investigated and their performances have been compared to each other [5]. Another hybrid modulation, which combines both PPM and binary phase shift keying subcarrier intensity modulation (BPSK-SIM), has been proposed in [6]. This scheme offers BER performance that is superior to that of both BPSK-SIM and PPM at the same average transmitted power and bit rate. Recently, an experimental work has been carried out to demonstrate a record sensitivity in an optically pre-amplified receiver by combining both polarization-division-multiplexed quadrature phase-shift keying (PDM-QPSK) and 16-PPM [7]. Pilot-assisted digital coherent detection has been used. The results indicate a 3 dB theoretical sensitivity advantages over both PDM-QPSK and BPSK in an optically pre-amplified receiver.

In this paper, we aim at enhancing the performance of ordinary multi-pulse pulse-position modulation (MPPM) scheme by combining it with binary phase shift keying (BPSK) format. Specifically, we propose a modified MPPM technique and modulate its signal pulses using ordinary BPSK format. We call the proposed modulation scheme hybrid binary phase shift keying-modified multi-pulse pulse-position modulation (hybrid BPSK-modified MPPM). In this scheme, the number of transmitted bits is increased (compared to traditional MPPM) by encoding extra bits using the BPSK format. Clearly, the number of these excess bits is equal to the
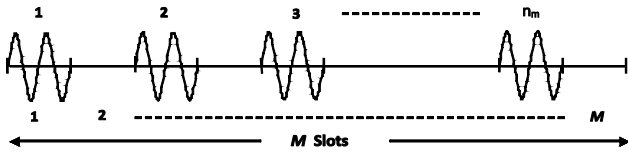
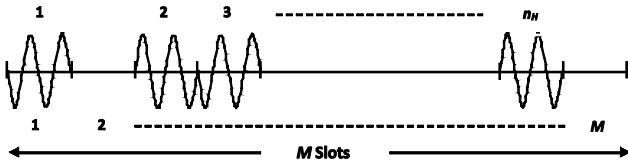Fig. 1.   Frame structure of coherent detection n-pulse MPPM

Fig. 2.   Frame structure of hybrid n-BPSK-modified MPPM scheme.

number of transmitted optical pulses in the hybrid frame. Also, as the demodulation of BPSK pulses requires the implementation of coherent detection (either homodyne or heterodyne), we propose to use coherent detection for demodulating both BPSK and MPPM symbols in the hybrid frame.

The rest of the paper is organized as follows. In Section II, we develop a general system model for the hybrid BPSK modified MPPM scheme and study its transmission characteristics. Also, the differences between the proposed hybrid scheme and the ordinary scheme are stated. In Section III, we present the transmitter and receiver structures for the hybrid scheme. Also, we state its maximum-likelihood decoding (optimal decoding) in optically pre-amplified channels with amplifier noise limited case. In Section IV, we derive performance measures in terms of the achieved symbol-error rates under both average and peak transmission power constraints. Next, the performance comparisons and numerical results are presented in Section V. Finally, the conclusion is given in Section VI.

II.   PROPOSED SYSTEM MODEL AND CHARACTERISTICS

Here, we propose a Hybrid BPSK-modified MPPM modulation scheme in which binary phase shift keying (BPSK) is combined with a modified version of multi-pulse pulse position modulation. Precisely, for frames of size M slots, instead of simply transmitting n_M unmodulated optical pulses in the ordinary MPPM frame; BPSK is used to modulate n_H optical pulses in the hybrid frame. The frame structure of both the proposed hybrid n-BPSK-modified MPPM scheme and the coherent detection n-pulse MPPM scheme are explained in Figs. 1 and 2, respectively. The term *modified* MPPM comes from the ability to increase number of transmitted optical pulses per hybrid frame to values more than $M/2$. This is in contrast to ordinary MPPM in which the maximum number of transmitted optical pulses per frame cannot increase above $M/2$.

Generally, the goal of our proposal of this hybrid technique is to enhance the performance of ordinary MPPM scheme in optical communications. One of the main enhancements of this
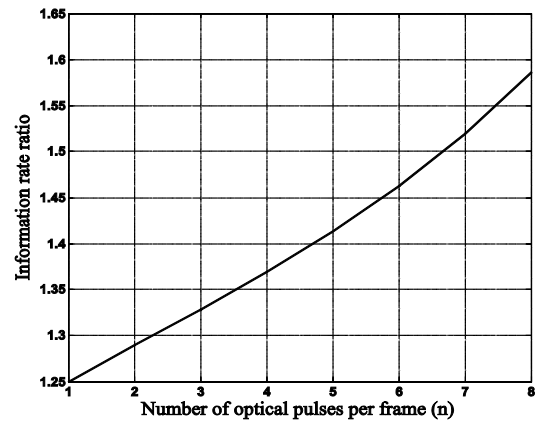

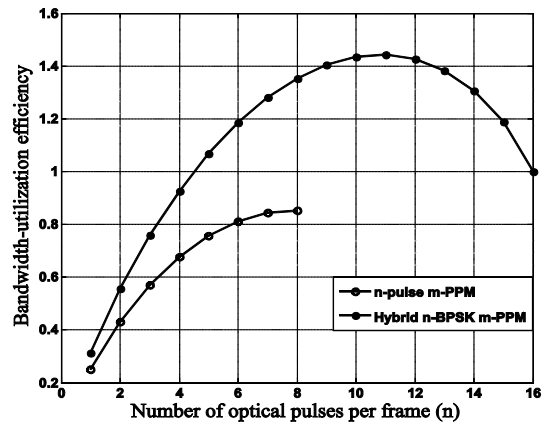Fig. 3.   Information rate ratio for $M = 16$.

Fig. 4.   Bandwidth utilization efficiency.

hybrid scheme is the significant increase in bandwidth utilization efficiency. Clearly, for ordinary MPPM, the number of transmitted bits per frame is $\log_2 \binom{M}{n_M}$ bits, whereas for the proposed hybrid n-BPSK-modified MPPM scheme, the number of transmitted bits per frame is $n_H + \log_2 \binom{M}{n_H}$. Therefore, at the same values of n_M and n_H, i.e., $n_M = n_H = n$, the information rate ratio for the two schemes is given by

$$\text{Information rate ratio} = \frac{n + \log_2 \binom{M}{n}}{\log_2 \binom{M}{n}} \qquad (1)$$

In Fig. 3, we plot the information rate ratio for the case of $M = 16$. The figure indicates that the information rate ratio increases by increasing the number of optical pulses per frame, allowing the transmission of more bits per frame. In other words, the proposed scheme could offer much higher transmission rate than that of the ordinary MPPM scheme with the same number of optical pulses per frame. Also, as stated before, the bandwidth-utilization efficiency is increased significantly using the proposed scheme. Clearly, the bandwidth utilization efficiency for ordinary MPPM scheme is
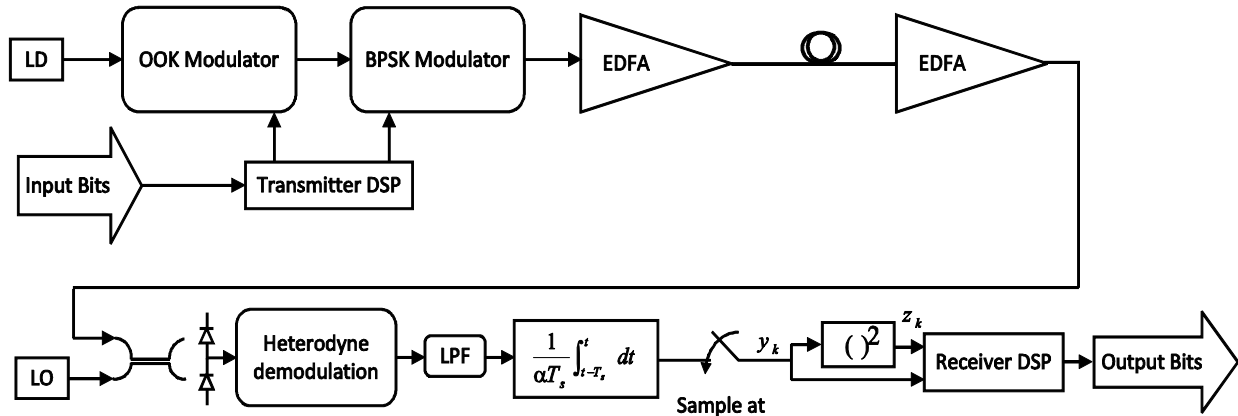
Fig. 5. Transmitter and receiver structures for hybrid BPSK modified MPPM scheme. The parameter $\alpha = 2RAL$ for a homodyne receiver or $\alpha = RAL$ for a heterodyne receiver.

given by

$$U_M = \frac{\log_2 \binom{M}{n_M}}{M} \quad (2)$$

Whereas for the hybrid BPSK-modified MPPM scheme, it is given by

$$U_H = \frac{n_H + \log_2 \binom{M}{n_H}}{M} \quad (3)$$

The bandwidth-utilization efficiencies for both schemes are compared at a fixed frame size of 16 slots. The comparison is carried out at different values of n_H and n_M, as shown in Fig. 4. Obviously, the figure indicates that the maximum achievable efficiency for the n-pulse 16-PPM scheme is about 85% and it occurs at $n_M = 8$ pulses, whereas for the hybrid n-BPSK 16-PPM scheme, the bandwidth utilization efficiency could approach levels higher than 100%. Specifically, for hybrid n-BPSK 16-PPM scheme, this efficiency has a maximum of 144.33% at $n_H = 11$ pulses. After reaching this maximum value, the efficiency decreases again by increasing the value of n_H until approaching a value of 100% at $n_H = 16$. This latter case represents the ordinary BPSK transmission. Clearly, from these results, the proposed modulation scheme is strongly intended to be used for applications that require high bandwidth utilization.

III.   TRANSMITTER AND RECEIVER STRUCTURES AND DECODING ALGORITHMS

The transmitter and the receiver structures for hybrid BPSK-modified MPPM are shown in Fig. 5. At the transmitter side, the transmitted data bits are first fed to a digital signal processing (DSP) device, which divides them into several blocks. Each block contains $\log_2 \binom{M}{n_H} + n_H$ bits. The first $\log_2 \binom{M}{n_H}$ bits determine the transmitted MPPM symbol, i.e.,

the positions of the n_H signal pulses within the MPPM frame, while, the remaining n_H bits are used to modulate these signal pulses with ordinary BPSK modulation. That is, the first $\log_2 \binom{M}{n_H}$ bits of the data block are encoded in the hybrid frame by intensity modulating a continuous wave (CW) laser source, generating n_H optical pulses. The remaining n_H bits are encoded in the hybrid frame by phase modulating the n_H optical pulses in the hybrid frame. After that, the optical signal is transmitted through an optical fiber and periodically amplified in the fiber span till reaching the receiver side.

At the receiver side, coherent detection, for both BPSK symbols and MPPM frames, is adopted to increase the receiver sensitivity. In addition, the coherent receiver implements balanced optical detectors in order to minimize the noise generated from local oscillator (LO). Generally, for coherent receivers limited by optical amplifier noise, both heterodyne and homodyne detection receivers achieve same performance [8]. The photodetector output of the homodyne receiver (or the IF demodulator output of the heterodyne receiver) is then fed to a slot integrator. The slot integrator output is then squared and both the integrator output and its square value are passed to a DSP to decode the received hybrid frame. The DSP selects the n_H pulses with the maximum square values and decode them as the signaling pulses in the received frame. This is the same as normal decoding of MPPM schemes [9]. After decoding the first $\log_2 \binom{M}{n_H}$ bits of the transmitted data block, the DSP proceeds to decode the remaining n_H bits by comparing the slot integrator values for the predetermined n_H signal slots with zero. Obviously, the slot is decoded as one if its integrator output is larger than zero; otherwise, it is decoded as zero.

Decoding Algorithm

1) Perform coherent detection for received hybrid frame by homodyne or heterodyne demodulation.

2) Get received signal amplitude in each slot.

3) Determine the energy received in each slot by integrating the received signal amplitudes and squaring the integrator output samples.

4) Determine n_H signal slots of received hybrid frame by selecting the n_H slots with the highest energies.

5) Decode the BPSK signals of these slots by comparing their integrated samples to zero.

IV. PERFORMANCE EVALUATION

In this section we aim at evaluating the symbol-error rate (SER) for the proposed hybrid BPSK-modified MPPM. In our evaluation we consider the optical fiber as the transmission medium for the hybrid scheme. Also, we assume that the optical fiber span contains many optical amplifiers so that the system is limited by the amplified spontaneous emission (ASE) noise generated from these amplifiers [8]. Generally, the extension of the carried analysis for both free space optical communications and deep space optical communications is straightforward and can be achieved by considering appropriate optical propagation models of these channels. Here, the input data stream is divided into continuous blocks, each block contains $\log_2 \binom{M}{n_H} + n_H$ bits. Each data block is encoded to form one hybrid frame. Thus, the SER for the hybrid BPSK modified MPPM scheme is the result of two independent events and is given by

$$\text{SER}_\text{H} = 1 - (1 - \text{SER}_\text{MPPM}) \times (1 - \text{BER}_\text{BPSK})^{n_H} \qquad (4)$$

Where BER_BPSK and SER_MPPM are the bit error rate of ordinary BPSK and the symbol error rate for ordinary MPPM, respectively. The first parentheses in (4) accounts for the event that the MPPM symbol is correctly decoded and its pulses' positions are correctly determined. The second parentheses of the equation accounts for the event that all BPSK symbols within the hybrid frame are correctly decoded. Clearly, the hybrid frame is considered to be correctly decoded only when both pulses' positions and BPSK symbols are correctly identified. In the analysis of pre-amplifiered coherent receivers there are many types of noise sources. The main three noise sources are the amplified spontaneous emission noise (ASE), the local oscillator noise, and the detector noise, which includes both the shot and thermal noises. Here, we use a dual-photodiode balanced receiver to reduce the LO noise and increase the signal power. Also, we assume that the detector shot noise variance is much larger than that of the thermal noise so that the detector thermal noise can be neglected.

The electric field for both the received optical field and the LO field are given by

$$E_r(t) = \left[A_s(t)e^{j\phi_s(t)} + n_x(t)\right]e^{j\omega_c t}\hat{x} + n_y(t)e^{j\omega_c t}\hat{y}$$

$$E_{LO}(t) = [A_L + n_L(t)]e^{j\omega_{LO} t}\hat{x}, \qquad (5)$$

where, $A_s(t)$, $\phi_s(t)$, and ω_c are the amplitude, phase, and frequency of the received signal, respectively, $\hat{x}$ is the polarization of the signal, $\hat{y}$ is the polarization orthogonal to $\hat{x}$, $n_x(t)$ and $n_y(t)$ are the ASE noise in the polarizations of $\hat{x}$ and $\hat{y}$, respectively, A_L and ω_{LO} are the amplitude and frequency of the local oscillator, respectively, and $n_L(t)$ is the local oscillator optical noise, originated from the relative intensity noise (RIN) of local oscillator laser. The amplifier noise can be expressed as a complex representation:

$$n_x(t) = n_{x1}(t) + jn_{x2}(t) \qquad (6)$$

Where $n_{x1}(t)$ + and $n_{x2}(t)$ are Gaussian distributed with zero mean and variance $\sigma_x^2 = S_{n_s}B_o/2$. S_{n_s} is the power spectral density of the received spontaneous emission (ASE noise) in each polarization ($\hat{x}$ or $\hat{y}$) and B_o is the optical bandwidth of the received optical filter [8]. Notice that $var\{n_x(t)\} = 2\sigma_x^2 = S_{n_s}B_o$. In our analysis below we ignore the thermal noise for simplicity. This would give more insight into the problem under consideration. However, as an additive noise, the effect of thermal noise can be added to the signal afterwards. The output current of the balanced detector, neglecting the small effect of beating of ASE noise with LO noise, is given by

$$i(t) = 2\mathcal{R}A_L A_s(t) \cos[\omega_{IF}\text{t} + \phi_s(t)] + 2\mathcal{R}\mathfrak{N}\big\{\big[A_L\, n_x(t) + A_s(\text{t})e^{j\phi_s(t)}n_L(t)\big]e^{j\omega_{IF} t}\big\} + i_{sh} \qquad (7)$$

Where $\mathcal{R}$ is the photodiode responsively, $\omega_{IF} = \omega_c - \omega_{LO}$ is the intermediate frequency, and i_{sh} is the summation of the shot noise currents of the two photodiodes. Generally, the value of signal-LO beating noise is small compared to that of both LO-ASE beating noise and detector shot noise. Furthermore, in the usual case where the LO power is significantly larger than the received power; the dominant noise source is LO-ASE beating. In this case we get an amplifier-noise limited system and the balanced detector current can be simplified as

$$i(t) = 2\mathcal{R}A_L A_s(t) \cos[\omega_{IF}\text{t} + \phi_s(t)]$$
$$+ 2\mathcal{R}\mathfrak{N}\{A_L\, n_x(t)e^{j\omega_{IF} t}\}$$

$$= 2\mathcal{R}A_L A_s(t) \cos[\omega_{IF}\text{t} + \phi_s(t)] + 2\mathcal{R}A_L\, n_{x1}(t)\cos\omega_{IF}\text{t} - 2\mathcal{R}A_L n_{x2}(t)\sin\omega_{IF}\text{t} \qquad (8)$$

In a heterodyne receiver, this current would pass to a subcarrier synchronous detector (to remove the effect of the IF frequency), followed by a low-pass filter (LPF) with electrical bandwidth of $B_e = 1/2T_s$. The LPF output can be expressed as

$$i_{LPF}(t) = \mathcal{R}A_L A_s(t) \cos[\phi_s(t)] + \mathcal{R}A_L n(t) \qquad (9)$$

where, $n(t)$ is a band-limited noise of bandwidth B_e. Also, it should be noticed that during any time slot within a frame, $A_s(t) \in \{0, A_H\}$, for some constant $A_H > 0$, and $\phi_s(t) \in \{0, \pi\}$. That is $A_s(t) \cos[\phi_s(t)] \in \{-A_H, 0, A_H\}$. Next $i_{LPF}(t)$

is passed through an integrator over slot duration. The integrator output over slot $k \in \{1,2,...,M\}$, also called the decision random variable, is

$$y_k \overset{\text{def}}{=} \frac{1}{\mathcal{R} A_L T_s} \int_{(k-1)T_s}^{kT_s} i_{LPF}(t)dt$$

$$= \begin{cases} A_H + n_k; & \text{if a pulse was transmitted, modulated by 1} \\ n_k; & \text{if a pulse was not transmitted} \\ -A_H + n_k; & \text{if a pulse was transmitted, modulated by 0} \end{cases} \quad (10)$$

Where T_s is the slot duration and

$$n_k \overset{\text{def}}{=} \frac{1}{T_s} \int_{(k-1)T_s}^{kT_s} n(t)dt \qquad (11)$$

It is clear that, for any $k \in \{1,2,...,M\}$, n_k is a Gaussian random variable with mean and variance given by

$$\mu_n \overset{\text{def}}{=} E\{n_k\} = 0$$

$$\sigma_n^2 \overset{\text{def}}{=} var\{n_k\} = \frac{1}{2} S_{n_s} B_e = \frac{S_{n_s}}{4 T_s}, \qquad (12)$$

respectively.

In a homodyne receiver, we can get the same decision random variable as given in (10) if we used an integrator $\frac{1}{2\mathcal{R} A_L T_s} \int_{(k-1)T_s}^{kT_s} (.)$ rather. For either a heterodyne or homodyne receiver, the output of slot integrator y_k is one of three Gaussian random variables, which are $A_H + n_k$, n_k, or $-A_H + n_k$, associated with the transmission of an optical pulse modulated by one, transmission of no optical pulse, or transmission of an optical pulse modulated by zero, respectively. The probability distributions of y_k for these three cases are given by

$$p_1(y_k) \overset{\text{def}}{=} p(y_k|1) = \frac{1}{\sigma_n \sqrt{2\pi}} e^{-(y_k - A_H)^2/2\sigma_n^2}$$

$$p_0(y_k) \overset{\text{def}}{=} p(y_k|0) = \frac{1}{\sigma_n \sqrt{2\pi}} e^{-y_k^2/2\sigma_n^2} \qquad (13)$$

$$p_{-1}(y_k) \overset{\text{def}}{=} p(y_k|-1) = \frac{1}{\sigma_n \sqrt{2\pi}} e^{-(y_k + A_H)^2/2\sigma_n^2}$$

respectively. The receiver gets the n_H slots with the highest energy in the received hybrid frame by squaring the integrator output. The resultant random variable $z_k = y_k^2$ takes one of two cases: $(A_H \pm n_k)^2$ or n_k^2, depending on the transmission of an optical pulse or no optical pulse, respectively. The probability distribution of z_k in the case of transmitting an optical pulse is a non-central chi-square $\mathcal{X}^2$ with one degree of freedom, given by

$$p_1(z_k) \overset{\text{def}}{=} p(z_k|1) = \frac{1}{2\sigma_n^2} e^{-(z_k + A_H^2)/2\sigma_n^2} \left(\frac{A_H^2}{z_k}\right)^{\frac{1}{4}} \times$$
$$I_{-\frac{1}{2}}\left(\frac{A_H}{\sigma_n^2}\sqrt{z_k}\right), \qquad z_k > 0 \qquad (14)$$

where $I_\alpha(v)$ is the αth-order modified Bessel function of the first kind, while, the probability distribution of z_k in the case of no optical pulse transmission, is a central chi-square with one degree of freedom (also called gamma distribution), given by

$$p_0(z_k) \overset{\text{def}}{=} p(z_k|0) = \frac{1}{\sigma_n \sqrt{2\pi z_k}} e^{-z_k/2\sigma_n^2}, \quad z_k > 0 \qquad (15)$$

Clearly, the receiver selects the n_H slots with the highest values of z_k (highest energies) and decodes them as the transmitted signal pulses. The probability of error in such decoding is the same as the symbol-error rate of the ordinary MPPM scheme, which is given by [11], with slight modifications. We proceed as follows. The probability of correct symbol detection equals to the probability that n_H signal slot energies are all greater than the largest energy of $M - n_H$ non-signal slot. Let Z be the largest non-signal slot energy, and then the probability of errors in such symbol decoding is given by

$$\text{SER}_{\text{MPPM}} = 1 - \int_0^\infty (M - n_H) P_0(Z)^{M-n_H-1} \times p_0(Z)[1 - P_1(Z)]^{n_H} dZ, \qquad (16)$$

where, $p_0(Z)$ and $p_0(Z)$ are the probability density functions (pdfs) of Z in signal and non-signal slots, and are given by (14) and (15), respectively. Also, $P_1(Z)$ and $P_1(Z)$ denote its cumulative distributions for both signal and non-signal slots, respectively. Clearly, the equation considers all probabilities for $M - n_H$ non-signal slots to have energy less than the n_H signal slots.

After getting the positions of the n_H signal slots in the received hybrid frame, the receiver proceeds to decode these BPSK modulated signal slots to find the remaining n_H bits of the transmitted data block. Clearly, the decoding decision will be based on the values of slot integrator for the predetermined signal slots. The integrator output of these slots takes one of two values which are $A_H + n_k$ or $-A_H + n_k$, depending on the transmission of data bit one or zero on the optical pulse, respectively. With the optimal threshold set at zero, the error probability in decoding these BPSK symbols (or bits) is the same as the bit error rate of ordinary BPSK [12]:

$$\text{BER}_{\text{BPSK}} = \frac{1}{2} \int_{-\infty}^0 p(y_k|1)dy + \frac{1}{2} \int_0^\infty p(y_k|-1)d$$
$$= \frac{1}{2} \text{ erfc}\left(\frac{A_H}{\sigma_n \sqrt{2}}\right) \qquad (17)$$

Substituting (16) and (17) into (4), we obtain the exact SER_H for the proposed hybrid BPSK-modified MPPM scheme.

For the purpose of performance comparison, we recall the SER expressions for both coherent and direct detection receivers of MPPM scheme. Clearly, the SER for each receiver is still given by equation (16), but with different

distributions, integration limits, and different number of optical pulses per frame n_M. For direct detection of MPPM frames, the distributions are given in [10] and [13], while for coherent detection of MPPM frames, the distributions are given by

$$p_1(z_k) = \frac{1}{\sigma_n\sqrt{2\pi}} e^{-(z_k-A_M)^2/2\sigma_n^2}$$

$$(18)$$

$$p_0(z_k) = \frac{1}{\sigma_n\sqrt{2\pi}} e^{-z_k^2/2\sigma_n^2}$$

where, A_M is the amplitude of demodulated signal in ordinary MPPM schemes (for both coherent and direct detection).

V. NUMERICAL RESULTS

In this section we compare the performance achieved by the proposed hybrid BPSK-modified MPPM scheme with that achieved by ordinary MPPM scheme. The comparison is carried out in terms of symbol-error rate. Although, the comparison is evaluated for optical fiber channels, it can be extended to other optical channels by including the appropriate optical transmission model. For fair performance comparison, we assume the usage of same frame size and same transmission rate for both schemes. Specifically, the evaluations are performed at two different frame sizes, namely, $M = 12$ and $M = 24$ slots. For the case of $M = 12$, two comparisons are carried out. Firstly, 3-pulse 12-PPM is compared to hybrid 2-BPSK 12-PPM and secondly, 6-pulse 12-PPM is compared to hybrid 3-BPSK 12-PPM. For these hybrid schemes, the numbers of transmitted bits per frame are 8.04 bits and 10.78 bits, respectively, which are slightly larger than that of the ordinary MPPM schemes (7.78 bits and 9.85 bits, respectively). Clearly, these selections achieve nearly the same transmission rates for both hybrid and ordinary schemes with larger rates for the hybrid ones. For the case $M = 24$, two comparisons are also performed. Particularly, we compare 6-pulse 24-PPM scheme to hybrid 4-BPSK 24-PPM scheme and compare 12-pulse 24-PPM scheme to hybrid 6-BPSK 24-PPM scheme. Again, in these comparisons, the hybrid schemes achieve higher transmission rates than that of ordinary MPPM schemes, which represents an extra advantage in favor of selected hybrid schemes. In terms of bandwidth utilization efficiency, the aforementioned selections result in near same bandwidth utilization efficiency for both schemes. However, the hybrid schemes can even achieve higher bandwidth utilization efficiencies than that of ordinary MPPM schemes by increasing the number of transmitted optical pulses in the hybrid frames above the selected values.

The bit encoding for hybrid BPSK-modified MPPM can be realized using nearly the same encoding techniques of ordinary MPPM. The only difference is to encode extra n_H bits in each hybrid frame. However, there is no known efficient method of encoding MPPM symbols [14]. The simplest, but inefficient, encoding scheme is to encode each symbol by the integer number of bits resulting from taking the logarithm of the number of available symbols in the system. As an example of such encoding, consider the case of the 3-pulse 12-PPM scheme, each frame is encoded only by 7 bits and the remaining fraction of bits (0.7814 bits) is discarded. Clearly, in this case not all available symbols are used for transmission and there is an optimal bit-symbol mapping that results in the lowest BER. Another simple and more efficient encoding scheme is to create compound symbols by cascading enough MPPM symbols to ensure that the total number just exceeds a power of 2 and then encode suitably larger blocks of information bits into this compound signal set [15]. The bit encoding and decoding for both the hybrid and ordinary MPPM along with the transmitter and receiver complexity are not in the scope of this paper. However, they represent important design issues that could be considered in other research works

Generally, coherent detection results in a better receiver sensitivity than direct detection, but it requires more complex receiver structure. In the carried evaluations below, we compare the performance achieved by the proposed coherent detection hybrid BPSK-modified MPPM scheme to that achieved by both coherent detection and direct detection MPPM schemes. Also, in all these cases, the system noise is assumed to be dominated by optical amplifier ASE noise. Furthermore, our comparisons are performed under the average power constraint which is imposed in many optical communications systems. For optical fiber based systems, it rises in the case of long haul transmission where optical repeaters with limited power are used and also in the case of DWDM transmission where thousands of optical carriers are launched together in a single core and the total average power launched to the fiber must not exceed a maximum value. For non-fiber systems, the average power constraint is imposed when the transmitter has limited power resources. This occurs in free-space optical systems working with solar energy and space optical communications between spacecrafts. Clearly, the modulation scheme that achieves higher performance at the same average power level is highly desirable in these cases.

Here, the average power for hybrid BPSK-modified MPPM and ordinary MPPM schemes can be expressed as $P_{avH} = A_H^2 . n_H/M$ and $P_{avM} = A_M^2 . n_M/M$, respectively. Clearly, under the average power constraint, we have $P_{avH} = P_{avM}$ and

$$A_H^2 = A_M^2 \frac{n_M}{n_H} \qquad (19)$$

It should be noticed that with same transmission rates for both hybrid and ordinary schemes, the average power constraint implies transmission of same energy per bit. In this case, the average received signal-to-noise ratio for both schemes is given by

$$\text{SNR}_{av} = \frac{P_{av}}{\sigma_n^2} = \frac{A_H^2 . n_H}{M\sigma_n^2} = \frac{A_M^2 . n_M}{M\sigma_n^2} \qquad (20)$$

The symbol-error rates achieved by the proposed hybrid scheme and the ordinary MPPM schemes (both coherent and direct detection) are plotted versus the average signal-to-noise ratio (SNR_{av}) in Figs. 6 and 7 for the cases $M = 12$ and $M = 24$, respectively. From these figures it is clear that at all levels of SNR_{av}, the hybrid schemes outperform the ordinary MPPM

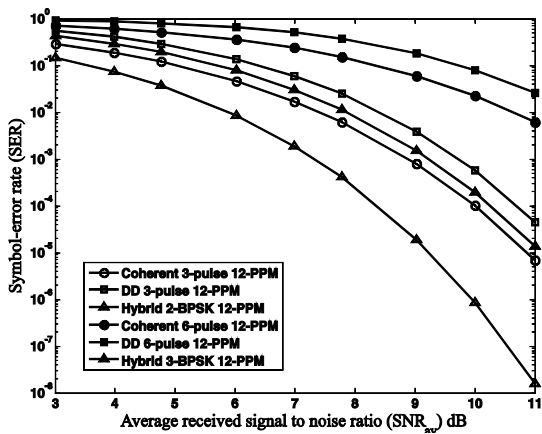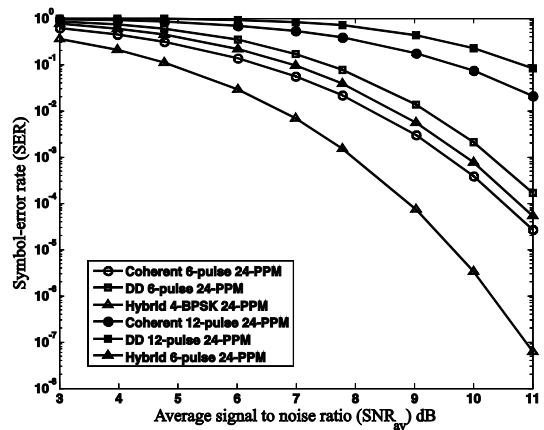Fig. 6. Symbol-error rate versus average received signal-to-noise ratio at $M = 12$.

Fig.7. Symbol-error rate versus average received signal-to-noise ratio at $M = 24$.

Fig. 8. Peak received optical power versus average received power at $M = 12$

schemes for both coherent and direct detection. Numerically, as indicated in Fig. 6, at $\text{SNR}_{av} = 10\text{dB}$, the hybrid 2-BPSK 12-PPM scheme achieves more than two order of magnitude less SER than those of the coherent detection and direct detection 3-pulse 12-PPM schemes. Also as expected, the coherent detection MPPM schemes have better performance than that of the direct detection ones. Furthermore, the performance gap between the hybrid schemes and ordinary ones is significantly increased by raising the level of SNR_{av}. Specifically, for coherent 3-pulse 12-PPM and hybrid 2-BPSK 12-PPM schemes, raising the SNR_{av} level from 6 dB to 8 dB nearly doubles the performance gap between both schemes. This may be interpreted as follows. With same average receiving power, raising the SNR_{av} level results in noticeable increasing in the received pulse power for the hybrid scheme over the ordinary ones which in turn leads to better signal detection and larger performance gap. Also as expected, increasing the number of optical pulses per frame degrades the achieved performance. Obviously, this comes from the fact that with the same SNR_{av} level increasing number of optical pulses per frame reduces the received slot power, which in turn decreases the capability of correct decoding.

Moreover, with the same number of optical pulses per frame, increasing the frame size would result in better performance. It is clear from Figs. 6 and 7 that, at the same levels of SNR_{av}, the performance of the hybrid 4-BPSK 24-PPM scheme(worse than that of the hybrid 3-BPSK 24-PPM scheme) is always better than that of the hybrid 3-BPSK 12-PPM scheme. This is because with same SNR_{av} level and same number of optical pulses per frame, increasing the frame size from 12 to 24 slots results in doubling the pulse power, which in turn increases the probability of correct decoding for the transmitted frame. The analysis of the previously achieved SERs could be further explained using Figs. 8 and 9. These figures indicate the comparison between hybrid and ordinary schemes in terms of the peak received power. Fig. 8. indicates the comparison for the case of $M = 12$, while Fig. 9. indicates it for the case of $M = 24$. Obviously, at the same transmission rates for both hybrid and ordinary MPPM schemes, the number
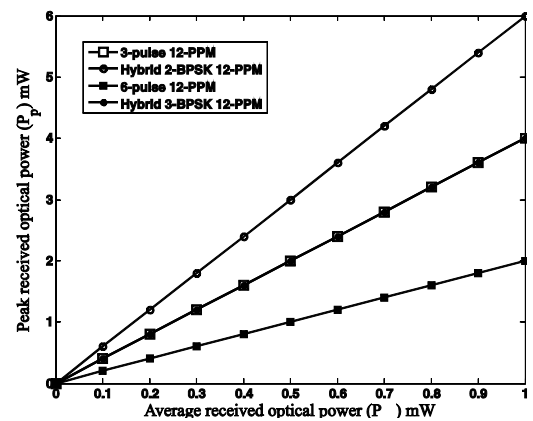
of signal slots per frame in the hybrid frames is less than that of the ordinary MPPM schemes. Thus, when receiving same average power per frame, a noticeable increasing in the pulse power (peak power) is achieved for hybrid schemes. Particularly, for hybrid 2-BPSK 12-PPM scheme, the peak received power is increased linearly versus average received power with a rate equals to one and half the rate of 3-pulse 12-PPM scheme. Moreover, increasing the number of optical pulses in hybrid frames raises the rate of increasing in the peak power. Clearly, for hybrid 3-BPSK 12-PPM scheme, the rate of increasing in the peak power is twice the rate of 6-pulse 12-PPM scheme. Thus, the enhancement in the performance achieved by the hybrid schemes comes with the price of increasing peak power levels. Obviously, these high levels of received peak power could raise the levels of both nonlinear distortion and cross phase noise which are not desirable for high speed optical fiber communications. Therefore, the increase in the peak power for hybrid scheme may limit its performance to values lower than that of the ordinary schemes when the same maximum peak power level is supported.
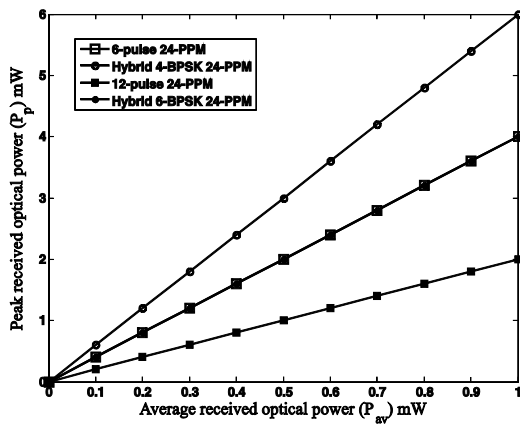
Fig. 9. Peak received optical power versus average received power at $M = 24$.

VI. CONCLUSION

A new hybrid modulation scheme, hybrid BPSK-modified MPPM, has been proposed for optical fiber communications. The proposed scheme achieves much higher bandwidth utilization efficiency than that of the ordinary MPPM scheme. Both the transmitter and receiver structures along with the optimal decoding algorithm have been presented and discussed for optical fiber channel systems. The performance measure of the proposed scheme in terms of exact symbol-error rate has been derived taking into account the effect of optical fiber noise. Intensive numerical evaluations have been performed to compare the performance achieved by the proposed hybrid scheme with that of both coherent and direct detection MPPM schemes. The numerical evaluations have been carried out under the average power constraint at nearly the same transmission rates for hybrid and ordinary schemes. Our results indicate the superior performance of the proposed hybrid scheme under average power constraints over both coherent and direct detection MPPM schemes.

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