Performance Analysis of a Hybrid QAM-MPPM Technique under Gamma-Gamma Turbulent Channels

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Abstract

The performance of a hybrid M-ary quadrature amplitude modulation multi-pulse pulse-position modulation (hybrid QAM-MPPM) technique is investigated in free space optical channels. The bit-error rates (BERs) of intensity-modulation direct detection (IM-DD) systems adopting the hybrid technique is obtained. Our results reveal that, under the conditions of comparable data rates, same bandwidth, and same energy per bit, the new technique shows better performance under different turbulent levels when compared with traditional techniques in FSO communication channels.

Index Terms

Hybrid modulation, quadrature amplitude modulation (QAM), multi-pulse pulse-position modulation (MPPM), gamma-gamma turbulent channels.

1. INTRODUCTION

The idea of superimposing different modulation techniques to improve both power and spectral efficiencies simultaneously has been proposed in many literatures. Hybrid modulation based on polarization-switched quadrature phase-shift keying (PS-QPSK) and polarization-division multiplexing QPSK (PDM-QPSK) superimposed on PPM signals have been proposed in [1]–[3]. The proposed schemes provide higher power efficiency than PDM-QPSK at the expense of reduced spectral efficiency. Selmy *et al.* have introduced and investigated the performance of innovative hybrid modulation techniques based on combining MPPM with binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) [4], [5]. Khallaf *et al.* have proposed new hybrid modulation techniques based on both orthogonal frequency-division multiplexing (OFDM)-PPM [6] and QAM-MPPM [7].

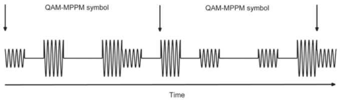
In this paper, we investigate the performance of power efficient hybrid QAM-MPPM modulation scheme, that we have proposed in [7], under gamma-gamma turbulent channels. Block diagrams for both transmitter and receiver are introduced. In addition, BER of systems adopting the hybrid scheme has been derived for free space optical channels.

2. HYBRID QAM-MPPM SYSTEM MODEL

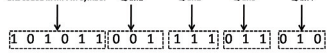
In MPPM modulation techniques, the symbol duration, T, is divided into N time slots, each with duration $T_s = \frac{T}{N}$, and has optical power in w time slots only. The cardinality of MPPM constellation is $\binom{N}{w}$ and the number of bits per MPPM symbol is $\left\lfloor \log_2 \binom{N}{w} \right\rfloor$, where $\lfloor x \rfloor$ is the maximum integer less than x. In hybrid QAM-MPPM scheme, QAM signals are used to modulate the optical pulses within an MPPM frame, as shown in Fig. 1a. An example for the hybrid technique symbol structure is given in Fig. 1b. Data rate, R_b, for system adopting the hybrid QAM-MPPM technique is given by $R_b = \frac{\lfloor \log_2 \binom{N}{w} \rfloor + w \log_2(M_q)}{NT_s}$. where M_q is the number of QAM modulation levels. The basic configurations of the transmitter and receiver for the hybrid QAM-MPPM scheme are shown in Fig. 2a and Fig. 2b, respectively.

The output optical power of the laser is proportional to the modulating QAM signals as follows [7]:

$$P(t) = \frac{Np}{w} \sum_{i=0}^{N-1} \left[1 + MD_i(t)\right] B_i(t)\, \mathrm{rect}\left(t - \frac{iT}{N}\right), \tag{1}$$

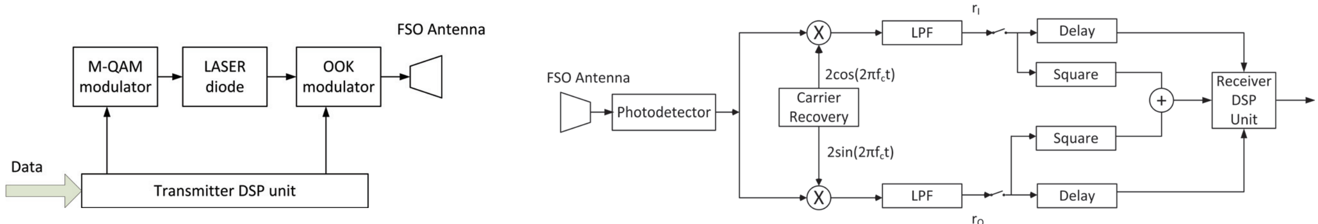


(a) Frame structure of a hybrid QAM-MPPM modulation scheme



(b) An example for hybrid QAM-MPPM with $(N, w, M_q) = (8, 4, 8)$.

Figure 1: Examples for time frame and symbol structure of hybrid QAM-MPPM scheme.



(a) Block diagram of a hybrid QAM-MPPM transmitter.

(b) Block diagram of a hybrid QAM-MPPM receiver.

Figure 2: Block diagrams for both transmitter and receiver.

where p is the average transmitted optical power and M is the modulation index.

$$
\begin{aligned}
D_i(t) &= \begin{cases} S_{QAM}(t); & \text{for a signal time slot,} \\ 0; & \text{for a non-signal time slot,} \end{cases} \\
B_i(t) &= \begin{cases} 1; & \text{for a signal time slot,} \\ 0; & \text{for a non-signal time slot,} \end{cases} \\
\text{rect}(t) &= \begin{cases} 1; & 0 \leq t < \frac{T}{N}, \\ 0; & \text{otherwise.} \end{cases} \\
S_{QAM}(t) &= A_I \cos(2\pi f_c t) - A_Q \sin(2\pi f_c t),\ 0 \leq t < \frac{T}{N}
\end{aligned} \tag{2}
$$

where A_I and A_Q are the signal amplitudes of in-phase and quadrature components, respectively, and f_c is the electrical carrier frequency. At the receiver side, the photodiode (PD) converts the received optical intensity variations into corresponding variations in the electrical domain. The output current of the PD can be written as:

$$
y(t) = I_{ph} \sum_{i=0}^{N-1} \left[1 + M D_i(t)\right] B_i(t)\, \text{rect}\left(t - \frac{iT}{N}\right) + n(t), \tag{3}
$$

where $I_{ph} = \mathcal{R}\frac{Np}{w}G$ is the dc component of the received photocurrent $y(t)$, $\mathcal{R}$ is the responsivity of the photodiode, $n(t)$ is Gaussian noise with variance σ_n^2, $G = \left(\frac{\eta A}{\lambda L}\right)^2 h$ is channel gain, η is the efficiency of both the transmitter and receiver optics, λ is the operating wavelength, $A = \frac{\pi D^2}{4}$ is the transceiver telescopic area, D is the telescopic diameter, L is the distance between the transmitter and receiver, and h is the channel state, which is modeled by a gamma-gamma distribution [8]:

$$
f(h) = \frac{2\left(\alpha\beta\right)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h}\right), \quad h \geq 0 \tag{4}
$$

where $\Gamma(\cdot)$ is the gamma function, $K_c(\cdot)$ is the c_{th} order modified Bessel function of the second kind, and α and β are scintillation parameters given in [8]. The QAM symbol desired signal power is given by $C = \frac{1}{2}M^2 I_{ph}^2$. [7] and the signal to noise ratio (SNR) of the received QAM symbol is $SNR = \frac{C}{\sigma_n^2}$. where $\sigma_n^2 = \frac{\frac{4K_b T_{abs} F}{R_L} + 2q(wI_{ph}/N) + (RIN)(wI_{ph}/N)^2}{T/N}$, K_b is Boltzmann's constant, T_{abs} is absolute temperature, F is the noise figure of receiver electronics and R_L is the PD load resistor, and q is the electron charge.

3. BER PERFORMANCE ANALYSIS

The BER of the hybrid QAM-MPPM scheme is the average of the BERs of both QAM and MPPM [9]:

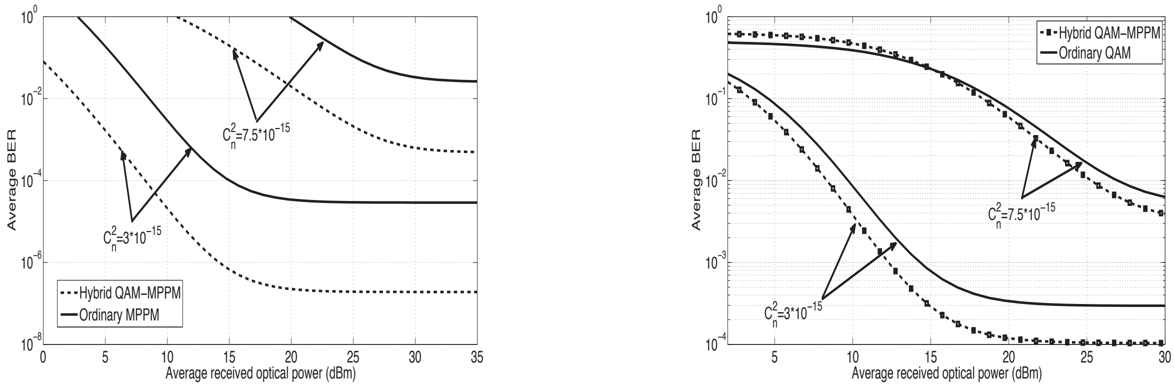
$$
BER = \frac{\log_2\binom{N}{w}}{\log_2\binom{N}{w} + w\log_2 M_q} BER_{MPPM} + \frac{w\log_2 M_q}{\log_2\binom{N}{w} + w\log_2 M_q}\left[\Big(1 - SER_{MPPM}\Big) BER_{QAM} + \frac{SER_{MPPM}}{2}\right], \tag{5}
$$

where BER_{QAM} is the bit-error rate of ordinary QAM and SER_{MPPM} is the symbol-error rate of the ordinary MPPM. The SER of MPPM is given by [10]:

$$
SER_{MPPM}(h) \leq \frac{\binom{M}{w} - 1}{2}\, \text{erfc}\left(\frac{\mathcal{R}p\left(\frac{\eta A}{\lambda L}\right)^2 h}{2w\sigma_n^2}\sqrt{N\log_2\binom{N}{w}}\right), \tag{6}
$$

Table 1: System Parameters.

Parameter	Symbol	Value
Tx/Rx optics efficiency	η	0.8
Photodiode resposivity	$\mathcal{R}$	0.5 A/W
Transmitter and receiver telescopic diameter	D	8 cm
Relatively intensity noise	RIN	-130 dB/Hz
Time slot duration	T_s	10^{-9} Second
PD load resistor	R_L	50 Ω



(a) Average bit-error rates for both hybrid QAM-MPPM (with $N = 12$, $w = 2$, $M_q = 4$ and $R_b = 833$ Mbps) and ordinary MPPM (with $N = 12$, $w = 5$ and $R_b = 750$ Mbps) versus average received optical power in dBm.

(b) Average bit-error rates for both hybrid QAM-MPPM (with $N = 4$, $w = 2$, $M_q = 8$, and $R_b = 2$ Gbps) and ordinary QAM (with $M_q = 4$ and $R_b = 2$ Gbps) versus average received optical power in dBm.

Figure 3: Performance of the hybrid QAM-MPPM scheme versus ordinary MPPM and QAM schemes.

The average of $SER_{MPPM}(h)$ is evaluated in [10] as given in Eq. (7).

$$SER_{MPPM} \leq \frac{\left(\binom{N}{w}-1\right)(2)^{\alpha+\beta-3}}{\pi^{3/2}\Gamma(\alpha)\Gamma(\beta)} \cdot G^{2,4}_{5,2}\left(\left\{\frac{4\left(\mathcal{R}p\left(\frac{\eta A}{\lambda L}\right)^2\right)^2 N\log_2\binom{N}{w}}{w^2<\sigma_n^2>\alpha^2\beta^2}\right\}\middle|\begin{matrix}\frac{1-\beta}{2},\frac{2-\beta}{2},\frac{1-\alpha}{2},\frac{2-\alpha}{2},1\\ 0,0.5\end{matrix}\right). \quad (7)$$

Based on the general integration formula in [11], the average BER for the QAM modulation technique over turbulent channels is given in Eq. (8).

$$BER_{QAM} = \begin{cases} \frac{(2)^{\alpha+\beta-1}\left(1-\frac{1}{\sqrt{M_q}}\right)}{\pi^{3/2}\Gamma(\alpha)\Gamma(\beta)log_2(M_q)}\sum_{i=1}^{\sqrt{(M_q)}/2} G^{2,4}_{5,2}\left(\left\{\frac{6(2i-1)^2\left(\mathcal{R}\frac{MNp}{w}\left(\frac{\eta A}{\lambda L}\right)^2\right)^2}{<\sigma_n^2>(M_q-1)(\alpha\beta)^2}\right\}\middle|\begin{matrix}\frac{1-\beta}{2},\frac{2-\beta}{2},\frac{1-\alpha}{2},\frac{2-\alpha}{2},1\\ 0,0.5\end{matrix}\right); & \text{if } k \text{ is even,}\\ \frac{(2)^{\alpha+\beta-1}}{\pi^{3/2}\Gamma(\alpha)\Gamma(\beta)log_2(M_q)} G^{2,4}_{5,2}\left(\left\{\frac{6\left(\mathcal{R}\frac{MNp}{w}\left(\frac{\eta A}{\lambda L}\right)^2\right)^2}{<\sigma_n^2>(M_q-1)(\alpha\beta)^2}\right\}\middle|\begin{matrix}\frac{1-\beta}{2},\frac{2-\beta}{2},\frac{1-\alpha}{2},\frac{2-\alpha}{2},1\\ 0,0.5\end{matrix}\right); & \text{if } k \text{ is odd.}\end{cases} \quad (8)$$

4. Numerical Results

In this section, we investigate the BER performance of FSO systems adopting hybrid QAM-MPPM modulation techniques, using expression obtained in previous section. We compare our results to that of the equivalent systems adopting ordinary MPPM and QAM schemes. We choose the parameters for systems so that they have comparable data rates, same average energy, same bandwidth, and same channel states. In addition, we analyze the effects of the cardinality of MPPM techniques on BER performance of FSO systems adopting the hybrid technique. In all our evaluations below we use the system parameters listed in Table 1.

Figures 3a and 3b show the performance of the hybrid QAM-MPPM scheme versus the two ordinary modulation techniques. The performance of the systems is investigated in case of both moderate and strong turbulence channel, $C_n^2 = 3 \times 10^{-15}$ and $C_n^2 = 7.5 \times 10^{-15}$, respectively. The modulation index value is $M = 0.4$. It is clear that the performance of the system adopting hybrid technique outperforms the ordinary MPPM by 6 dB at a BER $= 10^{-4}$ in moderate turbulent channels and has BER floor lower than that of ordinary MPPM in strong turbulent channels. When compared to ordinary QAM, the system adopting new technique outperforms by 2 dB at a BER $= 10^{-3}$ in moderate turbulent channels and by 1.5 dB at a BER $= 10^{-2}$ in strong turbulent channels.

Figure 4 shows the effect of the cardinality of the constellation of MPPM into the net BER of the new scheme. As shown in the figure, the higher the cardinality, the lower the system performance. As the number of MPPM symbols $\binom{N}{w}$ increases, the SER of MPPM would increase as given in (7) and the net BER of the hybrid modulation technique would increase as well.

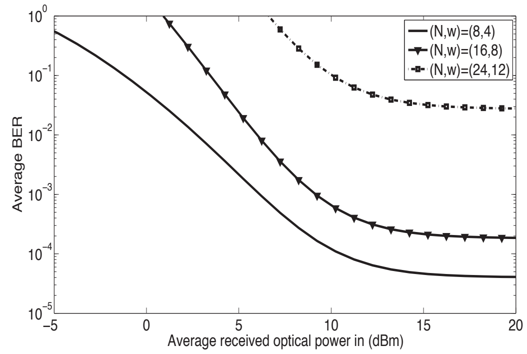


Figure 4: Average bit-error rates versus average received optical power in dBm for hybrid QAM-MPPM with different setting, (N, w, R_b) = ((8, 4, 2.25 Gbps), (16, 8, 2.3 Gbps), (24, 12, 2.37 Gbps)).

5. CONCLUSION

The BER performance of a hybrid QAM-MPPM modulation technique has been investigated. The block diagrams for both transmitter and receiver for new technique have been introduced. The BER performance of the hybrid scheme in free space optical channels has been investigated. The BER performance of the hybrid QAM-MPPM scheme has been compared to that of traditional QAM and MPPM schemes under the conditions of comparable transmitted data rate, same bandwidth, same average energy, and same channel state. Our results reveal that system adopting hybrid scheme outperforms system adopting traditional techniques and is more power efficient. The effect of the cardinality of the MPPM symbols on the BER of FSO systems adopting the new technique are investigated as well.

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