Proposal of A Hybrid OFDM-PPM Technique for Free Space Optical Communications Systems

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***Abstract*—A hybrid orthogonal frequency-division multiplexing pulse-position modulation (OFDM-PPM) technique is proposed. A closed form expression for the BER of free space optical systems adopting the proposed technique under gamma-gamma channel model is derived.**

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has a wide range of application in wireless systems because of its robustness against frequency selective fading, narrow-band interference, and high channel efficiency. Recently, OFDM has been shown to be a promising technology for optical communications [1].

In this paper, we propose a new hybrid modulation technique based on both OFDM and pulse-position modulation (PPM) techniques, called hybrid OFDM-PPM scheme. We investigate the average bit-error rate (BER) performance of the hybrid OFDM-PPM system over an atmospheric turbulent free space optics (FSO) channel. We are able to derive a closed-form expression for the BER of the proposed scheme, taking into account effect of the laser diode (LD) nonlinearity and receiver noise sources. In our analysis we assume a gamma-gamma fading channel due to the atmospheric turbulence.

II. FREE-SPACE OPTICAL CHANNEL MODEL

FSO suffers from channel fading during the optical signal transmission due to atmospheric turbulence. Several channel models have been assumed to characterize the atmospheric turbulence but gamma-gamma can be considered as a general model [2]. Its probability-density function is given by:

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

where α and β are the scintillation parameters, h is the channel state due to atmospheric turbulence, $\Gamma(\cdot)$ is the gamma function and $K_c(\cdot)$ denotes the c_{th} order modified Bessel function of the second kind. Both α and β are dependent on the unitless Rytov variance σ_R^2.

III. PROPOSED SYSTEM MODEL

We propose a hybrid OFDM-PPM modulation scheme as follows. An OFDM signal $S_{OFDM}(t)$ is used to modulate the optical intensity of the laser diode (LD) during the mark time slot of the PPM frame. The OFDM signal contains N subcarriers, each modulated using a quadrature-amplitude modulation (QAM) technique. So the hybrid OFDM-PPM signal is thus:

$$S_{OFDM-PPM}(t) = Mp\mathcal{R}\sum_{k=0}^{M-1} C_k(t)\,\mathrm{rect}\left(t-\frac{kT}{M}\right), \quad (2)$$

where p is the average received optical power, $\mathcal{R}$ is the responsivity of the photodiode, M is the number of time slots in the PPM frame, T is the frame duration of the proposed scheme,

$$\begin{aligned} C_k(t) &= \begin{cases} S_{OFDM}(t); & \text{for a signal time slot} \\ 0; & \text{for a non-signal time slot,} \end{cases} \\ \mathrm{rect}(t) &= \begin{cases} 1; & 0 \leqslant t < \frac{T}{M} \\ 0; & \text{otherwise.} \end{cases} \end{aligned} \quad (3)$$

We investigate the application of the proposed scheme in FSO systems. The basic configurations of the transmitter and receiver for the proposed scheme are shown in Figs. 1 and 2, respectively.

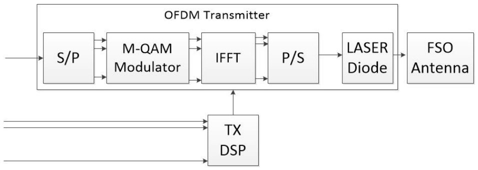

Fig. 1. Block diagram of a hybrid OFDM-PPM FSO transmitter.

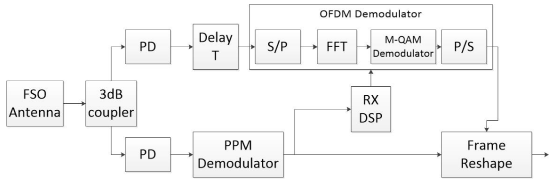

Fig. 2. Block diagram of a hybrid OFDM-PPM FSO receiver.

IV. BIT-ERROR RATE ANALYSIS

The BER of the proposed scheme is the average of the BERs of both OFDM and PPM [3] as given in Eq. (4), where M_q is the number of the modulation levels of the QAM modulation, $BER_{OFDM}(h)$ is the bit-error rate of ordinary OFDM, $SER_{PPM}(h)$ and $BER_{PPM}(h)$ are the symbol-

$$
\begin{aligned}
BER_{new}(h) = \frac{\log_2 M}{\log_2 M + N\log_2 M_q} BER_{PPM}(h) + \frac{N\log_2 M_q}{\log_2 M + N\log_2 M_q} \\
\times \left[\Big(1 - SER_{PPM}(h)\Big) BER_{OFDM}(h) + \frac{SER_{PPM}(h)}{2} \right]
\end{aligned} \tag{4}
$$

$$
\overline{BER}_{PPM} \approx \frac{M(2)^{\alpha+\beta-4}}{\pi^{3/2}\Gamma(\alpha)\Gamma(\beta)} \times G_{5,2}^{2,4}\left(\tfrac{4(\mathcal{R}p)^2}{\overline{\sigma_n^2}(\alpha\beta)^2} M\log_2(M) \,\middle|\, \begin{matrix} \frac{1-\beta}{2}, \frac{2-\beta}{2}, \frac{1-\alpha}{2}, \frac{2-\alpha}{2}, 1 \\ 0, 0.5 \end{matrix} \right) \tag{5}
$$

$$
\overline{BER}_{OFDM} \approx \frac{(1-(\sqrt{M_q})^{-1})(2)^{\alpha+\beta-1}}{\pi^{3/2} N \log_2(M_q)\Gamma(\alpha)\Gamma(\beta)} \times \sum_{n=0}^{N-1} G_{5,2}^{2,4}\left(\left(\tfrac{12(\mathcal{R}mMP_r)^2}{(\overline{\sigma_n^2}+\overline{\sigma_{IMD}^2})(M_q-1)(\alpha\beta)^2} \right) \,\middle|\, \begin{matrix} \frac{1-\beta}{2}, \frac{2-\beta}{2}, \frac{1-\alpha}{2}, \frac{2-\alpha}{2}, 1 \\ 0, 0.5 \end{matrix} \right) \tag{6}
$$

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and bit-error rates of the PPM, respectively. In our analysis we assume slow fading channel, so we average $BER_{new}(h)$ over $f_H(h)$:

$$
\overline{BER}_{new} = \int_0^\infty BER_{new}(h) f_H(h) dh.
$$

Since both $BER_{PPM}(h)$ and $BER_{OFDM}(h)$ are two independent random variables, we can get the average of each of them with respect to gamma-gamma distribution separately. Using [4] and [5], the average BERs of ordinary PPM and OFDM schemes are given by Eqs. (5) and (6) , respectively, where σ_n^2 is the variance of the Gaussian noise, σ_{IMD}^2 is the variance of the third order intermodulation distortion, as given in [6], and m is the optical modulation index, assumed the same for all the subcarriers. To get $\overline{BER}_{new}$ we substitute both $\overline{BER}_{OFDM}$ and $\overline{BER}_{PPM}$ in (4).

V. NUMERICAL RESULTS

Figure 3 shows the average BERs for both hybrid OFDM-PPM and ordinary OFDM systems versus average received power per bit, at different atmospheric turbulence strengths. Specifically at $\sigma_R = 0.6$ and $\sigma_R = 5$ for both moderate and strong turbulence, respectively. We choose the system parameters for both systems so that they transmit a comparable data rates and have the same bandwidth. In case of low power the thermal noise has the dominant effect on the performance of the system and since subcarriers in the proposed scheme have wider bandwidth so they have a lower signal to noise ratio and the BER performance of the ordinary OFDM scheme is better than that of the proposed scheme. However, as the power increases the intermodulation distortion has the dominant effect on the system performance and since the proposed scheme use small number of subcarriers so the effect of the IMD on its performance is limited, while it has a high effect on the ordinary OFDM scheme performance so the BER performance of the proposed scheme is better than that of ordinary OFDM scheme. Due to the IMD, the proposed scheme has a BER floor lower than that of ordinary OFDM. In addition, based on [7], the maximum peak-to-average power ratio (PAPR) for the proposed system, with the given setting, is 0.6 dB less than that for ordinary OFDM.

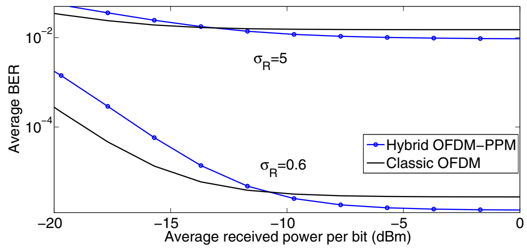

Fig. 3. Average bit-error rates for both hybrid OFDM-PPM (with $M = 4$, $N = 128$, and $M_q = 16$) and ordinary OFDM (with $N = 512$ and $Mq = 2$) versus average received power per bit in dBm, for a transmission data rate $\approx$ 200 Mb/s.

VI. CONCLUSION

A hybrid OFDM-PPM modulation technique has been proposed. Next, a closed form expression of the BER of a FSO system, adopting the proposed technique, has been derived. Finally, a comparison of the BER performance of the proposed scheme has been compared to that of ordinary OFDM scheme under the conditions of comparable data rate, same bandwidth and, same average received power per bit. Our results reveal that the proposed scheme has a lower BER floor and reduces the maximum PAPR

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