PDM-DPSK-MPPM hybrid modulation for multi-hop free-space optical communication*

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(Received 7 September 2016)

A hybrid polarization division multiplexed-differential phase shift keying-multipulse pulse position modulation (PDM-DPSK-MPPM) scheme for multi-hop free-space optical (FSO) communication is investigated. The analytical bit error rate (*BER*) of the proposed system in Gamma-Gamma turbulence channels is derived and verified using computer simulation. The results show that both multi-hop and hybrid modulation schemes are efficient techniques to improve the performance of FSO links. Compared with the traditional binary phase shift keying (BPSK) and MPPM, the hybrid scheme can improve the bandwidth-utilization efficiency and reliability of the system. Compared with the coherent demodulation of PDM-QPSK-MPPM, the system complexity is reduced at the cost of the degradation of *BER* performance, which can improve the practicality of hybrid modulation technology in FSO system.
Document code: A **Article ID:** 1673-1905(2016)06-0450-5
DOI 10.1007/s11801-016-6192-1

Multi-hop transmission is an alternative relay-assisted technique. There are several relay nodes between source and destination placed in series. Each relay node decodes the received signal and retransmits it to the next one until the receiver gets the information. Obviously, a long communication link is broken into several shorter ones, which can mitigate the effect of turbulence and improve the reliability of the FSO link.

In addition to multi-hop, hybrid modulation scheme is another way to mitigate turbulence effects. By combining the advantages of traditional modulations, the new hybrid scheme can modulate the laser signals from different aspects, which can improve the bandwidth-utilization efficiency and the bit error rate (*BER*) performance of the system.

A new hybrid scheme of pulse position modulation binary phase shift keying subcarrier intensity modulation (PPM-BPSK-SIM) is proposed and the analytical *BER* performance is carried out[1]. The equal gain combining (EGC) spatial diversity technique is further investigated for the PPM-BPSK-SIM system[2]. The performances of PPM-BPSK-SIM and MPPM-BPSK-SIM are compared[3]. By combining PPM and subcarrier minimum shift keying (MSK), a new hybrid PPM-MSK-SIM scheme is proposed and the *BER* performance over log-normal channels is analyzed[4]. The polarization division multiplexed-quadrature phase shift keying-multipulse pulse position modulation (PDM-QPSK-MPPM) is investigated but the coherent demodulation may increase the complexity of the system[5]. The outage performance of polarization shift keying (PSK) based multi-hop FSO system over a strong atmospheric turbulence channel with misalignment fading is derived[6]. Error analysis of multi-hop free-space optical communication using M-ary pulse amplitude modulation (MPAM) is presented[7]. In this paper, the *BER* performance of the PDM-DPSK-MPPM based multi-hop system is analyzed over Gamma-Gamma turbulence channels.

The random variation of atmosphere may cause inhomogeneity in temperature, density and refractive index. When the signal propagates through the atmosphere, the light intensity fluctuations occur, which will degrade the performance of the system. In order to reduce the effect, several probabilistic models are proposed for the turbulence, including log-normal, Gamma-Gamma and K distributions. The probability density function of Gamma-Gamma distribution is given by[8]

$$p(I)=\frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)}I^{\frac{\alpha+\beta}{2}-1}K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right),\ I>0\ , \quad (1)$$

where $\Gamma(\cdot)$ is the Gamma function, $K_{\alpha\text{-}\beta}(\cdot)$ is modified Bessel function of the second kind, I is light intensity, α and β are the effective numbers of small-scale and large-scale eddies of scattering environment, respectively. For a plane wave, they can be given by[8]

$$\alpha=\left[\exp\left(\frac{0.49\sigma_{\mathrm{R}}^{2}}{\left(1+1.11\sigma_{\mathrm{R}}^{12/5}\right)^{7/6}}\right)-1\right]^{-1},$$

* This work has been supported by the National Natural Science Foundation of China (No.61373124).
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$$\beta=\left[\exp\left(\frac{0.51\sigma_R^2}{\left(1+0.69\sigma_R^{12/5}\right)^{5/6}}\right)-1\right]^{-1}, \tag{2}$$

where σ_R^2 is the Rytov variance for plane wave, which can be given by

$$\sigma_R^2=1.23C_n^2k^{7/6}L^{11/6} \quad , \tag{3}$$

where $k=2\pi/\lambda$ is the number of optical wave, λ is the wavelength, L is the transmission distance, and C_n^2 is refractive index.

The sensitivity of the system can be greatly improved by using coherent phase modulation, nevertheless the complexity of the receiver is increased at the same time. This can be solved by differential phase modulation, for it doesn't require local optical signal (LO) or phase locked loop (PLL). In this paper, we combine differential binary phase shift keying (2DPSK), quadrature differential phase shift keying (QDPSK) with polarization division multiplexing and multi-pulse pulse position modulation, which can improve the practicality of hybrid modulation technology in FSO system.

In a duration T, there are M signal time slots to form a symbol period. Each symbol period sends n optical pulses, and the pulse width is $\tau=T/M$. During a symbol period, $\log_2\binom{M}{n}+2k$ bits information is transmitted. The former is modulated by MPPM, while the latter is modulated by DPSK. If we use 2DPSK with $k=n$, $N_H=[\log_2\binom{M}{n}]+2n$ bits are transmitted by PDM-2DPSK-MPPM signal. If we use QDPSK with $k=2n$, $N_H=[\log_2\binom{M}{n}]+2n$ bits are transmitted by PDM-QDPSK-MPPM signal.

The BER performance of the hybrid scheme is related to both current and previous symbol period. If the demodulation condition is bad, all the information is incorrectly decoded when the signal is wrongly detected by MPPM. So we can get upper bound BER given by[9]

$$BER_{H,U}\le\frac{1}{2k+N}\Big[N\times BER_{MPPM}^{current}+k\times SER_{MPPM}^{current}+$$
$$\left(1-SER_{MPPM}^{current}\right)SER_{MPPM}^{previous}\left(\frac{p}{2}+(2k-p)BER_{DPSK}\right)+$$
$$2k\times BER_{DPSK}\left(1-SER_{MPPM}^{current}\right)\left(1-SER_{MPPM}^{previous}\right)\Big], \tag{4}$$

where $N=[\log_2\binom{M}{n}]$, $k=n$ for 2DPSK and $k=2n$ for QDPSK, $SER_{MPPM}^{current}$ and $SER_{MPPM}^{previous}$ denote the current and previous symbol-error-rate (SER) of MPPM, respectively, and BER_{DPSK} is the BER of 2DPSK or QDPSK. If the current symbol is incorrectly decoded by MPPM, all the information encoded by DPSK is wrong with probability of 1/2. If the previous symbol is incorrectly decoded by MPPM, only the first p bits encoded by DPSK are wrong with probability of 1/2. So $SER_{MPPM}^{current}=SER_{MPPM}^{previous}=SER_{MPPM}$, Eq.(4) can be simplified to[9]

$$BER_{H,U}\le\frac{1}{2k+N}\big[N\,BER_{MPPM}+kSER_{MPPM}+$$
$$\left(1-SER_{MPPM}\right)SER_{MPPM}\left(\frac{p}{2}+pBER_{DPSK}\right)+$$
$$2k\left(1-SER_{MPPM}\right)BER_{DPSK}\big]. \tag{5}$$

The last inequality is the upper bound BER of the worst condition. If the previous wrong decoding of the signal by MPPM doesn't affect the detection of DPSK, and the current wrong decoding of the signal only affects the detection of the last pulse, we can get a better condition. So the lower bound BER is[9]

$$BER_{H,L}\ge\frac{1}{k+N}[N\times BER_{MPPM}+\frac{p}{2}SER_{MPPM}+$$
$$\left(1-SER_{MPPM}\right)k\,BER_{DPSK}]. \tag{6}$$

The relationship between BER_{MPPM} and SER_{MPPM} can be written as[10]

$$BER_{MPPM}\le\frac{2^{N-1}}{2^N-1}\times SER_{MPPM}. \tag{7}$$

The SER of MPPM can be written as[13]

$$SER_{MPPM}=1-$$
$$\int_0^\infty P_0\left(z_{min}\right)^{M-n}\cdot n\cdot p_1\left(z_{min}\right)\left[1-P_1\left(z_{min}\right)\right]^{n-1}dz_{min}, \tag{8}$$

where z_{min} is the minimum received signal energy for all pulse, $p_0(\cdot)$ and $p_1(\cdot)$ are the probability density functions of the received signal energy when there is signal or not, while $P_0(\cdot)$ and $P_1(\cdot)$ are their cumulative probability functions.

We use the maximum energy detection method to demodulate MPPM signal. The location of the first n pulses with the maximum energy in M slots is chosen to demodulate the information. If the received pulse energy of the tth slot is denoted by z_t, it can be written by non-central chi-squared distribution of two-degree-of-freedom as

$$p_1\left(z_t\right)=\frac{1}{2\sigma_n^2}\exp\left[-\frac{\left(A_SI(t)\right)^2+z_t}{2\sigma_n^2}\right]\cdot$$
$$K_0\left(\frac{A_SI(t)}{\sigma_n^2}\sqrt{z_t}\right), \; z_t\ge0, \tag{9}$$

where $I(t)$ is the normalized instantaneous receiving light intensity, K_α is the modified Bessel function of the first kind, σ_n^2 is the variance of white Gaussian noise, and A_s is the signal amplitude.

If there is no signal transmitted, the received pulse energy z_t can be denoted by central chi-squared distribution of two-degree-of-freedom as

$$p_0\left(z_t\right)=\frac{1}{2\Gamma(1)}\exp\left(-\frac{z_t}{2\sigma_n^2}\right), \; z_t\ge0. \tag{10}$$

The BER of 2DPSK can be written as[11]

$$BER_{\text{2DPSK}}=\frac{1}{2}\mathrm{e}^{-A_s^2/2\sigma_n^2}\ . \tag{11}$$

The approximate expression of *BER* for QDPSK is given by[11]

$$BER_{\text{QDPSK}}\approx erfc\left(\sqrt{\frac{A_s^2}{\sigma_n^2}}\sin\frac{\pi}{8}\right). \tag{12}$$

When the turbulence is modeled by Gamma-Gamma distribution, the *BER* expressions for 2DPSK and QPSK in the hybrid scheme are given by

$$BER_{\text{2DPSK}}=\frac{1}{2}\mathrm{e}^{-\left(A_sI(t)\right)^2M/2n\sigma_n^2}\ , \tag{13}$$

$$BER_{\text{QDPSK}}\approx erfc\left(\sqrt{\frac{M\left(A_sI(t)\right)^2}{n\sigma_n^2}}\sin\frac{\pi}{8}\right). \tag{14}$$

Substituting Eqs.(7), (8), (13) and (14) into Eqs.(5) and (6), we can get the upper bound and lower bound of *BER* for the hybrid PDM-DPSK-MPPM.

The average upper and lower bounds of *BER* over Gamma-Gamma turbulence channels are given by

$$\overline{BER_{\text{H,U}}}=\int_0^\infty BER_{\text{H,U}}\cdot p(I)\,\mathrm{d}I\ , \tag{15}$$

$$\overline{BER_{\text{H,L}}}=\int_0^\infty BER_{\text{H,L}}\cdot p(I)\,\mathrm{d}I\ , \tag{16}$$

where $BER_{\text{H,U}}$ and $BER_{\text{H,L}}$ are given in Eqs.(5) and (6), and $p(I)$ is the probability density function of Gamma-Gamma distribution.

Decoding and forward relay are discussed in this paper, and the relay demodulates the signal from the transmitter and retransmits it to the receiver. So the model of hybrid scheme at transmitter, relay and receiver should be discussed. The modulation unit is shown in Fig.1[9].

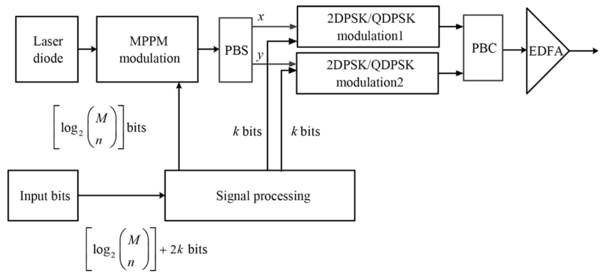

Fig.1 Modulation unit for PDM-DPSK-MPPM

A digital signal processor divides the binary information into two parts, which drive the MPPM modulator and DPSK modulator, respectively. The MPPM modulator outputs laser pulse signal through a polarization beam splitter (PBS), which is divided into two orthogonal polarization optical pulses by differential phase modulation. The modulated orthogonally polarized signal passes through the PBS and the erbium doped fiber amplifier (EDFA) and is transmitted to the atmospheric channel at last. The demodulation unit is shown in Fig.2[9].

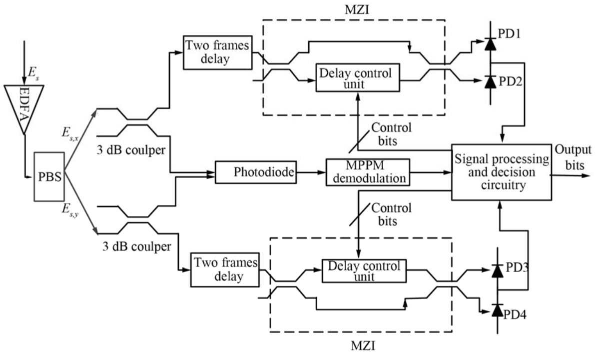

Fig.2 Demodulation unit for PDM-DPSK-MPPM

We use the asymmetric Mach-Zehnder interferometer (MZI) structure to achieve direct detection of differential phase shift signal. As shown in Fig.2, we use the PBS to receive the signal and each polarization direction is divided into two branches, one is demodulation of MPPM, and the other is demodulation of differential signal. The latter is further divided into two parts after two frames of delay, one of which is sent to the delay control unit. The signal processing unit identifies the additional delay according to pulse position and sends the control signal to drive the delay unit. Then the MZI detects the phase difference of pulse and recovers the information bits. The PDM-QDPSK-MPPM demodulation unit is similar to PDM-2DPSK-MPPM, but it needs $\pi/2$ phase difference to split in-phase and quadrature information.

Assuming that each hop has the same statistical model, the *BER* from $k-1$ to k can be presented by $BER(k)$ and the *BER* from 0 to k is denoted by BER_k. So we can get the correct transmission probabilities from 0 to $k-1$ and $k-1$ to k as $1-BER_{k-1}$ and $1-BER(k)$, respectively. As the channels of the hops are independent, the *BER* at the destination can be divided into two parts: the correct transmission from 0 to $k-1$ with $k-1$ to k wrongly transmitted, and the wrong transmission from 0 to $k-1$ with correct transmission between $k-1$ and k. So we can get BER_k as

$$BER_k=\left(1-BER_{k-1}\right)BER(k)+ \\ BER_{k-1}\left(1-BER(k)\right). \tag{17}$$

All the single-hops have the same statistical behavior with equal received signal to noise radio (*SNR*).

$$BER(k)=BER_{\text{hop}}\qquad k\in\{1,2,...K\}\ . \tag{18}$$

So the end-to-end *BER* depending on both BER_{hop} and the number of hops K of the multi-hop can be expressed as[12]

$$BER\approx\frac{1}{2}[1-(1-2BER_{\text{hop}})^K]\ . \tag{19}$$

Substituting Eqs.(15) and (16) into Eq.(17), we can get upper bound and lower bound of *BER* over multi-hop Gamma-Gamma turbulence channels.

The upper and lower bound *BER* curves of PDM-2DPSK-MPPM and PDM-QDPSK-MPPM in Fig.3 are basically consistent. Therefore, the accuracy of the *BER* expression is verified. In the following simulations, we choose the upper bound *BER* to evaluate the performance of the system.

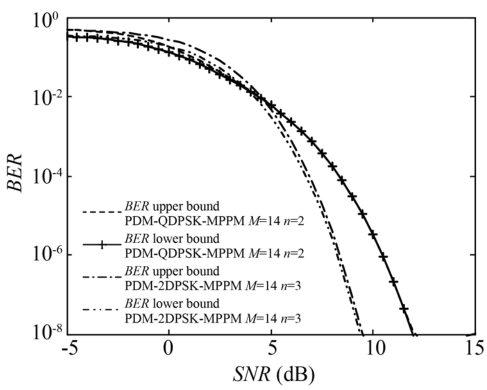

Fig.3 Upper and lower bound *BER* curves of PDM-2DPSK-MPPM and PDM-QDPSK-MPPM

In Fig4, we compare the *BER* performances of PDM-DPSK-MPPM, PDM-QDPSK-MPPMM, PPM and BPSK. In order to guarantee all the modulation schemes have the same transmission rate as BPSK, the symbol period is set to be *M*=14, indicating there is 14 bits information transmitted during a symbol. But when the maximum transmission pulse is set to be *n*=7, there is only 11 bits information transmitted. Results show that under the same average power, all the hybrid schemes perform better than their counterparts. The coherent demodulation of PDM-QPSK-MPPM gives the best performance, followed by PDM-DPSK-MPPM and PDM-QDPSK-MPPM. The PDM-2DPSK-MPPM can reduce the system complexity at the cost of the degradation of *BER* performance.

Figs.5—7 show the *BER* performances of PDM-2DPSK-MPPM and BPSK over weak, moderate and strong atmospheric turbulence channels, respectively. Results show that over weak turbulence channel, PDM-2DPSK-MPPM gives the optimal performance, followed by PDM-QDPSK-MPPM and BPSK. When the turbulence is stronger, the performance degrades but the hybrid scheme still performs better than the traditional one. Overall, compared with MPPM and BPSK, the PDM-2DPSK-MPPM shows stronger anti-turbulence interference performance.

Figs.8 and 9 show the *BER* performances of multi-hop FSO links using BPSK and PDM-2DPSK-MPPM, respectively. If we set one relay between source and destination over a certain distance, the transmission is divided into two shorter parts. The number of relays increase means the transmission is divided into several parts, and the information is decoded and retransmitted in each part,

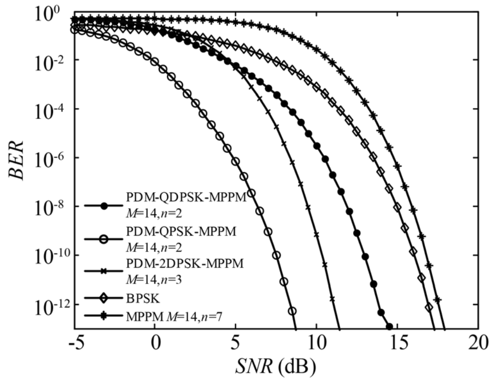

Fig.4 *BER* comparison of MPPM, BPSK, PDM-DPSK-MPPM and PDM-QPSK-MPPM

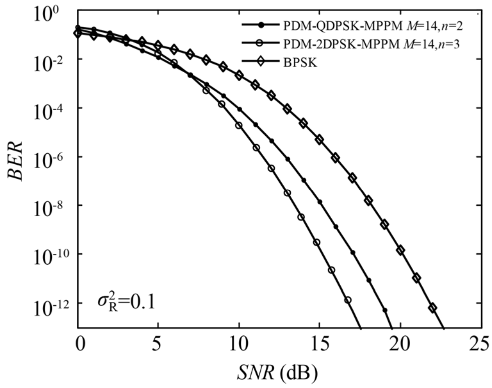

Fig.5 Different modulation performances over weak turbulence channel

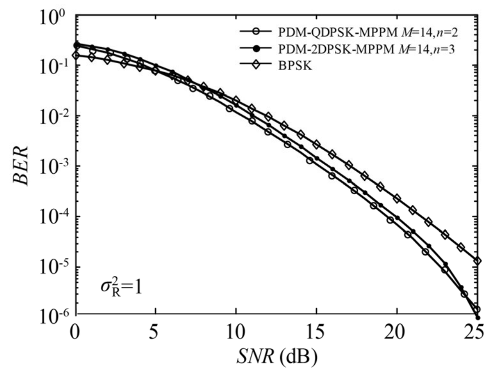

Fig.6 Different modulation performances over moderate turbulence channel

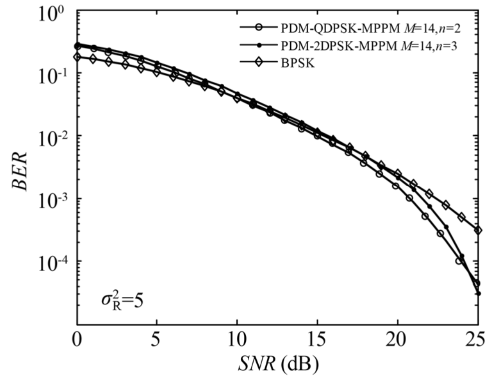

Fig.7 Different modulation performances over strong turbulence channel

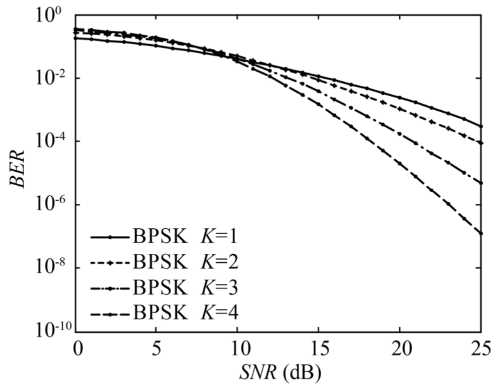

Fig.8 Multi-hop system performances using BPSK (*K*=1,2,3,4)

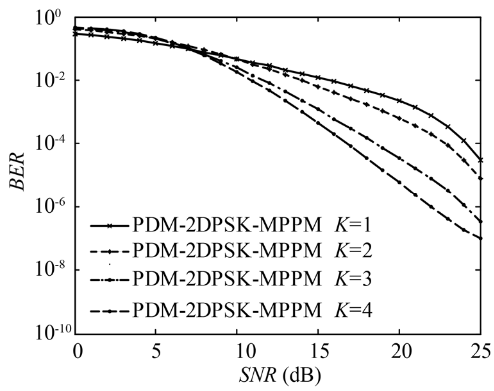

Fig.9 Multi-hop system performances using PDM-2DPSK-MPPM (*K*=1,2,3,4)

which can increase the system reliability significantly. Results show that over the same turbulence channel, the *BER* performance of the system enhances when the number of relays increases. However, if we set too many relays in a certain distance, the complexity of the system will increase.

A hybrid scheme of PDM-DPSK-MPPM for multi-hop FSO communication is discussed in this paper. We describe the modulation and demodulation unit models for transmitter, relay and receiver. The *BER* performance is further investigated over Gamma-Gamma turbulence channels. Results show that both hybrid scheme and multi-hop are effective ways to mitigate turbulence effect. Compared with traditional BPSK and MPPM, the new scheme has a stronger ability to resist the disturbance of turbulence and improve the practicality of hybrid modulation technology in FSO system. Increasing the number of relays can also enhance the system performance, but for a certain distance, too many relays may increase the system complexity at the same time.

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