A new modulation scheme of visible light communication*

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In order to use white light emitting diode (LED) as a lighting source and communication part, a new modulation scheme called reverse dual header pulse interval modulation (RDH-PIM) is proposed for indoor visible light communications based on the analyses of the structures of on-off keying (OOK), pulse position modulation (PPM), digital pulse interval modulation (DPIM) and dual header pulse interval modulation (DH-PIM). After analyzing and comparing the symbol structure, bandwidth requirement and average transmission power of different modulation methods, the slot error rate is derived. Simulation results show that OOK has the minimum bandwidth, while RDH-PIM has the highest average transmission power and its bandwidth efficiency is obviously better than those of PPM and DPIM. Hence, RDH-PIM is superior in optical wireless communication systems.
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Visible light communication (VLC) system based on the white light emitting diode (LED) has attracted much attention and becomes a highly potential and valuable method for wireless communication. In addition, VLC system can transmit high speed information in indoor communication along with the development of LEDs with wide modulation bandwidth[1-4].

Intensity-modulation/direct-detection (IM/DD) is widely used in the wireless optical communication systems due to the limitation of the mono-chromaticity and coherence of the optical carrier[5,6]. Many typical modulation methods can be adopted in free space optical (FSO) communication systems, such as on-off keying (OOK), pulse position modulation (PPM), digital pulse interval modulation (DPIM) and dual header pulse interval modulation (DH-PIM). OOK and PPM were firstly proposed by Kahn in Ref.[7]. The previous work shows that OOK has the minimum bandwidth requirement, and PPM has the best bit error rate performance. Moreover, DPIM was firstly applied in wireless optical communication by Ghassemlooy[8]. Aldibbiat[9] showed that DH-PIM based on DPIM can achieve better performance in bandwidth requirement and power efficiency. However, as the modulation method of VLC system, DH-PIM also has some limitations, such as flickering and dimming problems, and the lighting efficiency is not satisfactory.

In wireless optical communication, considering the human eye safety, it is necessary to reduce the transmission power as much as possible. While in VLC system, under the premise of meeting the condition of indoor lighting brightness, the higher average transmission power can reduce the number of LEDs[10]. Motivated by the high data rate demand under the constraint of low bandwidth requirement and high transmission power, we propose to adopt the reverse dual header pulse interval modulation (RDH-PIM) method for communication in this paper. By analyzing and comparing the symbol structure, bandwidth requirement and average transmission power of modulation methods, the slot error rate is derived. Simulation results show that OOK has the minimum bandwidth, while RDH-PIM has the highest average transmission power, and its bandwidth efficiency is obviously better than those of PPM and DPIM.

OOK modulation is the simplest modulation scheme for FSO communication systems, where LEDs are turned on or off depending on the data bits being 1 or 0. In PPM, each symbol interval of duration T is partitioned into $L=2^M$ sub-intervals or chips with duration of T/L, and the transmitter sends an optical pulse during one (and only one) of these chips. This way of modulation in essence is a kind of phase modulation[11,12]. In DPIM, the length of each symbol is not fixed. It conveys information by the relative distance between two consecutive pulses of light. Each symbol begins with a pulse signal, adding k+1 empty slots. In DH-PIM, the length of each symbol is not fixed either. It begins with two different initial pulse signals, and each symbol consists of α+1 head slots and m empty slots, where m is given by[13,14]

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$$m=\begin{cases}k, & k<2^{M-1}\\ 2^{M}-1-k, & k\geq 2^{M-1}\end{cases}. \tag{1}$$

And each head slot consists of α+1 slots, considering two different forms named H_1, H_2:

$$\begin{cases}H_1:\dfrac{\alpha}{2}\text{initial pulse slots}+\left(\dfrac{\alpha}{2}+1\right)\text{protection slots}, k<2^{M-1}\\ H_2:\alpha\text{ initial pulse slots+ one protection slot}, k\geq 2^{M-1}\end{cases}. \tag{2}$$

DH-PIM is found not to be the best modulation scheme in terms of lighting efficiency, so we adopt the negative logic coding way and get a new kind of modulation method named RDH-PIM. In RDH-PIM, we use no pulse time slot to represent bits of information and keep the LED working at the state of "1" as long as possible to reduce the number of LEDs.

Fig.1 shows the symbol structures for OOK, PPM, DPIM, DH-PIM and RDH-PIM when binary information bits are "001010101111" and the modulation order number M is 4.

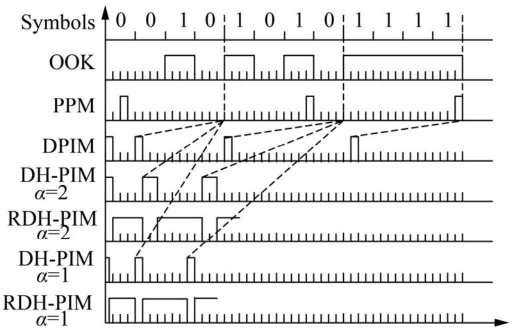


Fig.1 Symbol structures for OOK, PPM, DPIM, DH-PIM and RDH-PIM when *M*=4

In this paper, we consider an FSO communication system under the condition of the same source bit rate R_b. When the modulation order number is M, we assume that the time slot width of OOK is τ_{OOK}, so we can derive that the average time slot widths of PPM, DPIM and DH-PIM are $\frac{M}{2^M}\tau_{OOK}$, $\frac{2M}{2^M+3}\tau_{OOK}$ and $\frac{M}{\alpha+2^{M-2}+\frac{1}{2}}\tau_{OOK}$, respectively. And RDH-PIM has the same time slot width with DH-PIM.

We use B_{OOK} to represent the bandwidth of OOK, which can be expressed as $B_{OOK}=\frac{1}{\tau_{OOK}}=R_b$ [15]. Similarly, we can deduce the other bandwidths based on OOK. Tab.1 shows the bandwidths of OOK, PPM, DPIM, DH-PIM and RDH-PIM for a given value of R_b. Fig.2 shows the bandwidth requirement comparison of OOK, PPM, DPIM and RDH-PIM. From Fig.2, we can see that in the range of $M\geq 2$, when the modulation order number increases, the bandwidth requirement increases. And OOK has the minimum bandwidth while PPM has the maximum bandwidth. The bandwidth efficiency of RDH-PIM is obviously better than those of PPM and DPIM, and when α decreases, the bandwidth efficiency increases.

Tab.1 Bandwidths of OOK, PPM, DPIM, DH-PIM and RDH-PIM for a given value of R_b

Modulation scheme	Bandwidth
OOK	$B_{OOK}=R_b$
PPM	$\frac{2^M}{M}B_{OOK}$
DPIM	$\frac{2^M+3}{2M}B_{OOK}$
DH-PIM/ RDH-PIM	$\frac{2\alpha+2^{M-1}+1}{2M}B_{OOK}$

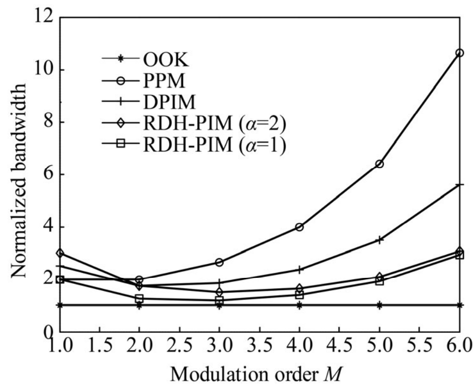


Fig.2 Bandwidth requirements of OOK, PPM, DPIM and RDH-PIM

Considering the condition of the same peak power P_s, we simply define the average transmission power as the probability of "1" multiplied by the transmission power[16,17]. We assume that the average transmission power of OOK is P_{OOK}, so we can deduce that $P_{OOK}=0.5P_s$. Tab.2 shows the average transmission power values of OOK, PPM, DPIM, DH-PIM and RDH-PIM for a given power of P_s.

Tab.2 Average transmission power of OOK, PPM, DPIM, DH-PIM and RDH-PIM for a given P_s

Modulation scheme	Bandwidth
OOK	$P_{OOK}=\frac{P_s}{2}$
PPM	$\frac{2}{2^M}P_{OOK}$
DPIM	$\frac{4}{2^M+3}P_{OOK}$
DH-PIM	$\frac{6\alpha}{4\alpha+2^M+2}P_{OOK}$
RDH-PIM	$\frac{2\alpha+2^{M+1}+4}{4\alpha+2^M+2}P_{OOK}$

Fig.3 shows the normalized average transmission power comparison of above modulation schemes. From Fig.3, we can see that when the modulation order number increases, the average transmission power decreases and gradually tends to zero for OOK, PPM, DPIM and DH-

PIM, while for RDH-PIM, the power increases and tends to a constant value of 2. When the modulation order is fixed, the transmission power of RDH-PIM is higher than those of other ways and has the optimal lighting efficiency.

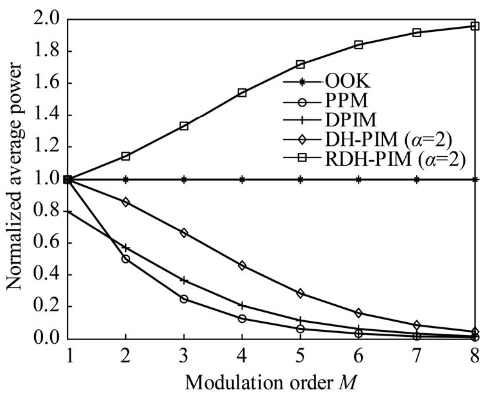


Fig.3 Normalized average transmitting power of OOK, PPM, DPIM, DH-PIM and RDH-PIM

In this paper, we consider an FSO communication system using IM/DD with OOK. We assume high signal-to-noise ratio (SNR) regime where we can use additive Gaussian white noise (AGWN) model with zero mean and variance of σ_n^2. In addition, we also assume that the bandwidth of the receiver is very wide, so at the receiver, we can make two hypotheses on the corresponding transmitted symbol:

$$x(t)=\begin{cases}1:\ \sqrt{P_s}+n(t)\\ 0:\ n(t)\end{cases},\tag{3}$$

where $x(t)$ is the input of the sampling judgment device. Assuming OOK modulation, the slot error rate is calculated as[18]

$$P_{se}=P_{0/1}P_1+P_{1/0}P_0,\tag{4}$$

where P_0 and P_1 are the probabilities of transmitting "0" and "1" bits, respectively, and $P_{0/1}$ and $P_{1/0}$ denote the conditional bit error probabilities when the transmitted bit is "1" or "0", which can be expressed as

$$P_{0/1}=\frac{1}{2}\left\{1+\mathrm{erf}\left[\left(b-\sqrt{P_s}\right)/\sqrt{2\sigma_n^2}\right]\right\}=\frac{1}{2}\mathrm{erfc}\left[\left(\sqrt{P_s}-b\right)/\sqrt{2\sigma_n^2}\right],\tag{5}$$

$$P_{1/0}=\frac{1}{2}\left\{1-\mathrm{erf}\left[b/\sqrt{2\sigma_n^2}\right]\right\}=\frac{1}{2}\mathrm{erfc}\left[b/\sqrt{2\sigma_n^2}\right],\tag{6}$$

where $\mathrm{erf}(x)=\frac{2}{\sqrt{\pi}}\int_0^x\exp(-u^2)\mathrm{d}u=1-\mathrm{erfc}(x)$, P_s is the peak power of the sampling judgment device, and b is the decision threshold. If we make $\frac{\partial P_{se}}{\partial b}=0$, the optimal decision threshold can be written as

$$b=\frac{\sqrt{P_s}}{2}+\frac{\sigma_n^2}{\sqrt{P_s}}\ln\frac{P_0}{P_1}.\tag{7}$$

We assume that the average power of all kinds of modulations is equal to P_{avg}, and $R_{SN}=\frac{P_{avg}}{\sigma_n^2}$ denotes the SNR. So we can deduce the peak power of all modulations as

$$P_{s,OOK}=2P_{avg},\tag{8}$$

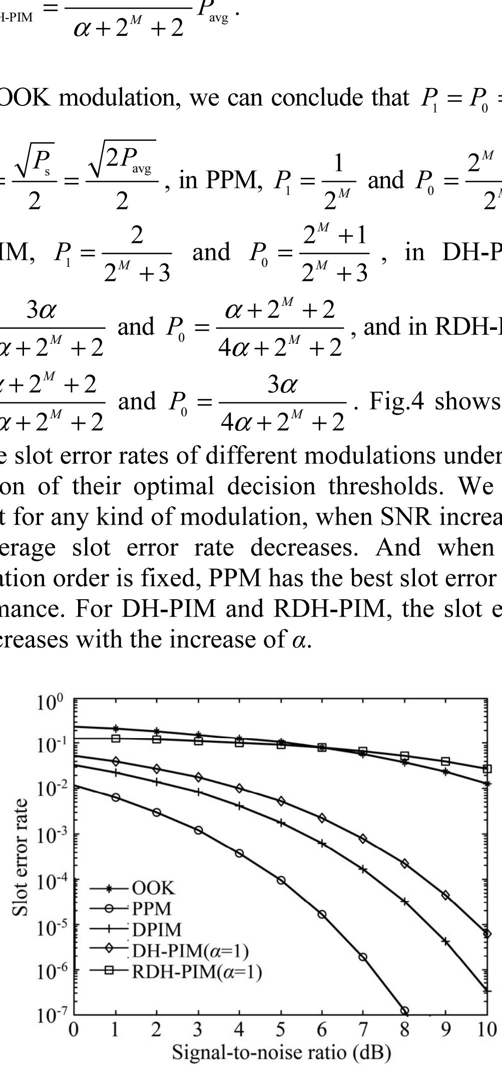
$$P_{s,PPM}=2^M P_{avg},\tag{9}$$

$$P_{s,DPIM}=\frac{2^M+3}{2}P_{avg},\tag{10}$$

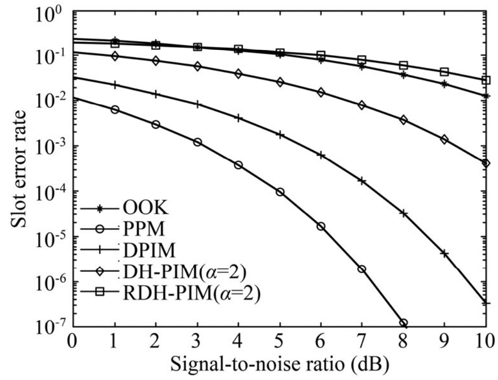
$$P_{s,DH\text{-}PIM}=\frac{4\alpha+2^M+2}{3\alpha}P_{avg},\tag{11}$$

$$P_{s,RDH\text{-}PIM}=\frac{4\alpha+2^M+2}{\alpha+2^M+2}P_{avg}.\tag{12}$$

For OOK modulation, we can conclude that $P_1=P_0=\frac{1}{2}$ and $b=\frac{\sqrt{P_s}}{2}=\frac{\sqrt{2P_{avg}}}{2}$, in PPM, $P_1=\frac{1}{2^M}$ and $P_0=\frac{2^M-1}{2^M}$, in DPIM, $P_1=\frac{2}{2^M+3}$ and $P_0=\frac{2^M+1}{2^M+3}$, in DH-PIM, $P_1=\frac{3\alpha}{4\alpha+2^M+2}$ and $P_0=\frac{\alpha+2^M+2}{4\alpha+2^M+2}$, and in RDH-PIM, $P_1=\frac{\alpha+2^M+2}{4\alpha+2^M+2}$ and $P_0=\frac{3\alpha}{4\alpha+2^M+2}$. Fig.4 shows the average slot error rates of different modulations under the condition of their optimal decision thresholds. We can see that for any kind of modulation, when SNR increases, the average slot error rate decreases. And when the modulation order is fixed, PPM has the best slot error rate performance. For DH-PIM and RDH-PIM, the slot error rate increases with the increase of α.



(a) α=1



(b) α=2

Fig.4 Slot error rates of OOK, PPM, DPIM, DH-PIM and RDH-PIM when *M*=4

In this paper, we propose a new modulation method named RDH-PIM based on DH-PIM, which is suitable for VLC. We analyze and compare the symbol structure, bandwidth requirement, transmission power and slot error rate performance of OOK, PPM, DPIM, DH-PIM and RDH-PIM. The results show that OOK is the simplest modulation, and has the minimum bandwidth but worst slot error rate performance. And RDH-PIM has the highest average transmission power, and its bandwidth efficiency is obviously better than those of PPM and DPIM. In practice, we should fully consider the conditions of the transmission distance, background light and other effects, such as geometric error, and choose an appropriate modulation to meet the requirements of communication.

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