A Differential Pulse Position Width Modulation for Optical Wireless Communication

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***Abstract*—A new scheme called differential pulse position width modulation (DPPM+PWM) in wireless optical communication is discussed. Compared to pulse position modulation (PPM), it does not need symbol synchronization when receiving signals. And it effectively solves the problem of the narrow transmitting pulse width in both differential pulse position modulation (DPPM) and PPM. The symbol structure, the power efficiency, bandwidth efficiency and error performance are analyzed and compared with OOK, PPM, DPPM and PWM. Basing on the given model, the stimulation results show that DPPM+PWM achieves greater ability to bandwidth efficiency and simplifies the receiver. Those improve DPPM+PWM a quite suitable scheme in the wireless optical communication system.**

***Index Terms*—wireless optical communication, differential pulse position width Modulation, power efficiency, bandwidth efficiency, packet error rate**

I. INTRODUCTION

As a transmission, infrared offers several advantages over radio, e.g. the wide bandwidth, low cost, high anti-electromagnet interference ability, good privacy etc.. Indoor wireless infrared communication is drawing increasing attention as an emerging technology [1, 2]. Pulse position modulation (PPM) [3~6], which is widely used in many applications, shows very good power efficiency and error performance. However, the bandwidth efficiency of PPM is low and the duration of pulse is short. Moreover, at the receiver, symbol and slot synchronization are needed which are not conductive to the realization of the system. Differential pulse position modulation (DPPM) [3, 7] always shows higher bandwidth efficiency than PPM, and it does not need symbol synchronization. But, the duration of Pulse in DPPM is too short. So, it is also difficult to realize this system. In this paper we put forward a new differential pulse position width modulation (DPPM+PWM) on the base of DPPM and PWM (Pulse Width Modulation) which is always used in automatic controlling, and compare it with other modulation schemes on the aspects of power and bandwidth requirement, as well as the error performance in the Gaussian channel.

II. CODING STRUCTURE

In a DPPM+PWM scheme, the first r bits of the whole binary M bits data in a symbol are modulated by differential pulse position modulation, the duration of the pulse is $T/2^r$. Then, the pulse is partitioned into a period of time that composes of 2^{M-r} slots with k+1 successive pulses and $2^{M-r}-(k+1)$ empty slots, just as pulse width modulation, whose duration is $T/2^M$. Here, k is the decimal number of the last $(M-r)$ bits of the symbol. If $M=4$, $r=2$, taking one of symbols for example, the coding process of DPPM+PWM is shown in Figure1. Table1 shows examples of mapping between source bits and transmitted chips.

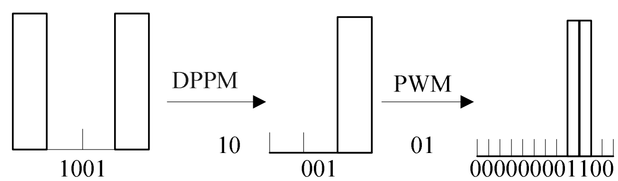

Figure 1. Coding process of the DPPM+PWM

TABLE I. EXAMPLES OF MAPPINGS BETWEEN SOURCE BITS AND TRANSMITTED CHIPS

Source bits	OOK	PPM	DPPM+PWM
0000	0000	1000000000000000	1000
0001	0001	0100000000000000	1100
0010	0010	0010000000000000	1110
0011	0011	0001000000000000	1111
0100	0100	0000100000000000	00001000
0101	0101	0000010000000000	00001100
0110	0110	0000001000000000	00001110
0111	0111	0000000100000000	00001111
1000	1000	0000000010000000	000000001000
1001	1001	0000000001000000	000000001100
1010	1010	0000000000100000	000000001110
1011	1011	0000000000010000	000000001111
1100	1100	0000000000001000	0000000000001000
1101	1101	0000000000000100	0000000000001100
1110	1110	0000000000000010	0000000000001110
1111	1111	0000000000000001	0000000000001111

In table1, we can see that the number of '1' pulse in DPPM+PWM is larger than that in PPM, which can help to improve bandwidth efficiency. Furthermore, each successive frame length in DPPM+PWM is different and determined by the value of the data being sampled, not by a predetermined clock period. According to those, it is well suited to wireless optical communication system by virtue of its increased bandwidth requirement and absence of receiver synchronization.

III. MODULATION TECHNIQUE ANALYSIS

A. power efficiency

To simplify analysis, we make the high-SNR assumption that the BER is dominated by the two nearest signals[8]: $BER = Q\left(d_{\min}/2/\sqrt{N_0}\right)$, $d_{\min}$ is the minimum Euclidean distance between any pair of valid modulation signals which satisfies $d_{\min}^2 = \min\limits_{i\neq j}\int\left[X_i(t)-X_j(t)\right]^2 dt$, $X(t)$ represents optical power in our application, N_0 is the power spectral density of White Gaussian noise, $Q(x)=\sqrt{2\pi}\int_x^{\infty} e^{-t^2/2}dt$. The minimum distance between the two signals in the OOK signal set is called d_{OOK} , which is equal to $2P/\sqrt{R_{\text{b}}}$, and the BER is $Q\left(P/\left(R_{\text{b}}\sqrt{N_0}\right)\right)$. We will use OOK as a benchmark to compare the power efficiency of various modulation schemes. The power required by OOK to achieve a given BER is $P_{\text{ook}} = \sqrt{N_0 R_{\text{b}}}Q^{-1}(\text{BER})$. The power required by any other modulation scheme to achieve the same BER is approximate $P = d_{\text{OOK}}/d_{\min}\times P_{\text{OOK}}$. Assuming the SNR is high enough that $BER = Q\left(d_{\min}/2/\sqrt{N_0}\right)$ is accurate. Therefore we will use the distance ratio $d_{\text{OOK}}/d_{\min}$ to characterize the power requirement of any modulation scheme. It is evident that DPPM+PWM does not display a regular periodic symbol structure, except the duration of a single pulse is equidistant. For DPPM+PWM, the minimum and the maximum symbol lengths are $2^{M-r}T_s$ and $2^M T_s$ respectively. So the mean symbol length is $\frac{2^{M-r}\cdot\left(1+2^r\right)\cdot T_s}{2}$, here T_s is the slot duration. Assuming the DPPM+PWM system encodes M bits data per symbol, the slot duration satisfies that the maximum symbol duration is equal to the time taken to transmit M bits of data using OOK. The slot duration is given as $T_s = \frac{T}{2^M}$. The transmitted optical power could be calculated according to the mean symbol length, and $d_{\text{D+W}} = PL_{\text{w}}(1+L_{\text{d}})\sqrt{T_{\text{s}}}/L/\left(1+L_{\text{w}}\right)$, in which $d_{\text{D+W}}$ is the minimum Euclidean distance of DPPM+PWM, $L_{\text{d}} = 2^r$ and $L_{\text{w}} = 2^{M-r}$ represent the largest number of slots in the part of DPPM and PWM of DPPM+PWM respectively, and $L = L_{\text{d}}\cdot L_{\text{w}} = 2^M$ .Therefore, the average power requirement is approximately,

$$\frac{P_{\text{D+W}}}{P_{\text{OOK}}} \approx \frac{d_{\text{OOK}}}{d_{\text{D+W}}} = \frac{2L\left(L_{\text{w}}+1\right)}{L_{\text{w}}(1+L_{\text{d}})\left(\log_2 L\right)^{1/2}} \tag{1}$$

And we can get the transmission power or the average one of other modulation schemes as follows in the same way.

$$P_{\text{PPM}} = \sqrt{2/L\times\log_2 L}P_{\text{OOK}} ,$$

$$P_{\text{DPPM}} = \sqrt{8\times L/\log_2 L}/\left(L+1\right)P_{\text{OOK}} ,$$

$$P_{\text{PWM}} = \left(L+1\right)/\left(\log_2 L\right)^{1/2}P_{\text{OOK}} \tag{2}$$

Figure 2 shows the required transmission power of the modulation schemes, normalized to OOK. We can assume $r=[M/2]$ (the same as follow) for simplify. We can see that the DPPM+PWM has better power efficiency than PWM, but not as good as OOK、DPPM and PPM. When M=4, the transmission power of DPPM+PWM is lower than that of PWM about 6.2dB, and higher than that of OOK, DPPM, PPM about 3.9dB, 8.5dB and 11dB, respectively. However, we can chose large r properly, which represents to add the length of L_{d} , to improve the power efficiency of DPPM+PWM.

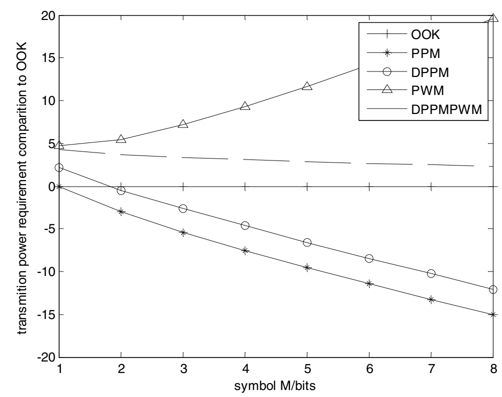

Figure 2. Transmission power of the modulation schemes compared with OOK

B. bandwidth efficiency

We assume that the duration of the conveying pulse is τ , and define the bandwidth requirement is $B=1/\tau$. If the duty cycle is $\tau_{\text{p}}=1$, then, $B=1/T_{\text{s}}$ (Hz). For OOK, the bandwidth requirement is roughly R_{b} bit/s , that is $B_{\text{ook}} = R_{\text{b}}$, the inverse of the pulse width. For DPPM+PWM, noting that the data rate is not a constant, we have to use the average bit rate based on average symbol rate. And the average duration of pulse is $T_{\text{D+W}} = (1+2+...+L_{\text{w}})T/L_{\text{w}} = \left(1+L_{\text{w}}\right)T/2$, basing on the average symbol duration, the bandwidth required to support communication at a bit rate, relative to OOK, is given as

$$B_{\text{D+W}} = \frac{1}{T_{\text{D+W}}} = \frac{2}{1+L_{\text{w}}}\cdot\frac{\left(1+L_{\text{d}}\right)\cdot L_{\text{w}}}{2\cdot\log_2 L}B_{\text{OOK}} \tag{3}$$

The bandwidth requirements of other modulation schemes also can be given in the same method. The results are plotted in figure 3, normalized to OOK. We can see, with the same M , bandwidth requirement of DPPM+PWM is lower than that of PPM and DPPM. Moreover, this superiority will be more obviously as M increase. With $M=4$, DPPM requires bandwidth 2 times of OOK, DPPM+PWM, which is equal to OOK , is the quarter of PPM.

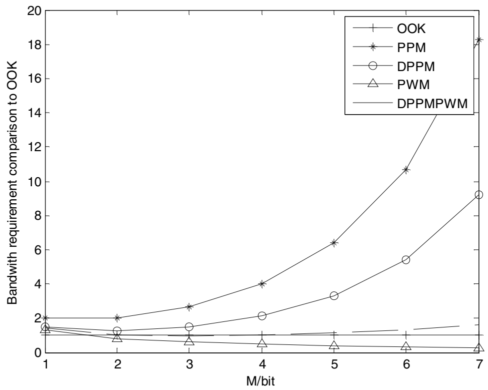

Figure 3. Bandwidth requirements of the modulation schemes compared to OOK

IV. ERROR PERFORMANCE ANALYSIS AND SIMULATION

A. theoretical analysis and calculation

In indoor wireless optical communication, the noise is mainly composed of shot noise resulting from a variety of background lights, e.g. sunshine, lightings [9]. But they are usually much greater than the signal light. So, we can assume that the shot noise can be independent of the transmitting signals. And there are other noises including dark and leakage current noise resulting from the photo-detector and heat noise resulting from resistance. Those are independent of the transmitting signal. Therefore, the system noise can be seen as the launch of the Gaussian white noise which is independent of the transmitting signals.

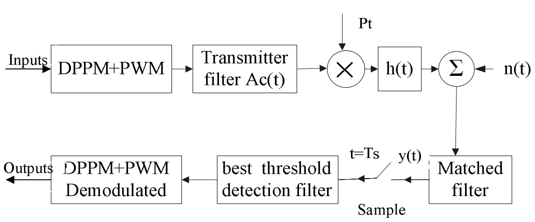

Figure 4. The system mode

Figure 4 [10] is the system model on above assumption. In the figure, the input of matched filter $x(t)$ is $\sqrt{gP_{\mathrm{t}}}+n(t)$ or $n(t)$, whether the optical pulse exists or not. Where, P_{t} is the peak power of transmitted pulse, $n(t)$ is a Gaussian white noise with 0 mean, $\sigma_0^2=N_0B$ variance. Therefore, the output of matched filter at $t=T_{\mathrm{s}}$ will be $E_{\mathrm{P}}+n_0(T_s)$ when optical pulse is transmitted or $n_0(T_s)$ without any pulse. If the waveform is rectangular, the output signal must be the convolution of $x(t)$ and $\sqrt{gP_{\mathrm{t}}}$ in one bit time, then $E_{\mathrm{P}}=gP_{\mathrm{t}}T_s$, $n_0(T_s)$ is still Gaussian noise with 0 mean, but the variance now is $\sigma^2=T_s^2N_0BgP_{\mathrm{t}}$. We further assume that the input bits of 1 and 0 have equal probability, and p_0 and p_1 are the probabilities receiving 1 and 0, respectively. Then $p_0=\dfrac{L-1}{L_{\mathrm{w}}\left(1+L_{\mathrm{d}}\right)}$, $p_1=\dfrac{L_{\mathrm{w}}+1}{L_{\mathrm{w}}\left(1+L_{\mathrm{d}}\right)}$, If the threshold is $kE_{\mathrm{P}}(0<k<1)$, P_{e0} and P_{e1} are the probabilities transmitting 0 but receiving 1 and transmitting 0 but receiving 1, respectively, then we have $p_{e0}=Q\left[k\sqrt{\dfrac{gP_t}{N_0B}}\right]$, $p_{e1}=Q\left[(1-k)\sqrt{\dfrac{gP_t}{N_0B}}\right]$, If P is the average transmitting power, we have different peak power for each modulation scheme,

$$P_{t,\mathrm{OOK}}=2P\ ,\ P_{t,\mathrm{PPM}}=LP\ ,$$

$$P_{t,\mathrm{DPPM}}=\frac{L+1}{2}P\ ,\ P_{t,\mathrm{D+W}}=\frac{L_{\mathrm{w}}\cdot\left(L_{\mathrm{d}}+1\right)}{L_{\mathrm{w}}+1}P \tag{4}$$

The signal noise rate in the receiver is defined as $SNR=\sqrt{\dfrac{gP}{N_0R_b/2}}$. Thus the average slot error rate of DPPM+PWM is

$$P_{s.e.\mathrm{D+W}}=\frac{L-1}{L_{\mathrm{w}}\left(1+L_{\mathrm{d}}\right)}\mathrm{Q}\left(\mathrm{k}\sqrt{\frac{(L_{\mathrm{d}}+1)L_{\mathrm{w}}\cdot SNR}{2(L_{\mathrm{w}}+1)}}\right)+ \frac{L_{\mathrm{w}}+1}{L_{\mathrm{w}}\left(1+L_{\mathrm{d}}\right)}\mathrm{Q}\left((1\text{-k})\sqrt{\frac{(L_{\mathrm{d}}+1)L_{\mathrm{w}}\cdot\mathrm{SNR}}{2(L_{\mathrm{w}}+1)}}\right) \tag{5}$$

For DPPM+PWM, one slot error doesn't only influence the symbol which it lies in, but also the following symbols. It is necessary to analyze the packet error rate (PER). For a packet of N bits, after modulated by DPPM+PWM, there are NL_{avg}/M slots, L_{avg} represents the average length of the symbols. The PER is

$$P_{\mathrm{p.e}}=1-(1-P_{\mathrm{s.e}})^{NL_{\mathrm{avg}}/M}\approx NL_{\mathrm{avg}}P_{\mathrm{s.e}}/M \tag{6}$$

Put (5) into (6), then the PER of the DPPM+PWM can be written as

$$P_{\mathrm{p.e.D+W}}=N/M\left(\frac{L-1}{2}\mathrm{Q}\left(\mathrm{k}\sqrt{\frac{(L_{\mathrm{d}}+1)L_{\mathrm{w}}\cdot\mathrm{SNR}}{2(L_{\mathrm{w}}+1)}}\right) +\frac{L_{\mathrm{w}}+1}{2}\mathrm{Q}\left((1\text{-k})\sqrt{\frac{(L_{\mathrm{d}}+1)L_{\mathrm{w}}\cdot\mathrm{SNR}}{2(L_{\mathrm{w}}+1)}}\right)\right) \tag{7}$$

Figure 5 shows PER of OOK, PPM, DPPM, PWM and DPPM+PWM at Gaussian channel for the values of $M=4$, $k=0.5$, $g=1$, $\sigma^2=1e-8$ and $N=1024$. The results show that DPPM+PWM is worse than PPM and DPPM, but better than OOK and PWM obviously. Moreover, it degrades sharply with the increase of average transmitting power. When PER is 10^{-6}, the SNR of DPPM+PWM when $r=2$ is lower than OOK by 1dB, and 2dB when $r=3$; when

SNR=6dB , the PER of OOK is about 0.0174, that of DPPM+PWM is 0.9×10^{-4} if $r=2$ and 1.9×10^{-12} if $r=3$.

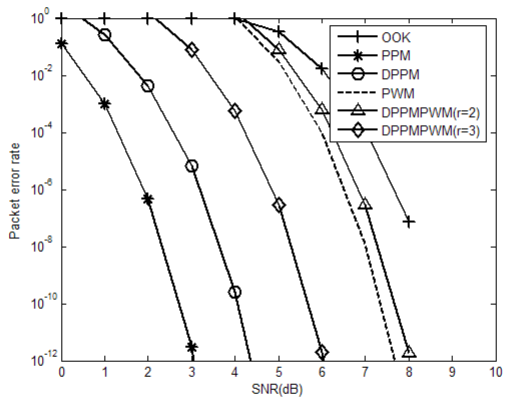

Figure 5. Packet error rate of the modulation schemes

B. Simulation

In simulation system, with Gaussian channel, the packet error rates of PPM, DPPM, PWM, DPPM+PWM with $r=2$ and $r=3$ are analyzed in figure 6 Here, we assume $M=4$ and $N=1024$. The simulation results accord with the theoretical estimate. DPPM + PWM is better than OOK and PWM, and worse than PPM and DPPM. That is to say, system with DPPM + PWM shows better error performance compared to that with OOK. For SNR=11dB, packet error rate of OOK system is about 0.5, which can not complete communication. DPPM + PWM system make the error rate 10^{-2} if $r=2$ and 10^{-3} if $r=3$.

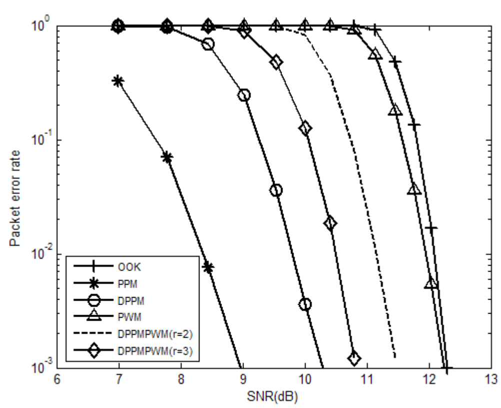

Figure 6. simulation of packet error rate of the modulation schemes

CONCLUSION

In this paper, a new differential pulse position width modulation in wireless optical communication is presented. Its symbol structure, power and bandwidth efficiency and error performance are analyzed, and compared with OOK, PPM, DPPM and PWM schemes by simulation. The results show that the power efficiency of DPPM+PWM is low, however, it is higher than that of PWM. Although, the error performance of DPPM+PWM is inferior to that of PPM and DPPM, it is better than that of OOK obviously. Compared with OOK, PPM, and DPPM, DPPM+PWM achieves higher bandwidth efficiency. DPPM+PWM overcomes the problem of narrow transmitting pulse in PPM and DPPM. Moreover, relative to PPM, it is not necessary to implement symbol synchronization in DPPM+PWM. These make DPPM+PWM a very good candidate to replace PPM in many applications.

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