I.J. Information Technology and Computer Science, **2012, 3, 45-50**
Published Online April 2012 in MECS (http://www.mecs-press.org/)
DOI: 10.5815/ijitcs.2012.03.07

Dual Amplitude-Width PPM for Free Space Optical Systems

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***Abstract*—The PPM (Pulse Position Modulation) is commonly used in Free Space Optic (FSO) systems owing to its power efficiency, but it shows a rapid decline in spectral efficiency with increase in the power efficiency and moderate data rate. In order to improve these two parameters, we present a modified modulation scheme of the existing PPM, on the basis of PPM, PAM (Pulse Amplitude Modulation) and PWM (Pulse Width Modulation). This modified version called DAWPPM (Dual Amplitude-Width PPM).**

The average power requirements, bandwidth efficiency and normalized data rate are studied after introducing symbol structure. The proposed scheme shows an improvement in terms of data rate and bandwidth efficiency, and when in come to power efficiency it shows lower efficiency compared to PPM. We present theoretical expressions of data rate, spectral efficiency, and normalized power requirements, and we present comparison results to PPM modulation scheme.

***Index Terms*—*PPM, PAM, PWM, DAWPPM,* data rate, power requirements and bandwidth efficiency.**

1. Introduction

Free Space Optic (FSO), also called Wireless Optical Communication (WOC), refers to the transmission of modulated visible or infrared beams through the free space (atmosphere) to transmit voice, video, and data information at speeds of up to 10 Gbps [1] between two ends, over several kilometers as long as there is a clear line of sight (LOS) between the transmitter and the receiver (Figure 1).

One of the major parameters in the realization of high performance FSO system is the choice of the modulation format, which should be carefully chosen. Because of the complexity and expensiveness of coherent modulation techniques like phase and frequency modulation [2], a great number of applications use Intensity Modulation/Direct Detection (IM/DD) as the transmission-reception technique due to its simplicity of implementation [3]. Intensity modulation is easily obtained through variations on the bias current of the transmitter device, which modulates the signal onto the instantaneous power of the transmitted beam.

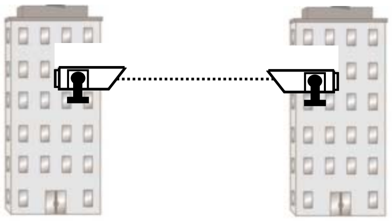

Fig 1: FSO transmitter and receiver mounted on top of two buildings in point to point connection

Various modulation techniques compatible with IM/DD have been proposed and studied for the successful operation of the Free Space Optical Communication. Each modulation scheme has its advantages and inconvenience for the particular system requirements.

In OOK (On-Off Keying) modulation scheme, the information bits are converted into some specific code pulses (NZ, NRZ, Manchester etc.), presence of a pulse denotes bit 1 and absence of a pulse denotes bit 0, during that slot. OOK is the simple and widely adopted modulation scheme used in commercial FSO communication systems [4] because of ease in implementation, simple receiver design, bandwidth efficiency and cost effectiveness. On the other hand considerable average power efficiency can be achieved by employing pulse modulation, in which a range of time dependent features of the pulse carrier is used to convey information. The PPM (Pulse Position Modulation) is a popular modulation format used in Free Space Optical (FSO) communications [5], the PPM modulation scheme is more power efficient than the modulation OOK, but it shows a rapid decline of spectral efficiency with increase in the power efficiency.

The PPM modulation is commonly used in FSO systems owing to its power efficiency. In this paper, we are interested in more efficient modulation technique that makes a good compromise between data rate, spectral and power efficiencies. In this view, we propose hybrid modified PPM modulation, DAWPPM (Dual Amplitude Width PPM), on the basis of PPM, PAM (Pulse amplitude Modulation) and PWM (Pulse Width Modulation). The proposed DAWPPM shows an improvement in terms of data rate and bandwidth efficiency over PPM modulation and when in come to power efficiency it shows lower efficiency as cost for the improvement in term of data rate and bandwidth efficiency.

The remainder of this paper is constructed as follows: Sections 2.3 and 4 covers the system models of PPM, PAM and PWM respectively. In section 5 and after introducing symbol structure of the proposed modulation, data rate improvement, average power requirements, and bandwidth efficiency are studied and compared to PPM, this is followed by a conclusion in section 6.

2. Pulse Position Modulation

Pulse Position Modulation (PPM) is a modulation technique proposed mainly to increase transmission efficiency in the FSO systems. In this scheme, each symbol interval of duration T=log$_2$ (M/R$_b$) is partitioned into M slots, each of duration Ts =T/M, and the transmitter sends an optical pulse during one of these M slots. The transmit pulse shape is given by:

$$\mathrm{P(t)} = \begin{cases} \mathrm{P,\ for\ t} \in \left[\mathrm{(m\text{-}1)T/M,\ mT/M}\right] \\ \quad 0,\ \ \mathrm{elsewhere} \end{cases} \tag{1}$$

Where m= {1, 2 … M}, and P is the pulse power.

PPM is known for its power efficiency, but the PPM based systems suffer from the disadvantage of bandwidth expansion and high complexity in implementation (due to higher level of accuracy required in slot and symbol synchronization).

A vital parameter to judge the performance of any modulation scheme is the average received optical power to get the desired BER (Bit Error Rate). The average received optical power for any modulation scheme can be normalized to the received average power required to get the desired BER while transmitting OOK through an ideal channel.

The normalized average power requirement is approximately [6]:

$$\frac{\mathrm{P_{PPM}}}{\mathrm{P_{OOK}}} = \sqrt{\frac{2}{\mathrm{M\log_2 M}}} \tag{2}$$

The bandwidth, B, required by the PPM scheme to achieve a bit rate of R, is approximately the inverse of one chip duration. Then, one can write:

$$B_{PPM} = M\,\frac{R}{\log_2 M} \tag{3}$$

This paper defines the spectral efficiency, η, as the ratio R/B, i.e.

$$\eta_{PPM} = \frac{R}{B_{PPM}} = \frac{\log_2(M)}{M} \tag{4}$$

3. Pulse Amplitude Modulation

Pulse amplitude modulation, acronym PAM, is a form of signal modulation where the message information is encoded in the amplitude of a series of signal pulses; Figure 2 shows an example of 2PAM mapping.

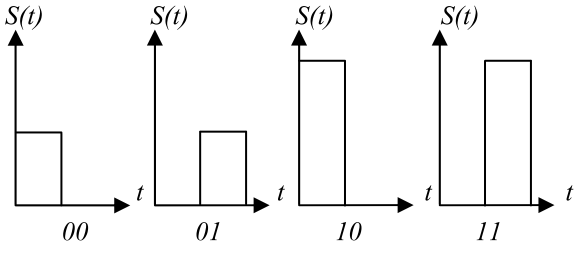

Fig 2 : Example of PAM mapping

Whene bandwidth efficiency is taken into account PAM is a prime candidate, for this reason PAM has been combined to various modulation schemes compatible with the optical wireless systems in order to acheave more spectrale efficiency and improve the data rate as well.

The normalized average power requirement of PAM is given by [7]:

$$\frac{\mathrm{P_{PAM}}}{\mathrm{P_{OOK}}} = \frac{\mathrm{M}-1}{\sqrt{\log_2 \mathrm{M}}} \tag{5}$$

The bandwidth efficiency is given by:

$$\eta_{\mathrm{PAM}} = \log_2 M \tag{6}$$

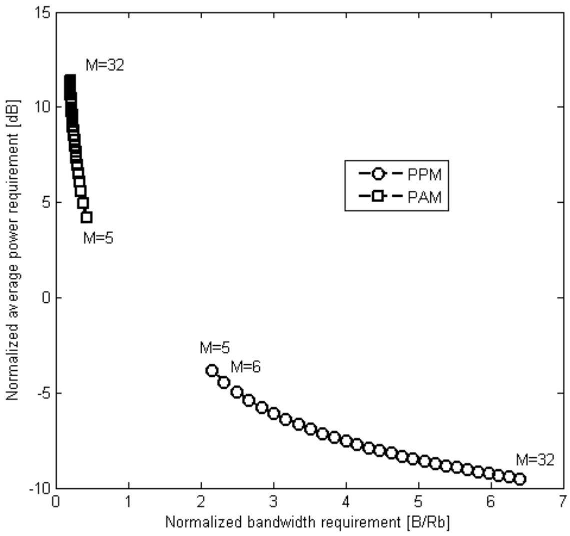

Fig 3 : Power requirement versus Band width requirement for PAM and PPM

Figure 3 show that higher average power efficiency can be achieved by Pulse Position Modulation schemes “PPM”. On the other hand the figure shows that PAM modulatio presents an attractive advantage in term of bandwidth efficiency, for this reason; various PTM (Pulse time Modulation) schemes had been combined to PAM.

4. Pulse Width Modulation

The difference between PPM and PWM schemes is in the way the symbol is expressed. In PWM modulation, the symbol is denoted by pulse width instead of pulse position. The PWM and the PPM approach are shown in Figure 4.

It is well known that a wider pulse has a greater ability to resist intersymbol interference when data are transmitted through a multipath channel [8], which make the combination of this modulation scheme to other modulation techniques suitable with the wireless optical systems a very attractive solution to benefit from the strength of two modulation categories in a new hybrid form of modulation system, that have the ability to resist intersymbol interference.

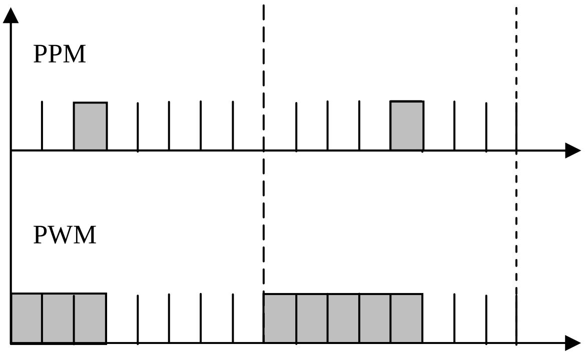

Fig 4 : Example of PWM and PPM mapping for M=8

5. Dual Amplitude-width PPM (DAWPPM)

The PPM modulation shows good power efficiency, but it shows a rapid decline in spectral efficiency with increasing power efficiency. The DAWPPM is a modified hybrid form of the existing PPM modulation scheme presented mainly to improve the data rate and the bandwidth efficiency over the existing PPM.

DAWPPM is a new approach of modulation technique presented on the basis of PPM, PAM and PWM, where the data are presented by the combination Position-Amplitude-Width. In this paper, we allow the pulses to take two levels (A_1, A_2), and two widths (W_1, W_2). The relationship between the two levels and the two widths is design parameters, in this papers we take:

$$A_2=2.A_1 \tag{7}$$

$$W_2=2.W_1 \tag{8}$$

In this modulation format, each sequence of b bits is mapped into one of $L=2^b$ symbols and transmitted to the channel.

By the combination Position-Amplitude-Width, the number of possible symbols in the DAWPPM signal set is:

$$L=3.M \tag{9}$$

Usually the value of L is not power of two, so generally we must discard some of the resulting signals to achieve $L=2^b$.

Examples of mapping between source bits and transmitted slots for PPM, and DAWPPM are shown in Table 1.

Where:

a: is a pulse with A_1 as amplitude
A: is a pulse with A_2 as amplitude

Table 1 : Mapping between source bits (OOK) and transmitted slots for PPM and DAWPPM

bits	***PPM***	***DAWPPM***
000	*1*0000000	a00
001	0*1*000000	0a0
010	00*1*00000	00a
011	000*1*0000	aa00
100	0000*1*000	0aa0
101	00000*1*00	00aa
110	000000*1*0	A00
111	0000000*1*	0A0

Figure 5 shows an encoding example of a serial data bit to DAWPPM.

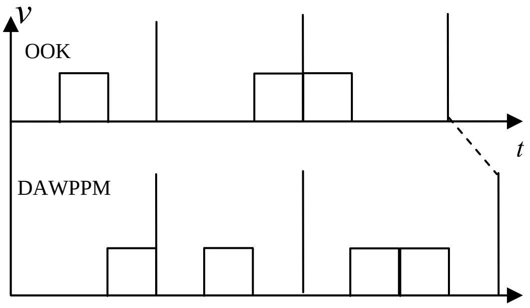

Fig 5: Encoding Example of a serial data bit to DAWPPM

5.1 Data rate

The data rate that can be achieved by a modulation format is a vital parameter to judge the performance of a modulation scheme. One of the main reasons of the proposition of DAWPPM is the improvement of the data rate over PPM modulation.

The data rate that can be achieved with PPM is:

$$D_{PPM} = \frac{\log_2 M}{M.T_s}(\text{bit/s}) \tag{10}$$

Ts: the slot duration.

Since the pulse width is not constant in DAWPPM, the symbols can take (M.Ts) or ((M+1).Ts) as lengths.
The mean symbol length is (2M+1 /2). Thus, the mean data rate achieved by DAWPPM based on mean symbol length is given by:

$$D_{DAWPPM} = \frac{2.\log_2 L}{(2M+1)T_s}(\text{bit/s}) \tag{11}$$

To show the improvement in information rate we define the parameter R, which presents the ratio in the data rate of DAWPPM modulation scheme to that of PPM.

$$R = \frac{D_M}{D_{PPM}} \tag{12}$$

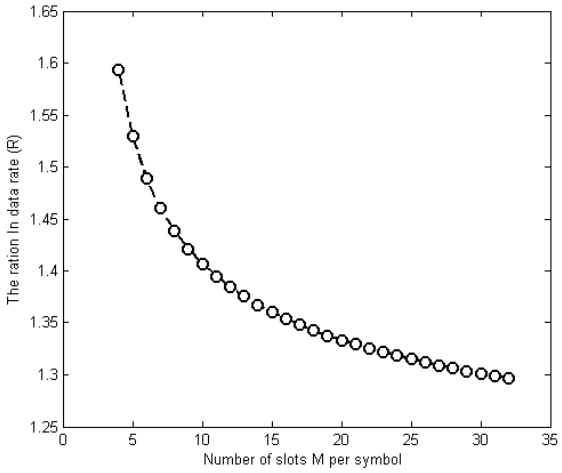

Fig 6: Number of bits per symbol for DAWPPM normalized to PPM

Figure 6 shows the ratio *R* for DAWPPM modulation based on symbol length *M*. DAWPPM modulation scheme shows a degrading improvement in term of data rate over PPM, where for M=4, the data rate achieved by DAWPPM is about 1.6 that of PPM, this multitude decrease as m increase to be about 1.3 at M=32.

These results show that the proposed method presents an improved data rate over PPM especially for low values of M.

3.2 Power requirements and bandwidth efficiency

The minimum and the maximum power requirements per symbol by DAWPPM modulation are $1A_1$ and $2A_1$ respectively. Thus, the average power requirement based on the average symbol length is given by:

$$p_{DAWPPM} = \frac{3/2}{(2M+1)/2} = \frac{3}{2M+2} \tag{13}$$

In PPM modulation, the average power requirement per symbol is (A_1/M), and we have in DAWPPM modulation the average power requirement is given by (13).
Therefore, the relationship between the two average powers PPM and that of DAWPPM modulation is given by:

$$\frac{P_{DAWPPM}}{P_{PPM}} = \frac{\frac{3}{(2M+2)}}{1/M} = \frac{3M}{2M+2} \tag{14}$$

In order to find the normalized average power requirement for the DAWPPM scheme, we multiply (2) by (14):

$$\frac{P_{PPM}}{P_{OOK}}.\frac{P_{DAWPPM}}{P_{PPM}} = \frac{P_{DAWPPM}}{P_{OOK}} \tag{15}$$

Consequently, the average power requirement by the DAWPPM normalized to OOK is given by:

$$\frac{\mathrm{P}_{\mathrm{DAWPPM}}}{\mathrm{P}_{\mathrm{OOK}}} = \frac{3\mathrm{M}}{2\mathrm{M}+2}\sqrt{\frac{2}{\mathrm{M}\log_2 \mathrm{M}}} \qquad (16)$$

The bandwidth required to support communication at a bit rate based on the average symbol duration relative to OOK, is given by.

$$B_{\mathrm{DAWPPM}} = \frac{(2M+1)R_b}{2\log_2 L} \qquad (17)$$

The band utilization efficiency is given by:

$$\eta_{\mathrm{DAWPPM}} = \frac{2\log_2 L}{2M+1} \qquad (18)$$

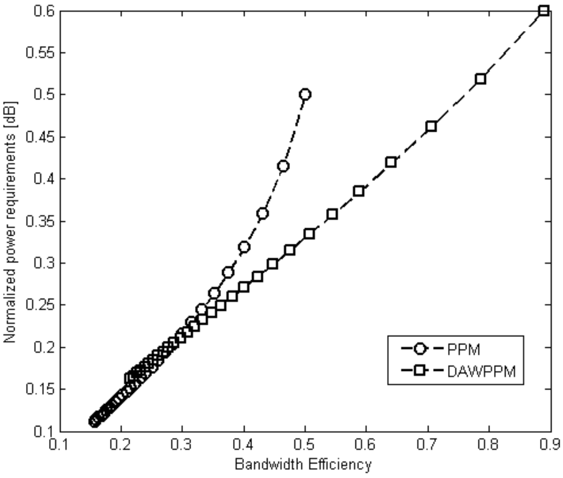

Fig 7 : Normalized Power Requirement based on Bandwidth efficiency for PPM and DAWPPM

Figure 7 shows the normalized power requirements based on the bandwidth efficiency for PPM and DAWPPM modulation schemes for different values of *M* from 4 to 32. The figure shows that for both schemes the spectral efficiency decreases as *M* increase, but with different behaviors, where DAWPPM is much efficient than PPM in this term for all the values of *M* and this outperformance decrease as M increase. When it comes to power efficiency the two schemes show an increase in this term with the value of *M* (decrease in power requirements), where PPM is much efficient in this term for all the values of *M*. For M=4 the spectral efficiency of DAWPPM is about 1.8 times the spectral efficiency of PPM modulation, and the efficiency of DAWPPM is about 0.1 dB lower than that of PPM. For M=32, the spectral efficiency of DAWPPM is about 1.4 that of PPM with 0.05 dB loss in the power efficiency.

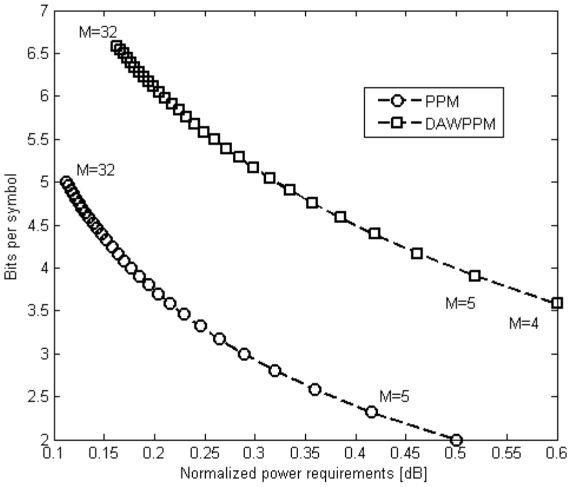

Fig 8: Bits per symbol based on Normalized Power Requirement for PPM and DAWPPM

These results show the outperformance of DAWPPM modulation in term of spectral efficiency, especially for low value of M. On the other hand a slight degradation in power efficiency is shown as cost of the improvement in the spectral efficiency and the data rate.

Figure 8 shows the number of bits per symbol based on Normalized Power Requirement for PPM and DAWPPM modulation schemes for different values of *M* from 4 to 32. The figure shows that with different power requirements DAWPPM always outperform PPM in term of data rate with an average of 1.5 bit per symbol. The power requirement to achieve this improvement decrease as M increase, where for M=4 we have 0.1 dB difference, and this value decrease to be at M=32 about 0.05 dB.

According to these results, we can say that beside the improvement in term of data rate, the proposed method shows a remarkable improvement in term of spectral efficiency and slight increase the power requirement as cost of the improvement in the bandwidth efficiency and data rate.

6. Conclusion

The PPM modulation is commonly used in FSO systems owing to its power efficiency. In this paper, we are interested in more efficient modulation technique that makes a good compromise between data rate, spectral and power efficiencies. In this view, we have presented hybrid modified PPM modulation, on the basis of PPM, PAM (Pulse Amplitude Modulation) and PWM (Pulse Width Modulation). This modulation scheme, called DAWPPM (Dual Amplitude-Width PPM) proposed essentially to improve the data rate and the bandwidth efficiency over PPM. The proposed DAWPPM shows an improvement in both data rate and spectral efficiency, but with degradation in term of power efficiency.

The proposed modified PPM may be well alternative modulation, suitable to be used in Free Space Optical Communications Systems that require high data rate and bandwidth efficiency.

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