Dual Amplitude-Width Pulse Interval Modulation for Optical Wireless Communications

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Abstract

In this paper, a new modified digital pulse interval modulation called Dual Amplitude-Width Pulse Interval Modulation (DAWPIM) is presented, on the basis of Pulse Amplitude Modulation (PAM) and Pulse Width Modulation (PWM), and its properties are presented. After introducing symbol structure, data rate improvement, average normalized power requirement and bandwidth efficiency are studied. The proposed concept showed to be well suited to use in Optical Wireless Communications links by virtue of its increased data rate, high spectral efficiency and the absence of receiver synchronization problems.

We present theoretical expressions of spectral efficiency, power requirements, and the data rate improvement normalized to PPM, and we present comparison results to DPIM and the hybrid PAM-DPIM.

Keywords: DAWPIM, DPIM, hybrid modulation, performance analysis, WOC.

1. Introduction

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

The choice of modulation scheme is one of the most important factors in realizing a high performance wireless optical communication system at a reasonable cost and acceptable complexity, and because of the complexity and expensiveness of coherent modulation techniques like phase or frequency modulation [1] current WOC systems typically use Intensity Modulation and Direct Detection (IM/DD) [2] for its simple implementation and low cost. There is various modulation schemes compatible with IM/DD such as PPM and DPIM. Selecting the most appropriate modulation scheme will depend on a number of system criteria. For optical wireless systems, the main criteria are power requirements, bandwidth efficiencies, data rate and complexity.

Multi-level modulation techniques such as PAM are powerful in terms of spectral efficiency. On the other hand, higher average power efficiency can be achieved by Pulse Time Modulation schemes "PTM" in which a range of time dependent features of a pulse may be used to convey information. These PTM techniques fall into two categories, namely isochronous and Anisochronous. Isochronous schemes encode data by varying the position or width of a pulse, but the overall symbol structure remains constant such as PPM, in contrast, Anisochronous schemes have no fixed symbol structure [3]. Among the anisochronous modulations, DPIM (Digital Pulse Interval Modulation) has been combined with PAM (Pulse Amplitude Modulation) in DAPIM "Dual-Amplitude Pulse Interval Modulation" [4] to achieve more efficiency in term of bandwidth, and to improve the data rate.

In order to more improve the data rate, and the spectral efficiency, we propose and analysis in this paper a new concept of modulation on the basis of DAPIM and PWM, called DAWPIM "Dual Amplitude-Width Pulse Interval Modulation", as a new potential alternative to the existing DPIM modulation.

2. Pulse Position Modulation "PPM"

Among the isochronous schemes, PPM has been used widely in optical communication systems, and has been adopted by the IEEE 802.11 working group for the infrared physical layer standard [5]. In PPM information is transmitted as follows: at the transmitter side the encoder maps blocks of b consecutive bits for each block into a single PPM symbol by placing a single laser pulse into one of $M = 2^b$ time slots. On the other end, the receiver detects the encoded PPM symbols by determining which one of the M slots contains the pulse, and performs the inverse mapping operation in order to recover the transmitted bit stream. The average power requirement for PPM is given by [6]:

$$\frac{P_{PPM}}{P_{OOK}} = \sqrt{\frac{2}{M \log_2 M}} \qquad (1)$$

The band utilization efficiency is given by:

$$\eta_{PPM} = \frac{R_b}{B_{PPM}} = \frac{\log_2 M}{M} \qquad (2)$$

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

3. Digital Pulse Interval Modulation “DPIM”

The DPIM is a modified form of PPM, instead of coding the data sequence by the location of the position of a pulse in a fixed frame width, the data sequence is represented by the time interval between the previous and the present pulse [7]. DPIM doesn’t require any synchronization, as every symbol starts with a header pulse. In order to avoid symbols in which the time between adjacent pulses is zero, an additional guard slot may be added to each symbol immediately following the pulse. Thus, a symbol which encodes *b* bits of data is represented by a pulse of constant power in one slot followed by *k* slots of zero power, where $1 \le k \le M$, ($M = 2^{b)}$. The minimum and the maximum symbol lengths are 2Ts and (M+ l)Ts respectively, so the mean symbol length is (M + 3)Ts/2 [7].

The average power requirement for the DPIM scheme normalized to OOK (On off Keying) modulation is given in [7]:

$$\frac{P_{DPIM}}{P_{OOK}} = \frac{\sqrt[4]{\dfrac{M+1}{\log_2 M}}}{(M+3)\sqrt{2}} \qquad (3)$$

In this paper we use another method -Accurate and Simple- to find the **normalized** average power requirement for the DPIM scheme. The average power requirement by PPM is (1 /M), and the average power requirement by DPIM is (1/ (M+3)/2). Therefore, the relationship between the two powers PPM and DPIM is given by:

$$\frac{P_{DPIM}}{P_{PPM}} = \frac{\dfrac{1}{(M+3)/2}}{1/M} = \frac{2M}{M+3} \qquad (4)$$

In order to find the average normalized power requirement for the DPIM scheme, we multiply (1) by (4):

$$\frac{P_{PPM}}{P_{OOK}} \text{ x } \frac{P_{DPIM}}{P_{PPM}} = \frac{P_{DPIM}}{P_{OOK}} \qquad (5)$$

Consequently, the average power requirement of the DPIM scheme normalized to OOK is given by:

$$\frac{P_{DPIM}}{P_{OOK}} = \frac{2M}{M+3}\sqrt{\frac{2}{M\log_2 M}} \qquad (6)$$

The bandwidth required to support communication at a bit rate based on the average symbol duration relative to OOK, is given in [7].

$$B_{DPIM} = \frac{(M+3)R_b}{2\log_2 M} \qquad (7)$$

The band utilization efficiency is given in [7]:

$$\eta_{DPIM} = \frac{2\log_2 M}{(M+3)} \qquad (8)$$

For DPIM, note that the data rate is not a constant; we have to use the average bit rate based on average symbol length. The throughput that can be achieved with DPIM based on mean symbol length is:

$$D_{DPIM} = \frac{\log_2 (M)}{T_{mean}} \qquad (9)$$

To show the improvement in data rate we define the parameter *R*, which presents the ratio in the data rate of any modulation scheme to that of PPM. The ratio *R* of DPIM modulation based on average symbol length is:

$$R = \frac{D_{DPIM}}{D_{PPM}} = \frac{(2M)}{(M+3)} \qquad (10)$$

4. Dual Amplitude Pulse Interval Modulation “DAPIM”

DAPIM is a modified version of the existing DPIM modulation scheme, where each symbol start with a pulse and this pulse can take one of two levels (A_1, A_2) to convey one of the *L* symbols, where the number of possible symbols *L* is given by:

$$L_{DAPIM}=2M \qquad (11)$$

The relationship between the two levels is a design parameter. In this paper we take:

$$A_2=2.A_1 \qquad (12)$$

The same as in DPIM, the minimum and the maximum symbol lengths are 2Ts and (M+1)Ts respectively, so the mean symbol length (T_{mean}) is (M+3)Ts/2.

4.1 Data rate

The symbol length in DAPIM is also not a constant; we have to use the average bit rate based on average symbol length. The data rate that can be achieved by DAPIM based on mean symbol length is:

$$D_{DAPIM} = \frac{\log_2 (2M)}{T_{mean}} \qquad (13)$$

The ratio *R* of the average data rate based on average symbol length of DAPIM is:

$$R = \frac{D_{DAPIM}}{D_{PPM}} = \frac{(2M)\log_2(2M)}{(M+3)\log_2 M} \tag{14}$$

Figure.1 shows the ratio *R* for DPIM and DAPIM based on symbol length *M*. The figure shows that DAPIM outperforms DPIM for all the values of *M*, where for M=4 the ratio *R* of DAPIM is about 1.5 time that of DPIM, and this multitude decrease slightly as *M* increase to be at M=32 about 1.2.

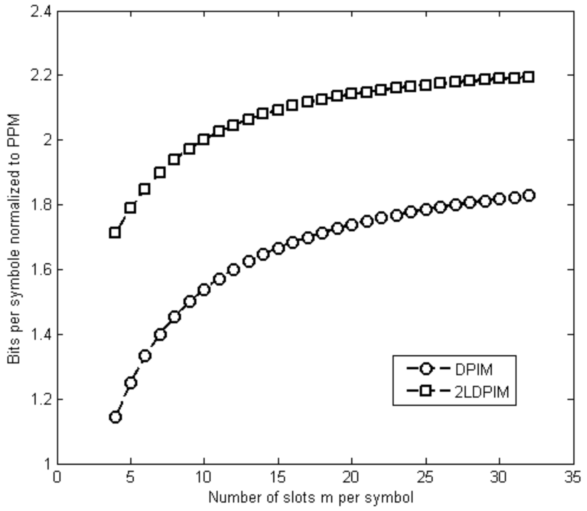

Fig. 1 Normalized data date of DPIM and 2LDPIM

4.2 Power requirement and bandwidth efficiency

We use the same method as we used for DPIM to find the average power requirements. The minimum and the maximum power requirement by DAPIM modulation are $1A_1$ and $2A_1$ respectively. Thus, the average power requirement based on the average symbol length is given by:

$$p_{DAPIM} = \frac{3/2}{(M+3)/2} = \frac{3}{M+3} \tag{15}$$

The relationship between the two averages powers: DAPIM and PPM is given by:

$$\frac{P_{DAPIM}}{P_{PPM}} = \frac{\frac{3}{(M+3)}}{1/M} = \frac{3M}{M+3} \tag{16}$$

In order to find the average normalized power requirement for the DAPIM scheme normalized to OOK, we multiply (16) by (2):

$$\frac{P_{PPM}}{P_{OOK}} \text{x} \frac{P_{DAPIM}}{P_{PPM}} = \frac{P_{DAPIM}}{P_{OOK}} \tag{17}$$

Consequently, the average normalized power requirement for the DAPIM scheme normalized to OOK is given by:

$$\frac{P_{DAPIM}}{P_{OOK}} = \frac{3M}{M+3}\sqrt{\frac{2}{M\log_2 M}} \tag{18}$$

Also based on average symbol length, the band utilization efficiency of DAPIM is given by:

$$\eta_{DAPIM} = \frac{3\log_2(2M)}{(M+3)} \tag{19}$$

Figure.2 shows the normalized power requirement based on the spectral efficiency for both DPIM and DAPIM with 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 behavior, where DAPIM is much more efficient than DPIM in this term. When it comes to power efficiency DAPIM is less efficient. The cost of spectral performance of DAPIM is paid as losses in power efficiency, and these losses decrease with the value of *M*. For M=4, the spectral efficiency of DAPIM is 2.2 times that of DPIM with 0.3 dB loss in power efficiency, and for M=32 the spectral efficiency of DAPIM is 1.9 time that of DPIM with 0.1 dB loss in power efficiency.

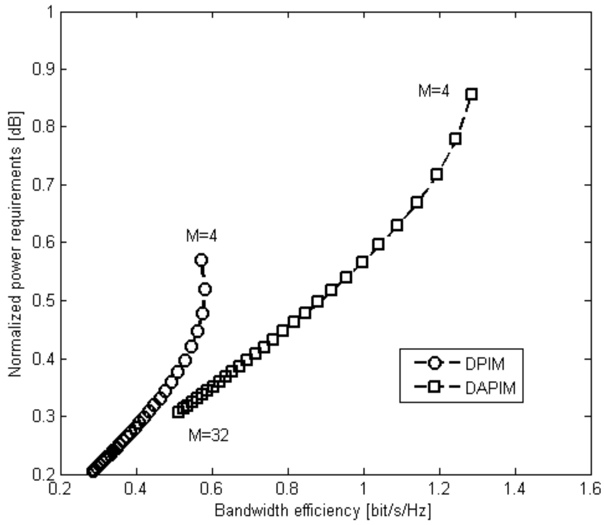

Fig. 2 Normalized Power Requirements based on Bandwidth efficiency for DPIM and DAPIM

In general, this results show that DPIM outperforms DPIM in term of spectral efficiency, but with loss in the power efficiency.

5. Dual Amplitude-Width Pulse Interval Modulation "DAWPIM"

The DAWPIM is a modified form of the existing DAPIM. Instead of coding the data sequence by the amplitude and the time interval between the previous and the present pulse of two adjacent symbols, the data in DAWPIM are presented by the combination Amplitude-Width and the time interval between the previous and the present pulse of two adjacent symbols, Figure. 3.

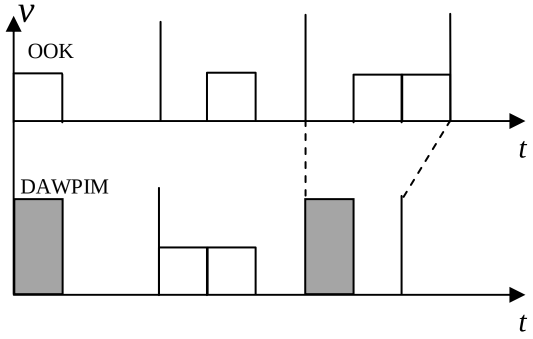

Fig. 3 Encoding Example of a serial data bit to DAWPIM

By the combination Amplitude-Width, the number of possible symbols in DAWPIM modulation scheme is given by:

$$L_{DAWPIM} = 2.\ L_{DAPIM} = 4M \qquad (20)$$

Examples of mapping between source bits and transmitted slots for PPM, PIM, DAPIM and DAWPIM are shown in Table.1, where:

a: is a pulse with A_1 as amplitude
A: is a pulse with A_2 as amplitude
aa: is a pulse with A_1 as amplitude, and W_2 as width.
AA: is a pulse with A_2 as amplitude, and W_2 as width.

In order to avoid symbols in which the time between adjacent pulses is zero, an additional guard slot may be added to each symbol immediately following the pulse. Thus the minimum and the maximum symbol lengths are 2Ts and (M+ 2)Ts respectively, so the mean symbol length is (M+4)Ts/2. Figure.3 presents an encoding example of a serial data bit (OOK) to DAWPIM modulation scheme.

Table 1: Mapping between source bits (OOK) and transmitted slots for PPM, PIM, DAPIM and DAWPIM

bits	*PPM*	*DPIM*	*DAPIM*	*DAWPIM*
000	*1*0000000	10	a0	a0
001	0*1*000000	100	a00	a00
010	00*1*00000	1000	a000	aa0
011	000*1*0000	10000	a0000	A0
100	0000*1*000	100000	A0	A00
101	00000*1*00	1000000	A00	AA0
110	000000*1*0	10000000	A000	aA0
111	0000000*1*	100000000	A0000	Aa0

5.1 Data rate

The same as in DPIM and DAPIM, the symbol length is not constant in DAWPIM, so, we have to use the average bit rate based on average symbol length. The data rate that can be achieved by DAWPIM based on mean symbol length is:

$$D_{DAWPIM} = \frac{\log_2(4M)}{T_{mean}} \qquad (21)$$

The ratio *R* of the average data rate based on average symbol length of DAWPIM modulation is:

$$R = \frac{D_{DAWPIM}}{D_{PPM}} = \frac{(2M)\log_2(4M)}{(M+4)\log_2 M} \qquad (22)$$

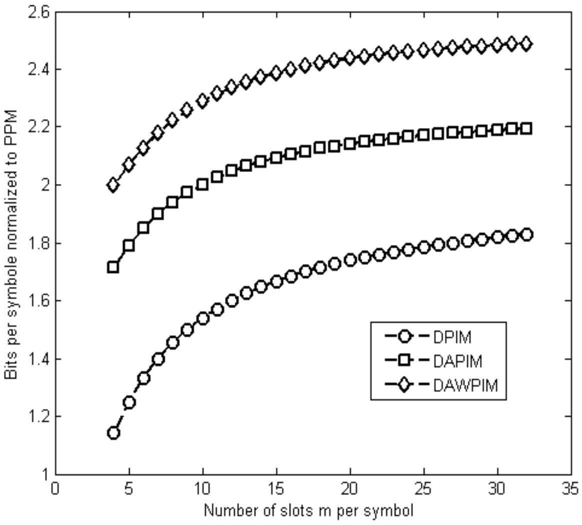

Fig. 4 Normalized data date of DPIM, DAPIM and DAWPIM

Figure.4 shows the ratio *R* for DPIM, DAPIM and DAWPIM based on symbol length *M*. The figure shows that DAWPIM outperforms both DPIM and DAPIM in term of data rate for all the values of *M*. These resultas show that DAWPIM id a good alternative to improve the data rate.

5.2 Power requirement and bandwidth efficiency

We use the same method as we used for DPIM and DAPIM to find the average power requirements. The minimum and the maximum power requirement by DAWPIM are $1A_1$ and $4A_1$ respectively, thus the average power requirement for the average symbol length is given by:

$$p_{DAPIM} = \frac{5/2}{(M+4)/2} = \frac{5}{M+4} \qquad (23)$$

By the same method, the normalized average power requirement of DAWPIM is given by:

$$\frac{P_{DAWPIM}}{P_{OOK}} = \frac{5M}{M+4}\sqrt{\frac{2}{M\log_2 M}} \qquad (24)$$

Also based on average symbol length, the band utilization efficiency of DAWPIM is given by:

$$\eta_{DAWPIM} = \frac{5\log_2(4M)}{(M+4)} \qquad (25)$$

Figure.5 shows the normalized power requirement based on the spectral efficiency for DPIM, DAPIM and DAWPIM for different values of *M* from 4 to 32. The figure shows that DAPIM presents the best spectral efficiency among the three modulation schemes, at the same time it presents the lowest power efficiency for all the values of *M*.

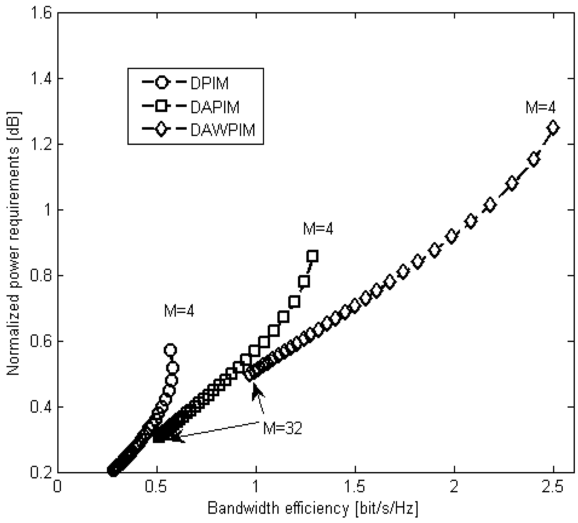

Fig. 5 Normalized Power Requirements based on Bandwidth efficiency for DPIM and DAPIM and DAWPIM

These and the previous results show that the modulation DAWPIM is a good candidate for those systems that require high spectral efficiency and data rate, beside the advantage of the symbol synchronization ability, and the only drawback of this scheme is the degradation in the power efficiency.

6. Conclusion

A modified modulation scheme called DAWPIM “Dual Amplitude-Width Pulse Interval Modulation” has been presented on the basis of Pulse Amplitude Modulation (PAM) and Pulse Width Modulation (PWM), as new digital member of the pulse time modulation family.

The combination PAM-DPIM was introduced like hybrid modulation scheme in a previous works, with the name DAPIM “Dual Amplitude Pulse Interval Modulation”, but it didn’t show remarkable improvement in terms of data rate and spectral efficiency. On the basis of DAPIM, our proposed scheme has improved the data rate and the spectral efficiency over DAPIM, but it shows degradation in term of power efficiency.

The proposed concept may be well suited to use in Optical Wireless Communications systems that require high data rate with simple receiver, by virtue of its increased data rate, high spectral efficiency and the absence of receiver synchronization problems.

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