A New Modified MPPM for High-Speed Wireless Optical Communication Systems

Mehdi Rouissat, Riad A. Borsali, and Mohammad E. Chikh-Bled

Previous work proposed combining multipulse pulse position modulation (MPPM) with pulse amplitude modulation to form multipulse amplitude and position modulation (MPAPM), which is a hybrid modulation that results in an improvement in bandwidth efficiency but a degradation in power efficiency. In this paper, to achieve greater power efficiency and a better data rate, we propose multipulse dual amplitude-width modulation, based on MPAPM and pulse width modulation. The proposed scheme shows a remarkable improvement in data rate and a 1.5-dB improvement in power efficiency over MPAPM, while sustaining the bandwidth efficiency. After introducing symbol structure, we present the theoretical expressions of spectral efficiency, the power requirements, and the normalized data rate, as well as the results of comparing the proposed modulation to MPPM and MPAPM.

Keywords: MPAPM, MPDAWM, MPPM, optical wireless communications, PWM, performance analysis.

I. Introduction

Wireless optical communication (WOC), also known as free space optical (FSO) communication, refers to the transmission of modulated infrared beams through the free space (atmosphere) to transmit data between two ends. The theory of WOC is essentially the same as that of fiber optic transmission, the main difference being that the energy of the beam is collimated and sent through the atmosphere from the source to the destination and intercepted by a photodetector. Optical wireless systems can function over distances of several kilometers. As long as there is a clear line of sight between the two ends, communication is theoretically possible.

One of the main factors in the realization of a high performance WOC system is the modulation format. Current WOC systems typically use intensity modulation and direct detection (IM/DD) [1] because of its simplicity and low cost. As a modulation compatible with IM/DD, multipulse pulse position modulation (MPPM) was proposed in [2] to achieve higher spectral efficiency and data rate over pulse position modulation (PPM); however, MPPM is not a strong candidate when the bandwidth efficiency and the data rate are of great importance. As alternatives, the combination pulse amplitude modulation (PAM) with pulse width modulation (PWM) was proposed in [3], and the combination PAM with MPPM in the form of multiple pulse amplitude and position modulation (MPAPM) was proposed in [4]. MPAPM has proven to be more efficient in terms of bandwidth and data rate, but it shows degradation in terms of power efficiency. To achieve more efficiency in terms of power, improve the data rate, and keep the advantage of the high bandwidth efficiency in MPAPM, we propose multipulse dual amplitude-width modulation (MPDAWM). MPDAWM is a new hybrid modulation that is a

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combination of MPAPM and PWM or, in other words, a combination of MPPM, PAM, and PWM, in which the information is presented according to the position, width, and amplitude of the pulses.

The aim of this paper is to present and analyze the new MPDAWM scheme and give the results of comparing it to MPPM and MPAPM, showing that this new hybrid modulation presents the best compromise between data rate, spectral efficiency, and power efficiency.

II. Multipulse Pulse Position Modulation (MPPM)

MPPM, also called “combinatorial PPM” [6], is a modulation method proposed mainly to improve the spectral efficiency and the data rate over PPM.

In MPPM, each sequence of b bits is mapped into one of the $L=2^b$ symbols and transmitted to the channel. Each symbol interval of duration ($T=\log_2 L/R_b$) is partitioned into M slots, each of duration T/M, and the transmitter sends w optical pulses every symbol duration. The number of possible symbols is

$$L_{\text{MPPM}} = \binom{M}{w} = \frac{M!}{w!(M-w)!}. \qquad (1)$$

Usually, L_{MPPM} is not a power of two, so we generally must discard some of the resulting signals to achieve $L_{\text{MPPM}}=2^b$. The average power requirement by the MPPM normalized to on-off keying (OOK) is given by [5]

$$\frac{P_{\text{MPPM}}}{P_{\text{OOK}}} = \frac{2w}{\sqrt{Mh \log_2 L_{\text{MPPM}}}}, \qquad (2)$$

where h represents the hamming distance.

The bandwidth B is roughly M/T the inverse of the slot duration. This paper defines the band utilization efficiency η as the ratio of R to B, that is,

$$\eta_{\text{MPPM}} = \frac{R_b}{B_{\text{MPPM}}} = \frac{\log_2 L_{\text{MPPM}}}{M}. \qquad (3)$$

III. Pulse Amplitude Modulation (PAM)

PAM is a form of signal modulation in which the information is encoded in the amplitude of the pulses; Fig. 1 shows an example of 2PAM mapping.

When the bandwidth efficiency is taken into account, PAM is a prime candidate; for this reason, PAM has been combined with various modulation schemes compatible with optical wireless systems to achieve more spectral efficiency and improve the data rate.

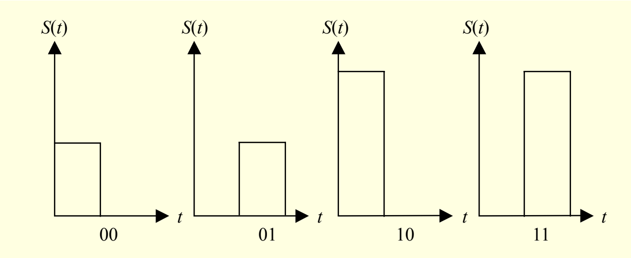

Fig. 1. Example of 2PAM mapping.

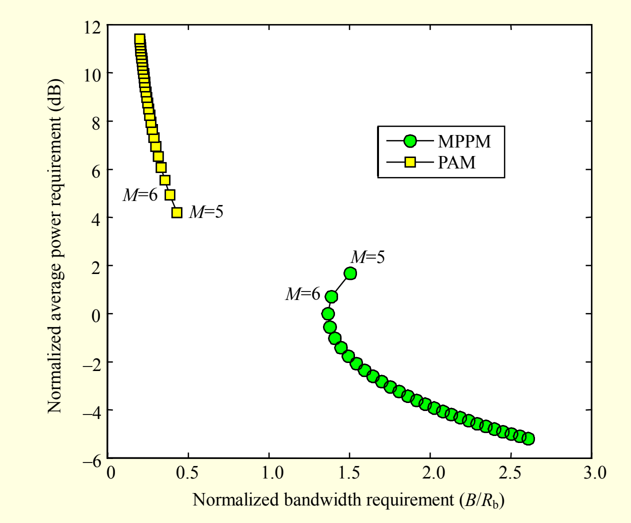

Fig. 2. Power requirement vs. bandwidth requirement for PAM and 3MPPM.

Since MPPM is a strong candidate in terms of power efficiency and PAM can achieve sufficient bandwidth efficiency (Fig. 2), combining these two modulations was a prime solution to ensure efficiency in both areas.

IV. Multipulse Amplitude and Position Modulation (MPAPM)

MPAPM was proposed mainly to improve the spectral efficiency over MPPM. In MPAPM, the amplitudes of the pulses change as well as their positions. Thus, it forms an amplitude-variable version of MPPM [4]. Each symbol interval of duration $T=\log_2(L_{\text{MPAPM}})/R_b$ is partitioned into M slots during each pulse train cycle, and there are w pulses generated [4]. The number of possible symbols in a MPAPM signal set with two amplitude levels is given by

$$L_{\text{MPAPM}} = 2^w \binom{M}{w} = 2^w \frac{M!}{w!(M-w)!}. \qquad (4)$$

There are several ways to define the bandwidth; the simplest method is the inverse of the slot duration.

$$B_{\text{MPAPM}} = \frac{MR_b}{\log_2 L_{\text{MPAPM}}}. \qquad (5)$$

The spectral efficiency of MPAPM η is given by R_b/B:

$$\eta_{\text{MPAPM}} = \frac{\log_2 L_{\text{MPAPM}}}{M}. \qquad (6)$$

The average normalized power requirement is given with the simple accurate method in [7]:

$$\frac{P_{\text{MPAPM}}}{P_{\text{OOK}}} = \frac{3w}{\sqrt{Mh \log_2 L_{\text{MPPM}}}}. \qquad (7)$$

V. Multipulse Dual Amplitude-Width Modulation (MPDAWM)

MPDAWM is a new modified MPPM, presented on the basis of MPAPM and PWM. In this scheme, the pulse can take two levels and two widths at a time (Fig. 3), so the information is presented by the combinations of position, width, and amplitude. The relationship between the two levels (A_1, A_2) and between the two widths (d_1, d_2) is a design parameter. In this paper, we take

$$d_2 = 3/2 \cdot d_1 \qquad (8)$$

and

$$A_2 = 2 \cdot A_1. \qquad (9)$$

In MPDAWM, the transmitter sends w optical pulses every symbol duration, and each sequence of b bits is mapped into one $L=2^b$ symbol and transmitted to the channel. Each symbol interval of duration $T=\log_2(L_{\text{MPDAWM}})/R_b$ is partitioned into M slots, $(M–w)$ of duration T_s, and the other w slots of variable duration, T_s or 3/2 T_s. The average number of slots that can be occupied by pulses is between M and $(M+w)$ (since each pulse starts at $T=x \cdot T_s$), which makes the average number of slots that can be occupied by pulses $(M+w/2)$.

The number of possible symbols in MPDAWM is given by

$$L_{\text{MPDAWM}} = 4^w \binom{M+\frac{w}{2}}{w} = 4^w \frac{(M+\frac{w}{2})!}{w!(M-\frac{1}{2}w)!}. \qquad (10)$$

As with MPPM, usually L_{MPDAWM} is not a power of two, so we must generally discard some of the resulting signals to achieve $L_{\text{MPDAWM}} = 2^b$.

1. Data Rate

The data rate that can be achieved by a modulation scheme is very important, but it is not the only parameter to judge the performance of a modulation. The data rate that can be achieved with MPDAWM is

$$D_{\text{MPDAWM}} = \frac{\log_2 L_{\text{MPDAWM}}}{\left(M+\frac{w}{2}\right)T_s} \text{(bit/s)}. \qquad (11)$$

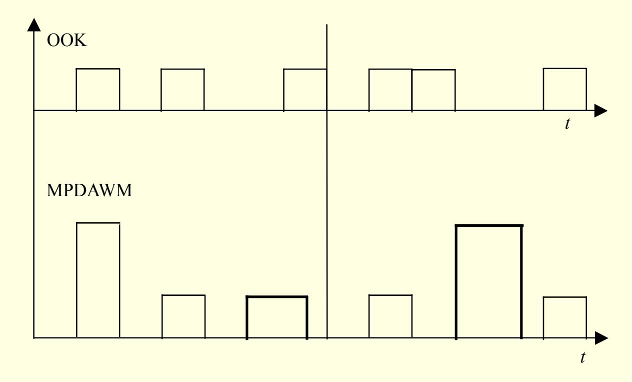

Fig. 3. Encoding example of serial data bit to 3-MPDAWM.

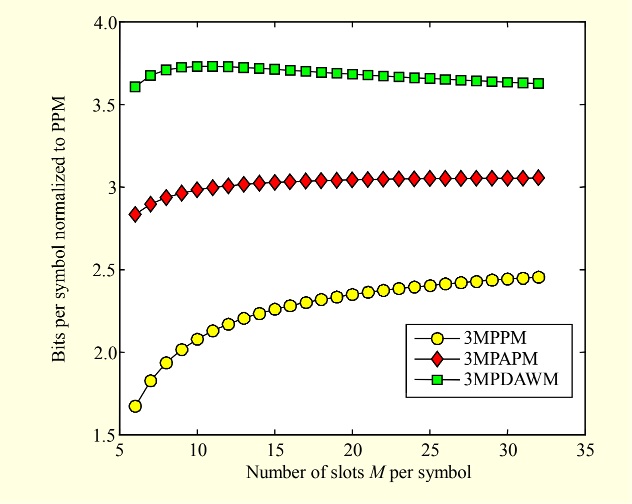

Fig. 4. Number of bits per symbol for MPPM, MPAPM, and MPDAWM normalized to PPM, with w=3.

To show the improvement in the information rate, we use the parameter R, which presents the ratio in the data rate of any modulation scheme to that of PPM:

$$R = \frac{D_{\text{M}}}{D_{\text{PPM}}}. \qquad (12)$$

D_{M}: D_{MPPM} or D_{MPDAWM}

$$R_{\text{MPDAWM}} = \frac{M \log_2 L_{\text{MPDAWM}}}{\left(M+\frac{w}{2}\right)\log_2 M} \text{(bit/s)}. \qquad (13)$$

Figure 4 shows the normalized data rate of MPPM, MPAPM, and MPDAWM with three pulses and for different values of M. The figure shows that the proposed scheme presents the highest data rate and MPPM presents the lowest one, where the differences between the modulations remain almost constant for high values of M. These results reveal MPDAWM to be a strong candidate for high-speed FSO communication systems.

2. Power Requirements and Bandwidth Efficiency

Each MPDAWM symbol must have one average power among the following:

$$\begin{cases} P_1 = 0A_1 + wA_2 + 0d_1 + 0d_2 \\ P_2 = 1A_1 + (w-1)A_2 + 0d_1 + 0d_2 \\ . \\ . \\ P_n = wA_1 + 0A_2 + 0d_1 + 0d_2 \\ P_{n+1} = 0A_1 + 0A_2 + 0d_1 + wd_2 \\ P_{n+2} = 0A_1 + 0A_2 + 1d_1 + (w-1)d_2 \\ . \\ . \\ P_{n+n} = 0A_1 + 0A_2 + wd_1 + 0d_2 \\ . \\ . \\ P_k = 1A_1 + 1A_2 + 1d_1 + (w-3)d_2. \end{cases} \tag{14}$$

To find the average power requirement, we define P_1 as the average power requirement for the case in which the information is presented only by the combination of position and amplitude. From [6], and by changing the relationship between the two levels, the power P_1 is given by

$$P_1 = (A_1 + A_2)\frac{w}{2}. \tag{15}$$

From (9) and (15), we have

$$P_1 = \frac{3}{2}wA_1. \tag{16}$$

We define P_2 as the average power requirement for the case in which the information is presented only by the combination of position and width. As with P_1, the power P_2 is given by (15). By taking the relationship between the two widths, as in (8), we find

$$P_2 = \frac{5w}{4}d_1. \tag{17}$$

By taking d_1=A_1 and from (16) and (17), we find

$$P_{\mathrm{MPDAWM}} = \frac{P_1 + P_2}{2} = \frac{11}{8}wA_1. \tag{18}$$

The average power requirement of MPPM is given as

$$P_{\mathrm{MPPM}} = wA_1. \tag{19}$$

From (18) and (19), the relationship between the average power of MPPM and that of MPDAWM is given by

$$\frac{P_{\mathrm{MPDAWM}}}{P_{\mathrm{MPPM}}} = \frac{11}{8}. \tag{20}$$

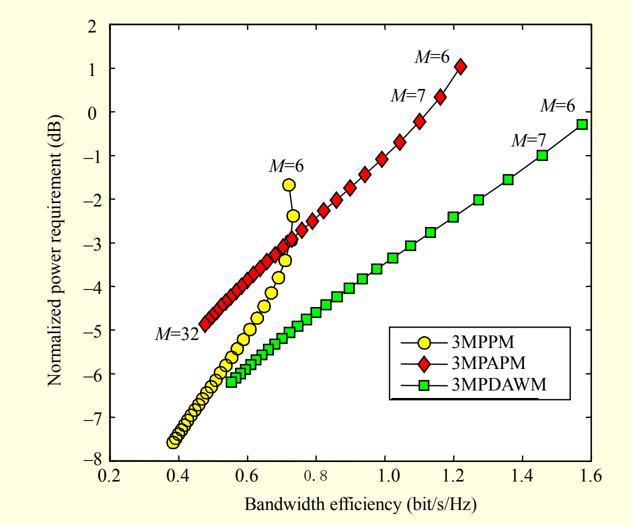

Fig. 5. Normalized power requirement based on bandwidth efficiency for MPPM, MPAPM, and MPDAWM, with w=3.

To find the average power requirement for the MPDAWM scheme normalized to OOK, we multiply (20) by (2):

$$\frac{P_{\mathrm{MPPM}}}{P_{\mathrm{OOK}}} \times \frac{P_{\mathrm{MPDAWM}}}{P_{\mathrm{MPPM}}} = \frac{P_{\mathrm{MPDAWM}}}{P_{\mathrm{OOK}}}. \tag{21}$$

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

$$\frac{P_{\mathrm{MPDAWM}}}{P_{\mathrm{OOK}}} = \frac{11}{4}\frac{w}{\sqrt{Mh\log_2 L_{\mathrm{MPPM}}}}. \tag{22}$$

There are several ways to define the bandwidth; the simplest method is the inverse of the slot duration.

$$B_{\mathrm{MPDAWM}} = \frac{MR_b}{\log_2 L_{\mathrm{MPDAWM}}}. \tag{23}$$

The spectral efficiency of MPDAWM is given by R_b/B:

$$\eta_{\mathrm{MPDAWM}} = \frac{\log_2 L_{\mathrm{MPDAWM}}}{(M+w)/2}. \tag{24}$$

Figure 5 shows the normalized power requirements based on the bandwidth efficiency for the MPPM, MPAPM, and MPDAWM schemes, with three pulses per symbol and different values of M ranging from 6 to 32. The figure shows that for all the schemes, the spectral efficiency decreases as M increases, but with different behaviors. MPDAWM is much more efficient than MPPM for all the values of M, and it is slightly more efficient than MPAPM, especially for low values of M. When it comes to power efficiency, the three schemes show an increase as M increases (decrease in power requirements), where MPDAWM is much more efficient in this respect than MPAPM and slightly less efficient than

MPPM.

According to these results, we can say that the proposed method shows a decrease of almost 1.5 dB in terms of power requirement compared to MPAPM. Additionally, MPDAWM achieves a slight improvement in terms of bandwidth efficiency.

VI. Conclusion

This paper introduced multipulse dual amplitude-width modulation (MPDAWM), which is a new hybrid modulation concept based on MPAPM and PWM. The normalized average power requirements, bandwidth efficiency, and the normalized data rate were studied, after introducing symbol structure.

Compared to MPAPM, the proposed scheme shows a remarkable improvement in terms of data rate, about a 1.5-dB improvement in terms of power efficiency, and a slight improvement in terms of bandwidth efficiency.

The proposed hybrid modulation scheme may be a promising addition to the modulation field and a solution for those wireless optical communication systems that require a high data rate and high power efficiency.

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