Optics Communications 345 (2015) 52–56

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Pulse Amplitude and Delay Modulation: Design and performance analysis

Iskandar Slaiman, Tong Boon Tang*, Nor Hisham Hamid

Universiti Teknologi PETRONAS, Department of Electrical and Electronic Engineering, Bandar Sri Iskandar, 31750 Tronoh, Perak, Malaysia

A R T I C L E I N F O

Article history:
Received 3 December 2014
Received in revised form
24 January 2015
Accepted 29 January 2015
Available online 2 February 2015

Keywords:
Visible light communications
Pulse modulation techniques
Indoor optical wireless

A B S T R A C T

Power efficient modulation techniques have previously been proposed to provide the uplink in visible light communication systems. However, such techniques have poor bandwidth utilization as multiple bits are mapped to single narrow pulse. When the bandwidth is limited, it has been found that degradation in optical power becomes very high and data rate poor. In this paper we introduce a new modulation technique called Pulse Amplitude and Delay Modulation (PADM). We compare its performance with Dual Header Pulse Interval Modulation (DH-PIM) that has the best reported bandwidth efficiency. Experiment results show that the data rate could be enhanced from 3.2 kps to 4.3 kbs using a red link (640 nm) under same error rate. This suggests PADM has better bandwidth efficiency than DH-PIM.

1. Introduction

Bandwidth limitation of the uplink channel is a major constraint when considering mobility (i.e. only limited power resource such as battery is available) in the visible light communication system. The causes of bandwidth limitation vary depending on the link type. For instance, when using an infrared link, a bandwidth of approximately 20 MHz could easily be available yet pulse dispersion occurs and the bandwidth is then degraded to a lower value as a result of multipath propagation [1]. The amount of dispersion and hence the degradation in bandwidth is determined by the path length. When using a visible light link, the available bandwidth is constraint by the large intrinsic capacitance of visible LEDs to a very small range between few kHz and almost 1 MHz [2–4]. In order to maintain mobility while providing the uplink, a diffused configuration is implemented at the transmitter and power efficient modulation techniques are used to attain high power level required for wide area coverage [1,5]. Such type of modulation maps few bits of the input bit block to single optical pulse, hence decreasing optical power needed per transmitted bit. Differential Pulse Position Modulation (DPPM), Pulse Interval Modulation (DPIM) and Dual-Header Pulse Interval Modulation (DH-PIM) are among the most commonly used power efficient modulation techniques for diffused optical wireless communications. Although these techniques maintain low power consumption, achieving high speed communications remains a challenge. Mapping multiple bits to single optical pulse leads to poor bandwidth efficiency, which limits the available bandwidth to less than 50% of the link's bandwidth. Few modulation techniques were recently proposed to enhance the bandwidth efficiency of the optical link [7–9], however, these techniques require high optical power that is critical for battery powered mobile devices.

In [10] a new technique called Pulse Amplitude and Delay Modulation "PADM" was proposed to enhance the bandwidth efficiency of an optical link. In this paper we report the hardware implementation of the PADM in bandwidth limited visible light link and compare its performance with an existing techniques. The paper is organized as follows: in Section 2 short description of the indoor visible light communication system is provided. In Section 3, the basic principle of PADM modulation scheme is introduced, then in Section 4 bandwidth characteristics of the PADM are extracted and compared with existing modulation techniques, finally in Section 5 the implementation and the performance of PADM in bandwidth limited visible light link are presented and compared with the DH-PIM scheme which has the best reported bandwidth efficiency [1,11].

2. Indoor visible light communication system (VLC)

Like any bi-directional communication system, the indoor VLC system has an uplink and downlink. The downlink is usually provided with illumination by modulating white light with

* Corresponding author.
E-mail address: tongboon.tang@petronas.com.my (T.B. Tang).

http://dx.doi.org/10.1016/j.optcom.2015.01.074
0030-4018/

transmitted data, while the uplink is provided through diffused infrared link. As huge number of LEDs can be used to achieve wide coverage area, besides multiple LEDs can formulate multiple data carriers, high data rate downlink is easily implemented. On the contrary, providing high speed uplink is still a challenge. As only one transmitter (usually a user's device) is used, a multipath propagation experienced by the uplink reduces the bandwidth available by the channel hence merely lower data rate can be achieved. The uplink channel is modeled as a low pass filter with −3 dB cut off frequency related to RMS pulse dispersion that results from multiple optical signals arrive to the receiver through multiple paths. In a typical room with $5 \times 5 \times 3\ m^3$ dimensions, RMS delay spread can vary between 0.5 ns and 2.5 ns, consequently the channel bandwidth varies between 31.8 MHz and 159 MHz. Rather than implementing complex signal processing techniques which increase cost and complexity of both transmitter and receiver, enhancing the bandwidth of the modulation technique is the first solution towards increasing the data rate. According to [1], DH-PIM can achieve data rate which is $0.66 \times$ *available bandwidth* hence the worst case data rate will be around 20 Mbps. VLC is proposed to be used as the basic indoor access technique for next generation wireless communications (5G). To meet the standards, 50 Mbps uplink at least should be provided, hence increasing the data rate is the major goal of any modulation technique enhancement.

3. Pulse Amplitude and Delay Modulation

Pulse Amplitude and Delay Modulation (PADM) is a combined technique in which both pulse amplitude and delay are varied to represent binary data. PADM symbol length varies according to the input bit block combination. For every input block of size M bits, an optical pulse with specified amplitude and delay values is generated, consequently 2^M distinct PADM symbols being available. To map to a symbol, each input block is divided into two parts according to the value of α, as illustrated in Fig. 1. The parameter α represents the number of bits being encoded as the amplitude. The first part of the block modulates the amplitude while second one modulates the delay. The delay is expressed by a number of empty time slots that precede the pulse. An extra guard slot T_s could be added into the beginning of each symbol to enhance the immunity against pulse dispersion. General formula for PADM symbols for each block size M can be written as in Eq. (1):

$$x(t) = \sum_{k=0}^{2^M-1} A_k.\, p[t-(k+1)T_s] \tag{1}$$

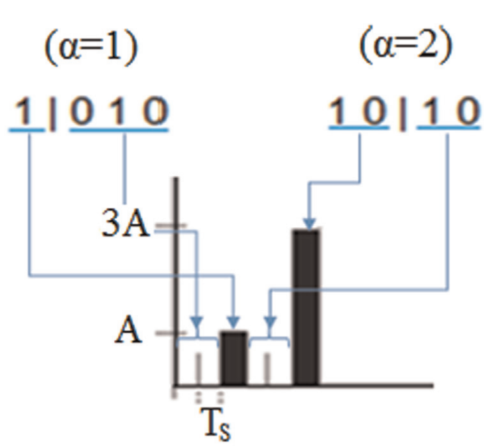

Fig. 1. PADM modulation principle for input block size $M=4$.

Table 1
PADM symbol representation for input block size $M=3$.

OOK	8-PPM	8-DPPM	8-DPIM	DHPIM $\alpha=2$	PADM $\alpha=1$	PADM $\alpha=2$
000	10000000	1	1	100	01	01
001	01000000	01	10	1000	001	001
010	00100000	001	100	10000	0001	02
011	00010000	0001	1000	100000	00001	002
100	00001000	00001	10000	110000	02	03
101	00000100	000001	100000	11000	002	003
110	00000010	0000001	1000000	1100	0002	04
111	00000001	00000001	10000000	110	00002	004

where

$A_k \in \{1, ...2^\alpha\}$: optical pulse amplitude.
k: is an integer.
$p(t)$: rectangular pulse of one time slot width.
T_s: time slot.

The integer α indicates the number of bits being encoded into the amplitude starting from the most significant bit (MSB), while the rest bits represent the decimal value of the delay.

Table 1 shows PADM symbol mapping to On–Off Keying (OOK) input block compared to some other modulation techniques used in power efficient optical wireless links.

4. Analysis of bandwidth characteristics of PADM

4.1. Average symbol length

Like all other modulation techniques with no fixed symbol length, scheme's characteristics are based on average symbol length. The average symbol length can be extracted from Table 1 as:

$$L_{\min} = 2,\ L_{\max} = 2^{(M-\alpha)} + 1 \tag{2}$$

Hence the average symbol length is:

$$L_{avg} = \frac{2^{(M-\alpha)} + 3}{2} \tag{3}$$

4.2. Bandwidth requirements

The bandwidth requirements of PADM at given data rate $R_b = 1/T_b$ is extracted as the inverse of PADM pulse width. The time slot duration is defined by the equation:

$$T_s = \frac{MT_b}{L_{avg}} \tag{4}$$

And the bandwidth requirement is:

$$B_{PADM} = \frac{1}{T_s} = \frac{L_{avg}}{MT_b} = \frac{2^{(M-\alpha)} + 3}{2MT_b} \tag{5}$$

4.3. Bandwidth utilization efficiency

Bandwidth utilization efficiency is determined by the amount of data (bits per second) that can be transmitted through 1 Hz of the link bandwidth using specified modulation technique and expressed by: