Indoor optical wireless systems employing dual header pulse interval modulation (DH-PIM)

N. M. Aldibbiat\textsuperscript{1,‡}, Z. Ghassemlooy\textsuperscript{2,*}.† and R. McLaughlin\textsuperscript{3,§}

\textsuperscript{1}School of Engineering and Technology, The University of Northumbria, Ellison Building, Ellison Place, Newcastle Upon Tyne NE1 8ST, U.K.
\textsuperscript{2}Optical Communications Research Group, School of Engineering and Technology, Northumbria University, Newcastle Upon Tyne NE1 8ST, U.K.
\textsuperscript{3}School of Computing and Management Sciences, Sheffield Hallam University, Pond Street, Sheffield S1 1WB, U.K.

SUMMARY

This paper assesses the performance of dual header pulse interval modulation (DH-PIM) over indoor optical wireless systems. DH-PIM being an asynchronous scheme offers a built-in symbol synchronization capability. Theoretical and simulation results demonstrate that DH-PIM offers shorter symbol length, improved transmission rate and bandwidth requirement and a comparable power spectral density profile compared with digital pulse interval modulation (DPIM) and pulse position modulation (PPM) schemes.

It is shown that DH-PIM\textsubscript{2}, with wider pulse duration is the preferred option when the available channel bandwidth is limited and higher optical power is tolerable. Whereas DH-PIM\textsubscript{1}, with narrower pulse width, exhibits comparable power requirements but a marginally higher bandwidth compared with DPIM, and is also more bandwidth efficient than PPM at the cost of increased power requirement. However, at higher bit resolutions, i.e. $M \geq 7$, DH-PIM\textsubscript{1} is both bandwidth and power efficient compared with PPM. Error rate analysis show that DH-PIM offers improved packet error rate compared with on-off-keying (OOK) and DPIM, but marginally inferior as compared with PPM. The power requirement and penalty due to intersymbol interference for non-dispersive and dispersive channels is analysed and the results show that for given parameters, DH-PIM requires marginally higher optical power compared with PPM and DPIM, but it supports the same bit rate at much less bandwidth requirement. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: optical wireless communications; pulse interval modulation; packet error rate; optical power requirement; bandwidth requirement; multipath dispersion

1. INTRODUCTION

Wireless systems, both optical and radio, offer a low cost, reliable, high speed and low power point-to-point and network connectivity in indoor environments. However, the combination of the need for effective short-range indoor wireless connectivity, relative security, and the promise...
of higher unregulated bandwidth and high data rate at a low cost make the optical wireless link an attractive alternative to radio link [1–5]. Future multimedia applications will demand high data rate and low optical power. Since the average optical power emitted by an infrared transceiver is limited for eye safety reason, then the choice of modulation technique that can offer bandwidth and power efficiencies at a low cost is important. On-off-keying (OOK) is the simplest scheme but is incapable of providing power efficiency [1, 6]. Dual header pulse interval modulation (DH-PIM) is one of the digital pulse time modulation (DPTM) schemes that offer the ability to improve signal-to-noise (SNR) performance at the expense of bandwidth [7, 8]. Other DPTM schemes used here for comparison with DH-PIM are pulse position modulation (PPM), digital pulse interval modulation (DPIM) and PPM offers an improvement in power efficiency at the cost of relatively poor bandwidth efficiency but it requires symbol and slot synchronization [6, 9]. On the other hand, DPIM requires no symbol synchronization, and offers an improvement in bandwidth efficiency compared with PPM and power efficiency compared with OOK and PPM [6, 7].

In this paper, we give an overview of DH-PIM scheme for indoor optical wireless links. We show that DH-PIM has a built-in symbol and slot synchronization capabilities and it offers higher transmission rate and requires less transmission bandwidth compared with PPM and DPIM [9, 10]. Because of these characteristics, this scheme is suitable for optical wireless applications where the need for high transmission capacity is desirable. The rest of the paper is organized as follows. In Section 2 the DH-PIM symbol structure is described and defined analytically, whereas bandwidth and transmission rate are specified in Section 3. Section 4 discusses the spectral characteristics of DH-PIM with comparison with DPIM and PPM. Section 5 presents a theoretical analysis and simulation results for the probability of errors in DH-PIM and its counterparts. In Section 6, the optical power requirement of DH-PIM is presented in the cases of dispersive and non-dispersive channels and results are compared with DPIM and PPM. Finally, Section 7 presents the conclusions of the study.

2. DH-PIM SYMBOL STRUCTURE

The nth symbol $S_n(h_n,d_n)$ of a DH-PIM sequence is composed of a header $h_n$, which initiates the symbol, and information slots $d_n$, see Figure 1. Depending on the most significant bit (MSB) of the input code word, two different headers are considered $H_1$ and $H_2$ that correspond to MSB = 0 and 1, respectively. $H_1$ and $H_2$ have equal duration of $T_h = (\alpha + 1)T_s$, where $\alpha > 0$ is an integer and $T_s$ is the slot duration, and are composed of a pulse and guard band. For $H_1$ and $H_2$ the pulse durations are $\alpha T_s/2$ and $\alpha T_s$, respectively. A guard band, with a duration $T_g \in \{0.5\alpha + 1\}T_s$, corresponding to $h_n \in \{H_1, H_2\}$ is used to cater for symbols representing zero. The information section is composed of $d_n$ empty slots. The value of $d_n \in \{0, 1, \ldots, 2^M-1\}$ is simply the decimal value of the $M$-bit input code word when the symbol starts with $H_1$, or the decimal value of the 1’s complement of the input data word when the symbol starts with $H_2$. The header pulse has the dual function of symbol initiation and time reference for the preceding and succeeding symbols resulting in built-in symbol synchronization.

With reference to Figure 1, DH-PIM pulse train can be expressed mathematically as

$$x(t) = V \sum_{n=0}^{\infty} \left\{ \text{rect} \left[ \frac{2(t - T_n)}{\alpha T_s} - \frac{1}{2} \right] + h_n \text{rect} \left[ \frac{2(t - T_n)}{\alpha T_s} - \frac{3}{2} \right] \right\}$$

(1)
where $V$ is the pulse amplitude, $h_n \in \{0,1\}$ indicating $H_1$ or $H_2$, respectively, $n$ the instantaneous-symbol number, and the rectangular pulse function is defined as [11]:

$$
\text{rect}(u) = \begin{cases} 
1 & -0.5 < u < 0.5 \\
0 & \text{otherwise}
\end{cases}
$$

The start time of the $n$th symbol is defined as

$$
T_n = T_0 + T_s \left[ n(\alpha + 1) + \sum_{k=0}^{n-1} d_k \right] 
$$

(2)

where $T_0$ is the start time of the first pulse at $n = 0$.

Throughout this paper, DH-PIM will be referred to as $L$-DH-PIM$_L$ according to the values of $L$ and $\alpha$, e.g. 8-DH-PIM$_1$ and 8-DH-PIM$_2$ refer to DH-PIM with $L = 8$ (i.e. $M = 3$), and $\alpha = 1$ and 2, respectively. Also DPIM and PPM will be referred to as $L$-DPIM and $L$-PPM according to the values of $L$, e.g. 8-PPM, 8-DPIM.

DH-PIM not only removes the redundant time slots that follow the pulse as in PPM symbol, but it also reduces the average symbol length compared with DPIM as shown on Table I, thus resulting in an increased overall data throughput.

The average symbol length and the slot duration of DH-PIM are given as

$$
\bar{L} = (2^{M-1} + 2\alpha + 1)/2
$$

(3)

$$
T_s = 2M/(2^{M-1} + 2\alpha + 1)R
$$

(4)

where $R_b$ is the bit rate of the input code word.
3. BANDWIDTH AND TRANSMISSION RATE

The bandwidth requirement of DH-PIM can be given as $B_{req} = \frac{\tau_{min}}{C_0}$ where the minimum pulse duration $\tau_{min} = 0.5zT_s$ [9]. Therefore, from (4):

$$B_{req} = R_s(2^M - 1 + 2z + 1)/zM$$  \hspace{1cm} (5)

For comparison the bandwidth requirements PPM, DPIM and DH-PIM are given in Table II [9].

Figure 2 shows the bandwidth requirements normalized to OOK-NRZ for PPM, DPIM, DH-PIM1, DH-PIM2 and DH-PIM3 against $M$. DH-PIM1 has comparable bandwidth requirements as DPIM but lower than PPM. For $z > 1$ and $M > 5$, DH-PIM shows a significant bandwidth improvement compared to its counterparts. For example, at $M = 6$, PPM, DPIM, DH-PIM1, DH-PIM2 and DH-PIM3 require 10.7, 5.6, 5.8, 3.1 and 2.2 times the bandwidth of OOK-NRZ, respectively. This is because the minimum pulse width of DH-PIM increases as $z$ increases, and as $M$ increases the symbol length of DH-PIM becomes far shorter than those of PPM and DPIM resulting in wider slot duration in the case of DH-PIM compared with its counterparts.

The packet transmission rate for DH-PIM signal can be given as $R_{pkt} = R_sL_{pkt}^{-1}$, where $R_s = T_s^{-1}$ is the slot rate, $L_{pkt} = N_{pkt}LM^{-1}$ is the average packet length in time slots, and $N_{pkt}$ is the packet length in bits, therefore,

$$R_{pkt} = \frac{zM_{req}}{N_{pkt}(2^M - 1 + 2z + 1)}$$  \hspace{1cm} (6)

For comparison, the packet transmission rate of PPM, DPIM and DH-PIM are given in Table III [9].

Figure 3 displays the packet transmission rate of PPM, DPIM, DH-PIM1, DH-PIM2 and DH-PIM3, normalized to that of PPM against $M$ for a fixed bandwidth of 1 MHz and $N_{pkt} = 1$ kbyte. For $M > 6$, DH-PIM1 displays similar transmission rate compared with DPIM and about twice that of PPM, however, DH-PIM2 and DH-PIM3 offer 4 and 6 times the transmission rate compared with PPM, respectively.

Table I. Mapping of 3-bit OOK code into 8-PPM, 8-DPIM and 8-DH-PIM2 symbols.

<table>
<thead>
<tr>
<th>OOK</th>
<th>8-PPM</th>
<th>8-DPIM</th>
<th>8-DH-PIM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>1 0 0 0 0 0 0 0</td>
<td>1 0 0</td>
<td>1 0 0</td>
</tr>
<tr>
<td>001</td>
<td>0 1 0 0 0 0 0 0</td>
<td>1 0 0</td>
<td>1 0 0</td>
</tr>
<tr>
<td>010</td>
<td>0 0 1 0 0 0 0 0</td>
<td>1 0 0</td>
<td>1 0 0</td>
</tr>
<tr>
<td>011</td>
<td>0 0 0 1 0 0 0 0</td>
<td>1 0 0</td>
<td>1 0 0</td>
</tr>
<tr>
<td>100</td>
<td>0 0 0 0 1 0 0 0</td>
<td>1 0 0</td>
<td>1 1 0</td>
</tr>
<tr>
<td>101</td>
<td>0 0 0 0 0 1 0 0</td>
<td>1 0 0</td>
<td>1 1 0</td>
</tr>
<tr>
<td>110</td>
<td>0 0 0 0 0 0 1 0</td>
<td>1 0 0</td>
<td>1 1 0</td>
</tr>
<tr>
<td>111</td>
<td>0 0 0 0 0 0 0 1</td>
<td>1 0 0</td>
<td>1 1 0</td>
</tr>
</tbody>
</table>

$H_1$ and $H_2$ are shown in bold font.
4. SPECTRAL CHARACTERISTICS

To determine the Fourier transform of DH-PIM signal, it is necessary to truncate the signal expressed in (1) to a limited number of symbols $N$. Therefore, from (1), the Fourier transform of DH-PIM can be given as follows:

$$X_N(\omega) = V \sum_{n=0}^{N-1} \int_{-\infty}^{+\infty} \left\{ \text{rect} \left[ \frac{2(t-T_n)}{\alpha T_s} - \frac{1}{2} \right] + h_n \text{rect} \left[ \frac{2(t-T_n)}{\alpha T_s} - \frac{3}{2} \right] \right\} \cdot e^{-j\omega t} \, dt$$

Table II. Bandwidth requirements of PPM, DPIM and DH-PIM.

<table>
<thead>
<tr>
<th>Modulation scheme</th>
<th>PPM</th>
<th>DPIM</th>
<th>DH-PIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth requirement</td>
<td>$\frac{R_b 2^M}{M}$</td>
<td>$\frac{R_b (2^M + 3)}{2M}$</td>
<td>$\frac{R_b (2^{M-1} + 2\alpha + 1)}{\alpha M}$</td>
</tr>
</tbody>
</table>

Table III. Packet transmission rates of PPM, DPIM and DH-PIM.

<table>
<thead>
<tr>
<th>Modulation scheme</th>
<th>PPM</th>
<th>DPIM</th>
<th>DH-PIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet transmission rate</td>
<td>$\frac{MB_{\text{req-PPM}}}{N_{\text{pkt}} 2^M}$</td>
<td>$\frac{2MB_{\text{req-DPIM}}}{N_{\text{pkt}} (2^M + 3)}$</td>
<td>$\frac{\alpha MB_{\text{req}}}{N_{\text{pkt}} (2^{M-1} + 2\alpha + 1)}$</td>
</tr>
</tbody>
</table>

Figure 2. Transmission bandwidth of PPM, DPIM, DH-PIM\textsubscript{1}, DH-PIM\textsubscript{2} and DH-PIM\textsubscript{3} normalized to OOK-NRZ versus the bit resolution $M$.  

Table II. Bandwidth requirements of PPM, DPIM and DH-PIM.

<table>
<thead>
<tr>
<th>Modulation scheme</th>
<th>PPM</th>
<th>DPIM</th>
<th>DH-PIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth requirement</td>
<td>$\frac{R_b 2^M}{M}$</td>
<td>$\frac{R_b (2^M + 3)}{2M}$</td>
<td>$\frac{R_b (2^{M-1} + 2\alpha + 1)}{\alpha M}$</td>
</tr>
</tbody>
</table>

Table III. Packet transmission rates of PPM, DPIM and DH-PIM.

<table>
<thead>
<tr>
<th>Modulation scheme</th>
<th>PPM</th>
<th>DPIM</th>
<th>DH-PIM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet transmission rate</td>
<td>$\frac{MB_{\text{req-PPM}}}{N_{\text{pkt}} 2^M}$</td>
<td>$\frac{2MB_{\text{req-DPIM}}}{N_{\text{pkt}} (2^M + 3)}$</td>
<td>$\frac{\alpha MB_{\text{req}}}{N_{\text{pkt}} (2^{M-1} + 2\alpha + 1)}$</td>
</tr>
</tbody>
</table>

4. SPECTRAL CHARACTERISTICS

To determine the Fourier transform of DH-PIM signal, it is necessary to truncate the signal expressed in (1) to a limited number of symbols $N$. Therefore, from (1), the Fourier transform of DH-PIM can be given as follows:

$$X_N(\omega) = V \sum_{n=0}^{N-1} \int_{-\infty}^{+\infty} \left\{ \text{rect} \left[ \frac{2(t-T_n)}{\alpha T_s} - \frac{1}{2} \right] + h_n \text{rect} \left[ \frac{2(t-T_n)}{\alpha T_s} - \frac{3}{2} \right] \right\} \cdot e^{-j\omega t} \, dt$$
where \( V \) is the pulse amplitude, \( \omega = 2\pi f \) the angular frequency and \( f \) the frequency. Therefore,

\[
X_N(\omega) = \frac{V}{j\omega} e^{(-j\omega T_s)}(1 - e^{-j\omega T_s/2}) \sum_{n=0}^{N-1} \left[ (1 + h_n e^{-j\omega T_s n(\pi+1)}) e^{-j\omega T_s \sum_{k=0}^{n-1} d_k} \right]
\]  

The power spectral density of DH-PIM pulse train can be given by [9]:

\[
P(\omega) = \begin{cases} 
\frac{4V^2 \sin^2(\frac{\omega T_s}{4}) \left\{ 5 - 4 \sin^2(\frac{\omega T_s}{4}) + 9 - 8 \sin^2(\frac{\omega T_s}{4}) \right\} \text{Re} \left( \frac{\psi}{1-\psi} \right)}{\omega^2 T_s (2^{M-1} + 2\pi + 1)} & \omega \neq \frac{2\pi K}{T_s} \\
0, & \omega = \frac{2\pi K}{T_s} \text{ and either } K \text{ even or } \pi \text{ even} \\
\infty, & \omega = \frac{2\pi K}{T_s} \text{ and both } K \text{ odd and } \pi \text{ odd} 
\end{cases}
\]

where \( K \) is a positive integer and \( \psi \) given by [9]

\[
\psi = \frac{1}{2^{M-1}} \{ 1 + e^{-j\omega T_s} + e^{-j2\omega T_s} + \cdots + e^{-j\omega(2^{M-1}-1)T_s} \} \cdot e^{-j\omega(\pi+1)T_s}
\]

Thus, the spectrum consists of a sinc envelope when \( \omega T_s/2\pi \) is not integer, distinct frequency components at the slot frequency and its harmonics when \( \omega T_s/2\pi \) is odd integer and nulls when \( \omega T_s/2\pi \) is even integer, thus the slot component and its harmonics may coincide with the nulls of the sinc envelope depending on the values of \( \pi \). Consequently, the existence of the slot components and the locations of nulls are affected by the pulse shape.
To substantiate the theoretical results, simulation of the PSD of DH-PIM has been carried out using MATLAB software. Ideal simulation requires infinite number of symbols, however due to computational limitations, 500 consecutive DH-PIM symbols have been generated and the PSD of signal was estimated using Welch’s averaged modified periodogram method. The slot duration $T_s = 1 \text{ s}$ and $V = 1 \text{ V}$. Figures 4(a) and (b) show the predicted and simulated PSD for 8-DH-PIM$_1$ and 8-DH-PIM$_2$, respectively. The predicted and simulated results show a very good agreement. However, at slot frequency and its harmonics, the simulated results are marginally lower than the predicted data. This is due to the limitations on the number of symbols used in simulation. These components should incline to infinity when the number of symbols tends to infinity. The spectral profile of DH-PIM$_1$ contains a DC component, a distinct slot component and its harmonics at odd multiples of the slot frequency, and nulls at even multiples of the slot frequency as shown in Figure 4(a).

Figure 4. (a) Predicted and simulated power spectral density of 8-DH-PIM$_1$ versus the frequency; (b) predicted and simulated power spectral density of 8-DH-PIM$_2$ versus the frequency; and (c) simulated power spectral density of DH-PIM$_2$, DPIM and PPM versus the frequency.
Figure 4(b) shows the PSD for DH-PIM$_2$ where the nulls coincide with the slot component and its harmonics, thus suppressing them to zeros. Therefore, at the receiver end a simple phase-locked loop (PLL) circuit is incapable of extracting the slot frequency. Nevertheless, the slot frequency can be extracted by employing a non-linear device followed by a PLL circuit [12, 13].

To compare the PSD of DH-PIM with those of PPM and DPIM, the latter two systems have been simulated using the same parameters as in DH-PIM. The pulse duty cycle of PPM and DPIM is chosen to be 100%, hence the slot components are masked by the nulls. The PSD profile for 8-DH-PIM$_2$, 8-PPM and 8-DPIM against the frequency is shown in Figure 4(c). The PSD curve of 8-DH-PIM$_2$ is similar to those of 8-DPIM and 8-PPM, however, 8-DH-PIM$_2$ has to some extent higher PSD profile. This result from the fact that, the slot duration of DH-PIM is wider than those of DPIM and PPM, and, unlike PPM and DPIM where the symbol contains one pulse only, each DH-PIM symbol may contain one or two pulses. This suggests that the effect of baseline wander, which arises from the use of a high-pass filter to mitigate ISI caused by fluorescent lighting [14–17], will be slightly higher on DH-PIM than PPM and DPIM.

5. ERROR RATE ANALYSIS

5.1. Theoretical analysis

Since the symbol length of DH-PIM is variable; an error is not necessarily confined to the symbol in which it occurs. This can be explained by considering a packet of a number of DH-PIM symbols. A pulse detected in the wrong slot would only affect symbols either side of the pulse, whereas detecting an additional pulse, i.e. false alarm error, would split a symbol into two shorter length symbols. On the other hand, a pulse not detected, i.e. erasure error, would combine two symbols into one longer symbol. Therefore, in the cases of erasure and false alarm errors, symbols following the erroneous slot will be shifted making it pointless to calculate the bit error rate (BER). Therefore, it is essential to base the analysis on the packet error rate (PER) [9, 18].

Here the following assumptions are made to attain the probability of errors for DH-PIM [6, 18, 19]: (1) line-of-sight channel with no multipath dispersion; (2) no path loss; (3) no artificial light interference; (4) no bandwidth limitations imposed by the transmitter and receiver; (5) $H_1$ and $H_2$ are equally likely; and (6) the dominant noise source is the background shot noise, which is assumed as a white Gaussian. Using a threshold detector with a threshold level set mid-way between logical zero and one, the probability of slot error for DH-PIM can be expressed by [9]

$$P_{se} = \frac{1}{4L} \left[ (4L - 3\xi)Q \left( \frac{R\bar{P}}{9\xi^2\eta R_b} \right) + 3\xi Q \left( \frac{R\bar{P}}{9\xi^2\eta R_b} \right) \right]$$

where $R$ is the photodetector responsivity, $\bar{P}$ the average received optical power, $\eta$ the one-sided power spectral density of the white Gaussian shot noise due to the ambient light, and $Q(x)$ is defined by [20]

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-z^2/2} \, dz$$
It is observed that any error in any time slot within the packet will invalidate that entire packet; therefore the packet error rate can be given by

\[ P_{pe} = 1 - (1 - P_{se})^{N_{pkt}L/M} \]  

(11)

For very small value of \( P_{se} \), \( P_{pe} \) can be approximated to

\[ P_{pe} \approx \frac{N_{pkt}}{4M} \left( 4L - 3\alpha \right) Q \left( R\tilde{P} \sqrt{\frac{8ML}{9\eta R_b}} \right) + 3\alpha Q \left( R\tilde{P} \sqrt{\frac{8ML}{9\eta R_b}} \right) \]  

(12)

5.2. System simulation

Figures 5(a) and (b) show block diagrams of DH-PIM transmitter and receiver, respectively. As shown in Figure 5(a), the latch fetches an \( M \)-bit code word. If the MSB = 0, the decimal value \( d \) of the binary word is calculated, otherwise the word is inverted using a NOT logic gate before \( d \) is calculated. A pulse generator generates the header pulse of duration \( \alpha T_s/2 \) corresponding to \( H_1 \) if MSB = 0, or \( \alpha T_s \) corresponding to \( H_2 \) for MSB = 1. The generated pulse is fed into an optical transmitter. After a delay period of \((d + \alpha + 1)T_s\), which is the duration of transmitting the present symbol, the latch will fetch the next input code word and repeat the same process as for the first input word.

At the receiver, see Figure 5(b), each symbol length is determined by simply counting the number of time slots between the received header pulses, a process that requires no symbol

---

**Figure 5.** (a) Block diagram of DH-PIM transmitter; and (b) block diagram of DH-PIM receiver.
synchronization to interpret the encoded values. The regenerated electrical signal is passed through the pre-detection filter, which composed of a matched filter, a sampler and a decision circuit. The output of the matched filter is sampled at the slot rate $1/T_s$ then fed into the decision circuit to regenerate the DH-PIM signal. On detecting a pulse, the edge detector works as follows:

- On the leading edge of the pulse, the data latch will latch the data from the slot counter that represents the information slots or $d$ of the previous symbol.
- After a delay of $(a + 1)T_s$, the duration of the header, the slot counter resets and starts counting the number of information slots for the new symbol.
- The header identifier measures the duration of the pulse and decides the type of header ($H_1$ or $H_2$).
- A decimal-to-binary converter (DBC) converts the number $d$ into the binary equivalent, which represents the input data word if the header is $H_1$ or its 1’s complement if the header is $H_2$. Therefore it is required to invert the binary word if the header is $H_2$.

The header identifier drives the switch of the data output between the two DBC outputs according to the header detected.

Simulation of the complete DH-PIM system as described above using MATLAB software has been carried out to verify the validity of the theoretical study. The input signal was composed of 12,000 bits of binary independent, identically distributed (i.i.d.) bits of ‘1’s and ‘0’s and the pulses were scaled to $\bar{P}$ before transmission. The detector responsivity, the background noise current, and the packet length were set to 0.6 A/W, 200 $\mu$A [19] and $N = 1$ kbyte [21], respectively. Figure 6 shows the predicted and simulated slot error rate results for DH-PIM$_1$.
and DH-PIM\(_2\) against the average optical power for a bit rate of \(R_b = 1\) Mbps and different values of \(M\).

Predicted and simulated results display a good agreement for \(P_{se} > 10^{-4}\). However, for lower values of \(P_{se}\), the simulated results begin to diverge from the predicted curves. This is because the number of data bits used in the simulation was limited to 12 000 bits due to the limited computational power.

The effect of bit rate on the packet error rate is shown in Figure 7. For both DH-PIM\(_1\) and DH-PIM\(_2\), the optical power requirement increases by \(\sim 5\) dBm when \(R_b\) increases from 1 to 10 to 100 Mbps. In Figure 8, the PER of 16-DH-PIM\(_1\) and 16-DH-PIM\(_2\) are compared with those of 16-DPIM, 16-PPM and OOK for \(R_b = 1\) Mbps. DH-PIM displays enhanced performance compared with the OOK. DH-PIM\(_1\) displays slightly improved performance compared with DPIM, but marginally inferior to the PPM requiring \(\sim 1\) dBm more optical power at \(P_{pe} = 10^{-6}\). On the other hand, DH-PIM\(_2\) shows deterioration in performance compared with the DPIM and PPM, requiring 2.5 and 4 dBm more optical power, respectively, at \(P_{pe} = 10^{-6}\). Note, that at the same \(P_{pe}\) 32-DH-PIM\(_1\) requires \(\sim 0.5\) dBm less optical power compared with 16-PPM.

6. OPTICAL POWER REQUIREMENTS

6.1. Non-dispersive channels

The optical power requirement is an important indicator of the system performance when designing optical systems. The most appropriate parameters of a system are those that result in the smallest amount of optical power requirement at the minimum bandwidth. From (12), the
The average optical power requirements for DH-PIM$_1$ and DH-PIM$_2$ normalised to that required by OOK-NRZ to send 1 kbyte packets at a standard $P_{pe} = 10^{-6}$ against the bandwidth requirements normalized to the bit rate $B_{req}R_b^{-1}$ have been calculated using (13), and the results are displayed in Figure 9. Figure 9 also shows the corresponding results for DPIM, PPM and OOK [22]. Numbers in Figure 9 indicate the values of $L$ and the percentage values correspond to the OOK duty cycles. Regardless of the value of $M$, DH-PIM$_2$ displays improved bandwidth efficiency compared with PPM and DPIM, but it requires additional power. For example, 16-DH-PIM$_2$ requires 67, 71, and 46% of the bandwidth compared with 16-DH-PIM$_1$, 16-DPIM, and 16-PPM. However, 16-DH-PIM$_2$ requires $\sim 2.6$, $\sim 2.5$, and $\sim 3.6$ dB additional optical power compared with 16-DH-PIM$_1$, 16-DPIM, and 16-PPM, respectively. DH-PIM$_1$ displays similar power and marginally higher bandwidth requirement compared with DPIM, however, it is more bandwidth efficient than the PPM at the cost of a small increase in the power requirement. It is also observed that 32-DH-PIM$_1$ shows improvement in both power and bandwidth requirements compared with 16-PPM, that is 0.7 dB less power and 95% bandwidth requirement, and furthermore it shows enhanced error performance, see Figure 8. At higher bit resolution, i.e. $M = 7$ or 8, DH-PIM$_1$ is both bandwidth and power efficient compared with PPM, hence making it a more suitable scheme for optical wireless communications systems. However, the bandwidth requirements increase significantly compared with smaller values of $M$. 

Figure 8. Predicted $P_{pe}$ for 16-DH-PIM$_1$, 16-DH-PIM$_2$, 16-DPIM, 16-PPM, OOK and 32-DH-PIM$_1$ against $P$ for $R_b = 1$ Mbps.
Therefore, for each scheme, the best parameters are those that result in the nearest points of the curve to the bottom left corner of Figure 9. 16-DH-PIM1 and 64-DH-PIM2 attain this best performance as shown in Figure 9.

6.2. Dispersive channels

Since in DH-PIM the symbol boundaries are not known prior to detection, therefore, practical implementation of maximum likelihood sequence detection for DH-PIM is not viable even in the absence of ISI. Therefore, the most practical implementations of DH-PIM would be to utilize a hard-decision detection scheme. A block diagram of the DH-PIM system with unequalized dispersive optical channels is shown in Figure 10. DH-PIM symbols are passed through a transmitter filter having a unit-amplitude rectangular impulse response $p(t)$ with a duration of one slot $T_s$. The output of the transmitter filter is scaled by the peak transmitted optical signal power $\frac{1}{3}(\bar{P}x^{-1})$, and passed through the multipath channel $h(t)$, where $\bar{P}$ is the
average transmitted optical power. The received optical signal power is converted into a photocurrent by multiplying it by the photodetector responsivity \( R \). Additive white Gaussian noise \( n(t) \) with a one-sided power spectral density of \( \eta \) is added to the detected signal, which is then passed to a unit energy filter \( r(t) \) matched to \( p(t) \), followed by a slot rate sampler. A threshold detector then assigns a one or zero to each slot. We analyse \( P_{\text{pe}} \) using the method proposed in Reference [23], which is described as follows: Let \( c_{\text{cont}} \) denote the continuous impulse response of the cascaded system given by \( c_{\text{cont}} = p(t) \underset{\otimes}{\ast} h(t) \underset{\otimes}{\ast} r(t) \), where \( \otimes \) denotes convolution. The discrete-time equivalent impulse response of the cascaded system \( c_k \) can be given by

\[
c_k = c_{\text{cont}}|_{t=kT_s}
\]

Suppose that \( c_k \) contains \( m \) taps. Let \( S_i \) be an \( m \)-slots DH-PIM sequence, and \( s_{i,m-1} \) the value of the \((m - 1)\)th slot (penultimate slot) in the sequence \( S_i \), where \( s_{i,m-1} \in \{0, 1\} \). Unless the channel is non-dispersive, for an \( S_i \) sequence of \( m \) slots, \( c_k \) will contain \( m \) taps: a single precursor tap, a zero tap \( c_0 \), which has the largest magnitude, and \((m - 2)\) post-cursor taps. Thus, only the penultimate slot will be affected by the dispersion of the signal appearing within the \( S_i \) sequence. Sequences that fall outside the boundaries of \( S_i \) will not contribute to the dispersion on the penultimate slot of \( S_i \). Therefore, when calculating the optical power requirement, only the penultimate slot will be considered for each sequence. Unlike the ideal channels, on a dispersive channel, the optimum sampling point may shift from the end of each slot period as the severity of the ISI changes. In order to isolate the power penalty due to ISI, two assumptions are made. First a perfect timing recovery is assumed, which is achieved by shifting the time origin so as to maximize the zero tap \( c_0 \) [23]. Secondly, an optimal decision threshold is assumed. The input signal at the threshold detector in the absence of noise is given by

\[
y_i = I_p S_i \otimes c_k|_{k=m}
\]

where \( I_p \) is the peak photocurrent in the absence of multipath dispersion. In the penultimate slot the energy \( E_{p,i} = y_i^2 T_s \) and the threshold level \( \rho = \sqrt{E_{p,i}} / 2 \). The probability of slot error for the penultimate slot \( s_{i,m-1} \) of sequence \( S_i \) is given as

\[
P_{\text{se},i,j} = \begin{cases} 
Q\left(\frac{\rho}{\sqrt{\eta/2}}\right) & \text{if } s_{i,m-1} = 0 \\
Q\left(\frac{\sqrt{E_{p,i}} - \rho}{\sqrt{\eta/2}}\right) & \text{if } s_{i,m-1} = 1
\end{cases}
\]

Multiplying the probability of slot error for each sequence by the probability of occurrence of that sequence \( P_{\text{occ},i} \) and summing up of the results for all the valid sequences give the average probability of slot error:

\[
P_{\text{se}} = \sum_{\text{all } i} P_{\text{occ},i} P_{\text{se},i}
\]

The PER is obtained by substituting (17) into (11). To calculate \( P_{\text{req}} \), assuming \( c_k \) has \( m \) taps, we generate all the possible sequences of \( m \)-slot length and ignore all sequences that cannot be generated by the DH-PIM symbols alone. Then calculate the corresponding probabilities of occurrence for each valid sequence, see a detailed flow chart in Figure 11.
Since the slots are not i.i.d, different $m$-slot sequences may have different occurrence probabilities, and when $m > 2$, the total number of valid sequences is always less than $2^m$. $h(t)$ is calculated by means of the ceiling-bounce model described in Reference [24] for different values of the RMS delay spread $D_{\text{rms}}$. $c_k$ is determined from (14), with the sampling instants chosen so as to maximize $c_0$. Knowing the probability of occurrence of each sequence, $P_{\text{se}}$ is determine from (15), (16), and (17) in order to achieve an average packet error of $10^{-6}$. $P_{\text{pe}}$ is calculated from (11) and then from (13), and the corresponding optical power requirement $P_{\text{req}}$ on
dispersive channel is found as

\[ P_{\text{req}} = \frac{3\alpha I_p}{4RL} \]  

\( \text{(18)} \)

The optical power penalty \( P_{\text{penalty}} \) defined as the difference between \( P_{\text{req}} \) and the optical power required on ideal (dispersive-free) channels \( P_{\text{req,ideal}} \) for a given value of the \( D_{\text{rms}} \) is given by

\[ P_{\text{penalty}} = P_{\text{req}} - P_{\text{req,ideal}} \]  

\( \text{(19)} \)

The optical power requirements are normalized to the average optical power required by OOK-NRZ, operating at a bit rate of 1 Mbps to achieve \( P_{\text{pe}} \) of \( 10^{-6} \) on a non-dispersive channel using a packet length of 1 kbyte. Results have been obtained assuming threshold detectors with no path loss, which implies that \( \bar{P} \) is equal to the average received optical power. As a trade off between realism and computation time, the number of slots over which the impulse response decays to a negligible value (i.e. <1% of the peak value) is chosen to be 9 slots (i.e. \( m = 9 \)). A packet length \( N_{\text{pkt}} \) of 1 kbyte and \( \bar{P} = 1 \) W are used in obtaining the following results.

Figure 12 shows the normalized optical power requirements of DH-PIM\(_1\) and DH-PIM\(_2\) against \( D_T \) for a range of values of \( L \), and an optimum threshold level \( \rho_{\text{opt}} = \sqrt{E_p}/2 \). DH-PIM\(_1\) displays an improvement of about 2.5 dB over DH-PIM\(_2\) at low values of \( D_T \) and improving further as \( D_T \) increases, which means that DH-PIM\(_1\) is less affected by multipath dispersion than DH-PIM\(_2\) particularly at high values of \( D_T \). This is due to the fact that the pulse duration in DH-PIM\(_1\) is half that of DH-PIM\(_2\). For both DH-PIM\(_1\) and DH-PIM\(_2\), the power requirement is reduced by \(~1.5\) dB by increasing the value of \( L \) from 4 to 8 to 16 to 32 at low values of \( D_T \) (<0.1). This means that 32-DH-PIM\(_1\) and 32-DH-PIM\(_2\) offer about \( 3 \) dB

---

**Figure 12.** Normalized optical power requirements for DH-PIM\(_1\) and DH-PIM\(_2\) against the normalized delay spread \( D_T \), for \( L = 4, 8, 16 \) and 32, and \( R_b = 1 \) Mbps.
improvement in power gain compared with 8-DH-PIM\textsubscript{1} and 8-DH-PIM\textsubscript{2}, respectively, but require slightly more bandwidth. However, as the normalized delay spread increases above 0.1, the power requirement increases much more rapidly for \(L = 32\) and 16 compared with \(L = 8\) and 4. This is due to ISI effecting larger number of shorter slots in high order \(L\)\textsubscript{-DH-PIM}\textsubscript{1} and \(L\)\textsubscript{-DH-PIM}\textsubscript{2}. For example 32-DH-PIM\textsubscript{1} curve crosses 16-DH-PIM\textsubscript{1} at \(D_T = 0.23\) and 32-DH-PIM\textsubscript{2} curve crosses 16-DH-PIM\textsubscript{2} at \(D_T = 0.1\). Above these two values of \(D_T\), 32-DH-PIM\textsubscript{1} and 32-DH-PIM\textsubscript{2} will necessitate more optical power compared with 16-DH-PIM\textsubscript{1} and 16-DH-PIM\textsubscript{2}, respectively.

The optical power penalty of DH-PIM\textsubscript{1} and DH-PIM\textsubscript{2} due to ISI is calculated from (19) and the normalized results against \(D_T\) for different values of \(L\) are shown in Figure 13. All orders of DH-PIM\textsubscript{1} and DH-PIM\textsubscript{2} display almost similar optical power penalty for \(D_T < 0.01\), which increases swiftly as \(D_T\) becomes \(> 0.01\). DH-PIM\textsubscript{1} shows a significant improvement over DH-PIM\textsubscript{2} particularly at \(D_T < 0.05\). For example, at \(D_T = 0.1\), 32-DH-PIM\textsubscript{1} requires \(~ 3.4\) dB less power compared with 32-DH-PIM\textsubscript{2}. Beyond \(D_T = 0.1\), the improvement become even more significant.

The above results are confirmed by simulation of the eye diagrams at the output of the receiver filter. The eye diagrams of 32-DH-PIM\textsubscript{2} at \(R_b = 1\) Mbps and \(D_T\) of 0.001, 0.01, 0.1 and 0.2 are shown in Figure 14(a), (b), (c), and (d), respectively. Notice that the amount of eye closure increases as the normalized delay spread increases; this results in shifting the optimum sampling point from the end of the slot and the optimum threshold level from the mid-way as the severity of ISI increases. For \(D_T = 0.2\), the eye diagram visibly shows the effect of multipath dispersion, and increasing \(D_T\) further will result in a total closure of the eye diagram.

![Figure 13. Normalized optical power penalty for DH-PIM\textsubscript{1} and DH-PIM\textsubscript{2} against \(D_T\), for \(L = 4, 8, 16\) and 32, and \(R_b = 1\) Mbps.](image-url)
7. CONCLUSIONS

The paper discussed the characteristics and performance of DH-PIM and results confirmed that DH-PIM represents a potential modulation candidate for indoor optical wireless systems. Since each symbol starts with a pulse, DH-PIM provides built-in symbol synchronization, which is an important advantage as it simplifies the design compared with PPM. Results show that DH-PIM offers shorter symbol length, improved transmission rate and bandwidth requirement compared with DPIM and PPM. Spectral analysis showed that it consists of a sinc envelope, slot components and nulls, and the presence of the slot components and the locations of the nulls depend on the header pulse duration \( \alpha \). Slot components are distinct only when \( \alpha \) is odd. DH-PIM has a similar PSD profile but slightly higher values compared to DPIM and PPM due to the use of dual headers and also the wider slot duration. Results on LOS non-dispersive
optical wireless channel confirmed that the slot and packet error rates of DH-PIM decrease with the bit rate and z decreasing and M increasing. DH-PIM2 only outperforms OOK, whereas DH-PIM1 offers similar performance to DPIM but marginally inferior to PPM. Regardless of M, DH-PIM2 displays improved bandwidth efficiency compared with DH-PIM1, PPM and DPIM, but it requires more optical power. Therefore, DH-PIM2 is the preferred technique when the available bandwidth is limited and higher optical power is acceptable. DH-PIM1 exhibits similar power requirements with a marginally higher bandwidth compared with DPIM, and is also more bandwidth efficient than PPM at the cost of a small increase in the power requirement. However, at higher bit resolutions, i.e. $M \geq 7$, DH-PIM1 is both bandwidth and power efficient compared with PPM. The optimum parameters to minimize both the optical power and bandwidth required by DH-PIM are those of 16-DH-PIM1 and 64-DH-PIM2.

The effect of multipath dispersion on DH-PIM has been presented and results indicate that DH-PIM1 is less affected by multipath dispersion compared with DH-PIM2 particularly at high levels of dispersion. M has little effect on the optical power penalty at low dispersion ($D_T < 0.01$). However, the power penalty increases rapidly as $D_T$ increases above 0.01. DH-PIM1 shows a significant improvement over DH-PIM2 particularly for $D_T < 0.05$. At very low dispersion ($D_T < 0.02$), the power requirements of 32-DH-PIM1 are similar to 32-DPIM, considerably lower than 32-DH-PIM2 and OOK, and higher than 32-PPM. However, as $D_T$ increases above 0.02, 32-DH-PIM1 outperforms 32-PPM and shows the best performance compared with its counterparts.

REFERENCES


Copyright © 2005 John Wiley & Sons, Ltd.


AUTHORS’ BIOGRAPHIES

Nawras Aldibbiat received his BEng in Electronics Engineering and a Postgraduate Diploma in Communications Engineering from the University of Aleppo, Syria in 1996, 1997, respectively. He received his PhD in optical wireless communications from Sheffield Hallam University, U.K. in 2002. During 1997 and 1998 he worked as an Electronic Engineer at the General Establishment for Mills, Syria. Between 1999 and 2001 he worked as an Associate Lecturer at Sheffield Hallam University, U.K. Between November 2001 and September 2003 he worked at the University of Leeds, U.K. as a Research Fellow on a research project in the area of 3G mobile networks. In September 2003 he joined Sheffield Hallam University where his research work includes optical fibre sensors and optical wireless communications. His research interests include optical wireless communications, optical fibres, mobile communications, radio networks and digital modulation. He is a member of the IEE and IEEE.

Z. Ghassemlooy received his BSc (Hons) degree in Electrical and Electronics Engineering from Manchester Metropolitan University in 1981, and his MSc and PhD from the University of Manchester Institute of Science and Technology, in 1984 and 1987, respectively. From 1987 to 1988 he worked as a Post-doctoral Research Fellow on optical sensors at the City University, London. He then joined Sheffield Hallam University as a Lecturer in 1988, and become a Professor in 1997. He was the Group Leader for Communication Engineering and Digital Signal Processing and also head of the Electronics Research Centre until 2004. In 2004 he moved to the University of Northumbria at Newcastle as an Associate Dean for research in the School of Engineering and Technology. In 2001 he was a recipient of the Tan Chin Tuan Fellowship in Engineering from the Nanyang Technological University, Singapore to work on the photonic technology. He is the Editor-in-Chief of The Mediterranean Journal of Computers and Networks, and also serves on the Publication Committee of the IEEE Transactions on Consumer Electronics, the editorial board of the International Journal of Communication Systems and the Sensor Letters. He is the founder and the Secretary (1998–2004) and now the Chairman of the International Symposium on Communication
Systems, Network and Digital Signal Processing, and is a member of technical committee of a number of international conferences. He has published around 200 papers and is a co-editor of an IEE book on ‘Analogue Optical Fibre Communications’, special issues of the IEE Proceeding Journal 1994, and 2000, and International Journal of Communication Systems 2000, the proceedings of the CSDSP’98 and first International Workshop on Materials for Optoelectronics 1995, U.K. His research interests are in the areas of photonic networks, modulation techniques, high-speed optical systems, optical wireless communications as well as optical fibre sensors. He is a Chartered Engineer, a Fellow of IEE and a Senior Member of IEEE. He is currently IEEE U.K./IR Communications Chapter Secretary.

R. McLaughlin received his BTech (Hons) degree in Engineering Mathematics from the University of Bradford in 1971, and his PhD from the University of St Andrews, in 1974. From 1974 to 1977 he worked as a Post-doctoral Research Fellow on Viscoelastic Composite Materials at Canfield Institute of Technology. He was a Lecturer at Wigan College of Technology from 1977 to 1978 and then joined Sheffield Hallam University as a Lecturer in 1979, being promoted to Senior Lecturer in the following year. His research interests now include the mathematics of optical wireless communications and digital modulation.