Optical Wireless Communication using Digital Pulse Interval Modulation

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ABSTRACT

This paper presents a study of digital pulse interval modulation (DPIM) as a candidate modulation scheme for optical wireless communications. DPIM code characteristics are discussed and the theoretical error probability performance of DPIM is analysed in terms of the packet error rate. Performance comparisons are made with the more established techniques of on-off keying (OOK) and pulse position modulation (PPM). We show that, for a simple threshold detector based receiver, DPIM can outperform PPM in terms of bandwidth efficiency and power efficiency, by taking advantage of its inherent variable symbol duration. Practical results are given for an experimental system in the form of eye diagrams. The use of a coding scheme with a non-uniform symbol duration does have implications for system design, which are discussed in the paper.

Keywords: Modulation, Wireless, Infrared, OOK, PPM, DPIM.

1. INTRODUCTION

Infrared transceivers usually operate in the presence of high levels of ambient light, emanating from both natural and artificial sources. Even when optical filtering is used in the receiver to reject some of the out of band ambient light, the resulting photocurrent gives rise to shot noise which is the dominant noise source in a well designed receiver\textsuperscript{1}. In addition to this, infrared channels have a high path loss and signal dispersion due to multipath propagation. The path loss is very much dependant on the physical parameters of the room, such as size, position of transmitter and receiver, materials, and the position of furniture and other objects within the room. Measured results show that losses of around 60 dB are not uncommon in typical rooms\textsuperscript{2}. Multipath propagation introduces a significant optical power penalty for bit rates above 10 Mbps\textsuperscript{3}. Dispersion results in intersymbol interference (ISI), which requires the use of complex equalization techniques to overcome the effects. Thus, as a result of these factors, relatively high optical transmit powers are required. However, the average optical power emitted by an infrared transceiver is limited by eye safety regulations and electrical power consumption in portable (battery powered) devices. Therefore, the use of power efficient modulation techniques is desirable.

Single-element diffuse receivers favour the use of large area photodetectors, which improve the received signal to noise ratio and subsequently increase the cell size in which the transceiver can operate effectively. However, the high capacitance associated with large area photodetectors limits the receiver bandwidth, and hence, the bandwidth efficiency of the modulation scheme must be taken into consideration.

Coherent optical detection is not feasible in non-directed applications and hence, practical optical wireless systems use intensity modulation and direct detection\textsuperscript{1}. The simplest modulation technique is on-off keying (OOK), in which a zero is represented by zero intensity and a one is represented by a positive intensity. OOK can use either non return to zero (NRZ) or return to zero (RZ) pulses, with a pulse duty cycle $\gamma$. OOK with RZ pulses requires an increase in transmission bandwidth by a factor of $1/\gamma$, but outperforms OOK-NRZ in terms of average power requirement since the $1/\gamma$ increase in peak power.
outweighs the increased noise due to the expanded bandwidth\(^4\). However, as the value of \(\gamma\) is reduced, there comes a point when it becomes more efficient to use other modulation techniques. PPM is one such technique, which maps \(\log_2L\) data bits to one of \(L\) possible symbols. Each symbol consists of a pulse occupying one slot and \((L - 1)\) empty slots. By increasing the value of \(L\), the performance of the modulation scheme is improved at the expense of bandwidth efficiency. PPM has been used widely in optical wireless systems, and is the chosen modulation scheme for the IEEE 802.11 infrared physical layer standard\(^5\) as well as Infrared Data Association (IrDA) serial data links operating at 4 Mbps\(^6\). Compared with OOK, PPM does increase system complexity since both slot and symbol synchronisation are required in the receiver in order to demodulate the incoming signal. An alternative to PPM is DPIM, a technique which can be used to yield an improvement in terms of bandwidth efficiency and power efficiency over PPM, for a threshold detection based receiver. Furthermore, receiver design is simplified since DPIM does not require symbol synchronisation. The following sections outline the code properties and error probability performance of DPIM.

2. DPIM CODE PROPERTIES

As with PPM, DPIM maps \(\log_2L\) data bits to one of \(L\) possible symbols. Unlike PPM however, the symbol duration is variable and is determined by the information content of the symbol. In order to avoid symbols which have no slots between adjacent pulses, a guard slot may be added to each symbol immediately following the pulse. Throughout this paper, we will assume each symbol contains one guard slot. An \(M\) bit symbol is represented by a pulse of constant power \(P\) in one slot, followed by \(k\) slots of zero power, where \(1 \leq k \leq L\) and \(L = 2^M\). This may be expressed as:

\[
S_{DPIM}(t) = \begin{cases} 
  P & nT_s \leq t < (n+1)T_s \\
  0 & (n+1)T_s \leq t < (n+k+1)T_s 
\end{cases}
\]

(1)

where \(T_s\) is the slot duration. The minimum and maximum symbol durations are \(2T_s\) and \((L + 1)T_s\) respectively. Fig. 1 shows the mapping of source data to transmitted symbols for 4-PPM and 4-DPIM.

<table>
<thead>
<tr>
<th>Source Data</th>
<th>4-PPM</th>
<th>4-DPIM</th>
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<tbody>
<tr>
<td>00</td>
<td></td>
<td></td>
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<tr>
<td>01</td>
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<td>10</td>
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<td>11</td>
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</tbody>
</table>

![Mapping of source data to transmitted symbols for 4-PPM and 4-DPIM.](image)

The duty cycle of \(L\)-PPM symbols remains fixed at \(1/L\), whereas \(L\)-DPIM symbols have a variable duty cycle, the average of which is higher than \(1/L\). Consequently, for a fixed value of \(M\), DPIM has a higher average power requirement compared with PPM. In \(L\)-PPM, the slot rate, \(R_s\), is set to \(R_s = \frac{L R_b}{\log_2 L}\). In \(L\)-DPIM, there are two options for the slot rate, as discussed in the following sections.

2.1 \(L\)-DPIMA

The slot rate may be chosen such that the average symbol duration is equal to the time taken to transmit the same number of bits using OOK / \(L\)-PPM. This is denoted as \(L\)-DPIMA. Thus, the slot rate is given as \(R_s = \frac{(L + 3)R_b}{2\log_2 L}\). This achieves the same average data rate as OOK / \(L\)-PPM, but requires only approximately half the bandwidth. As an example, if the
bandwidth, \( W \), required to support a data rate of \( R_b \) using OOK-NRZ is \( R_b \), then for 16-PPM, \( W = 4R_b \) whereas for the same average data rate, 16-DPIM\(_A\) has a bandwidth requirement of \( W \approx 2.4R_b \).

### 2.2 L-DPIM\(_M\)

Alternatively, the slot rate may be chosen such that the maximum symbol duration is equal to the time taken to transmit the same number of bits using OOK / L-PPM. This is denoted as L-DPIM\(_M\). Thus, the slot rate is given as \( R_s = \frac{(L + 1)R_b}{\log_2 L} \). If \( R_b \) is the data rate of L-PPM / OOK, the average data rate of L-DPIM\(_M\) is given as \( R_{DPIM_M} = \frac{2(L + 1)R_b}{L + 3} \). The average data rate of L-DPIM\(_M\) relative to OOK / L-PPM is shown in Fig. 2. It is clear that as \( L \) increases, the average data rate approaches twice that of OOK / L-PPM. Intuitively, this must be the case since the average symbol length of L-DPIM\(_M\) is approximately half that of OOK / L-PPM. This can be used to improve the power efficiency of DPIM since an extra bit per symbol can be encoded without increasing the slot rate or reducing the average data rate. As an example, consider 16-DPIM\(_M\) which has a slot rate of 4.25\( R_b \). 32-DPIM\(_A\) requires a slot rate of 3.5\( R_b \) and hence, without increasing the slot rate, 16-DPIM\(_M\) is capable of encoding 5 bits per symbol and still achieving an average data rate greater than \( R_b \). Note that, compared with L-PPM, L-DPIM\(_M\) requires a slight increase in bandwidth by a factor of \((L + 1)/L\) in order to accommodate the additional guard slot. The bandwidth requirements of L-PPM, L-DPIM\(_M\) and L-DPIM\(_A\) relative to OOK-NRZ are shown in Fig. 2.

![Fig. 2: Normalised average data rate and normalised bandwidth requirement versus number of bits per symbol.](image)

### 3. ERROR PROBABILITY ANALYSIS

In L-PPM, an error is confined to the symbol in which the error occurs. Therefore, assuming the \( L \) possible signals are equally likely and orthogonal, it is possible to convert the probability of symbol error into a corresponding probability of bit error using:

\[
P(\text{bit error}) = \frac{2^{M-1}}{2^M - 1} P(\text{symbol error})
\]  
(2)

In DPIM, the pulses define the symbol boundaries and hence, an error is not confined to the symbol in which the error occurs. Consider a packet of data encoded using DPIM. A pulse detected in the wrong slot would affect both symbols either side of the pulse, but would have no influence on the remaining symbols in the packet. A pulse not detected would combine two symbols into one longer length symbol, and conversely, detecting an additional pulse would split one symbol into two
shorter length symbols. Both these errors would result in a shift of the remaining symbols in the packet. Thus, it is clear that the conversion given in (2) is inaccurate for DPIM. In order to compare the performance of DPIM with other modulation schemes, we base our analysis on the packet error rate (PER). A packet is considered to be in error if one or more of the symbols within the packet are in error. This may be expressed as:

\[ P_{PE} = 1 - \prod_{n=1}^{Y} (1 - P_{SEP_n}) \]  

(3)

where \( P_{PE} \) is the probability of packet error, \( Y \) is the number of symbols in the packet and \( P_{SEP_n} \) is the probability that the \( n^{th} \) symbol is in error.

Following a similar approach to that used by Moreira et al.9, we make the following assumptions:

(i) There are no bandwidth limitations imposed by the transmitter or the receiver front-end.

(ii) The channel is free from distortion (multipath propagation is ignored.)

(iii) Only shot noise due to the background light level is considered. The receiver noise (shot noise and thermal noise) is assumed to be negligible.

(iv) The variation in received irradiance resulting from artificial light sources is ignored.

In the following sections, three modulation schemes are considered, namely OOK-NRZ, L-PPM and L-DPIM.

3.1 OOK-NRZ

The optimum threshold level, which minimizes the probability of error, is dependent on the received signal power and the noise in the receiver. Since these measurements can be difficult to implement precisely, the threshold level is often set to lie a fixed distance between zero and one distributions10. Assuming equally likely ones and zeros, symmetric probability densities, a receiver filter matched to the rectangular transmitted pulse and a threshold level which is set midway between the mean values of ones and zeros, the probability of bit error for OOK using NRZ pulses is given as8:

\[ P_{E_{OOK}} = \frac{1}{2} \text{Erfc} \left( \frac{P_{ave}R\sqrt{T_s}}{2gqI_b} \right) \]  

(4)

where \( P_{ave} \) is the average received irradiance, \( R \) is the photodetector responsivity, \( g \) is the charge of an electron and \( I_b \) is the average background photocurrent.

3.2 L-PPM

A threshold detection based receiver for L-PPM samples the incoming signal at the slot rate, and assigns a ‘one’ or a ‘zero’ depending on whether the received signal is above or below the threshold level at the sampling instant. A symbol is then assigned depending on which of the L samples is a ‘one.’ If the block of L samples consists entirely of ‘zeros’, we assume that a slot is chosen at random to receive the ‘one.’ If the correct slot has been assigned a ‘one,’ but there are one or more other slots in the block of L slots which are also ‘one,’ one of the slots containing a ‘one’ is chosen at random.

Let \( P_{01} \) denote the probability that a correct pulse is not detected and \( P_{10} \) denote the probability that a pulse is detected in a slot which should be empty. The probability of symbol error for a PPM system using threshold detection, \( P_{SEP_{pmm}} \), is given as9:

\[ P_{SEP_{pmm}} = 1 - \left[ \frac{1}{L} P_{01} (1 - P_{10})^{L-1} + \sum_{n=1}^{L} \frac{1}{n} \binom{L-1}{n-1} (1 - P_{01}) P_{10}^{n-1} (1 - P_{10})^{L-n} \right] \]  

(5)
The first term gives the probability that no pulses are detected and the randomly assigned pulse is placed in the correct slot. When \( n = 1 \), the second term gives the probability that a pulse is detected in the correct slot and no other pulses are detected. When \( n > 1 \), the second term gives the probability that the correct pulse is detected along with \( n - 1 \) incorrect pulses and the correct pulse is chosen from the detected pulses.

Assuming an equal probability of error receiver, i.e. \( P_{01} = P_{10} \). If the threshold level is set to half the amplitude of the received PPM pulses at the sampling instant, then the probability of slot error is given as:

\[
P_{01} = P_{10} = \frac{1}{2} \text{erfc} \left( \frac{L P_{\text{ave}} R \sqrt{T_s}}{2 \sqrt{2qI_b}} \right)
\]  

(6)

### 3.3 L-DPIM

As with the threshold detection based receiver for L-PPM, the incoming signal is sampled at the slot rate and a ‘one’ or ‘zero’ is assigned to each slot depending on whether the received signal is above or below the threshold level at the sampling instant. We make the assumption that the pulse indicating the start of the symbol is detected in the correct slot. As the pulse is followed by a guard slot, it is not possible to falsely detect a pulse in this slot. In order to detect a correct symbol, the pulse marking the start of the following symbol must be correctly detected and all preceding slots (excluding the guard slot) must be ‘zero.’ Since the symbol length is variable, the probability of symbol error increases with increasing symbol length. If the maximum symbol length is reached and the pulse indicating the start of the following symbol has not been detected, a ‘one’ is assigned at random to one of the \( L \) slots. Note that unlike PPM, if more than one pulse is received during the maximum symbol length, this is interpreted as being more than one symbol.

The probability of symbol error for a DPIM system using threshold detection, \( P_{\text{SE,DPIM}} \) is given as:

\[
P_{\text{SE,DPIM}} = 1 - \left[ \frac{1}{L} \sum_{n=0}^{L-1} (1 - P_{01}) (1 - P_{10})^n + \frac{1}{L} P_{01} (1 - P_{10})^{L-1} \right]
\]  

(7)

The first term gives the average probability of correctly detecting the pulse indicating the start of the following symbol and that all preceding slots, excluding the guard slot, are ‘zero.’ The second term gives the probability that the maximum symbol length is reached without detecting a single pulse, and a randomly assigned ‘one’ is placed in the correct slot.

Again assuming \( P_{01} = P_{10} \) and a threshold level set to half the amplitude of the received DPIM pulses at the sampling instant, then the probability of slot error is given as:

\[
P_{01} = P_{10} = \frac{1}{2} \text{erfc} \left( \frac{(L + 3) P_{\text{ave}} R \sqrt{T_s}}{4 \sqrt{2qI_b}} \right)
\]  

(8)

Note that \( L \) in (6) has been replaced by \((L + 3)/2\), which is the mean symbol duration in slots.

For a simple threshold detection based receiver, the PER was calculated for OOK, PPM and DPIM based on the following parameters: packet length set to 1024 bits, data rate of 1 Mbps and a background power of –10 dBm/cm². Fig. 3 shows the calculated PER versus average received irradiance for OOK-NRZ, L-PPM and L-DPIM, for \( L = 8 \) and 16. 16-DPIM, has approximately a 5 dB power advantage over OOK-NRZ, but requires about 1 dB more power than 16-PPM. Fig. 4 shows the PER for 16-PPM, 16-DPIM, 16_DPI, and 32-DPI, 16-DPI is approximately 1.3 dB inferior to 16_DPI, but does give nearly twice the throughput. 32-DPI is particularly attractive, since it gives approximately a 0.6 dB power advantage over 16-PPM and has a lower bandwidth requirement. 32-DPI has an average symbol length of 17.5 slots compared to 16 slots for 16_PPM, but encodes one more bit and therefore, the slot rate is lower. However, it should be noted that in the absence of ISI, the optimum maximum likelihood receiver for L-PPM (in which the largest of \( L \) samples is
designated as the slot containing the ‘one’) has been shown to give an improvement of 1.5 dB over a threshold detector based receiver\(^9\), and hence, this would out perform 32-DPIMA.

![Graph 1](image1)

Fig. 3: PER versus average received irradiance for OOK-NRZ, L-PPM and L-DPIMA (for \(L = 8\) and 16).

![Graph 2](image2)

Fig. 4: PER versus average received irradiance for 16-PPM, 16-DPIMA, 16-DPIM\(_M\) and 32-DPIMA.

4. EXPERIMENTAL SYSTEM

The block diagram of the Infrared transceiver is shown in Fig. 5. In the transmitter, data is loaded into the Modulator in \(M\) bit blocks. An \(M\) bit counter is used, incremented by the slot clock. When the output from the counter is equal to the data held in the latch, the output from the magnitude comparator goes high for one slot clock period. The rising edge of this pulse is used to load the next \(M\) bits into the latch and reset the counter. The output from the comparator is connected to an optical driver circuit, which uses high speed switching transistors to drive an array of six vertically oriented LEDs, each having a radiant power of 38 mW @ 100 mA forward current, centered on 875 nm.
The receiver uses a silicon pin photodiode with an active area of 1 cm$^2$, followed by a 14 kΩ transimpedance amplifier. The differential output of the transimpedance amplifier is connected to a wideband differential amplifier followed by an additional gain stage which uses a high speed video op-amp. A 10 MHz Bessel low pass filter is then employed to limit the receiver bandwidth, before the signal is passed to a threshold detector. The threshold level is set to half the amplitude of the received pulses at the sampling instant, which is close to the optimum value when the received SNR is high. The output from the threshold detector represents an estimate of the transmitted DPIM pulse stream, which is then passed to the demodulator. The demodulator consists of an $M$ bit counter and a latch. The positive edges of the incoming pulse stream are used to load the counter value into the data latch and the negative edges then reset the counter. The clock recovery circuit incorporates a pulse shaping circuit, in which the received pulses are processed into half slot duration pulses, followed by a PLL which tracks the discrete slot frequency component. The recovered slot clock is used to generate the sampling points for the threshold detector and increment the counter.

![Diagram of infrared transceiver block diagram: (a) transmitter, (b) receiver.](image)

Using a slot frequency of 6 MHz, Fig. 6(a) and (b) show the eye diagram at the input to the threshold detector for an average received irradiance of –42 dBm/cm$^2$ and –49 dBm/cm$^2$ respectively, with an RG-780 optical high-pass filter placed in front of the photodiode. The ambient power was –10 dBm/cm$^2$ (unfiltered.) The closing of the eye can be observed as the received signal power falls.
Fig. 6: Eye Diagram for an average received irradiance of: (a) –42 dBm/cm², (b) –49 dBm/cm².

5. IMPLEMENTATION ISSUES

In the absence of multipath distortion, the optimum maximum likelihood receiver for L-PPM employs a continuous-time filter matched to one slot, the output of which is sampled at the slot rate. Each block of \( L \) samples is passed to a block decoder which makes a symbol decision by choosing the largest of the \( L \) samples. When ISI is present, the optimum receiver for PPM employs a whitened-matched filter followed by a maximum likelihood sequence detector, which may be performed on a symbol-by-symbol basis using the Viterbi algorithm. As stated by Shiu et al. for differential PPM, symbol boundaries are not known prior to detection, optimal decoding of DPIM requires the use of maximum likelihood sequence detection, even when ISI is not present. In order to decode a packet \( S \) slots long containing \( Y \) symbols, every possible combination of \( Y \) symbols which gives a combined length of \( S \) slots must be compared. Therefore, practical implementations of DPIM favour a sub optimum threshold detection based receiver.

As a consequence of the variable duration of DPIM symbols, the time required to transmit a packet containing a fixed number of bits is not constant. This could result in hardware inefficiencies, in terms of the required size of transmitter and receiver buffers. Packets containing predominantly shorter length symbols will be transmitted relatively quickly, possibly resulting in transmitter buffer underflow, receiver buffer overflow or a temporary violation of eye safety requirements. Conversely, packets containing mainly longer length symbols require a greater time for transmission, which may result in transmitter buffer overflow and receiver buffer underflow. In order to avoid these problems, it is necessary to employ some form of coding scheme to limit the variation in packet size. As suggested by Shiu et al., a dual mapping technique could be employed, whereby source bits are mapped to symbols either normally or in reverse fashion, which ever yields the shortest packet length. Empty slots are then added to the end of a packet until the mean packet duration is reached.

6. CONCLUSIONS

This paper has outlined the basic properties of DPIM. The theoretical error probability performance of DPIM has been given in terms of the packet error rate, and results have been compared with those of OOK-NRZ and PPM. Practical results have been given for an experimental system in the form of eye diagrams. We have shown that, for a simple threshold detector based receiver, the lower average symbol duration of DPIM can be used to improve the power efficiency and bandwidth efficiency compared with PPM, by allowing an extra bit per symbol to be encoded. DPIM also yields a simplified receiver structure, since symbol synchronisation is not required. However, since symbol boundaries are not known prior to detection, practical implementations of DPIM would favour the use of simpler threshold detection receivers, which have been shown to be approx. 1.5 dB inferior to maximum likelihood receivers for PPM systems. Nevertheless, DPIM has proven itself to be a promising modulation technique for optical wireless communications, which could replace PPM in many applications.

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REFERENCES


