Performance of DH-PIM Employing Equalisation for Diffused Infrared Communications

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Abstract
The performance of dual header-pulse interval modulation (DH-PIM) employing a linear zero forcing equaliser (L-ZFE) in diffused infrared indoor environment is presented. The work is based on the ceiling bounce channel model and the Monte Carlos simulation. A 3-tap L-ZFE is used and the results are compared with unequalised DH-PIM as well as digital pulse interval modulation (DPIM) and on-off keying (OOK) schemes. For highly dispersive medium, results show that equalised DH-PIM offers an improved slot error rate (SER) performance compared with equalised OOK.

1. Introduction
The demand for mobile connectivity and the need for higher data rates in wireless computing, wireless video and wireless (interactive) multimedia are some of the reasons for the increased interest in the research on indoor infrared (IR) wireless communications. IR communications have immense unregulated bandwidth available that can satisfy the quest of present day bandwidth hungry applications. IR radiations do not penetrate walls and other opaque objects, i.e. no interference from other light sources in the adjacent rooms, and also offers the use of the same wavelength in the adjacent rooms, building etc [1-4]. The use of intensity modulation and direct detection (IM/DD) in IR wireless communication only prevents multipath fading, but the intersymbol interference (ISI) due to multipath propagation constitute a major system impairment especially at high bit rates [2]. In dispersive environment, maximum likelihood sequence detection (MLSD) technique gives the optimum result; however, its complexity and delay may be prohibitive in many applications [5]. Therefore, various suboptimum equalisation techniques have been employed to combat the effect of ISI due to multipath propagation.

DH-PIM offers good characteristics for IR wireless systems because of its built-in symbol synchronisation and relatively straightforward slot synchronisation, higher bit rate, short symbol length, reduced bandwidth requirements. It offers improved immunity to multipath dispersion at high dispersive medium at the cost of slightly higher optical power and higher probability of slot errors compared with digital pulse interval modulation (DPIM) [3]. The performance of unequalised DH-PIM is well documented in the literature [3]; however no work has been reported on DH-PIM employing equalisation. In this paper we analyse and simulate equalised and unequalised DH-PIM using L-ZFE equaliser and Monte Carlos simulation and compare results with other modulation techniques such as OOK and DPIM. In DH-PIM symbols, the guard band after the pulse can be given as integer $\alpha > 0$ and depends on the values of α and *L;* 2 and 8 are used for α and *L* respectively throughout this work. The following section presents the channel model and its characteristics. Section 3 gives the system model and the results are presented in section 4. The conclusions of the paper are in section 5.

2. Optical Channel Model/Characteristics
The practical multipath channel can be modelled as a base band linear system where the output current can be represented by the equation [1, 6]:

$$Z(t) = RX(t) \otimes h(t) + N(t) \qquad (1)$$

Where, $\otimes$ stands for convolution, $h(t)$ represents the impulse response of the dispersive channel, $X(t)$ is the input optical power, R is the responsivity of the photodetector, and $N(t)$ is the additive noise. The noise component is usually modelled as white Gaussian and independent of $X(t)$ [2-4, 6]. The channel is assumed to be time invariant [6], and its impulse response $h(t)$ is fixed for a given position of transmitter, receiver and intervening reflectors within a room and only changes when any of these is moved by a few centimetre [2]. This fact suggests the suitability of non-adaptive equalisers on diffuse IR wireless communication channel. The channel is characterised by the RMS delay spread D_{rms} and optical path loss $H(0)$, contributing to ISI and signal attenuation, respectively. The optical path loss is assumed to be negligible and therefore normalise the optical path loss to unity. The multipath power requirement is related to the normalised delay spread given as:

$$DT = D_{rms}/T_b \qquad (2)$$

where, T_b is input bit duration.

Practical measurements have shown that for diffused IR systems D_{rms} is in the range of 1 to 15 ns [3]. The impulse response of channel for the ceiling bounce model for diffuse IR is given by [1, 6]:

$$h(t) = H(0)\frac{6a^6}{(t+a)^7}u(t) \qquad (3)$$

where *u(t)* is the unit step function and *a* is a constant which depends on the room size, transmitter and receiver positions. If the transmitter and receiver are collocated, then $a = 2H/c$ where *H* is the height of the ceiling from the transmitter and receiver and *c* is the speed of light. The parameter *a* is related to the RMS delay spread by:

$$a = 12\sqrt{11/13}D_{rms}\,. \qquad (4)$$

3. System Model

The mappings of 3-bit OOK word into DH-PIM, DPIM and PPM are shown in Table 1 [3]:

Table1. Mapping of 3-bit OOK code into 8-PPM, 8-DPIM and 8-DH-PIM symbols

OOK	8-PPM	8-DPIM	8-DH-PIM
0 0 0	1 0 0 0 0 0 0 0	1 0	**1** 0 0
0 0 1	0 1 0 0 0 0 0 0	1 0 0	**1** 0 0 0
0 1 0	0 0 1 0 0 0 0 0	1 0 0 0	**1** 0 0 0 0
0 1 1	0 0 0 1 0 0 0 0	1 0 0 0 0	**1** 0 0 0 0 0
1 0 0	0 0 0 0 1 0 0 0	1 0 0 0 0 0	**1 1** 0 0 0 0
1 0 1	0 0 0 0 0 1 0 0	1 0 0 0 0 0 0	**1 1** 0 0 0
1 1 0	0 0 0 0 0 0 1 0	1 0 0 0 0 0 0 0	**1 1** 0 0
1 1 1	0 0 0 0 0 0 0 1	1 0 0 0 0 0 0 0 0	**1 1** 0

Detailed description of the DH-PIM code word, modulator and demodulator can be found in many literature papers such as [3]. In DH-PIM where there is no fixed symbol boundary, the occurrence of slot error(s) in a symbol does not only affect the symbol containing that slot but also the symbols after it, therefore one can't describe its performance in terms of bit error rate. Appropriate performance indicators would be slot error rates and packet error rate P_{pe} given by [3]:

$$P_{pe} = 1 - (1 - P_{se})^{N\bar{L}/M} \qquad (5)$$

Where, *N* is the number of DH-PIM symbols, $\bar{L} = (2^{M-1} + 2\alpha + 1)/2$ is the average symbol length of DH-PIM, and P_{pe} is the slot error rate which can be given as [3]:

$$P_{se} = \frac{1}{4\bar{L}}\left[(4\bar{L} - 3\alpha)Q\left(R\bar{P}\sqrt{\frac{8M\bar{L}}{9\alpha^2\eta R_b}}\right) + 3\alpha Q\left(R\bar{P}\sqrt{\frac{8M\bar{L}}{9\alpha^2\eta R_b}}\right)\right] \qquad (6)$$

where, R_b is the bit rate, $\bar{P}$ the average received optical power, η the one-sided power spectral density of the white Gaussian shot noise due to the ambient light.

The system model for the DH-PIM employing equalisation is shown in Fig. 1. The input bits I_k are assumed to be independent, identically distributed (i.i.d.). The DH-PIM encodes each *M*-bits input symbol into one of $L = 2^M$ possible DH-PIM symbols according to the decimal value of the input code word [3].

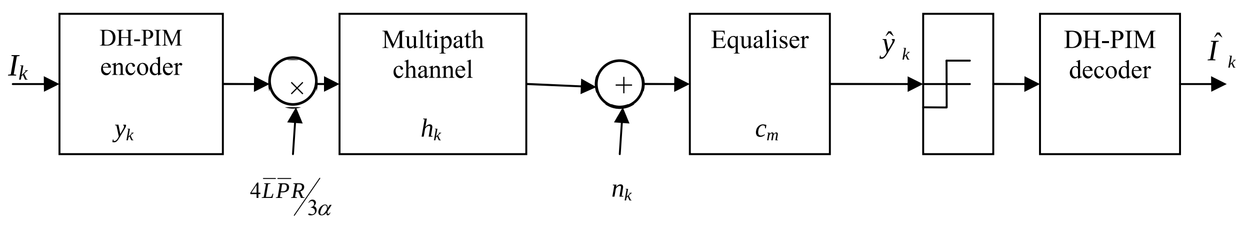

Fig. 1: Equalised DH-PIM system block diagram

The DH-PIM sequence y_k is scaled by the received peak optical signal power $4\overline{L}\overline{P}R/3\alpha$ where $\overline{P}$ is the average transmitted optical power. The scaled y_k is then passed through the causal, minimum phase discrete equivalent channel with impulse response h_k representing the combination of the transmitter filter, multipath channel and whitened matched filter. The noise n_k added is white and Gaussian with zero mean and single-sided power spectral density η_o. The linear equaliser compensates for ISI induced on the signal due to multipath dispersion. The threshold detector decides whether a '1' or '0' is received before the DH-PIM decoder translates the sequence back into the estimate of the input bit stream $\hat{I}_k$.

3.1 Zero-Forcing Linear Equaliser

The signal at the output of the equalizer is expressed as:

$$\hat{y}_k = I_k q_o + \sum_{\substack{m=-\infty \\ m\neq k}}^{m=\infty} I_n q_{k-n} + \sum_{m=-\infty}^{m=\infty} c_m \eta_k \tag{7}$$

where $q_n = \sum_{m=-\infty}^{m=\infty} c_m h_{n-m}$ (8)

The first, second and third terms are the scaled version of DH-PIM sequence, ISI component, and the noise component, respectively. The ISI component is made zero to eliminate ISI. The equalizer used to achieve this is termed zero-forcing equaliser having an infinite number of taps c_m as in (7). However, in real situation an equalizer with finite number of taps is used to reduce (not to eliminate completely) ISI. The tap-coefficients c_m can be given as:

$$q_n = \sum_{m=-k}^{m=k} c_m h_{n-m} = \begin{cases} 1 & \text{for } n = 0 \\ 0 & \text{elsewhere} \end{cases} \tag{9}$$

The range of m depends on the number of pre-cursor and post-cursor ISI that need to be forced to zero. With no precursor ISI, the value of m is positive integers only.

4. Results

The system shown in Fig. 1 was simulated using Matlab software. Due to computational power a set of 900,000 random bits were generated for every simulation process. The equaliser tap coefficients c_m were obtained from (9). Figure 2 shows the probability of slot error rate against SNR for equalised and unequalised DH-PIM signal with bit rate of 100 Mbps and different values of D_{rms}.

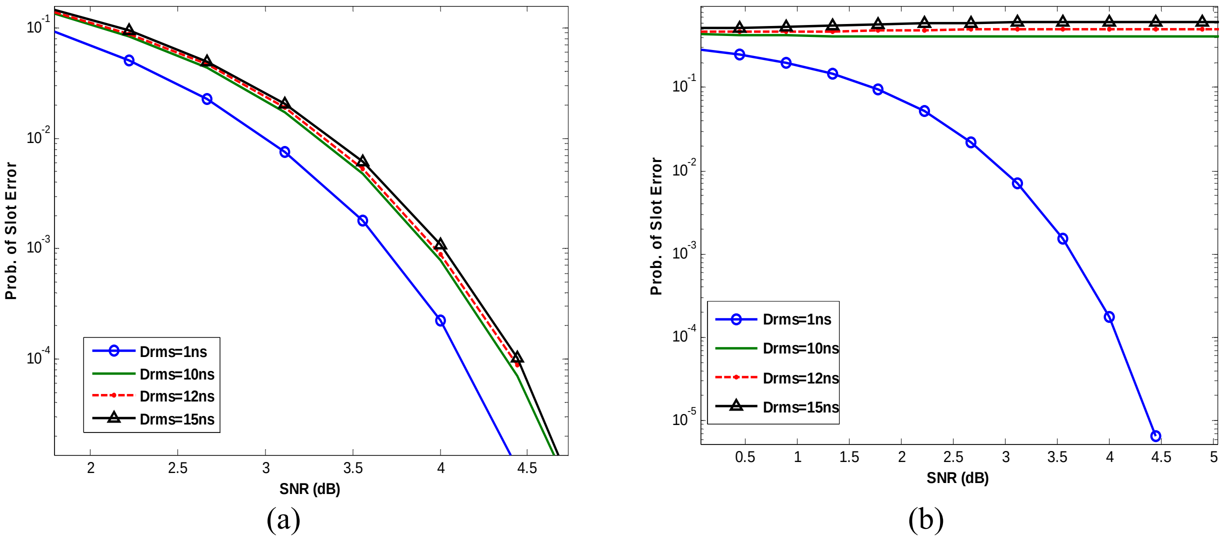

Fig. 2: SER against SNR for different D_{rms} Values at a bit rate of 100Mbps. (a) Equalised 8-DH-PIM, and (b) unequalised 8-DH-PIM

The figure shows that the equalisation gives slight improvement to the SER for low dispersive channels (D_{rms} < 10ns), however for severe multipath dispersion (D_{rms} > 10ns) the improvement on the SER becomes significant. For

example at a SER of 10^{-4}, the severely dispersive system (D_{rms}=15ns) requires < 0.5 dB more SNR to match the performance of D_{rms}=1ns.
Figure 3 shows the error performance of equalised 8-DH-PIM at D_{rms} = 10ns and a range of bit rates. The ISI effect is more pronounced at high bit rates (Rb > 10 Mbps). For example DH-PIM with Rb = 100 Mbps requires ~ 1dB additional SNR to match the performance at Rb < 10 Mbps at SER = 10^{-4}.

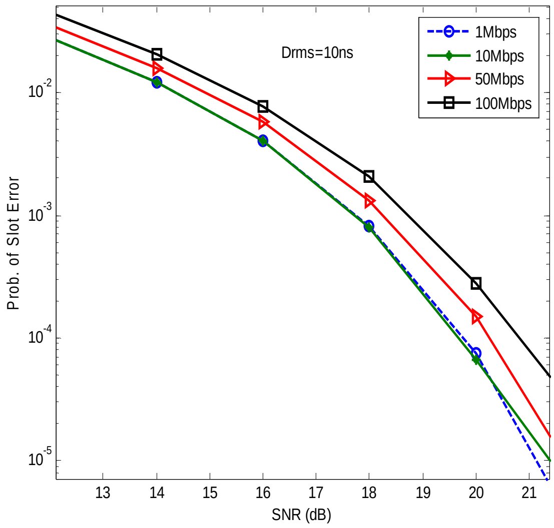

Fig. 3: Slot Error Rate against SNR for 8-DH-PIM with R_b = 1, 10, 50 and100Mbps

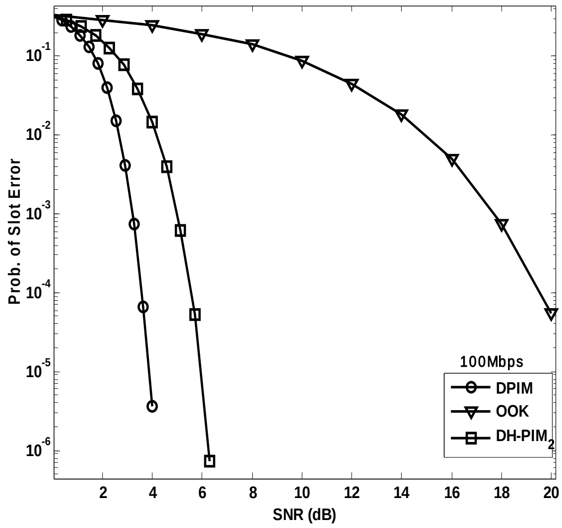

Fig. 4: Slot error rate against SNR at D_{rms}=10ns and at R_b = 100Mbps for OOK, 8-DPIM and 8_DH-PIM

The slot error rate of equalised DH-PIM is compared with equalised OOK and 8-DPIM in Fig. 4 for R_b = 100Mbps and D_{rms}=10ns. The results show that DH-PIM gives significant improvement over OOK and slightly outperformed by DPIM. For example to achieve a SER of 10^{-4} DH-PIM requires 14 dB less SNR compared with OOK and just 2 dB more SNR compared with DPIM.

5. Conclusions

The results show that the performance of DH-PIM improved with equalisation particularly at high bit rates (>10Mbps) and highly dispersive channels (D_{rms} > 10ns). DH-PIM showed a significant improvement in slot error rate compared with OOK slightly lower performance compared with DPIM. Therefore DH-PIM with equalisation is a very promising modulation technique for use in severely dispersive multipath IR links.

References

[1] K.K. Wong, T. O'Farrell and M. Kiatweerasakul: 'The performance of optical wireless OOK,2-PPm and spread spectrum under the effects of multipath dispersion and artificial light' Inter. J. Commu. Syst.2000, 13, pp.551-576.
[2] J.B. Carruthers: 'Wireless infrared communications' Wiley Encyclopaedia of Telecommunications, 2002.
[3] N. M. Aldibbiat, Z. Ghassemlooy and R. McLaughlin: 'Indoor optical wireless systems employing dual header pulse interval modulation (DH-PIM)', Intern. J. Communications Systems, 2005, Vol.18, No.3, pp.285-306.
[4] D.C. Lee and J.M. Kahn: 'Coding and equalisation for PPM and wireless infrared channels' IEEE Transactions on communications. 1999, Vol. 47, No. 2
[5] J.G. Proakis: 'Digital Communications' 3rd Edition, McGraw-Hill, Inc. New York 1995.
[6] J.B. Carruthers and J.M. Kahn: 'Modelling of non-directed wireless Infrared channel' IEEE Trans. Commu. 1997, Vol.45, No 10, pp.1260-1267.

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