Abstract—This paper presents an experimental diffuse infrared link employing digital pulse interval modulation (DPIM) scheme. System slot error rate (SER) performance is investigated under a number of ambient light conditions, both with and without optical filtering. Optical filtering was found to give only 1 dB reduction in the average optical power penalty. Practical results for the SER are also compared with the predicted data, shown a good agreement.

Key words: pulse modulation, infrared link, slot error rate, artificial light interference.

I. INTRODUCTION

Infrared (IR) wireless communications have recently emerged as a suitable alternative to radio-frequency transmission for short-range indoor data communications [1-4]. A Diffuse system relies on reflections from the ceiling and other reflectors within a room, and is susceptible to the ambient light noise, high signal attenuation, and intersymbol interference caused by the multipath propagation [5-6]. These factors drive the requirement for emitting high optical power levels. However, IR wireless transceivers are subject to eye safety regulations, which limit the average optical power level that can be emitted. Digital pulse interval modulation (DPIM) is a technique which has been shown to be a good alternative to the more established techniques of on-off keying (OOK) and pulse position modulation (PPM) for wireless infrared communications [7]. In DPIM, each block of $M$ data bits is mapped to one of $L$ DPIM symbols, each different in length, where, $L = 2^M$. Each symbol begins with a pulse, followed by a number of empty slots which is dependent on the decimal value of the data bits for that particular symbol. In order to provide some immunity to the effects of multipath propagation, a guard band consisting of one or more empty slots, may be added to each symbol immediately following the pulse. According to the value of $L$, we’ll refer in this paper to DPIM symbol as $L$-DPIM. Previous papers on DPIM have been mainly on theoretical analysis and computer simulation [8-9]. Here for the first time we present an experimental DPIM system operating at a modest data rate of 2.5 Mb/s. The objective has been to demonstrate hardware implementation rather achieving a very high bit rate. However, the proposed system with minor changes could be adopted for transmission of higher bit rates. The paper is organised as follow; section 2 gives an overview of DPIM system, and section 3 describes the practical link setup used in the experiments. The results and conclusions are given in sections 4 and 5, respectively.

II. DPIM SYSTEM OVERVIEW

A block diagram of the DPIM experimental system is shown in Fig. 1.

The transmitter is comprised of an information source, a DPIM modulator and an optical transmitter. The DPIM modulator encodes data from the information source into 16-DPIM symbols. The circuitry required to perform this task is synthesised on a field programmable gate array (FPGA) device. The slot sequence emerging from the DPIM modulator is passed to an optical transmitter which consists of an array of 12 infrared LEDs, each of which can be enabled or disabled separately such that the optical transmit power can be varied and all are aligned vertically, pointing at the ceiling of the room. The LEDs have a centre wavelength of 875 nm, a viewing angle of $30^\circ$, and are operated such that the specified radiant optical power for each LED is 38 mW. With all 12 LEDs on, the peak optical power of the array is 456 mW, which for 16-DPIM, corresponds to an average optical power of 48 mW. At the receiver, photodetection is carried out by an array of 5 silicon PIN photodiodes connected in parallel. The photodiodes have a spectral range of 400 - 1100 nm, a half angle of 60°, and an active
area of 7 mm², giving a total active area of 35 mm² for
the detector array. The optical front end also contains a
second detector array, identical to the first, which is used
to measure the received photocurrent due to both the
transmitted signal and the ambient light sources. At a
wavelength centred on 875 nm, the photodiodes have a
specified responsivity $R$ of 0.6 A/W. Knowing this, the
measured average photocurrent $I_B$ may be converted into
an average received irradiance $H_{avg}$ with units dBm/cm²
using:

$$H_{avg} = 10 \log_{10} \left( \frac{I^2}{35RI_B} \right)$$

The photocurrent generated by the first photodiode array
is amplified by a transimpedance preamplifier, which is
then followed by an additional gain stage. A two stage
post amplifier is then used to further increase the gain,
resulting in an overall transimpedance of ~12 MΩ. The
AC coupling within the post amplifier forms a high-pass
filter, and was initially tuned to give a cut-on frequency
of ~50 kHz, which is sufficient to reject interference
resulting from fluorescent lamps driven by low-
frequency ballasts, whilst introducing only a negligible
amount of baseline wander [7]. The amplified signal is
then passed to a predetection filter, the fundamental
purpose of which is to increase the likelihood of
successfully detecting pulses in the presence of noise. A
4th order Bessel low pass filter with a cut-off frequency
of 3.6 MHz was used, which was found to give a
performance close to that of a matched filter. A threshold
detector is then used to compare the output of the
predetection filter with a reference voltage level, and
assign a logic one or zero to each slot depending on
whether the signal is above or below the threshold level
at the sampling instant.

The sampling pulses are derived from the transmitter
clock, thereby eliminating the effect of timing jitter from
the results obtained. The output of the threshold detector
is passed to a guard slot circuit, which automatically
assigns a zero to any slot which immediately follows a
pulse. The regenerated DPIM slot sequence is then
compared with the transmitted sequence, and the number
of slots in which the two signals differ is counted.

### III. LINK SETUP

The experimental link was set up in a laboratory with
dimensions 6.85 m x 6.64 m x 2.9 m, with large windows
on two walls facing north and west. The position of the
transmitter and receiver within the room, which was
fixed throughout all the measurements, is shown in Fig.
2.

The horizontal distance between the transmitter and
receiver was 2 m. Both the transmitter and receiver were
situated on benches, pointing vertically upwards towards
the ceiling, i.e. a diffuse configuration. The positioning
of the light sources is shown in Fig. 3.

The room was illuminated by 18 x 36 W ceiling mounted
low-frequency fluorescent lamps, which generated an
average background photocurrent of 17.9 µA at the
receiver location indicated in Fig. 2, when no optical
filter being used. Consequently, the position of the
fluorescent lamp indicated in Fig. 3 was chosen such that
a similar photocurrent was obtained from a single lamp,
thus making the results valid for a typical indoor
environment. Note that the fluorescent lamp was
positioned such that the centre of the tube was on the
transmitter-receiver axis. The position of the
incandescent bulb (B) was chosen to simulate a desk
lamp. The average background photocurrent $I_B$ generated
by these artificial ambient light sources, with and without
the RG780 optical filter, are listed in Table 1, along with
daylight measurements.
The performance of the experimental link was measured in terms of the slot error rate (SER). Measurements were taken under a variety of ambient light conditions, both with and without optical filtering.

The optical transmit power was varied by switching on/off the 12 individual LED drivers. This allowed the average received irradiance, due to the transmitted signal, to be varied between -39.7 and -50.2 dBm/cm². Note that, without optical filtering, the ambient light sources resulted in an average background irradiance which is 29 - 37 dB higher than the maximum average received signal irradiance. For each measurement taken, the threshold level was manually adjusted to minimize the SER.

### IV. RESULTS

For low-frequency electronic ballasts, the detected electrical spectrum contains harmonics which do not extend beyond a few tens of kHz. Consequently, a HPF cut-on frequency of 50 kHz is sufficient to filter out the majority of this interference signal. Note that for a bit rate \( R_b \) of \( \approx 2.5 \) Mbit/s, this corresponds to a normalized cut-on frequency \( f_c/R_b \) of \( \approx 0.02 \), which should introduce virtually no baseline wander power penalty [7]. To achieve this cut-on frequency, the capacitors \( C_1 \) and \( C_2 \) in the post amplifier, shown in Fig. 4, were set to 2.2 nF, giving a cut-on frequency of ~48 kHz.

For each of the ambient light sources listed in Table 1, the SER performance was measured both with and without the optical filter. Plots of SER versus the average received irradiance in the presence of natural and artificial ambient light sources are shown in Figs. 5 and 6, respectively.

With reference to Fig. 5, for the link to achieve an average SER of \( 10^{-5} \) when operating in total darkness, an average received irradiance of -43.4 dBm/cm² is required. When operating in daylight, an average optical power penalty of 1.2 dB is incurred due to the shot noise resulting from the 40 - 50 µA background photocurrent. Whilst the optical filter reduces the background photocurrent by 70% (see Table 1), it only results in a modest 0.2 dB reduction in average optical power penalty. Figure 4 also shows the theoretical SER for an ideal system, limited only by the shot noise resulting from an average background photocurrent of 50 µA. The average optical power requirement of this ideal system is 3.2 dB less than the value obtained for the experimental link when operating in daylight with no optical filter. Some of this difference is due to the bandwidth limitations of the transmitter and receiver, and the use of a suboptimum predetection filter. Additionally, in the theoretical analysis we assumed that all other noise sources are negligible when compared with the shot noise, which may not be the case in practice, particularly when considering receiver noise.

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\text{Figure 4: Post amplifier}
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\text{Figure 5: SER versus the average received irradiance in the presence of natural light with } f_c \approx 48 \text{ kHz}
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In the chosen receiver location, the incandescent bulb generated a background photocurrent which was more than twice that generated in daylight conditions. Consequently, an increased amount of shot noise is generated which, with reference to Fig. 6, results in a 2.3 dB average optical power penalty compared with the darkness case.
whilst optical filtering does reduce the background photocurrent by 34% (see Table 1), the error performance of the link using the optical filter is almost identical to that achieved without it. It is worth noting that along with attenuating the background photocurrent, the optical filter also attenuates the signal photocurrent slightly. This attenuation has been measured to be ~1.4 dB. Figure 7 shows the measured eye diagrams of the signal at the predetection filter output for the case of incandescent bulb with no optical filtering.

V. CONCLUSIONS

The performance of an experimental 2.5 Mbps 16-DPIM diffuse infrared link has been examined under a variety of ambient light conditions. An electrical high pass filter with cut-off frequency of 48 kHz, which corresponds to a normalized delay spread of ~0.02, was found to be sufficient to reject the interference signal from all the artificial ambient light sources. Using this cut-off frequency, an average received irradiance of -43.4 dBm/cm² is required to achieve a SER of 10⁻⁵ when operating in darkness, and average optical power penalties in the range 1.2 – 2.3 dB are incurred when operating in the presence of daylight, an incandescent bulb or a low-frequency fluorescent lamp. Optical filtering was found to give a 1 dB reduction in the average optical power penalty.

REFERENCES