Indoor Optical Wireless Communication Systems – Part I: Review

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1.1 Introduction

The emergence of portable computing devices such as laptops, palmtops and personal digital assistants (PDAs) has fuelled the demand for mobile connectivity and hence, led to the development of wireless local area networks (LANs). Wireless LANs offer users increased mobility and flexibility compared with traditional wired networks, and may be classified as either infrastructure wireless or ad hoc wireless networks [1]. Untethered from conventional network connections, infrastructure wireless LANs allow users to maintain network connectivity whilst roaming anywhere within the coverage area of the network. This configuration requires the use of access points, or base stations, which are connected to the wired LAN and act as interfaces to the wireless devices. Each access point may accommodate multiple clients. Examples of practical applications for wireless infrastructure LANs which are often cited include medical professionals accessing patient records, real-time vital signs and other reference data at the patient bedside, and factory floor workers accessing part specifications and process information as and when required. In contrast, ad hoc wireless LANs are simple peer-to-peer networks in which each client only has access to the resources of the other clients on the network and not a central server. Ad hoc wireless LANs require no administration or pre-configuration, and are created on demand only for as long as the network is needed. Examples of practical applications for wireless ad hoc LANs include employees sharing information during a meeting, and colleagues electronically swapping business cards.

The term wireless is synonymous with radio, and there are numerous radio LAN products on the market today. The majority of these products operate in the industrial, scientific and medical (ISM) band located at 2.4 GHz, which has the advantage of being licence free in most countries. However, the available bandwidth is limited to 83.5 MHz, and must be shared with numerous other products on the market such as cordless telephones and baby monitors. Consequently, robust spread spectrum modulation techniques are required, which result in low data rates. As an example, the IEEE 802.11-1997 standard for wireless LANs specifies two radio physical layers for operation in the 2.4 GHz ISM band. These two physical layers use frequency-hopping spread spectrum (FHSS) and direct sequence spread spectrum (DSSS), and offer maximum user data rates of just 2 Mbit/s [2]. This was improved upon in 1999 with the ratification of IEEE 802.11b, which adds two higher data rates of 5.5 Mbit/s and 11 Mbit/s to the DSSS standard [3]. Many of the products currently on the market today are either based on this standard, or the Home RF standard, which also operates in the 2.4 GHz ISM band, and achieves a maximum data rate of 10 Mbit/s using FHSS [4]. The next generation of radio LAN products, which are just starting to emerge, operate in the so-called 5 GHz band, which has been allocated solely for use by wireless LAN products. Consequently, this allows systems to be optimised in terms of data rate and efficiency, free from the constraints associated with coexisting with other products. There are currently two competing standards in this band, these being IEEE 802.11a and HiperLAN2, both of which specify maximum data rates of 54 Mbit/s [5, 6]. One final radio LAN standard worthy of a mention is Bluetooth, which is a short range, point-to-multipoint standard for voice and data transfer, which again operates in the 2.4 GHz ISM band [7]. Whilst standard class 2 devices have an expected operating range of just 10 metres, and a maximum asymmetric data rate of a mere 723.2 kbit/s, the rationale behind bluetooth is low cost, allowing it to be integrated into a variety of portable electronic devices which may then communicate with each other via ad hoc wireless networks termed piconets. Products equipped with Bluetooth are just starting to appear on the market.

Along with radio, the term wireless is also applicable to systems which utilise other regions of the electromagnetic spectrum, such as infrared. First proposed as a medium for short-range wireless communication more than two decades ago [8, 9], infrared offers a number of advantages over its radio frequency counterpart, such as [10]:

- Abundance of unregulated bandwidth: *200 THz in the 700-1500 nm range*
- No multipath fading: *intensity modulation and direct detection*
- High security
- Higher capacity per unit volume (bps/m3): *due to neighbouring cells sharing the same frequency*
- Cost effective at rates near 100 Mbps
- Small cell size
- At 800-890 nm and 1550 nm absorption effects are minimal.

To an extent, radio and infrared may be viewed as complementary rather than competitive media. For example, if a wireless LAN is required to cover a large area, where users can roam freely and remain connected to the network at all times, then radio is the only cost-effective medium which can achieve this. If, however, a wireless LAN is required to cover a more modest area, but deliver advanced bandwidth-hungry multimedia network services such as video conferencing and video on demand, then infrared is the only medium which truly has the bandwidth available to deliver this. The comparison between radio and infrared for indoors wireless communications is shown in Table 1.1

Table 1.1: Properties of radio and infrared wireless

Property	**Radio**	**Infrared**	**Implication for infrared**
Bandwidth regulated	Yes	No	Approval not required World-wide compatibility
Passes through walls	Yes	No	Inherently secure Carrier reuse in adjacent rooms
Multipath fading?	Yes	No	Simple link design
Multipath dispersion	Yes	Yes	Problematic at high data rates
Path loss	High	High	
Dominant noise	Other users	Background light	Short range
Average power proportional to	$\int \lvert f(t)\rvert^2\, dt$	$\int f(t)\, dt$	$f(t)$ is the input signal with high peak-average ratio

Although, to date, commercially available optical wireless systems have not come close to delivering the high data rates which are potentially available from the infrared medium, the reasons for this are more to do with the limited range, difficultly to operate outdoor, high power requirement and cost constraints rather than any fundamental limitations of the core technology. This is proven by the existence of experimental solid state tracked systems which have been demonstrated operating at 155 Mbit/s [11, 12], which is significantly faster than the latest radio LAN products that are currently emerging. Nevertheless, infrared is a challenging medium and there are numerous considerations which must be taken into account when designing high speed indoor infrared links. Non-directed LOS and diffuse links incur a high optical path loss and must also contend with multipath propagation. Whilst multipath propagation does not result in multipath fading in indoor infrared systems, since detector sizes are huge in comparison with the wavelength, it does give rise to intersymbol interference, which is one of the primary impairments to achieving high speed communication. In addition to this, infrared links must be capable of operating in environments where intense ambient light levels exist, which degrades link performance in two ways. Firstly, the average power of the background radiation generates shot noise in the receiver, which is independent of the transmitted signal, and secondly, artificial sources of ambient light generate a periodic interference signal, which can contain harmonics into the MHz region for fluorescent lamps driven by electronic ballasts [13, 14]. Finally, all these factors must be overcome without breaching eye safety regulations, which place limitations on the maximum optical transmit power which can be used.

This paper aims to provide a general introduction to indoor optical wireless links. In section 1.2, the unique properties of indoor optical wireless links are reviewed, and the constraints imposed on system design are highlighted. Indoor optical wireless links can be configured in a variety of ways, each suitable for different applications. In section 1.3, the various configurations are described, and their advantages and disadvantages discussed. In order to achieve efficient link design, it is imperative that the characteristics of the channel are well understood. A considerable amount of work has been published on channel characterisation, covering both experimental measurement and computer modelling. This work is reviewed in section 1.4. There are a number of considerations which must be taken into account when selecting the optical components of a system. These considerations are discussed in section 1.5. Infrared links usually operate in the presence of intense ambient light emanating from both natural and artificial sources. These ambient light sources are discussed in section 1.6, and measurements taken of various sources are presented. Finally, the chapter is summarised in section 1.7.

1.2 Properties of Indoor Optical Wireless Links

For low-cost optical wireless communication systems, intensity modulation with direct detection (IM/DD) is the only feasible method of communication [10]. In this mode of operation, the intensity or power of the optical source $x(t)$ is directly modulated by varying the drive current. At the receiver, a photodetector is used to generate a photocurrent $y(t)$, which is proportional to the instantaneous optical power incident upon it. An optical wireless system using IM/DD has an equivalent baseband model which hides the high-frequency nature of the optical carrier [15]. This model is illustrated in Fig. 1.1 [10], in which R is the photodetector responsivity and $h(t)$ is the linear baseband channel impulse response.

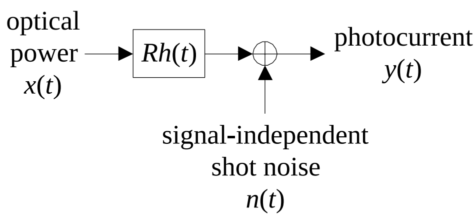


Fig. 1.1: Equivalent baseband model of an optical wireless system using IM/DD

As with radio systems, indoor optical wireless links are subject to multipath propagation, which is most pronounced in links using non-directional transmitters and receivers. For both systems, multipath propagation causes the received electric field to undergo severe amplitude fades on the scale of a wavelength, and consequently, a detector smaller than one wavelength would experience multipath fading. However, infrared wireless receivers have detector areas which are typically millions of square wavelengths, and since the total photocurrent generated is proportional to the integral of the optical power over the entire photodetector surface, this provides an inherent spatial diversity, thus preventing multipath fading [10]. Whilst indoor infrared links are not susceptible to multipath fading, multipath propagation does lead to dispersion, which is modelled as a linear baseband channel impulse response $h(t)$. Linearity follows from the fact that the received signal is comprised of multiple spatial modes [10]. The channel is fixed for a given position of the transmitter, receiver and intervening reflectors, and changes significantly only when any of these are moved by distances in the order of centimeters. Due to the high bit rates under consideration and the relatively slow movement of people and objects within a room, the channel will vary significantly only on the time scale of many bit periods, and therefore may be considered to be time invariant.

Infrared wireless transceivers will usually operate in environments containing an intense amount of ambient light, emanating from both natural (solar) and artificial sources. The average combined power of this background radiation generates a DC photocurrent I_B in the photodetector, giving rise to shot noise $n(t)$, which has a single-sided power spectral density N_o, given as [16]:

$$N_o = 2qI_B\,, \tag{1.1}$$

where q is the electron charge. Even when optical filtering is used to reject out of band light sources, the received signal power is much lower than the power from ambient light sources (typically 25 dB lower [10]). Consequently, I_B is much larger than the maximum photocurrent generated by the signal, and hence, the shot noise may be regarded as white, Gaussian and independent of the received signal [17]. In the presence of intense ambient light, which is usually the case, shot noise is the dominant noise source in a typical diffuse receiver [10]. Note that, if little or no ambient light is present, the dominant noise source is receiver preamplifier noise, which is also signal independent and Gaussian [15]. In addition to contributing to the generation of shot noise, artificial ambient light sources also generate a periodic interference signal, which must be added to $n(t)$.

The equivalent baseband model of an optical wireless link, as illustrated in Fig. 1.1, can be summarised by [15]:

$$y(t) = Rx(t) \otimes h(t) + n(t)\,, \tag{1.2}$$

where R is the photodetector responsivity and the symbol "⊗" denotes convolution. Simply stated, the received photocurrent $y(t)$ is the convolution of the transmitted optical power $x(t)$ with the channel impulse response $h(t)$, scaled by the photodetector responsivity, plus an additive noise $n(t)$. Whilst (1.2) is simply a linear filter channel with additive noise, optical wireless systems differ from conventional electrical or radio systems since $x(t)$ represents power rather than amplitude. This places two constraints on the transmitted signal. Firstly, $x(t)$ must be non-negative, i.e.

$$x(t) \geq 0\,. \tag{1.3}$$

Secondly, eye safety requirements limits the maximum optical transmit power which may be employed. Generally, it is the average power requirement which is the most restrictive and hence, the average value of $x(t)$ must not exceed a specified value P_{max}, i.e. [10]:

$$P_{\max} \geq \lim_{T\to\infty} \frac{1}{2T}\int_{-T}^{T} x(t)\, dt\,. \tag{1.4}$$

This is in contrast to the time averaged value of $|x(t)|^2$, which is the case on conventional channels when $x(t)$ represents amplitude.

These differences have a profound effect on system design. On conventional channels, the signal to noise ratio (SNR) is proportional to the average received power, whereas on optical wireless links, it is proportional to the square of the average received optical signal power; thus implying that relatively high optical transmit powers are required, and only a limited path loss can be tolerated. The fact that the average optical transmit power is limited, suggests that modulation techniques possessing a high peak-to-mean power ratio are favourable. This is generally achieved by trading off power efficiency against bandwidth efficiency. When shot noise is dominant, the SNR is also proportional to the photodetector area. Thus, single element receivers favour the use of large area detectors. However, as the detector area increases so does its capacitance, which has a limiting effect on receiver bandwidth. This is in direct conflict with the increased bandwidth requirement associated with power efficient modulation techniques, and hence, a trade off exists between these two factors.

1.3 Link Configuration

Indoor optical wireless links may be configured in a variety of ways to support a multitude of applications. Street *et. al*. [18] grouped these into four generic system configurations, these being: directed LOS, non-directed LOS, diffuse and tracked, as illustrated in Fig. 1.2.

The directed LOS configuration, illustrated in Fig. 1.2(a), achieves a high power efficiency by utilising narrow beam transmitters and narrow field of view (FOV) receivers. The use of narrow FOV receivers allows optical concentrators to be employed along with thin film optical filters, since the angular dependence of the filter response does not pose a problem. Furthermore, directed LOS systems do not suffer from multipath propagation, and ambient background light is largely rejected. Thus, the potential data rate is limited only by the available power budget rather than multipath dispersion [19]. However, directed LOS links must be pointed prior to use, and require an uninterrupted line of sight path between the transmitter and receiver, thus making them susceptible to blocking. In addition to this, by their very nature, they are more suited to point-to-point links rather than point-to-multipoint broadcast type links, thus reducing their flexibility. Directed LOS is the most well known link topology, and has been used for many years in low bit rate, simplex remote control applications for domestic electrical equipment, such as televisions and audio equipment. Additionally, directed LOS is the chosen configuration for IrDA links [20], which offer simple peer-to-peer networking between portable electronic devices such as laptops, palmtops, PDAs and digital cameras. These devices are specified to operate over a maximum range of 1 metre, and offer data rates from 9.6 kbit/s to 4 Mbit/s [20]. Whilst IrDA transceivers offer wireless connectivity at very low cost, and have found their way into many of the portable electronic devices on the market over the past 5 years or so, they are not widely used. One of the main reason for their lack of uptake is convenience of use, since before products equipped with IrDA serial ports can communicate with one another they must be in close proximity, have line of sight and be roughly aligned. In their current form, IrDA links look destined to loose out to the Bluetooth, which is more convenient to use and offers a similar data rate. A number of experimental links using the directed LOS configuration have been reported [21-23], along with a demonstration of an IEEE 1394 multimedia home network [24].

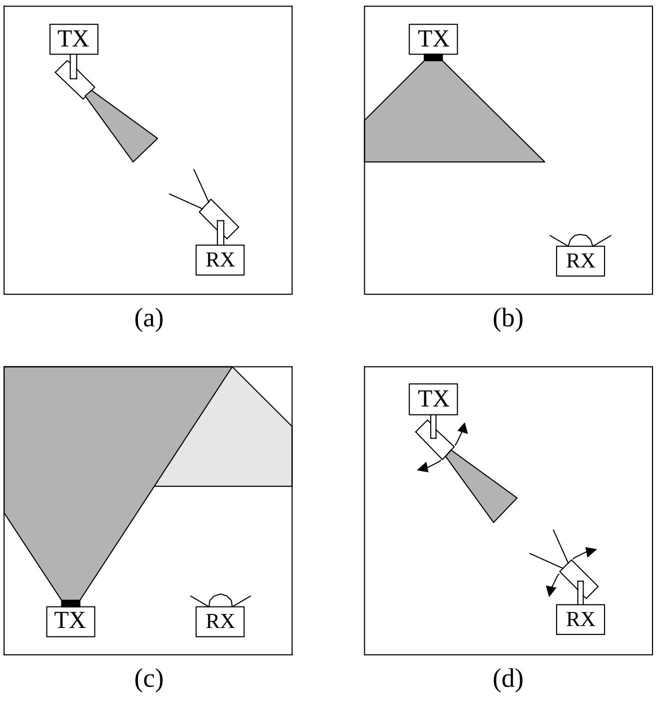


Fig. 1.2: Link configurations: (a) directed LOS, (b) non-directed LOS, (c) diffuse, and (d) tracked

The non-directed LOS configuration, illustrated in Fig. 1.2(b), uses wide beam transmitters and wide FOV receivers to achieve an increased coverage area and alleviate the need for pointing. Compared with the directed LOS configuration, these benefits are achieved at the expense of a reduced irradiance, for a given range and transmit power. The use of wide angle transmitters and receivers means that a portion of the received signal may have undergone one or more reflections from walls and room objects, thus giving rise to multipath propagation. Additionally, since the majority of power incident on the photodetector is due to the LOS path, non-directed LOS links are still prone to blocking. Non-directed LOS links are well suited to point-to-multipoint broadcast type applications. A typical scenario for this link topology would be an infrared access point located on the ceiling of a room, providing connectivity to the portable devices within its coverage area. Computer generated holograms have been proposed as a means of accurately defining the coverage area of nondirected LOS links [25]. By controlling the coverage area, large rooms may be divided into 'optical cells', each serviced by a different infrared access port. Such architecture has been used in experimental systems [26, 27] and proposed for a number of practical applications including telepoints [28], trading desks [29] and desk area networks [30]. An example of a commercial non-directed LOS system is VIPSLAN-10 manufactured by JVC [31]. The system generates a cell radius of up to 10 m, and offers a data rate of 10 Mbit/s, which is shared between the users operating within the cell.

Exhibiting a similar behaviour to that of visible light, infrared signals are absorbed by dark objects, diffusely reflected by light-coloured objects and directionally reflected from shiny surfaces [15]. Such characteristics have given rise to another link configuration referred to as diffuse, in which reflections from room boundaries are relied upon to provide coverage. The diffuse configuration, illustrated in Fig. 1.2(c), was first proposed in 1978 by Gfeller and Bapst [8, 9]. Typically, a diffuse transmitter points vertically upwards towards the ceiling, emitting a wide beam of infrared energy. The receiver has a wide FOV, and collects the signal after it has undergone one or more reflections from the ceiling, walls and room objects. Measurements to determine the reflection coefficient for a variety of materials commonly used in indoor environments were carried out by Gfeller and Bapst [9]. Reflection coefficients were found to range from 0.4 to 0.9, with white plaster walls varying between 0.7 and 0.85 depending on surface texture and angle of incidence. From a users point of view, the diffuse link topology is the most convenient since it does not require any pointing of the transmitter or receiver, nor does it require a LOS path to be maintained. In addition to this, the configuration is also extremely flexible, and can be used for both infrastructure and ad hoc networks [18]. However, along with nondirected LOS links, diffuse links incur a high optical path loss, which is typically 50 - 70 dB for a horizontal separation distance of up to 5 m [32]. The path loss is increased further if a person is standing next to the receiver such that the main signal path is obstructed, a situation referred to as shadowing. In addition to this, diffuse links must also contend with severe multipath propagation. Intersymbol interference limits the maximum unequalized bit rate to ~260 Mbitm/s [9]. Thus, for a coverage volume of 10 x 10 x 3 m, the unequalized bit rate would be limited to ~16 Mbit/s [25]. Nevertheless, to date, the diffuse configuration has received the greatest interest from the research community, and the a number of experimental diffuse links have been reported covering bit rates up to 50 Mbit/s [33-41]. Diffuse is also the chosen link configuration for the IEEE 802.11 infrared physical layer standard [2], and diffuse systems are now commercially available. An example of a commercial diffuse system is the wireless network manufactured by Spectrix Corporation [42]. The system is specified to work over a coverage area of 1000 square feet, and achieves a data rate of 4 Mbit/s, which is shared between all the users within the cell.

For nondirected LOS and diffuse links, rather than using a single element detector, significant performance improvements can be achieved using an angle-diversity receiver, which may be implemented in one of two ways. A non-imaging angle-diversity implementation consists of multiple receiving elements that are oriented in a different directions, each element having its own nonimaging concentrator. The main drawback of this approach is that it can lead to an excessively bulky and costly receiver. A more elegant implementation is the imaging angle-diversity receiver, the so called 'fly-eye receiver' first proposed by Yun and Kavehrad [43], which consists of an imaging optical concentrator (e.g. a lens) with a segmented photodetector array placed at its focal plane. Regardless of the implementation method, the photocurrent generated by each element is amplified separately and may then be processed in a variety of ways, which vary in terms of performance and complexity. Angle-diversity receivers can simultaneously achieve a high optical gain and a wide field of view. By exploiting the fact that unwanted signals are generally received from different directions to that of the desired signal, they can significantly reduce the effects of ambient light noise, co-channel interference and multipath distortion [44]. The performance gains achieved by angle-diversity receivers have been analysed in [45-51]. A further improvement in the power efficiency of diffuse links can be achieved by replacing the single wide-beam diffuse transmitter with a multi-beam transmitter, sometimes referred to as a quasi-diffuse transmitter, which consists of multiple narrow beams pointing in different directions [43]. The performance of diffuse links using multi-beam transmitters and angle-diversity receivers is presented in [43, 44, 52-56]. Details of an experimental 70 Mbit/s link using a multi-beam transmitter and an angle-diversity receiver are given in [54].

The final configuration is the tracked system, illustrated in Fig. 1.2(d), which offers the high power efficiency and potentially high bit rates of directed LOS links, with the increased coverage enjoyed by nondirected LOS systems. In an early experimental tracked system developed by B.T. Labs, which achieved a bit rate of 1 Gbit/s, the tracking was performed using mechanical steerable optics [57]. However, mechanical steerable optics are prohibitively expensive and difficult to miniaturise. Consequently, in the same paper, Wisely et. al. proposed a solid state tracked system, using multi-element transmitter and receiver arrays along with a lens arrangement. Using this arrangement, steering is merely a matter of selecting the appropriate array element. Conceptually, this is similar to the angle-diversity receiver discussed earlier. Solid state tracked systems are analysed in [58, 59], and experimental systems achieving data rates of 34 Mbit/s [60], 100 Mbit/s [61] and 155Mbit/s [11, 12] have been demonstrated. Note that, along with diffuse links using multi-beam transmitters and angle-diversity receivers, tracked systems offer the potential to implement space-division multiplexing, whereby multiple users can communicate without suffering a loss of per-user capacity, since each user is located in a different cell.

Table 1.2: Practical systems reported for indoor applications.

Year	**Type**	**Data rate (b/s)**	**Range (m)**
1978-Gfeller	Non-directed, Non-LOS	125 k	20
1985 – C S Yun *et al*	1st LOS	1 M	50
1987 - T S Chu *et al*	LOS	50 M	30
1992- G Berline *et al*	LOS	4 M	24
1993- JOLT Ltd.	LOS	125 M	30
1995- J R Barry, *et al*	Non-direct LOS	100 M	4
1997- J M Kahn, *et al*	Diffused	50 M	10x10
1998- P F Szajowski, *et al*	DLS at 1550 nm	2.5 G	2.4 km free space
1999- D J Heatley, *et al*	LOS	1 G	a few
2000- Bell lab	LOS (out-door)	10 G	~5 km

1.4 Standards and Eye Safety

There are several "Infrared Data Association" IrDA [62] standards in existence today, covering a wide range of bit rates from 9.6 kb/s to 4Mb/s. However, all links require a LOS and are only specified to work over a one metre range. All IR serial ports found on laptop and palmtop computers are IrDA compliant. IR serial ports are now also found on some digital cameras, personal digital assistants and mobile phones. For IR LANs there exists the IEEE 802.11 standard, which specifies 3 physical layers, two using radio with spread spectrum modulation and one using IR. The IR physical layer specifies optical signals in the 780-950 nm wavelength range, and bit rates of 1 or 2 Mbps using diffuse propagation [2]. However, radiation in this wavelength can be focussed onto the retina, causing thermal damage. Therefore, IR transceivers must conform to inherently safe class 1 of the IEC 825 standard. The eye safety limit is a function of the viewing time, wavelength and apparent size of the optical source. The standard makes a distinction between point sources (which the eye can focus) and large area sources, which form an extended image on the retina. The standard treats laser and LED sources equally. For modulated optical sources, generally, the average power level limits the transmitted optical power. In general, the average power for a pulse train of duration 100s must not exceed the power of a single pulse of duration 100s [63]. Table 1.3 shows the Class 1 power limits for both point and extended sources for a number of important wavelengths [18].

Table 1.3: Class 1 source maximum permissible exposure (MPE) power limits.

Wavelength	**Point source MPE** ($\alpha<\alpha_{min}$ = 0.011 rad, exposure time > 1 s)	**Extended source MPE** ($\alpha>\alpha_{max}$= 0.1 rad, exposure time > 1 s)
850 nm	0.44 mW	$0.8(\alpha_{max}/\alpha_{min})$ mW
980 nm	0.8 mW	$0.8(\alpha_{max}/\alpha_{min})$ mW

Note:
1. α is the angle subtended by the source at measurement point.
2. MPE is equal to power captured by 50 mm diameter aperture 100 mm from the optical detector.

1.5 Review of Channel Characterisation

Detailed characterisation of the indoor optical wireless channel is essential for effective link design. The power penalties directly associated with the channel may be separated into two factors, these being optical path loss and multipath dispersion [64, 65]. For directed LOS and tracked configurations, reflections do not need to be taken into consideration, and consequently the path loss is easily calculated from knowledge of the transmitter beam divergence, receiver size and separation distance. For nondirected LOS and diffuse links, the optical path loss is more complex to predict, since it is dependent on a multitude of factors, such as room dimensions, the reflectivity of the ceiling, walls and objects within the room, and the position and orientation of the transmitter and receiver, to name but a few. In order to predict the path loss for nondirected LOS and diffuse links, it is necessary to analyse the distribution of optical power for a given setup.

Gfeller and Bapst [8] studied the power distribution for diffuse links, basing their model on single reflections only. The authors showed that by using an optical source consisting of multiple elements oriented in different directions, a more uniform coverage can be obtained over a larger area, compared with a single wide-beam optical source. Lomba et. al. [66] addressed the optimization of the optical power distribution for diffuse and nondirected LOS links. Based on this work, the authors proposed a specification for the emitter radiation pattern (ERP) of the IEEE 802.11 infrared physical layer standard [2, 67]. Pakravan and Kavehrad [68] also analysed the optical power distribution for a typical conference room using various link configurations. For nondirected LOS links, as an alternative to adjusting the ERP, several researches have considered using a grid of ceiling mounted transmitters [69-71] in order to reduce the dynamic range of signal power.

Whilst determining the distribution of optical power throughout a room is adequate for basic power budget calculations, it does not allow the power penalty due to multipath propagation to be accurately predicted, since multiple reflections are not taken into consideration. Although the optical power associated with two or more reflections is relatively small, the signal arrives at the receiver much later than that undergoing only one reflection, and hence, cannot be ignored when considering high speed nondirected LOS and diffuse links. In order to generate an impulse response which includes higher order reflections, Barry et. al. [72,73] developed a ray tracing algorithm in which the path loss and time delay for every path containing a given number of reflections are calculated. The algorithm then sums together all contributions to give an overall impulse response. The authors considered empty rectangular rooms and assumed the optical receiver was pointing vertically toward the ceiling. Abtahi et. al. [74] modified this work to consider the effects of furniture and people within the room, and also rooms of irregular shape. Pakravan [68] used a neural network to speed up the algorithm developed by Barry, whereby only a fraction of the total number of points need to be calculated, from which the neural network learns the rest. Lomba et. al. [75] developed a computationally efficient ray tracing algorithm which uses look up tables and progressively decreased resolution to speed up the simulation. Hernandez et. al. also developed a computationally efficient algorithm based on Monte Carlo analysis [76, 77]. A different approach was taken by Carruthers and Kahn [64, 65], who developed the ceiling bounce model based on the claim that realistic multipath infrared channels can be characterised by only two parameters, these being optical path loss and root mean square (RMS) delay spread. The authors adopt a two stage modelling approach: first assuming an infinitely large room, i.e. considering only a single reflection from the ceiling, and than making a correction which takes into account the position of the transmitter and receiver within the room.

Practical channel characterisation was carried out by Kahn et al. [33], who measured channel frequency responses over the range 2-300 MHz using a swept frequency technique. From these measurements the authors computed impulse responses, path losses and RMS delay spreads. Both line of sight and diffuse link configurations were considered, using different receiver locations in 5 different rooms, giving a total of ~100 different channels. Hashemi et. al. [78], measured 8 rooms at various positions and also took measurements for different orientations and rotations of the photodetector, giving a total of 160 frequency response profiles. The authors show that the channel response is not only sensitive to the position of the photodetector, but also its orientation and rotation. Based on this knowledge, the authors proposed the angle-diversity receiver structure described in section 1.3.

1.6 Optical Component Selection

From a commercial point of view, the wavelength band between 780 and 950 nm is currently the best choice for most infrared applications due to the availability of low cost light-emitting diodes (LEDs) and laser diodes (LDs), and because it coincides with the peak responsivity of inexpensive silicon photodetectors [15]. However, electromagnetic radiation in this band can cause damage to the human eye, and is therefore subject to eye safety regulations. The latest version of the most widely adopted standard on laser safety is IEC 825-1 (1993), published by the International Electrotechnical Commission [79]. In European member countries, this standard has been adopted as EN 60825-1 (1993) [63]. The standard contains a number of classifications, the lowest power of which is Class 1, implying that a device is safe under all foreseeable circumstances of use. Class 1 products require no warning labels, and only need to declare the classification in the product literature. The classification limits are dependent on a number of parameters, these being wavelength, apparent source size, pulse duty factor and exposure duration. The standard treats LD and LED sources equally, the only difference being that LDs are generally categorised as point sources, which can be focussed to a small area on the retina, whilst LEDs usually fall under the extended source category, and form a larger image on the retina. Note that products compliant with or merely interoperable under IrDA specifications must be classified as eye safe [80]. In contrast, compliance with the IEEE 802.11 standard does not ensure conformance with eye safety standards [26].

From a power budget point of view, the wavelength band around 1.5 μm would be a much better choice, since the safety standard permits larger optical transmit powers to be used, and as shown in Fig. 1.3, ambient light sources emit less power at these wavelengths. However, the major drawback to operating at such wavelengths is the lack of low cost optoelectronic devices available at present.

The choice of optical source is largely dependent on cost and performance. LEDs benefit from low cost and simple drive circuitry, but suffer from poor electrical-to-optical conversion efficiency, limited bandwidth and broad spectral width (typically 40 nm), which prevents the use of narrow-band optical filtering at the receiver. Consequently, LEDs are generally used in low speed, cost sensitive applications such as IrDA serial ports. In contrast, laser diodes are more expensive than LEDs and require more complicated drive circuitry, but offer a number of advantages such as improved conversion efficiency, wide modulation bandwidth and narrow spectral width, thus making them the obvious choice for high speed links. In terms of eye safety, LEDs are generally supplied in a lensed package and do not require any additional components to make them eye safe. Laser diodes, on the other hand, are essentially point source devices and must be diffused in some way in order to be classified as eye safe. There are a number of methods of achieving this, including the use of computer generated holograms [81, 82] and integrating sphere diffusers [83, 84].

There are two options for the photodetector, these being the positive-intrinsic-negative (PIN) photodiode and the avalanche photodiode (APD). APDs use the avalanche effect to achieve low noise gain, and are well suited to applications where the background radiation is negligible. However, in optical wireless systems where shot noise due to intense ambient light is generally the dominant noise source, the gain of an APD is actually detrimental to performance. Consequently, PIN photodiodes are generally used in optical wireless receivers. Throughout the remainder of this thesis, it is assumed that a PIN photodiode is used.

Optical wireless receivers generally employ some form of optical concentrator in order to increase the effective area of the detector. High gains can be achieved using compound parabolic concentrators, but these devices have a narrow FOV and are therefore limited to use in directed links. Nondirected links generally make use of a hemispherical lens, which achieves a wide FOV and an omnidirectional gain. Optical filtering is also generally used to attenuate the out of band background radiation. Two basic types of optical filter exist, these being long pass and band pass filters. Long pass filters are generally constructed of coloured glass, and pass all wavelengths longer than a specified cut-on wavelength. In conjunction with a silicon PIN photodiode, which typically have a sensitivity range from 400 nm to 1.1 μm, high pass optical filters result in a bandpass response with a spectral width in the order of several hundred nm. In contrast, band pass filters, also referred to as interference filters, are constructed of multiple layers, and can achieve extremely narrow bandwidths. Such filters can be extremely effective when used in conjunction with laser diode sources. However, one of the characteristics of band pass optical filters is that the pass band shifts as the angle of incidence changes. This can therefore result in a narrowing of the FOV, which may be unacceptable in nondirected links. In the experimental systems developed by Kahn et. al., the authors alleviated this problem by bonding the band pass filter to the curved surface of a hemispherical lens [35-37, 42].

1.7 Ambient Light Sources

Artificial sources of ambient light introduce a periodic interference signal in optical wireless receivers which, if ignored, has the potential to degrade link performance. Consequently, knowledge of ambient light sources, both in terms of their optical power spectra and detected electrical spectra, is necessary in order to develop effective methods of mitigating the interference they produce. Moreira et. al carried out extensive measurements of a variety of ambient light sources, and from these measurements, produced a model to describe the interference signal [85, 86]. Boucouvalas also carried out similar measurements, which included a number of consumer products which use infrared transmission [87]. Along with experimental characterisation of ambient light sources, a significant amount of work has been done on analysing the effect of ambient light interference on link performance [13,14,16, 88-93]. This is subject is covered in other chapter.

The three main sources of ambient light are sunlight, incandescent lamps and fluorescent lamps. The optical power spectra of these sources are shown in Fig. 1.3 [15]. Note that the spectra have been scaled to have equal maximum value, and the longer wavelength region of the fluorescent lamp spectrum has been amplified by a factor of 10 in order to make it clearly visible. When present, direct sunlight is typically much stronger than the other two sources, and represents an unmodulated source of ambient light with a very wide spectral width and a maximum power spectral density located at ~500 nm.

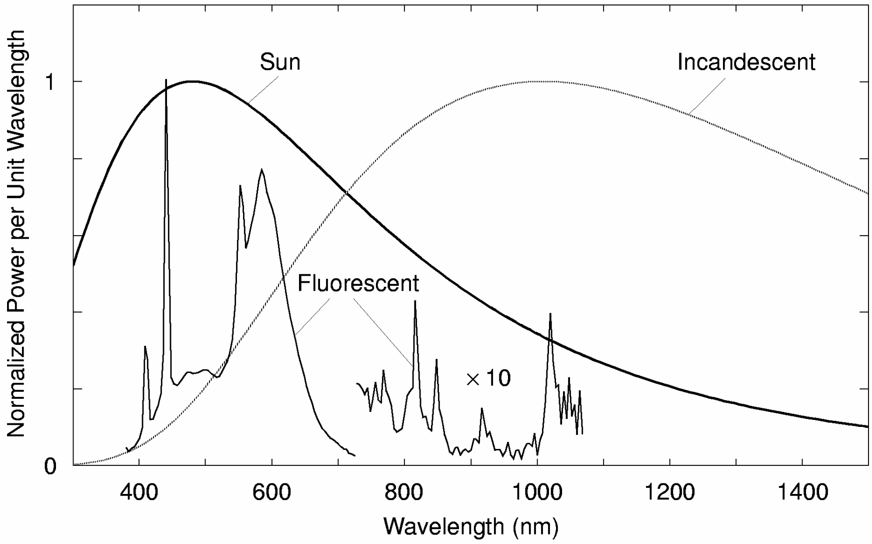


Fig. 1.3: Optical power spectra of common ambient light sources [15]

All artificial ambient light sources are modulated, either by the mains frequency or, in the case of some fluorescent lamps, by a high frequency switching signal. Measurements have been carried out to determine the time-domain waveforms and detected electrical spectra for the ambient light sources listed in Table 1.4.

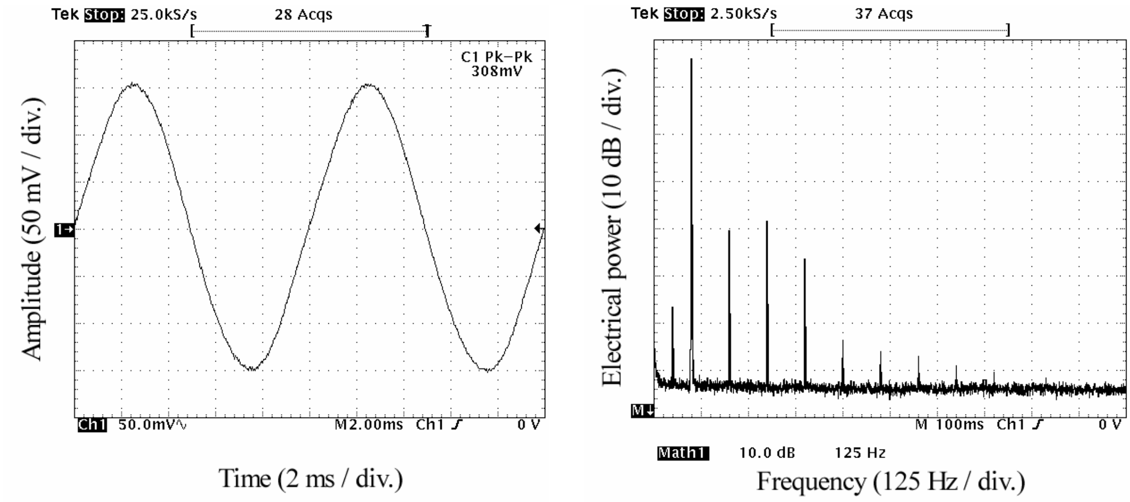
Table 1.4: Artificial ambient light sources

Source	**Details**
Incandescent lamp	Bulb: Osram 60W
Low frequency fluorescent lamp	Ballast: Crompton C237 1 × 75W Tube: Osram L 70W/23
High frequency fluorescent lamp	Ballast: Thorn G81016.4 1 × 70W or 1 × 75W (specified frequency = 35 kHz) Tube: Osram L 70W/23

The measurements were taken using a Thorlabs PDA55 amplified silicon detector, with a transimpedance of 15 kΩ and a 3 dB bandwidth ranging from 25 Hz to 7.9 MHz. For each measurement, the distance between the source and the detector was set such that the average received photocurrent was 100 μA. For the fluorescent lamps, all measurements were taken at the centre of the tube. Additionally, the effects of an RG780 optical long-pass filter were also investigated. The filter passes all wavelengths longer than 780 nm and when combined with the spectral response of the PDA55, results in an optical bandpass response ranging from 780 nm to ~1.1 μm.

1.7.1 Incandescent lamp

Incandescent lamps have a maximum power spectral density around 1 μm, and produce an interference signal which is a near perfect sinusoid with a frequency of 100 Hz. The slow response time of the filament means few harmonics are present. Fig. 1.4. shows the time domain waveform and detected electrical spectrum for the incandescent bulb listed in Table 1.1. No optical filtering was used.



(a) (b)

Fig. 1.4: Incandescent bulb: (a) time domain waveform, and (b) detected electrical spectrum

Only harmonics up to 400 Hz carry a significant amount of power, and beyond that, all harmonics are more than 60 dB below the fundamental. The average received photocurrent I_B and peak-to-peak interference signal photocurrent I_{pk-pk} are given in Table 1.5, with and without optical filtering.

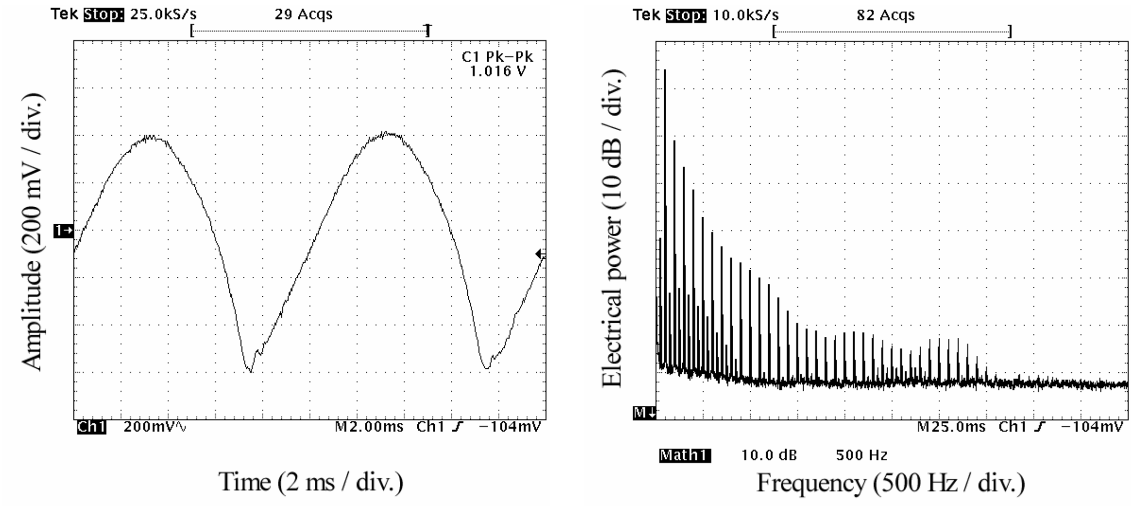
Table 1.5: I_B and I_{pk-pk} for incandescent bulb with and without optical filtering

	Without optical filter	**With optical filter**	**Reduction**
I_B	100 μA	20.5 μA	79.5 %
I_{pk-pk}	65.2 μA	12 μA	81.6 %
I_B/I_{pk-pk}	1.53	1.71	

When optical filtering is used, I_B is reduced by 79.5 %, and the peak-to-peak amplitude of the interference signal is reduced by 81.6 %. The ratio of I_B / I_{pk-pk} is fairly similar both with and without optical filtering.

1.7.2 Fluorescent lamp driven by conventional ballast

Low frequency fluorescent lamps are driven by the mains frequency. The interference signal is a distorted 100 Hz sinusoid, and the electrical spectrum contains harmonics into the tens of kHz. Figure 1.5 shows the time domain waveform and detected electrical spectrum for the low-frequency fluorescent lamp listed in Table 1.4. No optical filtering was used.



(a) (b)

Fig. 1.5: Low-frequency fluorescent lamp:
(a) time domain waveform, and (b) detected electrical spectrum

The average received photocurrent and peak-to-peak interference signal photocurrent, with and without optical filtering, are given in Table 1.6.

Table 1.6: I_B and I_{pk-pk} for low-frequency fluorescent lamp with and without optical filtering

	Without optical filter	**With optical filter**	**Reduction**
I_B	100 μA	5.4 μA	94.6 %
I_{pk-pk}	67.7 μA	9.6 μA	85.8 %
I_B/I_{pk-pk}	1.48	0.56	

Optical filtering gives a significant reduction in both the average background photocurrent and the peak-to-peak interference amplitude. Since the reduction in I_B is greater than the reduction in I_{pk-pk}, with the optical filter in place, the peak-to-peak variation of the photocurrent is actually greater than the average background photocurrent.

1.7.3 Fluorescent lamp driven by electronic ballast

In recent years, fluorescent lamps have been introduced which are driven by high frequency electronic ballasts. This type of lamp has a number of advantages over its low frequency counterpart, such as a reduced electrical power consumption for a given level of illumination and increased life-expectancy of the tubes. The actual switching frequency used varies from one manufacturer to another, but is typically in the range 20 - 40 kHz. The detected electrical spectrum contains harmonics of the switching frequency and also harmonics of the mains frequency, similar to low frequency fluorescent lamps. Harmonics of the switching frequency can extend into the MHz range, and therefore present a much more serious impairment to optical wireless receivers [13]. Figure 1.6 shows the time-domain waveform and detected electrical spectrum for the high frequency fluorescent lamp listed in Table 1.4.

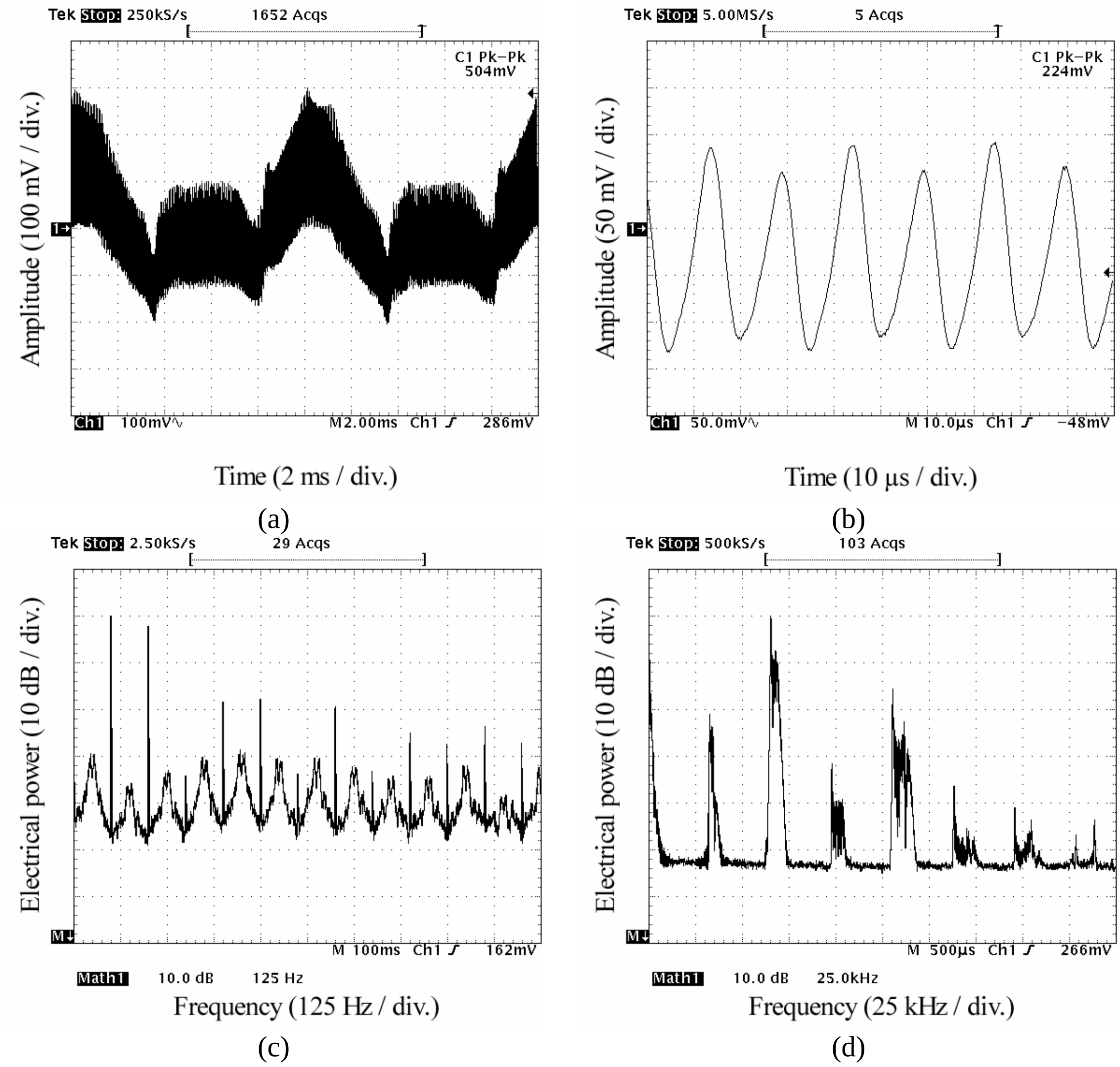


Fig. 1.6: HF fluorescent lamp:
time domain waveform: (a) low frequency component, (b) high frequency component and
detected electrical spectrum: (c) low frequency component, (d) high frequency component

The average received photocurrent and peak-to-peak interference signal photocurrent, with and without optical filtering, are given in Table 1.7.

Table 1.7: I_B and I_{pk-pk} for high-frequency fluorescent lamp with and without optical filtering

	Without optical filter	**With optical filter**	**Reduction**
I_B	100 μA	3.9 μA	96.1 %
I_{pk-pk}	33.6 μA	4.9 μA	85.4 %
I_B/I_{pk-pk}	2.98	0.80	

Without optical filtering, for a given background photocurrent, the interference amplitude produced by the high frequency fluorescent lamp is only about half that produced by the low frequency fluorescent lamp. Optical filtering gives a similar reduction in I_B and I_{pk-pk} as it did for the low frequency fluorescent lamp.

1.8 Modulation Schemes

At low frequencies, generally below 100 kHz, noise and interference from ambient light dominates receiver performance. For this reason, base-band data transmission is not considered adequate to ensure stable signal transmission. Therefore, modulation of some kind needs to be employed in order to shift the spectrum beyond a few hundred Hertz. There are many different types of modulation schemes, which are suitable for IR communication systems each with its particular advantages and disadvantages. Since the average optical power emitted by an IR transceiver is limited, the performance of modulation techniques is compared in terms of the average received optical power required to achieve a desired bit error rate at a given data rate.

1.8.1 On-and-off Keying (OOK)

Of all the various modulation schemes for IM/DD, OOK is the simplest, in which a zero and one are represented by zero intensity and some positive intensity, respectively. OOK can use either non-return-to-zero (NRZ) or return-to-zero (RZ) pulses. With OOK-RZ, the pulse duration is lower than the bit duration (see Fig. 1.7), giving an improvement in power efficiency over OOK-NRZ at the expense of an increased bandwidth requirement. The detailed performance analysis of OOK on AWGN channel can be found in [9, 15, 16, 94] OOK has found use in commercial IR systems such as IrDA links operating below 4Mbps. In these links, return-to-zero-inverted (RZI) signalling is used, in which a pulse represents a zero rather than a one. At bit rates ≤ 115.2 kb/s, the pulse duration is nominally 3/16 of the bit duration, whereas, for data rate of 576 kb/s and 1.152 Mb/s the pulse duration is nominally ¼ of the bit duration [95].

1.8.2 Pulse Position Modulation (PPM)

OOK keying is unable to provide the power efficiency required by many optical wireless applications. But there are alternative modulation schemes, better known as pulse modulation techniques, see Fig. 1.7, which offer an improvement in power efficiency at the cost of relatively poor bandwidth efficiency. One such a technique is known as pulse position modulation (PPM), in which M data bits are mapped to one of L possible symbols, where $L = 2^M$, see Fig. 1.7. Each symbol consists of a pulse occupying one slot and L-1 empty slots. The information is encoded by the position of the pulse within the symbol. By increasing the number of bits per symbol the power efficiency of the code is improved at the expense of bandwidth efficiency. PPM has been used widely in IR communication systems and is adopted for the IEEE 802.11 infrared physical layer standard. [6] It is also used in IrDA serial data links operating at 4Mbps [95]. There are several types of PPM, such as differential PPM, multiple PPM and overlapping PPM. In addition to these, coded schemes such as convolutional-coded PPM and trellis-coded overlapping PPM also exists each with their own advantages and disadvantages as outlined in [96, 97]. Compared with OOK, PPM does increase system complexity since both slot and symbol synchronizations are required in the receiver.

1.8.3 Digital Pulse Interval Modulation (DPIM)

In each PPM symbol, the empty slots following a pulse are essentially redundant, and it is this redundancy which is removed when adopting digital pulse interval modulation (DPIM). In DPIM, information is encoded by varying the number of empty slots between adjacent pulses [98, 99]. As with L-PPM, L-DPIM maps each block of $M = \log_2 L$ input bits to one of L possible symbols, see Fig. 1.7. Unlike L-PPM however, symbol durations are variable and determined by the information content of each particular 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. Thus, each symbol consists of a pulse of constant power with duration ≤ one slot, followed by k slots of zero power, where $1 \le k \le L$. The minimum and maximum symbol duration are $2T_s$ and $(L + 1)T_s$, respectively. In L-PPM each symbol has a fixed duty cycle of $1/L$, whereas in L-DPIM symbols have a variable duty cycle, the average of which is higher than $1/L$. Consequently, for a fixed value of L, DPIM has a higher average power requirement compared with PPM. In L-PPM, the slot rate is given as $R_S = LR_b / M$, where R_b is the OOK bit rate. In L-DPIM, there are two options for the slot rate, as discussed in the following sections.

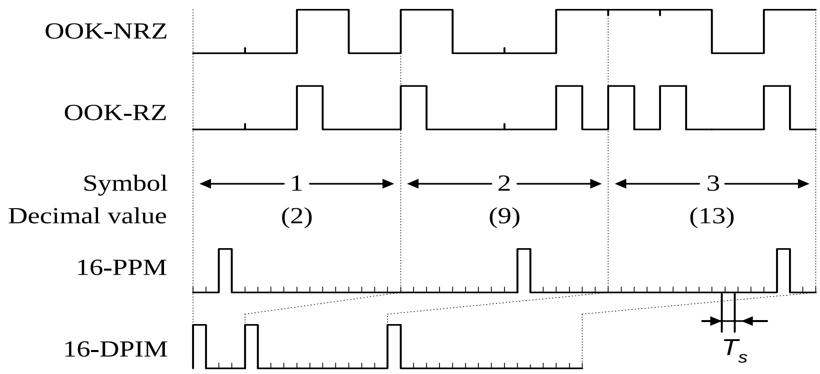


Fig. 1.7: OOK, PPM and DPIM modulation schemes.

1.9 Summary

There are a variety of ways in which indoor optical wireless links may be configured, each offering suitability for different applications. In terms of system design, the limitations directly imposed by the channel, such as path loss and dispersion, are largely dependent on the chosen link configuration. For example, directed links have a small path loss and do not suffer from multipath propagation. However, in order to achieve a degree of mobility, it is necessary to use a tracked configuration, which greatly increases the cost and complexity of the system. In contrast, nondirected links offer some mobility without increasing system complexity, but must overcome high path loss and multipath propagation.

When deployed in a typical indoor environment, optical wireless links are required to operate in the presence of intense ambient light. Along with contributing to the generation of shot noise, artificial sources of ambient light also introduce a periodic interference signal in optical wireless receivers. Of all the artificial ambient light sources, fluorescent lamps driven by electronic ballasts are potentially the most detrimental to system performance, since their detected electrical spectrum can contain harmonics into the MHz region. The extent to which ambient light sources affect link performance is also dependent, to a degree, on the chosen link configuration. Due to the directional nature of their transmitters and receivers, directed links can reject much of the background radiation, whilst nondirected links are more susceptible.

Irrespective of the chosen link configuration, the indoor optical wireless channel is unique, combining the filtered Gaussian noise characteristics of conventional wire based channels with the IM/DD constraints of fibre-optic systems [10]. From a system design point of view, the diffuse configuration suffers the most severe channel parameters and consequently presents the greatest challenge to achieving robust, high speed communication.

1.8 Reference:

[1] F. Halsall, *Data Communications, Computer Networks and Open Systems*, Fourth Edition. Addison-Wesley, 1996.

[2] IEEE Standard 802.11-1997, Institute of Electrical and Electronics Engineers, 18 November 1997.

[3] IEEE Standard 802.11b-1999, Institute of Electrical and Electronics Engineers, 20 January 2000.

[4] L. Chinitz, “HomeRF technical overview,” HomeRF Technical Committee, 9 May 2001, http://www.homerf.org/data/events/past/pubseminar_0501/tech_overview.pdf.

[5] IEEE Standard 802.11a-1999, Institute of Electrical and Electronics Engineers.

[6] M. Johnsson, "HiperLAN/2 - the broadband radio transmission technology operating in the 5 GHz frequency band," HiperLAN/2 Global Forum, 1999.

[7] Bluetooth Specification, Version 1.1, 22 February 2001.

[8] F. R. Gfeller, H. R. Muller and P. Vettiger, "Infrared communication for in-house applications," in *Proceedings of IEEE Conference on Computer Communication*, Washington DC, U.S.A., 5-8 September 1978, pp. 132-138.

[9] F. R. Gfeller and U. H. Bapst, "Wireless in-house data communication via diffuse infrared radiation," Proceedings of the IEEE, vol. 67, no. 11, pp. 1474-1486, November 1979.

[10] J. R. Barry, *Wireless Infrared Communications*. Kluwer Academic, 1994.

[11] J. Bellon, M. J. N. Sibley, D. R. Wisely and S. D. Greaves, "Hub architecture for infra-red wireless networks in office environments," IEE Proceedings – Optoelectronics, vol. 146, no. 2, pp. 78-82, April 1999.

[12] V. Jungnickel, T. Haustein, A. Forck and C. von Helmolt, "155Mbit/s wireless transmission with imaging infrared receiver," Electronics Letters, vol. 37, no. 5, pp. 314-315, March 2001.

[13] A. J. C. Moreira, R. T. Valadas and A. M. de Oliveira Duarte, "Performance of infrared transmission systems under ambient light interference," IEE Proceedings - Optoelectronics, vol. 143, no. 6, pp. 339-346, December 1996.

[14] R. Narasimhan, M. D. Audeh and J. M. Kahn, "Effect of electronic-ballast fluorescent lighting on wireless infrared links," IEE Proceedings - Optoelectronics, vol. 143, no. 6, pp. 347-354, December 1996.

[15] J. M. Kahn and J. R. Barry, "Wireless infrared communications," Proceedings of the IEEE, vol. 85, no. 2, pp. 265-298, February 1997.

[16] A. J. C. Moreira, A. M. R. Tavares, R. T. Valadas and A. M. de Oliveira Duarte, "Modulation methods for wireless infrared transmission systems: performance under ambient light noise and interference," in *Proceedings of SPIE Conference on Wireless Data Transmission*, Philadelphia, U.S.A., 23-25 October 1995, vol. 2601, pp. 226-237.

[17] E. A. Lee and D. G. Messerschmitt, *Digital Communication*, Second Edition. Kluwer Academic, 1994.

[18] A. M. Street, P. N. Stavrinou, D. C. O'Brien and D. J. Edwards, "Indoor optical wireless systems – a review," Optical and Quantum Electronics, vol. 29, pp. 349-378, 1997.

[19] P. P. Smyth, P. L. Eardley, K. T. Dalton, D. R. Wisely, P. McKee and D. Wood, "Optical wireless: a prognosis," in *Proceedings of SPIE Conference on Wireless Data Transmission*, Philadelphia, U.S.A., 23-25 October 1995, vol. 2601, pp. 212-225.

[20] Serial Infrared Physical Layer Specification, Version 1.4, Infrared Data Association, 30th May 2001.

[21] C. S. Yen and R. D. Crawford, "The use of directed optical beams in wireless computer communications," in *Proceedings of IEEE Global Communications Conference*, New Orleans, U.S.A., 2-5 December 1985, pp. 1181-1184.

[22] T. S. Chu and M. J. Gans, "High speed infrared local wireless communication," IEEE Communications Magazine, vol. 25, no. 8, pp. 4-10, August 1987.

[23] L. B. Ribeiro, "Point-to-point optical wireless network for factory communications," in *Proceedings of International Symposium on Industrial Electronics*, vol. 1, pt. 1, Guimaraes, Portugal, 7-11 July 1997, pp. 103-105.

[24] J. I. Matsuda, T. Nyu, T. Saito and S. Yamazaki, "125 Mbps IR wireless link for IEEE 1394 multimedia home network," in *Proceedings of European Conference on Optical Communication*, Madrid, Spain, 20-24 September 1998, pp. 343-344.

[25] P. P. Smyth, M. McCullagh, D. Wisely, D. Wood, S. Ritchie, P. Eardley and S. Cassidy, "Optical wireless local area networks - enabling technologies," BT Technology Journal, vol. 11, no. 2, pp. 56-64, April 1993.

[26] M. J. McCullagh, D. R. Wisely, P. L. Eardley and P. P. Smyth, "A 50 Mbit/s optical wireless LAN link using novel optical and electronic enabling technologies," in *International Zurich Seminar on Digital Communications*, Zurich, Switzerland, 1994, pp. 298-309.

[27] M. J. McCullagh and D. R. Wisely, “155 Mbit/s optical wireless link using a bootstrapped silicon APD receiver,” Electronics Letters, vol. 30, no. 5, March 1994.

[28] P. Nicholls, S. D. Greaves and R. T. Unwin, “Optical wireless telepoint,” in *Proceedings of IEE Colloquium on Optical Free Space Communication Links*, London, U.K., 19 February 1996, pp. 4/1-4/6.

[29] D. J. T. Heatley, I. B. Cockburn, F. T. Lyne, A. K. Williamson, K. J. Fisher, I. Neild and N. Haque, “Concept 2010 – BT’s new generation dealing desk,” BT Technology Journal, vol. 14, no. 4, October 1997.

[30] D. J. T. Heatley and I. Neild, “Optical wireless - the promise and the reality,” in *Proceedings of IEE Colloquium on Optical Wireless Communications*, London, U.K., 22 June 1999, pp. 1/1-1/6.

[31] JVC VIPSLAN-10, JVC Professional Products (UK) Ltd., London.

[32] J. M. Kahn, W. J. Krause and J. B. Carruthers, “Experimental characterization of non-directed indoor infrared channels,” IEEE Transactions on Communications, vol. 43, no. 2/3/4, pp. 1613-1623, February/March/April 1995.

[33] T. H. Tsaur, K. C. Chen, C. Lien, M. T. Shih and C. P. J. Tzeng, “A nondirective infrared transceiver for indoor high speed wireless data communication,” IEEE Transactions on Consumer Electronics, vol. 40, no. 1, pp. 20-27, February 1994.

[34] J. R. Barry and J. M. Kahn, “Design of non-directed infrared links for high-speed wireless networks,” in *Proceedings of the 7th Annual Meeting of the IEEE Lasers and Electro-Optic Society*, Boston, U.S.A., 31 October – 3 November 1994.

[35] G. W. Marsh and J. M. Kahn, “50-Mb/s diffuse infrared free-space link using on-off keying with decision feedback equalisation,” IEEE Photonics Technology Letters, vol. 6, no. 10, pp. 1268-1270, October 1994.

[36] G. W. Marsh and J. M. Kahn, “Performance evaluation of experimental 50-Mb/s diffuse infrared wireless link using on-off keying with decision-feedback equalisation,” IEEE Transactions on Communications, vol. 44, no. 11, pp. 1496-1504, November 1996.

[37] D. Roviras, M. Lescure, R. Bensalah and T. Bosch, “Wireless infrared factory network for hand-held terminals,” European Transactions on Telecommunications, vol. 6, no. 2, pp. 207-217, March/April 1995.

[38] A. M. R. Tavares, A. J. C. Moreira, C. R. A. T. Lomba, L. M. V. Moreira, R. J. M. T. Valadas and A. M. de Oliveira Duarte, “Experimental results of a 1Mbps IR transceiver for indoor wireless local area networks,” in *5th International Conference on Advances in Communication and Control*, Crete, Greece, 26-30 June 1995, pp. 717-727.

[39] R. Valadas, A. Moreira, C. Oliveira, L. Moreira, C. Lomba, A. Tavares and A. M. de Oliveira Duarte, “Experimental results of a pulse position modulation infrared transceiver,” in *Proceedings of the 7th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Taipei, Taiwan, 15-18 October 1996, pp. 252-256.

[40] P. Nicholls, R. T. Unwin and K. T. Dalton, “A 10 MB/s optical wireless ethernet – practical results,” in *Proceedings of SPIE Conference on Wireless Data Transmission*, Philadelphia, U.S.A., 23-25 October 1995, vol. 2601, pp. 294-304.

[41] D. C. Lee and J. M. Kahn, “Experimental 25-Mb/s wireless infrared link using 4-PPM with scalar decision-feedback equalization,” in *Proceedings of IEEE International Conference on Communications*, Atlanta, U.S.A., 7-11 June 1998, pp. 26-30.

[42] Spectrix Wireless Network, Technical Overview, Spectrix Corporation, 30 November 2000, http://www.spectrixcorp.com/techoverview.pdf.

[43] G. Yun and M. Kavehrad, “Spot diffusing and fly-eye receivers for indoor infrared wireless communications,” in *Proceedings of the 1992 IEEE Conference on Selected Topics in Wireless Communications*, Vancouver, Canada, 25-26 June 1992, pp. 286-292.

[44] J. M. Kahn, P. Djahani, A. G. Weisbin, K. T. Beh, A. P. Tang and R. You, “Imaging diversity receivers for high-speed infrared wireless communication,” IEEE Communications Magazine, vol. 36, no. 12, pp. 88-94, December 1998.

[45] R. T. Valadas and A. M. de Oliveira Duarte, “Sectored receivers for indoor wireless optical communication systems,” in *Proceedings of the 5th IEEE International*

Symposium on Personal, Indoor and Mobile Radio Communications, The Hague, Netherlands, 21-23 September 1994, pp. 1090-1095.

[46] C. R. A. T. Lomba, R. T. Valadas and A. M. de Oiveira Duarte, "Sectored receivers to combat the multipath dispersion of the indoor optical channel," in *Proceedings of the 6th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Toronto, Canada, 27-29 September 1995, pp. 321-325.

[47] A. M. R. Tavares, R. J. M. T. Valadas and A. M. de Olveira Duarte, "Performance of an optical sectored receiver for indoor wireless communication systems in presence of artificial and natural noise sources," in *Proceedings of SPIE Conference on Wireless Data Transmission*, Philadelphia, U.S.A., 23-25 October 1995, vol. 2601, pp. 264-273.

[48] R.T. Valadas, A.R. Tavares and A.M. de Olveira Duarte, "Angle diversity to combat the ambient noise in indoor optical wireless communication systems," International Journal of Wireless Information Networks, vol. 4, no. 4, pp. 275-288, 1997.

[49] K. L. Sterckx, J. M. H. Elmirghani and R. A. Cryan, "Pyramidal fly-eye detection antenna for optical wireless systems," in *Proceedings of IEE Colloquium on Optical Wireless Communications*, London, U.K., 22 June 1999, pp. 5/1-5/6.

[50] K. L. Sterckx, J. M. H. Elmirghani and R. A. Cryan, "Sensitivity assessment of a three-segment pyramidal fly-eye detector in a semidisperse optical wireless communication link," IEE Proceedings - Optoelectronics, vol. 147, no. 4, pp. 286–294, August 2000.

[51] K. L. Sterckx, J. M. H. Elmirghani and R. A. Cryan, "Three-segment pyramidal fly-eye detection antenna for optical wireless communication systems under the constraint of ambient noise introduced by highly directive spotlights," International Journal of Communication Systems, vol. 13, no. 7 & 8, pp. 577-588, November-December 2000.

[52] A. P. Tang, J. M. Kahn and K. P. Ho, "Wireless infrared communication links using multi-beam transmitters and imaging receivers," in *Proceedings of IEEE International Conference on Communications*, Dallas, U.S.A., 23-27 June 1996, pp. 180-186.

[53] S. Jivkova and M. Kavehrad, "Indoor wireless infrared local access, multi-spot diffusing with computer generated holographic beam-splitters," in *Proceedings of IEEE International Conference on Communications*, Vancouver, Canada, 6-10 June 1999, vol. 1, pp. 604-608.

[54] J. B. Carruthers and J. M. Kahn, "Angle diversity for nondirected wireless infrared communication," IEEE Transactions on Communications, vol. 48, no. 6, pp. 960-969, June 2000.

[55] S. Jivkova and M. Kavehrad, "Multispot diffusing configuration for wireless infrared access," IEEE Transactions on Communications, vol. 48, no. 6, pp. 970-978, June 2000.

[56] P. Djahani and J.M. Kahn, "Analysis of infrared wireless links employing multi-beam transmitters and imaging diversity receivers," IEEE Transactions on Communications, vol. 48, no. 12, pp. 2077-2088, December 2000.

[57] D. R. Wisely, "A 1Gbit/s optical wireless tracked architecture for ATM delivery," in *Proceedings of IEE Colloquium on Optical Free Space Communication Links*, London, U.K., 19 February 1996, pp. 14/1-14/7.

[58] A. M. Street, K. Samaras, D. C. O'Brien and D. J. Edwards, "High speed wireless IR-LANs using spatial addressing," in *Proceedings of the 8th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Helsinki, Finland, 1-4 September 1997, pp. 969-973.

[59] E. B. Zyambo, D. C. O'Brien, G. E. Faulkner and D. J. Edwards, "Design of a high speed wireless LAN at long wavelengths," in *Proceedings of SPIE Conference on Optical Wireless Communications III*, Boston, U.S.A., 7 November 2000, vol. 4214, pp. 115-124.

[60] F. Parand, G. E. Faulkner, D. C. O'Brien and D. J. Edwards, "A cellular optical wireless system demonstrator," in *Proceedings of IEE Colloquium on Optical Wireless Communications*, London, U.K., 22 June 1999, pp. 12/1-12/6.

[61] D. Wisely and I. Neild, "A 100Mbit/s tracked optical wireless telepoint," in *Proceedings of the 8th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Helsinki, Finland, 1-4 September 1997, pp. 964-968.

[62] IrDA URL: http://www.irda.org/

[63] BS EN 60825-1 : 1994 Standard, British Standards Institution, Issue 3, June 1997.

[64] J. B. Carruthers and J. M. Kahn, "Modeling of nondirected wireless infrared channels," in *Proceedings of IEEE International Conference on Communications*, Dallas, U.S.A., 23-27 June 1996, vol. 2, pp. 1227-1231.

[65] J. B. Carruthers and J. M. Kahn, "Modeling of nondirected wireless infrared channels," IEEE Transactions on Communications, vol. 45, no. 10, pp. 1260-1268, October 1997.

[66] C. R. A. T. Lomba, R. T. Valadas and A. M. de Oliveira Duarte, "Propagation losses and impulse response of the indoor optical channel: a simulation package," Document IEEE P802.11-93/78, IEEE, May 1993.

[67] C. R. A. T. Lomba, R. T. Valadas and A. M. de Oliveira Duarte, "Radiation pattern specification for the baseband IR PHY," Document IEEE P802.11-94/173, IEEE, August 1994.

[68] M. R. Pakravan and M. Kavehrad, "Design considerations for broadband indoor infrared wireless communication systems," International Journal of Wireless Information Networks, vol. 2, no. 4, pp. 223-238, October 1995.

[69] J. J. G. Fernandes, P. A. Watson and J. C. Neves, "Wireless LANs: physical properties of infrared systems vs. MMW systems," IEEE Communications Magazine, vol. 32, no. 8, pp. 68-73, August 1994.

[70] G. N. Bakalidis, E. Glavas, Ph. Tsalides, "Optical power distribution in wireless infrared LANs," IEE Proceedings - Communications, vol. 143, no. 2, pp. 93-97, April 1996.

[71] H. Yang and C. Lu, "Infrared wireless LAN using multiple optical sources," IEE Proceedings - Optoelectronics, vol. 147, no. 4, pp. 301-307, August 2000.

[72] J. R. Barry, J. M. Kahn, E. A. Lee, and D. G. Messerschmitt, "Simulation of multipath impulse response for indoor diffuse optical channels," in *Proceedings of IEEE Workshop on Wireless Local Area Networks*, Worcester, U.S.A., May 1991, pp. 81-87.

[73] J. R. Barry, J. M. Kahn, W. J. Krause, E. A. Lee, and D. G. Messerschmitt, "Simulation of multipath impulse response for indoor wireless optical channels," IEEE Journal on Selected Areas in Communications, vol. 11, no. 3, pp. 367-379, April 1993.

[74] M. Abtahi and H. Hashemi, "Simulation of indoor propagation channel at infrared frequencies in furnished office environments," in *Proceedings of the 6th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Toronto, Canada, 27-29 September 1995, vol. 1, pp. 306-310.

[75] C. R. Lomba, R. T. Valadas and A. M. de Oliveira Duarte, "Efficient simulation of the impulse response of the indoor wireless optical channel," International Journal of Communication Systems, vol. 13, no. 7 & 8, pp. 537-550, November-December 2000.

[76] F. J. Lopez-Hernandez, R. Perez-Jimenez and A. Santamaria, "Monte Carlo calculation of impulse response on diffuse IR wireless indoor channels," Electronics Letters, vol. 34, no. 12, June 1998.

[77] F. J. Lopez-Hernandez, R. Perez-Jimenez and A. Santamaria, "Modified Monte Carlo scheme for high-efficiency simulation of the impulse response on diffuse IR wireless indoor channels," Electronics Letters, vol. 34. no. 19, September 1998.

[78] H. Hashemi, G. Yun, M. Kavehrad, F. Behbahani and P. A. Galko, "Indoor propagation measurements at infrared frequencies for wireless local area networks applications," IEEE Transactions on Vehicular Technology, vol. 43, no. 3, pp. 562-576, August 1994.

[79] IEC 60825-1, Edition 1.2, International Electrotechnical Commission, August 2001.

[80] Hewlett-Packard, "Compliance of infrared communication products to IEC 825-1 and CENELEC EN 60825-1," Application Note 1118, 1997.

[81] P. McKee, D. Wood, J. Towers and P. Smyth, "Applications of computer generated, free-space diffractive optics from interconnections and packaging to optical wireless antennas," in *Proceedings of 4th International Conference on Holographic Systems, Components and Applications*, Neuchatel, Switzerland, 13-15 September 1993, IEE Conference Publication no. 379, pp. 260-264.

[82] P. L. Eardley, D. R. Wisely, D. Wood and P. McKee, "Holograms for optical wireless LANs," IEE Proceedings - Optoelectronics, vol. 143, no. 6, pp. 365-369, December 1996.

[83] V. Pohl, V. Jungnickel, R. Hentges and C. von Helmolt, "Integrating sphere diffuser for wireless infrared communication," in *Proceedings of IEE Colloquium on Optical Wireless Communications*, London, U.K., 22 June 1999, pp. 4/1-4/6.

[84] V. Pohl, V. Jungnickel and C. von Helmolt, "Integrating sphere diffuser for wireless infrared communication," IEE Proceedings - Optoelectronics, vol. 147, no. 4, pp. 281-285, August 2000.

[85] A. J. C. Moreira, R. T. Valadas and A. M. De Oliveira Duarte, "Characterisation and modelling of artificial light interference in optical wireless communication systems," in *Proceedings of the 6th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Toronto, Canada, 27-29 September 1995, pp. 326-331.

[86] A. J. C. Moreira, R. T. Valadas and A. M. de Oliveira Duarte, "Optical interference produced by artificial light," Wireless Networks, vol. 3, no. 2, pp. 131-140, 1997.

[87] A. C. Boucouvalas, "Indoor ambient light noise and its effect on wireless optical links," IEE Proceedings - Optoelectronics, vol. 143, no. 6, pp. 334-338, December 1996.

[88] A. J. C. Moreira, R. T. Valadas and A. M. de Oliveira Duarte, "Reducing the effects of artificial light interference in wireless infrared transmission systems," in *Proceedings of IEE Colloquium on Optical Free Space Communication Links*, London, U.K., 19 February 1996, pp. 5/1-5/10.

[89] R. Narasimhan, M. D. Audeh and J. M. Kahn, "Effect of electronic-ballast fluorescent lighting on wireless infrared links," in *Proceedings of IEEE International Conference on Communications*, Dallas, U.S.A., 23-27 June 1996, pp. 1213-1219.

[90] K. Samaras, A. M. Street, D. C. O'Brien and D. J. Edwards, "Error rate evaluation of wireless infrared links," in *Proceedings of IEEE International Conference on Communications*, Atlanta, U.S.A., 7-11 June 1998, vol. 2, pp. 826-831.

[91] A. M. R. Tavares, R. J. M. T. Valadas and A. M. de Oliveira Duarte, "Performance of wireless infrared transmission systems considering both ambient light interference and inter-symbol interference due to multipath dispersion," in *Proceedings of SPIE Conference on Optical Wireless Communications*, Boston, U.S.A., 5 November 1998, vol. 3532, pp. 82-93.

[92] K. K. Wong, T. O'Farrell and M. Kiatweerasakul, "Infrared wireless communication using spread spectrum techniques," IEE Proceedings - Optoelectronics, vol. 147. no. 4, pp. 308-314, August 2000.

[93] 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 interference," International Journal of Communication Systems, vol. 13, no. 7 & 8, pp. 551-576, November-December 2000.

[94] M. D. Audeh and J. M. Kahn, 'Performance simulation of baseband OOK modulation for wireless infrared LANs at 100 Mb/s', ICWC'92, p 271-274. 1992.

[95] IrDA serial infrared physical layer link specification – version 1.2.

[96] H. Park, and J. R. Barry, 'Modulation analysis for wireless infrared communications', IEEE International Conference on Communications, **2**, pp. 1182-1186, Jun 18-22 1995, Seattle, WA, USA.

[97] H. Park, and J. R. Barry, John R., 'Performance analysis and channel capacity for multiple-pulse position modulation on multipath channels', IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC, **1**, pp. 247-251, Taipei, Taiwan Oct 15-18 1996.

[98] E. D. Kaluarachchi, 'Digital pulse interval modulation for optical communication systems', PhD Thesis, Sheffield Hallam University, U.K. 1997.

[99] A. R. Hayes, Z. Ghassemlooy, and N. L. seed, 'Optical wireless communication using digital pulse interval modulation', Procee. SPIE, on Optical Wireless Communnications, 3532, pp. 61-69, 1999.