A Review on Indoor Optical Wireless Systems

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Abstract- Optical wireless communications offer a viable alternative to radio frequency (RF) communication for indoor use and other applications where high performance links are needed. These systems use infrared technology (IR), which has significant advantages over RF. This paper presents a review of the most significant issues related to infrared communication technology, which will enable the realization of future high performance and cost-effective indoor optical wireless systems. Several possible configurations for indoor optical wireless systems, modulation, and multi-access techniques are presented as well as their advantages and limitations discussed.

I. INTRODUCTION

The number of personal computers and personal digital assistants for indoor use are rapidly growing in offices, manufacturing floors, shopping areas and warehouses. In near future, one will find very often several such devices clustered within small indoor areas. This will result in the need for flexible interconnection through the distributed or centralized data communication systems. The traditional way to meet this requirement is to use wired physical connections. But, wired physical connections have some inherent problems, in setting up and in its expansion. Further, these need more space, time to setup, monetary investment in copper, maintenance etc. Wireless systems offer an attractive alternative. Both, radio frequency (RF) and infrared (IR) radiation are possible options in implementing wireless systems. Unfortunately, the RF can support only limited bandwidth because of restricted spectrum availability and interference; while this restriction does not apply to IR. Thus, optical wireless (IR) technology [1] seems to be ideal for wireless communication systems of the future. It can provide cable free communication at very high bit rates (a few Gbps as compared to tens of Mbps supported by radio). In indoor optical wireless systems, laser diodes (LDs) or light emitting diodes (LEDs) are used as transmitter and photo-diodes as the receivers for optical signals. These opto-electronic devices are cheaper as compared to RF equipment as well as wireline systems. Further, IR transmission does not interfere with existing RF systems and is not governed by Federal Communications Commission (FCC) regulations. The IR signal does not penetrate walls, thus providing a degree of privacy within the office area. In addition to privacy, this feature of IR systems makes it easier to build a cell-based network. For example, in an office building each room would be a cell and there would be no interference between the cells. Therefore, all units can be identical in a cellular architecture as compared to RF configuration in which the operating frequencies of neighboring cells have to be different. Due to the above reasons, optical wireless systems are becoming more popular in various operating environments, such as houses (consumer electronics), offices, medical facilities, manufacturing plants, and business establishments.

Although infrared offers significant advantages as a medium for indoor communication, it also has drawbacks. Several aspects impair the performance of indoor IR transmission systems. Some of the causes of impairments are: i) speed limitations of the opto-electronic devices, ii) high path losses leading to the requirement of higher transmission power levels, iii) multipath dispersion, iv) receiver noise, v) shot noise induced by the background ambient light, and vi) the interference induced by the artificial light sources [2,3,4]. The concern of eye safety and power consumption limits the average transmitter power. For these reasons, the indoor optical wireless systems are not easy to design and hence new design solutions need to be explored. In this paper, current status and research trends are surveyed along with the work already done in the field of optical wireless communications, with main focus on indoor optical wireless (IR) systems. The paper is organized as follows. Section 2 presents an overview of indoor optical wireless systems and looks at the various transmission techniques and user modes that have been proposed. Section 3 examines the link budget limitations due to ambient light and safety considerations. Section 4 gives an overview of the modulation schemes that have been proposed for infrared systems and compares their bandwidth and power efficiencies. Section 5 gives the brief details of multi-access techniques for multiple use of the infrared medium. Section 6 details the applications of optical wireless for wireless local area networks (WLANs). Section 7 details the standards for indoor optical wireless systems that are currently in place. Section 8 concludes this review and indicates future directions and areas for potential research.

II. INDOOR OPTICAL WIRELESS SYSTEMS

A. System Overview

Since the late 1970's, significant research has been done on the applications of optical wireless (IR) technology to high-speed indoor data communications; this is still an active area of research [2,5,6]. Also, in the past several years, extensive effort has been devoted to understanding and implementing optical wireless technique for long distance inter-satellite systems (outdoor applications). But it is the indoor applications that are the driving force behind optical wireless. The first indoor optical wireless system was developed in 1979 [7]. This system used the infrared radiation which was spread in all directions. Such systems are called diffused infrared systems. Since then several products using IR radiation have been successfully commercialized [2,5,6,8,9]. The advancement of inexpensive opto-electronic devices, such as LEDs and LDs, p-intrinsic-n (PIN) photo-diodes and avalanche photo-diodes (APDs) and various optical components, has resulted in the improvement of these systems. Indoor optical wireless systems have been used in many applications in the past few years, ranging from simple remote controls in home to more complex wireless local area networks. Many other applications are envisaged for the future, including data networking in the indoor environment and the delivery of broadband multimedia services to mobile users within such an environment together with general connectivity to base networks. Several companies have introduced data communication products using optical wireless technology and many other computer communication products are entering the market [8,10,11].

B. An Indoor Optical Wireless System

A block diagram of a typical indoor optical wireless system is illustrated in Fig.1. A basic optical wireless system consists of a transmitter (using LEDs or LDs), free space as the propagation medium and the receiver (using APDs or PIN diodes). Information, typically in the form of digital data, is input to electronic circuitry that modulates the transmitting light source (LEDs/LDs). The source output passes through an optical system (typically has telescope and optical diplexer) into the free space (propagation medium). The received signal also comes through the optical system and passes along the optical signal detectors (PIN diodes/APDs) and thereafter to signal processing electronics. The wavelength band from 780nm to 950nm is the best choice for indoor optical wireless systems. In this range, low cost

LEDs and LDs are readily available. Also, this band coincides with the peak responsivity of inexpensive, low-capacitance silicon photodiodes. The optical wireless system uses IR technology in which links are based on intensity modulation and direct detection (IM/DD) of the optical carrier. Intensity modulation is performed by varying the drive current of LED or LD (direct modulation). Direct detection is performed by PIN photo-diodes or APDs which produce an electric current proportional to the incident optical power.

1) Transmitter

For indoor optical wireless transmitter, LDs are preferable over LEDs because they have higher optical power outputs, broader modulation bandwidths and linear electrical to optical signal conversion characteristics [12]. Linearity in signal conversion is particularly important when sophisticated modulation schemes such as multi-subcarrier modulation or multilevel signaling are used. But due to safety reasons (eye safety) laser diode cannot be used directly for the indoor IR systems, where radiation can enter a human eye quite easily. LDs are highly directional radiation sources and can deliver very high power within a small area on the retina thereby resulting in permanent blindness. On the other hand, LEDs are large-area emitters and thus can be operated safely at relatively higher powers. They are also less expensive and more reliable. Consequently, LEDs are the preferred light source for most indoor applications. To compensate for the lower powers, array of LEDs can be used. However, LEDs cannot be used beyond 100 Mbps due to the limitations imposed by the mechanism by which they emit light, whereas LDs can be used for transmission at bit rates of the order of a few Gbps. A comparison between LEDs and LDs is shown in Table 1 [13].

2) Propagation Medium

Like any wireless system, the link power budget for an optical wireless system is strongly dependent on atmospheric loss along the path of the propagation. Since indoor atmosphere is free of environmental degradation, such as mist, fog, particulate matter, clouds etc., indoor optical wireless systems encounter only free space loss and signal fading.

Free Space Loss: It is that part of the transmitted power, which is lost or not captured by the receiver's aperture (Fig.2). A typical figure for a point-to-point system that operates with a slightly diverging beam would be 20dB, whereas an indoor system using a wide-angle beam could have a free space loss of 40dB or more [13].

Signal Fading: This can be observed in both indoor and outdoor optical wireless systems. The reason for this is reception of signals via different paths by the receiver. Some of these interfere destructively (i.e. they are out of phase), so that the received signal power effectively decreases. This type of degradation is also known as multi-path signal fading [12].

3) Receiver

As mentioned earlier, there are two basic detectors; the PIN diodes and the APDs. PIN receivers are commonly used due to their lower cost, tolerance to wide temperature fluctuations and operation with an inexpensive low-bias voltage power supply. PIN receivers are about 10 to 15 dB less sensitive [14] than APD receivers. Increasing the transmitter power and using larger receiver lens diameter can compensate the reduced sensitivity of these receivers. On the other hand, the increased power margin afforded by the APDs provides a more robust communication link, which reduces the criticality of accurate aiming of lenses. This allows in reduction of transmitter power. In addition to this, the better internal gain of APDs increases the Signal-to-Noise Ratio (SNR). However, the APD receivers are costly and need high operating voltages.

C. Transmission Techniques

Several transmission techniques are possible for indoor optical wireless systems; these techniques may be classified according to the degree of directionality of transmitter and receiver [15]. A transmitter and receiver may have a narrow or broad radiation pattern or field of view (FOV) and can be combined to make directed, non-directed, or hybrid systems (Fig.3).

1) Directed beam infrared (DBIR) radiation

In DBIR (Fig.3a) system, the optical beam travels directly without any reflection from the transmitter to the receiver. The optical wireless link using this technique is established between two fixed data terminals with highly directional transmitter and receiver at both ends of the link. As there is no mobility, the beam aperture angle and the FOV of the transmitter and the receiver respectively can be reduced. As a result, this technique of infrared transmission minimizes path loss and maximizes power efficiency and systems using this technique can achieve higher transmission rates. The main drawback of this technique is the lack of mobility, and susceptibility to blocking by personnel and machines. The narrow beams also create pointing problems. The beam-width should be chosen such that any inexperienced operator should be able to manually aim the transmitter towards the receiver unit.

2) *Diffuse infrared (DFIR) radiation*

In DFIR (Fig.3b) system, the transmitters send optical signals in a wide angle to the ceiling and after one or several reflections the signals arrive at the receivers. This is the most desirable configuration from a users' point of view, since no alignment is required prior to use, and the systems do not require a line-of-sight path for transmission. However, systems using this technique have a higher path loss than their DBIR counterparts, requiring higher transmitter power levels and receivers with larger light collection area. Another challenging problem in this technique is the multipath dispersion. When a short duration pulse is transmitted in a wide angle, it travels through multiple paths, resulting in a broadened pulse. This effect is known as multipath dispersion. This causes inter-symbol- interference (ISI) at higher data rates or in larger cell system [13]. In this configuration, the data rate depends on the room size and the reflection coefficients of the surfaces inside the room.

3) *Quasi-diffuse infrared (QDIR) radiation*

In QDIR (Fig.3c) system, there is a base station (BS) with a relatively broad coverage made of passive or active reflector. The BS is usually mounted on the ceiling. The BS transmits (receives) the signal power to (from) the remote terminals (RTs). In a link between any terminal and the BS, the line of sight always must be maintained. Consequently, the RTs cannot be fully mobile. The RT's transceiver must be aimed to the BS, or its FOV must be wide enough to enable communication between itself and the BS from any position in the room. In another form of QDIR technique, the transmitter may send the optical signal to a designated area on the ceiling and the receiver is supposed to face that area.

In general, the QDIR architecture provides a compromise between the DFIR and DBIR options. Infrared transmission techniques may also be classified as line-of-sight (LOS) or non-line-of-sight (non-LOS) depending on whether or not, they rely on the existence of a directed path between transmitter and receiver [1]. Fig. 4 shows all the possible configurations for IR transmission. In the cases (a), (b) and (c), the transmitter (T) and receiver (R) are in transmit-LOS mode. The beam can travel directly from the transmitter to the receiver, without reflection. In cases (d), (e) and (f) there is no direct path and before reaching the receiver, the signal is reflected by the ceiling and walls.

The two most common configurations are directed-LOS systems and non-directed non-LOS systems. Non-directed non-LOS systems are commonly referred to as diffuse systems. In general, directed LOS links minimize path loss and maximize power efficiency, and they can achieve higher transmission rates. However, such systems require careful aiming and are not capable of supporting one-to-many and many-to-one connections. Furthermore, shadowing can significantly degrade such systems. While supporting lower transmission rates, non-directed non-LOS (diffuse) systems have increased robustness against shadowing and provide ease of use, allowing high user mobility. They also allow links to operate even when barriers are there between the transmitter and receiver [1].

III. DESIGN CHALLENGES

Achieving a high electrical signal to noise ratio (SNR) is the single biggest problem facing the designer of an infrared system. The difficulty arises due to two reasons. Firstly, the SNR of an IM/DD system depends upon the square of the average power of the received optical signal. This implies that one should transmit at relatively higher power levels, even though available transmitter power may be limited due to considerations of eye safety regulations [16] and power consumption. It also implies that one should design the system to minimize path loss, and employ a receiver having a large light-collection area. Secondly, in many environments there exists intense ambient infrared noise, which introduces white shot noise and low-frequency cyclostationary noise into the receiver. Besides ambient noise, the bandwidth of wireless infrared systems is also limited due to inter-symbol interference produced by the multipath dispersion of the optical channel. Thus the eye safety requirement, power consumption of portable devices, interference from ambient light sources and multipath characteristics of the channel for diffused radiation mainly limit the data transfer rate with indoor optical wireless systems.

A. Eye Safety

Eye safety consideration puts limit on the amount of optical power that should be emitted by the transmitter, thus limiting the coverage of an optical wireless system. Both indoor and outdoor optical wireless systems can pose a hazard if LDs are operated at high output power. The eye safety standards are set by International Electro-technical Commission (IEC), where LDs are classified based on their total emitted power into Class 1, 2, 3A and 3B [13] as shown in Table 3. They dictate that all transmitters must be Class 1 eye safe under all conditions and launch power must not exceed 0.5 mW for the systems employing laser sources. Some LDs operating inside the class 3B category can be made Class 1 safe by passing their beam through a transmissive diffuser, such as a thin plate of translucent plastic. Efficiencies of about 70 percent can be achieved by using such type of diffusers. Computer-generated holograms (CGHs) [17] offer a means to generate arbitrary radiation patterns with efficiencies approaching 100 percent. These holograms break up the wave front of the optical beam in a designated pattern. This diffuses the image of the laser-spot on the retina of the eye.

B. Interference from ambient light sources

The dominant source of noise in indoor optical wireless systems is ambient light, which is typically a combination of fluorescent light, sunlight, and incandescent light. All three modes of infrared propagation suffer from the presence of ambient light. The illumination sources of indoor environments radiate in the same wavelengths as the infrared data signal. Also, typical intensity levels of the ambient light collected at the photo detector are usually much higher than data signal intensity levels. Ambient light provokes shot noise due to the random nature of the photo-detection process. Moreover, artificial light provokes interference due to periodic variations of light intensity. These variations can occur at a frequency double the power line frequency, and at the switching frequency of electronic ballasts of the fluorescent lamps. In general, for low and moderate data rates the ambient noise is the main factor degrading the performance of wireless IR systems [3,4].

C. Multipath characteristics of the channel for diffused radiation

Channel dispersion associated with multipath propagation is another major issue in indoor optical wireless systems. A multipath phenomenon occurs when the transmitted signal follows different paths on its way to the receiver due to its reflection by walls, ceilings and other objects. Multipath phenomena can cause inter-symbol-interference (ISI). Diffusive systems are more prone to multipath effects than directed beam systems. This is because of their larger beam widths leading to more potential reflectors, and the larger FOV of their detectors resulting in more reflected light being detected. As the speed of transmission increases to 10 Mbps and beyond, the ISI caused by the multipath dispersion becomes a major degrading factor.

IV. MODULATION TECHNIQUES

In optical wireless communications, modulation takes place in two stages. First the transmitted information is coded as waveforms and then these waveforms modulate signal intensity (amplitude) of emitted infrared light. In practice direct amplitude modulation by the message is not preferred, because optical wireless links suffer from extensive amplitude fluctuations.

Several modulation and detection schemes have been considered for use in optical wireless systems in the past. Most common schemes suitable for indoor optical wireless are the On-Off Keying (OOK), Pulse Modulation (PM) and Sub-carrier Modulation. [1,19-23]. These schemes are compared for power and bandwidth efficiency in the following sections.

A. On-Off Keying (OOK)

OOK is the simplest technique to implement in wireless infrared transmission. Prior to transmission, the information is translated to a specific code such as Manchester, RZ, or NRZ codes, to get a stream of pulses. In OOK, a pulse is transmitted if the code bit is 'one' during a fixed time slot and a 'zero' is represented by the absence of the pulse during the time slot. The pulse can have different duty cycles (d). When using a duty cycle $d < 1$, the required bandwidth is increased by a factor of $1/d$ while the average power requirement is decreased. This is the reason why OOK with RZ pulses is common in infrared systems. Figure 7 shows the waveforms of OOK/NRZ, and OOK/RZ with duty cycle d=0.5 [3]. When the duty cycle gets smaller, PPM (described later) is more efficient [3].

In the absence of distortion, the "ideal maximum-likelihood (ML)" receiver for OOK in the presence of Additive White Gaussian Noise (AWGN) is a "continuous-time matched filter" which is matched to the pulse shape. The output of the filter is sampled and detected based on a threshold [3]. However, when a multipath phenomenon is encountered, other types of filters are employed. In general, the optimum OOK receiver can be implemented by using a "Whitened Matched Filter (WMF)" that performs "maximum-likelihood sequence detection (MLSD)".

B. Pulse Modulation (PM)

Indoor optical wireless communication systems require modulation techniques, which make high-speed digital transmission possible with less average transmitter power. Higher average power efficiency can be achieved by employing pulse modulation schemes in which a range of time-dependent features of a pulse carrier may be used to convey information. Examples of such modulation schemes are: 1) Pulse-position modulation (PPM), 2) Differential pulse-position modulation (DPPM), and 3) Digital pulse interval modulation (DPIM).

1) Pulse-position modulation (PPM)

PPM [3] and its variants are widely considered as the best modulation techniques for power-limited intensity modulation with direct detection (IM/DD) communication systems. PPM has been widely used in optical communication systems, and has been adopted by the IEEE 802.11 working group for the infrared physical layer standard. *L*-PPM is defined to have *L* slots in a single symbol time. These slots are called "chips". So, in an *L*-PPM, a constant optical power of LP_t watts is transmitted within only one of chips while the remaining (*L*-1) chips will have zero power. Here, P_t is average transmitted power. Therefore, $\log_2(L)$ bits can modulated into *L*-PPM. Figure 8 shows the four possible waveforms of 4-PPM that represent the two bits of information [3].

Even though, PPM offers higher average power efficiency, due to its poor bandwidth efficiency, it is more susceptible to multipath-induced ISI as compared to NRZ OOK. The effects of ISI in PPM can be mitigated using MLSD, equalization, and trellis-coded modulation [19-20]. The trellis-coded modulation technique can be applied to PPM to combat the effects of ISI with much less decoding complexity. Rate-2/3, trellis-coded 8-PPM has greater average power-efficiency than uncoded 16-PPM, even though both modulation techniques have the same bandwidth and similar decoding complexity [3]. Similarly, rate-3/4, trellis-coded 16-PPM has greater average power-efficiency than uncoded 32-PPM. Preliminary work [20] has shown that decision-feedback equalization (DFE) of trellis-coded PPM with much less decoding complexity provides nearly the same performance as optimal sequence detection.

2) *Differential PPM (DPPM)*

Differential PPM (DPPM) [21] is a simple modification of PPM that can achieve improved power and/or bandwidth efficiency in applications where low cost dictates the use of hard-decision detection, and multipath ISI is minimal (e.g., at low bit rates or in directed-LOS links). The 4-PPM and 4-DPPM signal sets are shown in Fig. 9(a) and (b), respectively. Each 4-PPM symbol consist of four chips, of which one is “high” and three are “low”. A DPPM symbol is obtained from the corresponding PPM symbol by deleting all of the “off” chips following the “on” chip. Since the 4-DPPM symbols omit the “low” chips that follow the “high” chip, and it has unequal durations, symbol boundaries are not known prior to detection. Hence, optimal soft decoding of DPPM requires the use of MLSD, even in the absence of coding or ISI. If hard decoding is used, DPPM is easier to decode than PPM, since the former requires no symbol-level timing recovery.

One of the advantages of DPPM over PPM [20] is that symbol synchronization, which is an important requirement for PPM detection, is not necessary with DPPM. But more importantly, DPPM achieves higher power and bandwidth efficiency than PPM.

3) *Digital pulse interval modulation (DPIM)*

PPM offers greater average power efficiency but increases system complexity compared to OOK, since both slot- and symbol-level synchronization are required in the receiver, and are critical to system performance. As a potential alternative to PPM, DPIM is a technique, which displays a higher transmission capacity by eliminating all the unused time slots within each symbol, and requires no symbol synchronization since each symbol is initiated with a pulse. In DPIM (Fig.10) data is encoded as a number of discrete time intervals, or slots, between adjacent pulses [22].

The symbol length is variable and is determined by the information content of the symbol. In order to avoid symbols in which the time between adjacent pulses is zero, an additional guard slot may be added to each symbol immediately following the pulse. Thus, a symbol which encodes M bits of data is represented by a pulse of constant power in one slot followed by k slots of zero power, where $1 \leq k \leq L$ and $L = 2^M$, as shown in Figure 10. Here M is number of bits being transmitted per symbol. For comparison, OOK and PPM symbols are also shown in Figure 10. The minimum and maximum symbol lengths are $2T$ and $(L + 1)T$

seconds, respectively, where T is the slot duration. For a given value of M, the duty cycle of PPM symbols remains fixed, unlike DPIM symbols, which vary since the symbol length varies. Thus, a DPIM encoded pulse stream has a higher average optical power than a pulse stream encoded using PPM since, on an average, the symbol length is shorter. Figure 10 shows the average optical power of DPIM and PPM, normalized to OOK, versus the number of bits per symbol. For $M = 4$, DPIM has an average power ~6.8 dB lower than OOK, but ~2.2 dB higher than PPM. By changing the mapping of source data to transmitted symbols, it is possible to reduce the average power of DPIM at the expense of information capacity, or vice versa.

C. Sub-carrier Modulation

High-speed single-carrier modulation schemes such as OOK and L-PPM are wide band and suffer from ISI due to multipath dispersion when the symbol rate exceeds 100 Mbps. When a bit stream modulates a single radio frequency, which is then further used to modulate optical carriers; the modulation is called single-sub-carrier modulation (SSM). For example, Binary Phase Shift Keying (BPSK) can be used as sub-carrier modulation. Figure 11 shows such single-sub-carrier modulation signals [3]. However, when a group of bit streams modulates different radio frequencies (multiplexed), the modulation is called a multiple-sub-carrier modulation (MSM) [23]. In MSM, the symbol rate of each sub-carrier is reduced relative to that of a sub-carrier with the same total bit-rate. Hence each sub-carrier becomes a narrow band signal, and since it experiences little distortion, the receivers need not employ equalization.

It is true that MSM is less power conservative than OOK or L-PPM but some advantages are gained when MSM is used as compared to OOK or L-PPM. MSM is more suitable for transmission of multiplexed bit streams between a base station and several mobile terminals. Also, by transmitting several narrow-band sub-carriers, high data rates are achievable without the need of adaptive equalization to eliminate ISI. In addition, both SSM and MSM schemes can provide higher immunity than OOK to the low frequency noise caused by fluorescent lamps. However, BPSK sub-carrier needs twice the bandwidth while QPSK requires the same bandwidth as that of OOK. Furthermore, a single BPSK or QPSK sub-carrier needs 1.5dB more optical power than OOK [3].

V. MULTI-ACCESS TECHNIQUES

Multiple access techniques define the way the terminals can share the infrared medium simultaneously. These techniques are performed in the physical layer. If different users share the infrared medium optimally, it means their signals can occupy the same time slot, code or carrier frequency. Before going through the multiple access techniques, it is good to mention some of the infrared media features as follows [3]:

1. The short wavelength of infrared signals makes it possible to get "high angular resolution in an angle-diversity receiver" [3].
2. Using a short duty cycle pulse with IM reduces the transmitted power, which makes the time-division-multiple-access preferred over the other techniques.

Multiple access techniques can be classified into two types; optical and electrical multiplexing techniques [3].

A. Optical Multiplexing Techniques:

Optical multiplexing techniques can be divided into two techniques; Wavelength-Division Multiple Access (WDMA) and Space-Division Multiple Access (SDMA) [3].

1) WDMA

In this technique, each transmitter transmits at different infrared wavelengths using narrow-band emitters such as LDs. The receiver has a band pass optical filter that extracts the wanted infrared wavelengths before the detection process. The transmitter may be tunable so that it can transmit at different wavelengths (e.g. tunable LDs); however, such transmitters are currently expensive and need complex techniques to accurately tune them to a certain wavelength. Also large-area tunable band pass filters such as "single or multiple-stage Fabry-Perot filters" are expensive and difficult to manufacture with "wide-FOV (field of view)" [3].

2) SDMA

This technique makes use of an angle diversity receiver (having multiple receiving elements that are directed in different directions) to receive signals from different directions. For example, a hub may be capable of establishing a direct line-of-sight (LOS) with several portable transceivers. This hub can use an angle diversity receiver to reduce co-channel interference between channels in the same cell.

B. Electrical Multiplexing Techniques

When different users share the same optical channel, multiplexing can be used to enable reliable transmission. There are three multiplexing techniques *viz*., Time-Division Multiple Access (TDMA), Frequency-Division Multiple Access (FDMA) and Code-Division multiple Access (CDMA).

1) TDMA

In this, the time access is divided into time slots. In each time slot the user transmits his signal. TDMA transmissions having low duty cycles reduce the transmitted power but these require synchronization. The reduction in transmitted power makes the TDMA technique popular in wireless infrared systems [3]. TDMA is efficient under steady flow of information; however, it can be very inefficient for busty transmission [24].

2) FDMA

In this case, the frequency axis is sliced into frequency bands where each channel occupies a certain band. Upon reception, the receiver filters out the desired signal. FDMA is efficient in steady information flow applications [24]. However, the power efficiency achieved by FDMA gets poorer as the number of users increases.

3) CDMA

This technique assumes that different users use different orthogonal code sequences in a way that no interference is encountered [3]. CDMA can be considered as a hybrid combination of FDMA and TDMA where multiple users operate at the same time over the entire bandwidth of the time-frequency signal domain [24]. The user signals are separable since the codes used to modulate their signals are re-generated by the receiver [24]. There are two common CDMA techniques; Direct Sequence CDMA (DS-CDMA) and Frequency Hopping CDMA (FH-CDMA) [24].

In *DS-CDMA,* the information bits are modulated by certain codes. Each user may be assigned a code in such a way that users' signals don't interfere. Upon reception, the receiver re-generates the codes, which are used to demodulate the information. The DS-CDMA is built upon the spread spectrum techniques.

In *FH-CDMA,* the information bits modulate a group of frequencies, which are hopping according to pseudo random numbers. This technique involves a two-layer modulation technique. In the first stage, a bit or symbol can modulate a carrier frequency, while in the second stage, the modulated carrier frequency can modulate different frequencies in a way that these frequencies are independent.

VI. OPTICAL WIRELESS NETWORKS

A. Wireless LAN Objectives

Traditionally, the communication connectivity for offices and commercial buildings is achieved using hard wires consisting of coax, twisted pairs or fibre-optic cables. This type of connectivity is expensive and troublesome to install, maintain and especially, change. In office data communications, where the ratio of workers to data terminals or personal computers (PCs) is rapidly approaching one to one, local area networks (LANs) are very difficult to manage. Beyond costs, performance of connectivity itself is a factor. Unshielded twisted pair (UTP) wiring supports the 10 Mbps speeds which is adequate for existing LANs, but may not support the high speed, reliable data transport needed in coming years. In addition to limited speed, problems such as cross talk, impedance matching, signal degradation, and data security are often thorny problems for network planners. Clearly, a less expensive and yet a high performance wireless alternative i.e. wireless LAN which is functionally compatible with existing systems, is badly needed for in-building communications. A wireless LAN can be implemented as an extension to, or as an alternative for, a wired LAN. A wireless LAN uses electromagnetic waves to communicate information from one point to another without relying on any physical connection. Hence, users can access shared information without looking for a place to plug in, and network managers can set up or augment networks without installing or moving wires. The market for wireless LAN products is growing rapidly due to the flexibility and mobility of wireless LANs that make them both effective extensions and attractive alternatives to wired networks. Table 2 summarizes the technical features of various wireless LAN technologies [2,7,32] (including the radio and microwave portion of the spectrum which is not being examined in detail in this paper).

Wireless LANs are designed for a small number of users, usually operating in indoor areas. Their coverage range depends on the transmission technology used. The transmission technology used in existing wireless LANs can be mainly divided into two categories: radio frequency (including microwave) and optical wireless (infrared). Radio/microwave technology can be subdivided into standard radio (RF), direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS). On the other hand, optical wireless (IR) technology can be subdivided into DFIR, DBIR and QDIR as mentioned in Section II (Figure 3).

B. Optical Wireless LAN Technology

Wireless LANs traditionally use radio or microwave techniques; however the radio spectrum is a scarce resource and the pressure to be economic is ever increasing. Allocated channels are therefore usually narrow band (typically 20 MHz), which means that broadband wireless transmission for densely populated buildings is not possible. Optical wireless, on the other hand, uses IR technology and supports the required mobility within buildings. It is intrinsically broadband, and by operating in the infrared (850 nm), low cost LED/lasers and silicon photo-diodes can be used. In addition, since the radiated signals are completely contained within the room in which the system is operating, security is intrinsically better than either radio or microwave wireless systems.

1) Classification Of Optical Wireless LANs

The propagation of optical signals inside a room may use one of three basic propagation modes: DFIR, DBIR and QDIR as mentioned in Section II. Optical wireless LANs can also use all these propagation modes and accordingly, the optical wireless LANs can be classified as below.

Diffuse Infrared (DFIR) LANs: DFIR LANs, use a diffused link in which the light is reflected off various surfaces (e.g., walls, ceiling) and after some reflections, the irradiance is almost uniform. Full mobility within the room is allowed and there are no shadowing effects caused by moving persons or machines. The primary advantage of using DFIR LANs is that there is no need of accurate alignment between transmitter and receiver. This is especially important in portable applications, in which readjusting a receiver antenna after every movement is not practical. The disadvantages of these LANs are that they require higher power to cover a given area and data rates are limited by multipath. There is also a higher risk of eye exposure. In simultaneous two way communications, each receiver collects its own transmitted reflections which are some times stronger than the transmitted signal from the other end of the connection. Therefore, DFIR LANs tend to be used primarily for applications demanding portability, such as cordless phones or communication with laptop or pen-pad computers. A good example of a DFIR LAN is manufactured by Spectrix [8], which utilizes LED emitters (Class 1 eye safe) to keep the cost low. A single base station can comfortably irradiate a room 10 m on each side and deliver 4 Mbps, which is shared by the users within the cell. These systems permit wireless communication with base stations connected to a backbone network.

A typical deployment strategy for DFIR LAN in an office is shown in Figure 5. The base station (BS) on the ceiling illuminates the walls and floor of a room creating a diffused optical field. It also receives signals from terminals located within the room. The ceiling BS could be interconnected via a conventional metal cable network, or via an optical-fibre network. To avoid interaction between the various users, such systems would utilize multiple sub-carriers of differing frequencies, with one pair (i.e., send and receive channels) being assigned to each user. The number of sub-carriers that can be simultaneously supported by the system establishes an upper limit to the number of users in one room. The same sub-carrier frequencies can of course be re-used in different rooms.

Point-to-Point or Directed Beam Infrared (DBIR) LANs: In recent years, the application of point-to-point or DBIR radiation to wireless information networking has been extensively investigated [5] and some products using this technology have appeared in the market. Both IBM and Photonics [10,11] are marketing modems that permit ad hoc, peer-to-peer interconnection of notebook computers. With this mode of radiation, the transmitted radiation pattern must be adjusted in the direction of receiver. The LANs based on this technique require less optical power for reliable communication and do not suffer from extensive multipath. They also can handle bi-directional communications better than DFIR LANs. As a result of the above facts, higher data rates and better coverage can be achieved in these LANs. The disadvantages of these are the need for terminal alignments and the severe interruption caused by shadowing. Consequently, the DBIR LANs are typically used for applications in which the terminals are relatively fixed, such as desktop computers in an office. A good example of such a system is manufactured by JVC [9]. In this system, data rate of 10

Mbps can be transmitted over a span of around 20m. Such systems can be used to extend a 10 Mbps LAN port to a different part of an office where no convenient port exists, or to link two separate offices via a link corridor.

Quasi-Diffused Infrared (QDIR) LANs: In QDIR LANs (Fig. 6), one base station made of passive or active reflector usually mounted on the ceiling broadcasts to all remote terminals (RTs) on a forward link. The reverse link is a directional beam from each mobile to base station. Passive reflectors are mirror like devices with high scattering and reflecting properties. The active reflector amplifies and rebroadcasts the received signal. Passive reflectors require more transmission power from the terminals but they avoid the installation and maintenance problems associated with the active reflectors. Similar to the DFIR LANs, the QDIRs LANs are broadcast systems in which all terminals receive the transmitted message. The required radiated light from the terminals in QDIR LANs is less than that for DFIR LANs and the flexibility and coverage are better than for DBIR LANs.

A good example of a commercial QDIR LAN is also manufactured by JVC [9]. It generates a cell of about 10m diameters, which is sufficient for up to six simultaneous users. Each cell delivers a capacity of 10 Mbps shared between the users via conventional LAN protocols. Line-of-sight paths are required between the base station and all the user terminals.

VII. STANDARDS FOR INDOOR OPTICAL WIRELESS SYSTEMS

An exciting development in recent years has been the arrival of very short distance optical wireless systems for laptop computers, personal digital assistants (PDAs), palmtops, printers, calculators, and mobile phones. The importance shown by industry in this technology is demonstrated by the formation of Infrared Data Association (IrDA). IrDA was established in 1993 and is committed to developing and promoting infrared standards for the hardware, software, systems, components, peripherals, communications, and consumer markets. Over the past seven years, the Infrared Data Association (IrDA) has established standards [25-27] for short range, half-duplex line-of-sight (LOS) systems operating at bit rates up to 4 Mbps. To date, the design of IrDA-standard transceivers has emphasized low cost and low power consumption. Current IrDA standards [25-27] describe directional transmitters and short-range, half-duplex, point-to-point systems, and make no provision for multiple-access use of the IR medium. In view of this, Hewlett-Packard Company and IBM Corporation have collaborated on a new IR standard, proposed in April 1997, called Advanced Infrared (AIr) [28-29]. In addition to IrDA, the executive committee of the IEEE 802 project (United States) created the IEEE 802.11 group in July 1990, to work on the specification of a wireless local area network (WLAN) for different technologies, including radio and infrared. This new IEEE 802.11 standard [30] for wireless local area networks was approved in June 1997 and defines a specification for an infrared physical layer. Valadas et al. [31] have presented the overview of infrared technology and described the IEEE 802.11 specification. The infrared physical layer has been designed for diffuse systems supporting two data rates (1 and 2 Mbps) and includes provisions for a smooth migration to higher data rates. The specification is suitable for low-cost transceivers but allows interoperability with high performance systems.

VIII. CONCLUSIONS

The emergence of portable information terminals in work and living environment of future is expected to accelerate the introduction of high capacity wireless systems. Such portable terminals should have access to all the services that will be available on wired networks. Unlike their wired counterparts, portable devices are subject to severe limitations on power consumption, size, and weight. This paper has provided a review of the main issues associated with the physical layer of a wireless infrared communications system. It has highlighted the significant problems of high ambient light levels and restrictions on transmit power and discussed some of the techniques for mitigating these effects.

To summarize, there are three generic system configurations for indoor optical wireless applications, namely: directed beam infrared (DBIR), diffuse infrared (DFIR) and quasi-diffuse infrared (QDIR). There are no physical layer technological challenges in low speed-DBIR systems. The major concerns in these systems are at the protocol level and the commercial issues of achieving integration with existing computer architectures at sufficiently low cost for consumer acceptance. The design and implementation of other system configurations are more challenging. Cellular systems will typically require a holographic diffuser or other means of beam shaping to define the cell coverage. Typically, relatively large area detectors will be required at the receivers because any concentrator gain will be limited by field of view considerations. Thus, techniques for mitigating the large detector capacitance, such as bootstrapping may be used to achieve shot-noise limited operation at bit rates in excess of around 10 Mbps. DFIR systems provide the maximum scope in the market, but adaptive equalizers need to be used to support data rates in excess of 10-20 Mbps. To counter the high link losses, large transmit powers are needed, which require the use of extended sources or multiple point sources. At the receiver, hemispherical concentrators are used to collect the signal from a wide range of angles. QDIR systems offer the potential for extremely high bit rate transmission. Owing to the highly directive nature of the link, large optical concentration ratios can be exploited. This also allows relatively small area detectors to be used, as it will be the concentrator area that collects the signal.

Although, optical wireless products are already a commercial reality, they have yet to fully exploit all the potential benefits offered by the medium. The majority of these products comply with the international standards promoted by the IrDA for data rates up to 4 Mbps [33]. At present, indoor optical wireless systems operating at data rates up to 4 Mbps are commercially available. With the recent standardization of a 16 Mbps data rate option called Very Fast Infrared (VFIr) [34], optical wireless can be extended to the applications requiring connectivity beyond 4 Mbps [35]. Hence infrared will play a significant role in future high-capacity indoor wireless systems.

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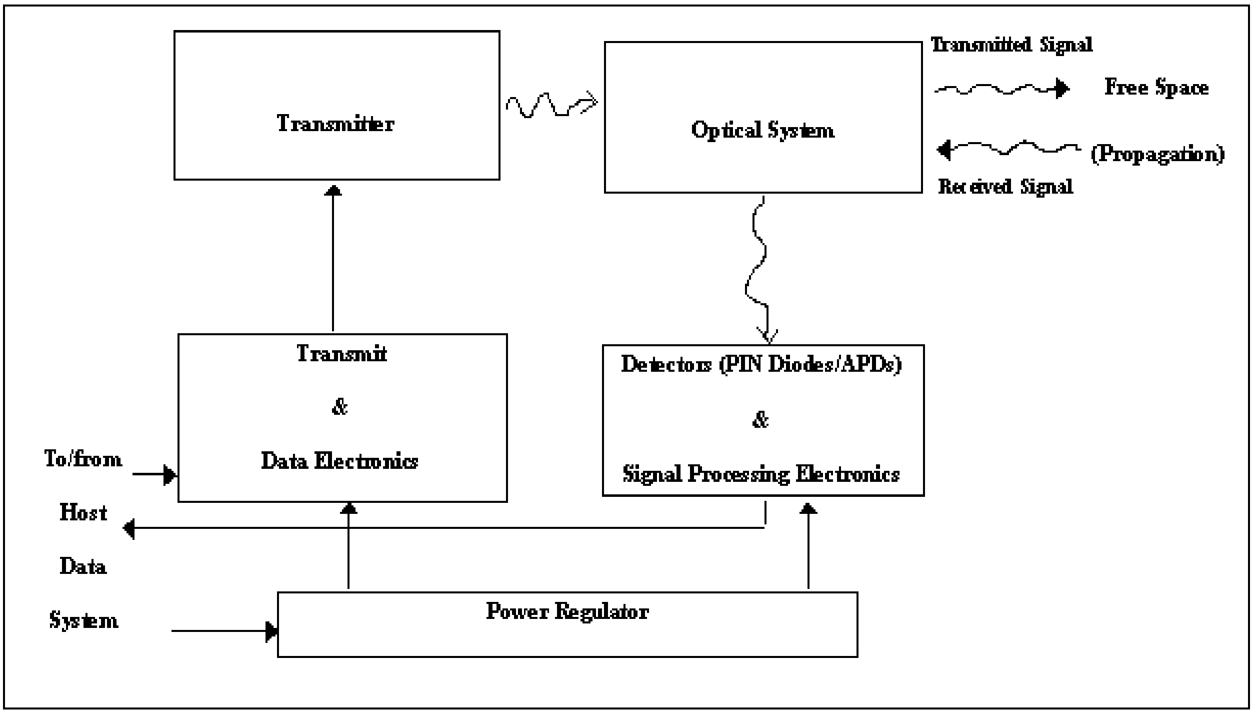

Transmitter
Optical System
Transmitted Signal
Free Space
(Propagation)
Received Signal
Transmit
&
Data Electronics
Detectors (PIN Diodes/APDs)
&
Signal Processing Electronics
To/from
Host
Data
System
Power Regulator

Fig.1

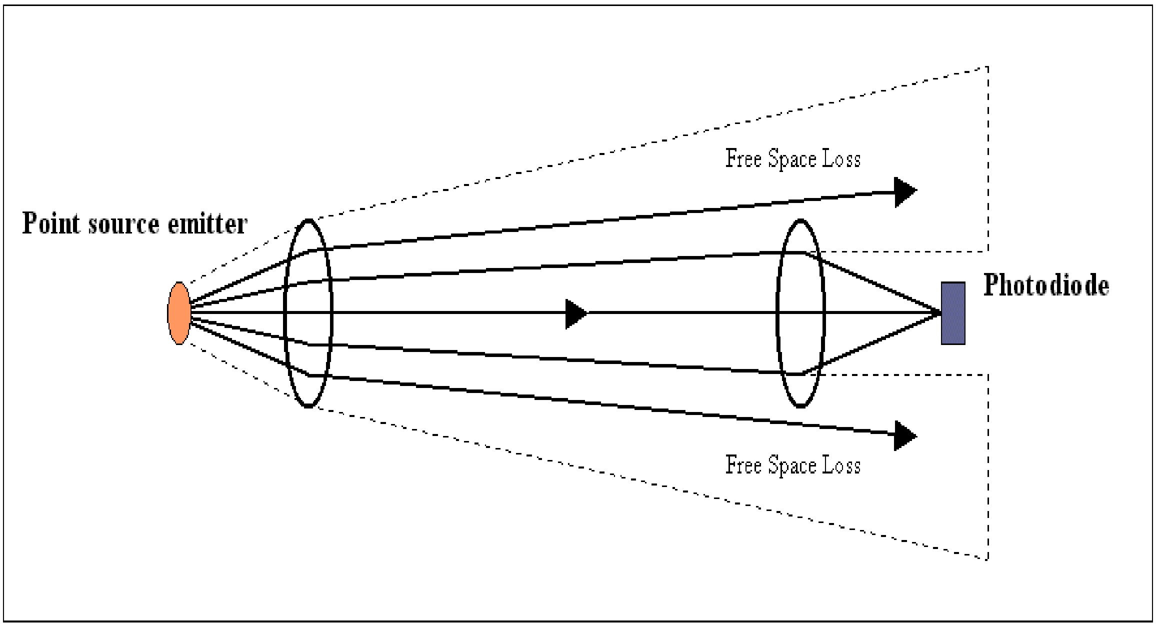

Point source emitter
Free Space Loss
Photodiode
Free Space Loss

Fig. 2

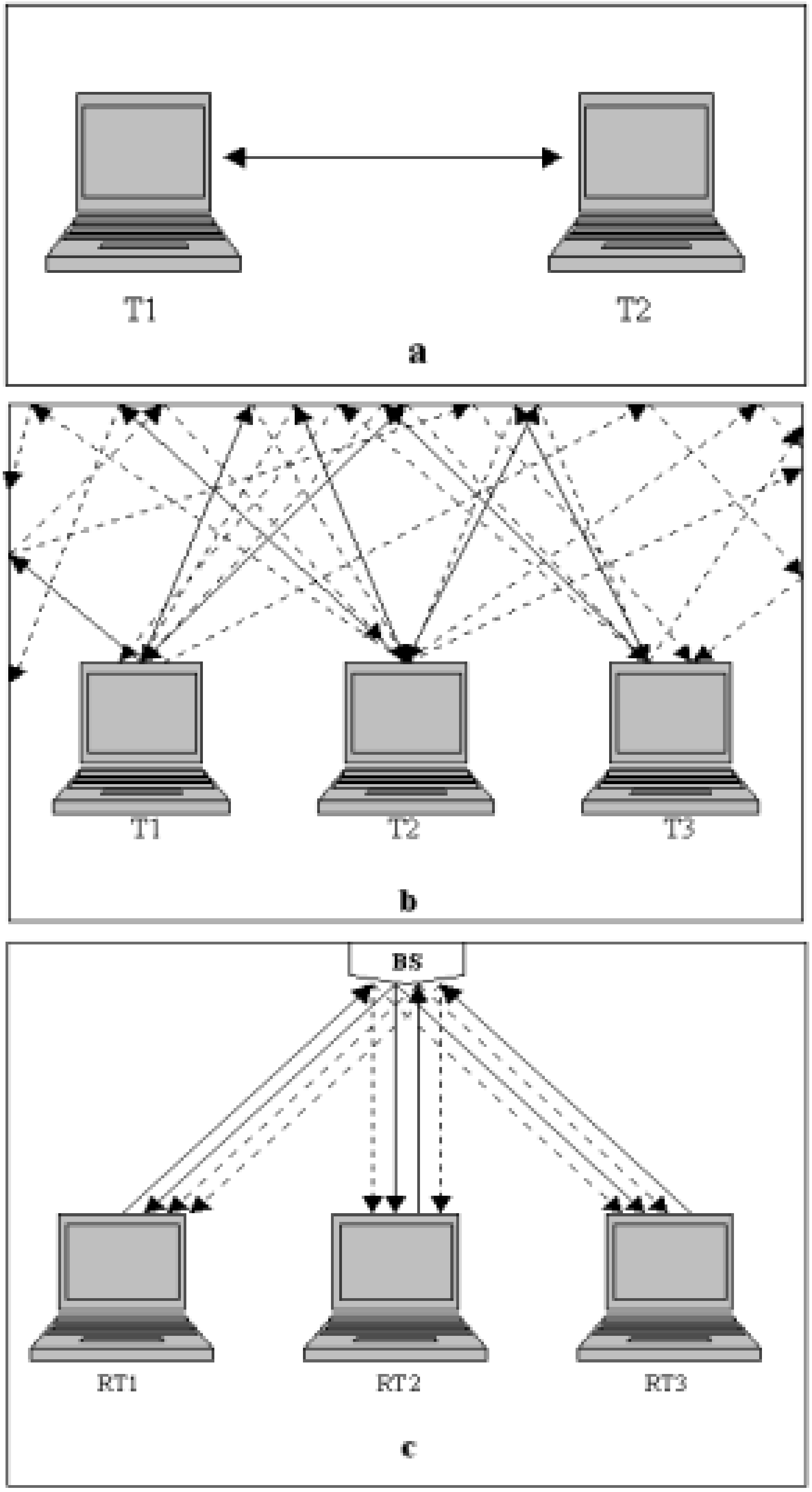


Fig. 3.

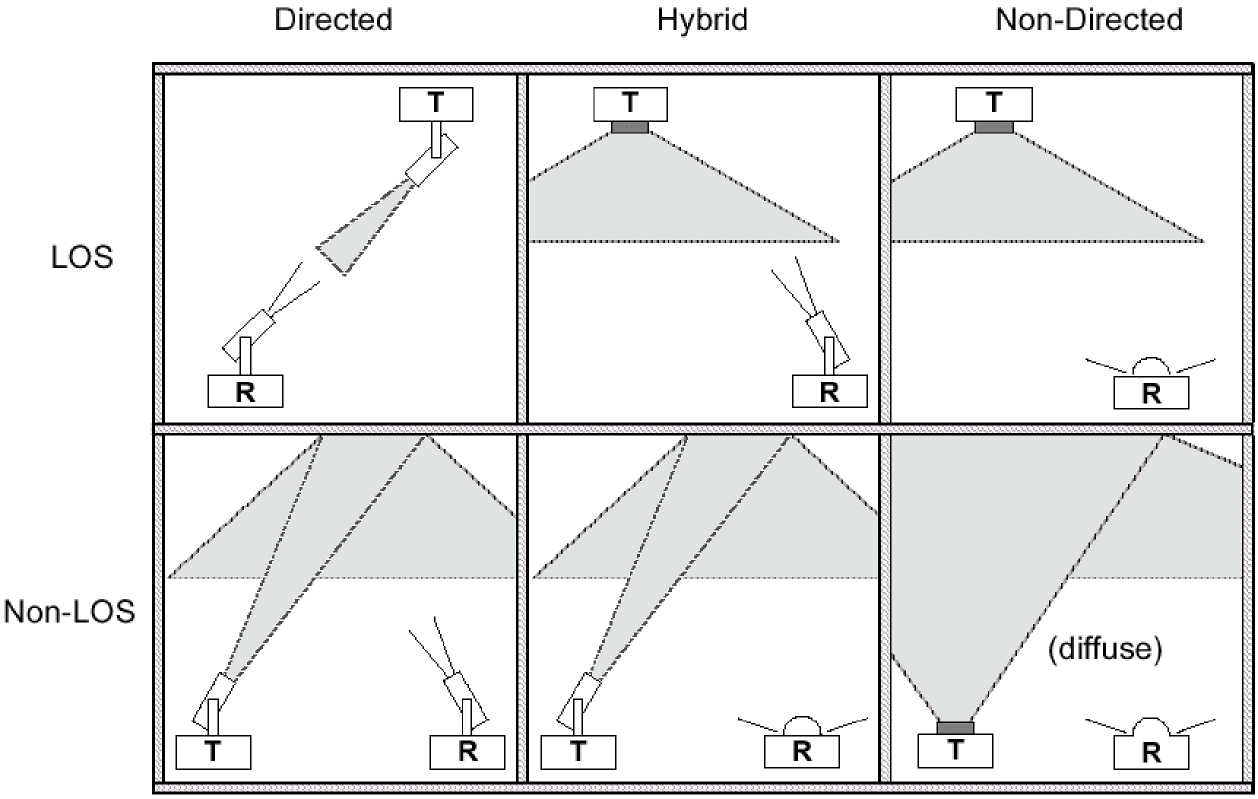


Fig. 4.

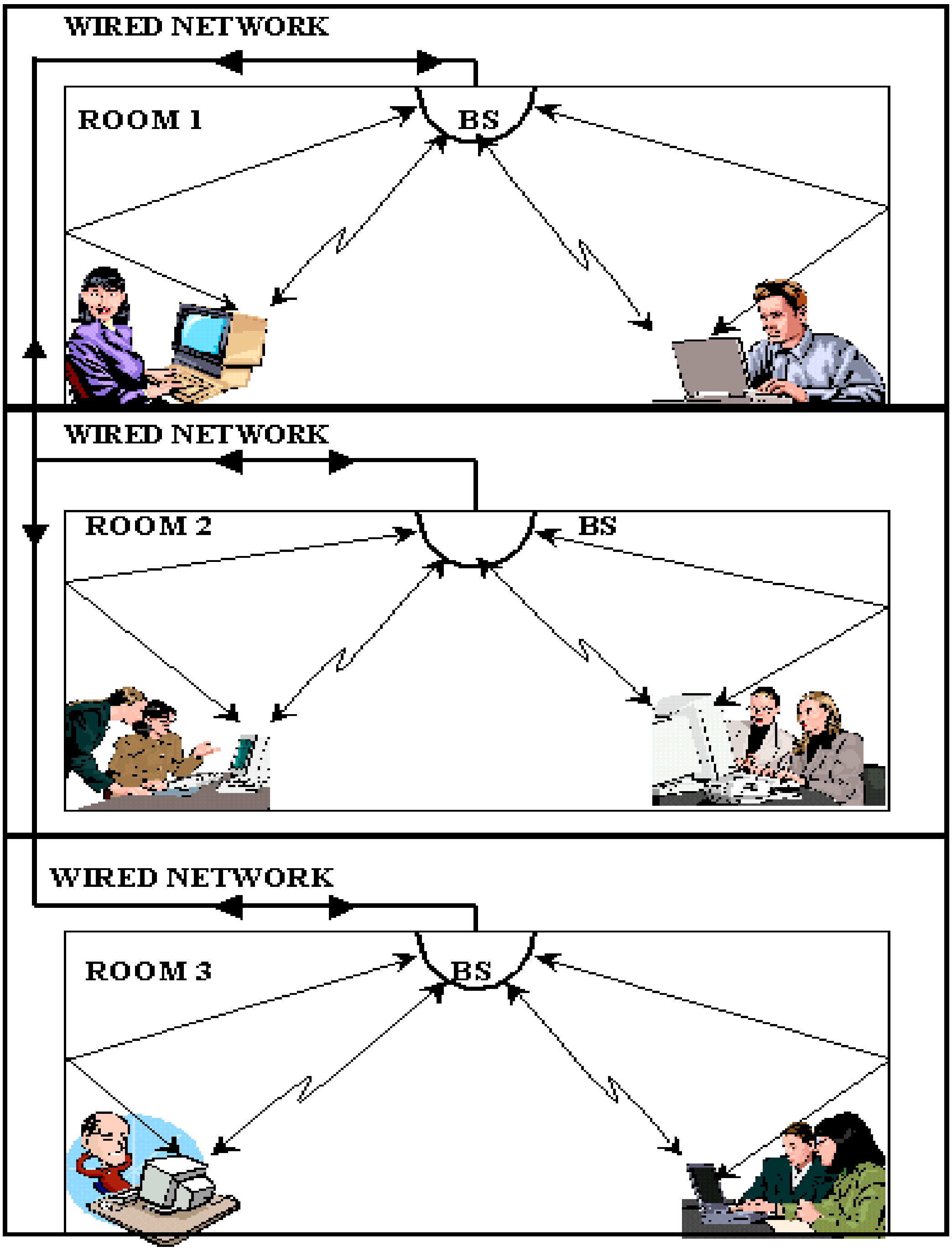

WIRED NETWORK
ROOM 1
BS
WIRED NETWORK
ROOM 2
BS
WIRED NETWORK
ROOM 3
BS

Fig 5.

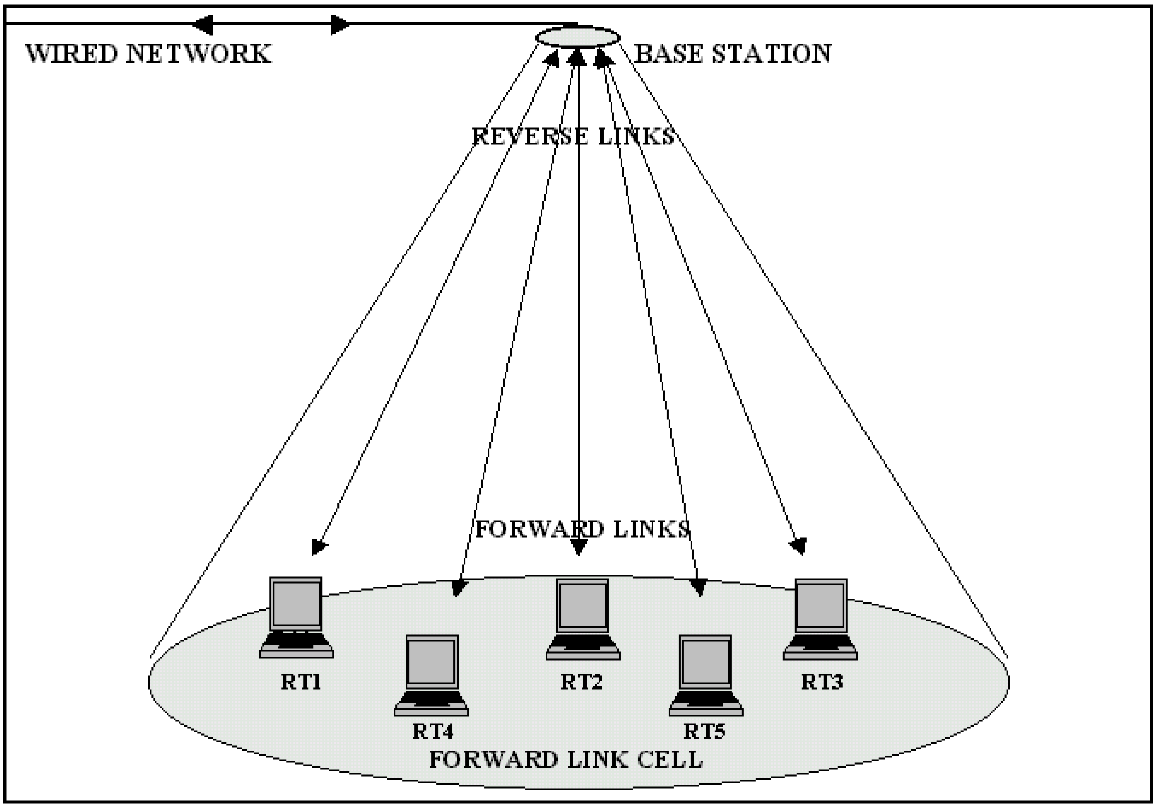
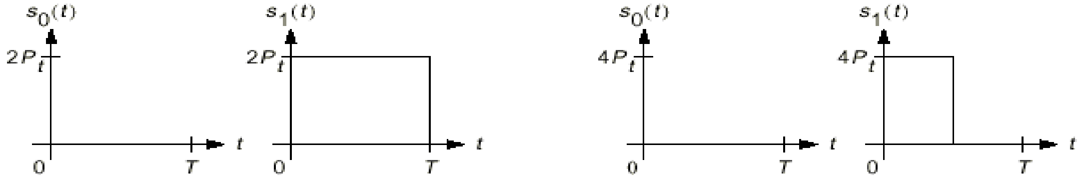

WIRED NETWORK
BASE STATION
REVERSE LINKS
FORWARD LINKS
RT1
RT2
RT3
RT4
RT5
FORWARD LINK CELL

Fig. 6



(a) OOK (NRZ)

(b) OOK (RZ, γ = 0.5)

Fig. 7

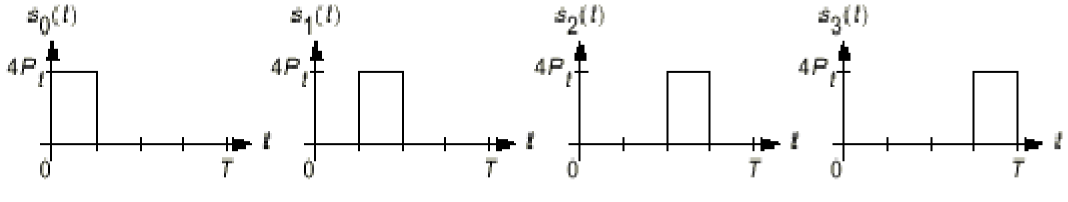
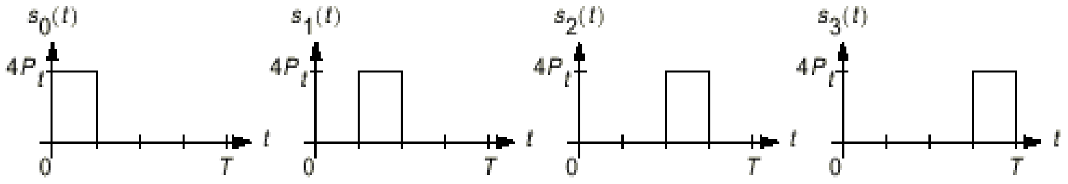
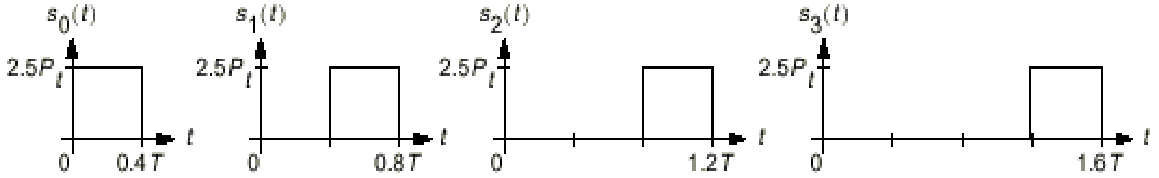


Fig 8



(a) 4-PPM



(b) 4-DPPM

Fig. 9.

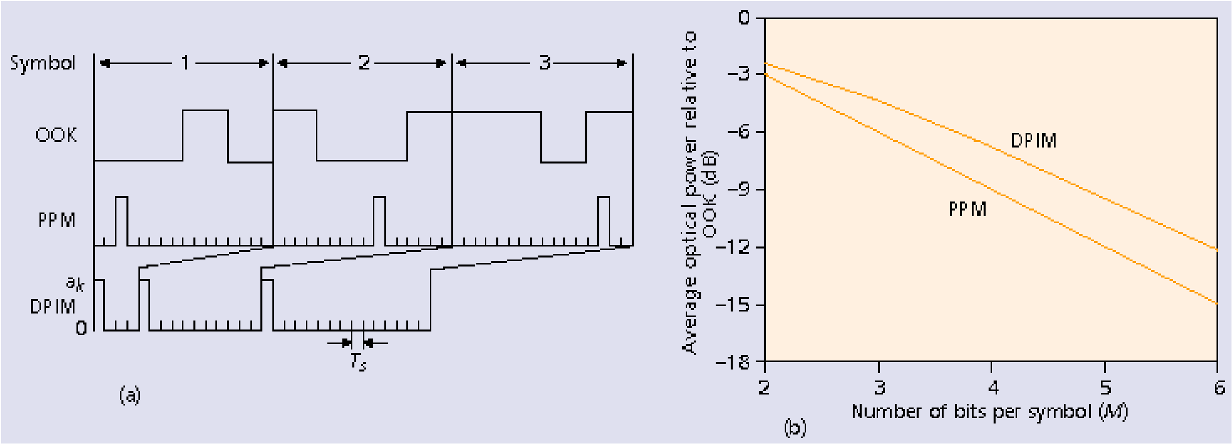


Figure 10

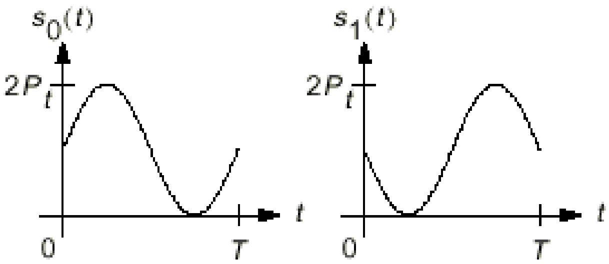


Fig 11

Table 1

Characteristic	Light-Emitting Diodes	Laser Diodes
Spectral Width	25 to 100 nm (10 to 50 THz)	$<10^{-5}$ to 5 nm (<1 MHz to 2 MHz)
Modulation Bandwidth	Tens of KHz to tens of MHz	Tens of MHz to tens of GHz
E/O Conversion Efficiency	10 to 20%	30 to 70%
Eye Safety	Generally considered eye-safe	Must be rendered eye-safe, Especially for $\lambda < 1400$ nm
Cost	Low	Moderate to high

Table 2

Technology	Optical wireless			Radio/Microwave	
	DFIR[a]	DBIR[b]	QDIR	RF[c] (18 GHz)	DSSS[d]/ FHSS[e]
Data rate	<10 Mbps[f]	<150 Mbps[f]	<20 Mbps	5-10 Mbps	2-20 Mbps / 1-3 Mbps
Mobility	Stationary/ portable	Stationary with LOS[g]	Stationary/ portable	Stationary	Stationary/ portable
Coverage (meters)	5-10	20-30	10-20	10-40	30-200 / 30-100
Radiated Power	<0.5 mW	<10 mW	<5 mW	25 mW	<1W
Safety Problems	Significant	Significant	Significant	Just very close to transmitter	Just very close to transmitter
Multipath Fading	No	No	No	Yes	Yes
Technology cost	Medium[j]	Low	Medium[h]	Medium	High

[a] Diffused infrared.

[b] Directed-beam infrared.

[c] Radio frequency

[d] Direct sequence spread spectrum.

[e] Frequency hopping spread spectrum.

[f] Megabits per second.

[g] Line of sight.

[h] it should be low in near future

Table 3.

	650nm (visible)	880nm (infrared)	1310nm (infrared)	1550nm (infrared)
Class 1	< 0.2 mw	< 0.5 mw	< 8.8 mw	< 10 mw
Class 2	0.2 - 1 mw	N/A	N/A	N/A
Class 3A	1 - 5 mw	0.5 - 2.5 mw	8.8 - 45 mw	10 - 50 mw
Class 3B	5-500 mw	2.5-500 mw	45-500 mw	50-500 mw