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Wireless Access Method and Physical Layer Specifications

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SUMMARY

This contribution consists of two papers which were done when the author was with the IBM Thomas J. Watson Research Center. These two papers are:

1. Kwang-Cheng Chen, et al., "Indoor High Speed Wireless Networks via Optical Transmission", International Telecommunciation Union Telecom'91 Technical Forum, Geneva, Siwtzerland, 1991.
2. Kwang-Cheng Chen, "On-Off Keying Optical Transmission and Channel Capacity for Indoor High Rate Wireless Data Networks", Globecom'91, Pheonix, 1991.

Indoor High Speed Wireless Networks via Optical Transmission

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ABSTRACT

We present the results of an ongoing investigation into the realization of free space indoor wireless optical networks for data rates of 10Mbps and above. Physical transmission issues are discussed and two prototype designs are presented. Our results show that it is possible to construct free space optical transceivers for data rates of 10M bps using both direct and diffuse path propagation. We also discuss requirements and possible approaches to multiple access protocols for wireless optical networks.

I. INTRODUCTION

In the late 1980's and early 1990's two new computing trends for the personal computer user have emerged: portability and connectivity. Computers of all types from "Palmtops" to "Laptops" are becoming personal mobile computing devices. Connectivity, especially that of networked communications, is apparent as more and more computer users are connecting their computers to networks of all types from simple bulletin boards to complex client - server computing systems. However, currently these two emerging computing paradigms are at odds with each other as most computer communications, especially for high speed networks, requires a tethered connection to the communication system. Tethered connectivity is inherently incompatible with portability. True portable connectivity can only be provided by wireless communication. Here we concern ourselves with wireless communication which can be used to provide local area network (LAN) function. Furthermore, our intended application is for indoor, or in-building, networks. An important consideration for such networks is that user interface trends are towards graphical user interfaces (GUIs) which will soon be further extended by multimedia enhancements. These new user interfaces often require significant data bandwidths from the LAN and so to bring these interfaces to portables, wireless networks will have to provide at least the capability of common wired LANs such as Ethernet and Token Ring.

Wireless communication is most commonly accomplished by radio frequency (RF) communication techniques. However, limited spectrum availability may constrain the development of high speed (10 Mbps and above) wireless networks. In addition, the indoor RF channel is a difficult channel for coherent communication since it suffers from fast, deep, frequency selective fades, rapid time varying, and very unpredictable characteristics [1]. Low cost, high speed, RF transceivers for the indoor channel will require much innovation and will be difficult to develop. An alternative, especially in indoor environments, which is capable of providing much higher bandwidth and is currently free from regulatory constraints is optical (most likely, infrared) free space transmission. Gfeller [2] at the IBM Zurich research laboratory pioneered the study of free space infrared data networks in 1979. His basic architecture is shown in Figs. 1 and 2. Portables communicate with repeaters which are interconnected by a wired LAN. The available data bandwidth is shared by all interconnected repeaters. Gfeller was able to successfully demonstrate that diffused propagation of optical beams can transmit data between base stations and transceivers. Since then the feasibility of optical wireless data transmission has been investigated by many researchers ([3, 4]). However, very few commercial systems exist. Previous investigations have primarily considered systems with modest data rates usually in the range of 0.1-1 Mbps. Here we report on an investigation at the IBM Thomas J. Watson Research Center into providing high speed (10 Mbps and above) wireless LANs using optical transmission.

Our fundamental network architecture is shown in Figs. 1 and 2 and is similar to Gfeller's original network. We make use of both the direct path and diffused path optical propagation. When direct path propagation is available the range is greater than that when just a diffused path is available. In addition, the diffused path will create multi-path effects in our receiver increasing our bit error rate. However, it is important to provide diffused path capability since blocking of the direct path may occur in practical applications. It is also greatly desirable to avoid an aiming procedure. Hence a wide optical beam is broadcast by the transmitter and a wide field of view at the receiver is used. Two types of base stations are provided. The first is simply a ***repeater*** base station which can be used to extend the coverage area of a cell by repeating the transmission at higher power or by directly communicating over a wired connection to other repeaters which simply rebroadcast the transmission. No processing of data packets is made and the coverage is extended to include all interconnected repeaters. Therefore, the available bandwidth is extended over the combined coverage areas of all repeaters. We define the effective coverage area of a repeater, or base station, as a cell. It is important to note that coverage areas may create overlapping cells. The second type of base station provides store and forward capability and is referred to here as simply a ***base station***. A base station provides the capability to use different protocols in the wired and wireless networks and the base station acts as a bridge between the two networks. The available wireless bandwidth is not shared across all interconnected base stations as is the case with repeaters. Thus, spatial reuse of wireless bandwidth in cells is possible.

An example which could be covered by either repeaters or base stations is shown in Fig. 2. Here each office has a base station or a repeater installed. For a repeater based system, all the data bandwidth of the wireless network is shared by all offices through the interconnecting wired extension. However, in the case of base stations each office is separated and hence can utilize the entire wireless data bandwidth, provided the interconnecting wired network can handle the extra capacity. In an actual implementation the wired and wireless network must be balanced and this will likely be achieved by a mixture of base stations and repeaters.

2. PHYSICAL LAYER TRANSMISSION

In the design of our physical transmission system for the free space indoor optical channel, we have made several assumptions:

1. Wide Beam Transmission: To avoid an aiming procedure, the optical sources at both the mobile units and base stations emit their power into a wide solid angle and receivers have a wide field of view.
2. Propagation: Optical transmission is typically line of sight. However, when the direct path is blocked the signals can be successfully transmitted using a diffuse propagation path.
3. Multi-Path Effects: In addition to the primary propagation path (either direct or diffuse), other secondary propagation paths may create interference power which smears the pulse waveform and results in intersymbol interference.
4. Power Consideration: We intend to minimize the power consumption at both transmitter and receiver in order to maximize the battery life of the mobile units.
5. System Complexity: The network must be applicable to portable personal systems. Hence its hardware complexity must be contained to that which can be implemented by just a few VLSI chips.

2.1 Features and Technical Approaches

Our initial investigations concerned both measurement and modelling of the free space indoor optical channel. A simulation program to model the impulse response of a typical room was created, measurement of potential interfering light sources was made, a thorough review of available device technology was conducted and several prototypes were built and tested. Based on above work, we have the following observations:

1. Indoor lighting, fluorescent and tungsten, at the infrared wavelengths of interest, create electrical power in the receiver at frequencies up to 300 kHz.
2. Output power of 1 W optical from the transmitter is required to adequately "flood" a typical room for optical transmission.
3. Received power falls off rapidly with distance and angle from the transmitting source.
4. Indoor lighting at infrared wavelengths creates incident power at the receiver which is 10^3 to 10^4 times the signal power.
5. Infrared wavelength band pass filters can effectively reduce indoor lighting interference.
6. Most indoor surfaces act as diffuse reflectors with the notable exception of mirrors and windows which provide specular reflection.
7. The single bounce delay spread for most rooms is 10-15 ns, other recent work shows that for multiple bounces the delay spread can be up to 30-40 ns [5].

We further analyzed for physical layer transmission employing on off keying (OOK) modulation [6]. The multi-path propagation was modeled as a channel filter and the net noise (including shot noise, thermal noise, and background noise) was approximated as an additive white Gaussian noise. From the numerical results of this analytical study, we reached the following conclusions:

1. The bit error rate performance depends heavily the received power. The free space indoor optical channel is clearly a power limited channel when direct detection modulation is employed.
2. Utilization of low cost device technology constrains the channel to be bandwidth limited.
3. Utilization of the diffuse propagation path at 10 Mbps is difficult but possible.
4. Low bit error rates like that of wire is possible.
5. Multipath effects cause power leakage to subsequent bit/symbol periods which degrade the bit error rate, especially for high speed transmission systems.
6. Short duration pulses can resist and even take advantage of multi-path effects and hence improve bit error rate.
7. Blocking of the direct path reduces the received power and smears the waveform, enhancing the multi-path effects.
8. Only around 10% channel capacity will be used even for a 10 Mbps system using low cost devices.

The modulation method used is a critical design consideration for the physical layer transmission system design. We consider only noncoherent baseband modulation here due to the difficulty of optical coherent modulation in practical applications. In addition to OOK, pulse position modulation (PPM) is another possibility. Both are well known direct detect modulation techniques with OOK being the most straightforward choice. However, it suffers from [7] the following difficulties:

1. the necessity of an equalizer to alleviate multi-path effects above 10 Mbps signalling.
2. difficulties in determining the optimal detection threshold due to the dynamic range of received power and background noise.
3. difficulties in timing recovery for runs of "1"'s or "0"'s.

The second and third problem can be removed by using Manchester coded signal waveforms and differential detection techniques. Our analysis [6] shows that short pulses with higher instantaneous power such as those used in PPM can dramatically reduce the multi-path effects. It is also possible to use *M*-ary PPM coded with multiple bits per symbol. This could be used to reduce the average transmission power, an important consideration for battery powered equipment, or to create a more powerful pulse for the same average power. It is also possible to install forward error correcting codes in PPM. However, PPM requires finer timing recovery and more hardware complexity, due to the increased bandwidth, than an OOK receiver. Suboptimal detection can also introduce extra error probability.

We have not considered other direct detection methods such as pulse amplitude modulation (PAM) primarily due to concerns in the design of low cost multi-level signalling receivers for our application.

2.2 Prototyping Experience

We have designed two 10 Mbps prototype transceivers; one based on a light emitting diode (LED) transceiver and the second using a laser diode based transceiver. In both designs a standard PIN photodiode is used as the light detector. The LED based unit uses a seven channel receiver, each channel consists of a 1 cm^2 PIN photodiode amplified by a transimpedance amplifier. The channels are then combined to produce a single output. A multiple channel receiver was used to reduce the noise characteristics of a capacitive signal source such as a single large PIN photodiode at 10 Mbps receiver bandwidths. A single channel implementation was tested and verified operational at data rates of 10 Mbps using Manchester encoded OOK modulation. The seven channel receiver is just entering final test. No attempt was made at miniaturization for this prototype hence its shoebox size, a picture of the receiver is shown in Fig. 3.

The second design was created to take advantage of the high switching speeds and narrow wavelengths of a laser diode source. The design concept is to imbed the photodiode detector in a reactive network so that the integral of the impulse response of the network is a "Boxcar" whose duration is one half of the bit interval. The prototype network has eight resonant branches and an array of inductors for the pulse shaping network has been designed as printed circuit board coils. Measurements on this array of coils show that the design of a cost effective PCB based network is possible for a 10 Mbps receiver. This design allows us to use high power short duration pulses from the laser diode, yielding a more power efficient transmitter at lower average output power. The narrow wavelength emission of the laser diode also allows us to create a full duplex system as well as reduce receiver noise through the use of wavelength bandpass filters.

3. MULTIPLE ACCESS PROTOCOLS

In the design of a wireless optical network a medium access control (MAC) protocol must be created for sharing the channel within each cell. The protocol must efficiently utilize the data bandwidth available and handle traffic flow requirements both within and between cells. The MAC protocol must resolve conflicts due to overlapping cells and intracell interference between mobile units. Also the number mobile units and their identities is constantly changing as users of network move about. Hence the MAC protocol must support a new requirement for traditional computer data networks, mobility. For the implementation of multimedia interfaces and applications, the MAC should also provide message priority mechanisms. Cost of implementation is another important factor to consider. A subtle but important requirement for this application concerns the power consumption due to the MAC protocol. If it is necessary to constantly send messages between units to maintain the link then power may be wasted. Hence the MAC protocol must create minimum overhead and ideally would require an active transceiver only when data is being transmitted.

3.1 Possible Medium Access Control Protocols

Code division multiple access (CDMA) is a way to reduce the MAC protocol problem provided a sufficiently large bandwidth is available to assign orthogonal codes to each user. In this case the mobile units simply transmit whenever they have data to transmit. The base station then simply retransmits the message onto the wired network. Note that the base station acts as a repeater but must process the message in order to remove the CDMA coding and conform to the protocol of the wired LAN. One should ensure that only one base station actually repeats the message from a mobile unit, to avoid synchronization difficulties. In addition, the assignment of codes to base stations and mobile units creates a difficult network management problem since a base station or mobile unit can only listen to a finite number of simultaneous codes, all other transmitters appear as noise. Therefore some mechanism must be used to initially register a mobile unit with a base station. Another problem lies in the selection of the CDMA code system to be used. Traditional Gold codes do not work well in noncoherent modulation systems. For optical CDMA, other codes are available, for example, [8] (an optimal, but hardly realizable, code structure), [9] (prime codes for synchronous optical CDMA LANs), and [10] (a modification of [9] for asynchronous CDMA). Another major difficulty for optical CDMA is the lack of optical signal processing technology and integrated optics to support a large spreading ratio (around 1000). Furthermore, high data rates (10 Mbps and above) will require chip rates of tens of GHz. Therefore, while the MAC protocol may be simpler using CDMA, the network structure required above, and the physical layer transmission required below, are greatly complicated. It is not feasible, at this time, to use CDMA for high speed wireless optical networks.

Token passing and polling based schemes provide for conflict free channel access to mobile units within a cell of a wireless data network. Traditionally, these protocols have been used in LANs with stationary users, i.e., both the number of users in a LAN as well as their location is assumed fixed and known *a priori*. However, new problems arise because of mobility of users in a multiple overlapping cell wireless LAN. The primary reason for these problems is the dynamic nature of the mobile unit location. A polling based approach to provide conflict free access for mobile units within a cell follows. In [11], the concept of *registration* of each mobile unit with a base station has been applied. The base station with which a mobile unit is registered is called the *owner* of the mobile unit. The owning base station is responsible for handling all wireless communication needs of the mobile unit. All communication to/from the mobile unit occurs through the owning base station. A base station provides conflict free channel access to the mobile units owned by it. Base stations with overlapping cells must coordinate their MAC protocols. Since users are mobile, the owner of a mobile unit must change as he moves across cells. To handle movement the system must *automatically* define unique owner relationships between mobile units and base stations. This requires:

1. establishment of unique ownership for each mobile unit that becomes active (i.e., turned ON for the first time) in the system
2. automatic and transparent detection of movement of mobile units that cross from one cell to another
3. handling the change of ownership of users as they move from one cell to another
4. mechanisms for assigning a unique owner to a mobile unit that falls in an overlapping area covered by multiple base stations
5. updating owner relationships in local and global directories
6. readjusting routing information pertinent to the mobile unit at the affected base stations

By dynamically maintaining a list of registered users, each base station can provide conflict free access to its registered users.

Carrier sense multiple access (CSMA) and its variants are attractive candidates for MAC in wireless networks. Many protocol implementations are available such as the IEEE 802.3 and widely applied Ethernet standards for wired LANs. CSMA is attractive for wireless applications because mobile units are only active when they have data to transmit. Hence no overhead is wasted in the MAC other than collision resolution. Furthermore, the carrier sense function can be easily created in receivers. Finally, with the addition of collision detection, more efficient bandwidth utilization can be achieved. However, CSMA faces several technical difficulties for wireless optical networks:

1. The mobile units may not be able to hear each other.
2. Collision detection is only possible using code rule violations and addressing mismatches which is less desirable than the traditional voltage detection technique used in wired CSMA-CD networks.
3. Overlapping regions may experience increased jitter due to simultaneous transmissions from multiple repeaters.
4. Extra control mechanism is required to apply CSMA, a random access protocol, to support multi-media applications.

One way to overcome some of these problems is a modification of the well known busy tone solution to solve the hidden terminal problem in CSMA radio networks [12]. The base station can either simply rebroadcast whatever it receives or send an artificial symbol stream as a pseudo carrier when a message is being received. Another possible approach is to add an busy tone period in front of transmission. This tone could be more easily sensed than the data carrier creating a more reliable carrier sense function. It might also be possible to wake up the receiver using this tone.

As we consider various aspects of wireless networking it becomes clear that the primary difficulty is mobility. Most current data network operating systems do not understand the concept of mobility and so must be extended to handle this new requirement. How this is accomplished is currently also under study.

3.2 Physical Layer Considerations

In high speed wireless networks, propagation delay may occupy a significant fraction of bit period. The time difference between transmission and reception and additional timing inaccuracies due to multi-path effects may cause serious synchronization problems. Therefore, robust timing control is an important issue not only in receiver design but also in design of MAC protocols for wireless networks.

Another consideration is that of the well known capture phenomenon in radio networks. Our studies [13] have shown that stronger received signals cause the receiver to ignore the presence of weaker signals in multiple access lightwave networks employing direct detection transmission. This can be used to increase the throughput of the stronger signal but it will create problems in network access for mobile units which have weak received signals.

4.CONCLUSIONS

Free space indoor optical networks provide a cost effective and tremendous bandwidth alternative for indoor environments to the traditional RF approach. Our investigations show that it is possible to build free space indoor optical networks for data transmission at data rates up to 10 Mbps using both direct and diffuse propagation paths. Specific directions toward efficient physical layer transmission and medium access control schemes have been pointed out. Furthermore, network operating systems should be extended to transparently handle the problem of mobility by portable users.

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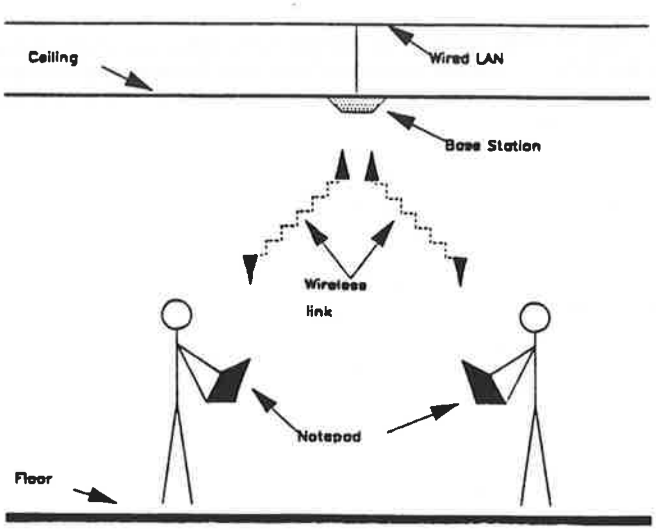

Figure 1 Indoor Wireless Optical Networks

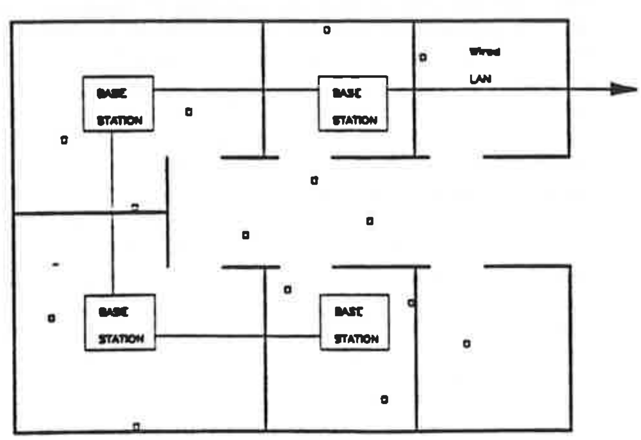

Figure 2 Floor Plan of Indoor Optical Wireless

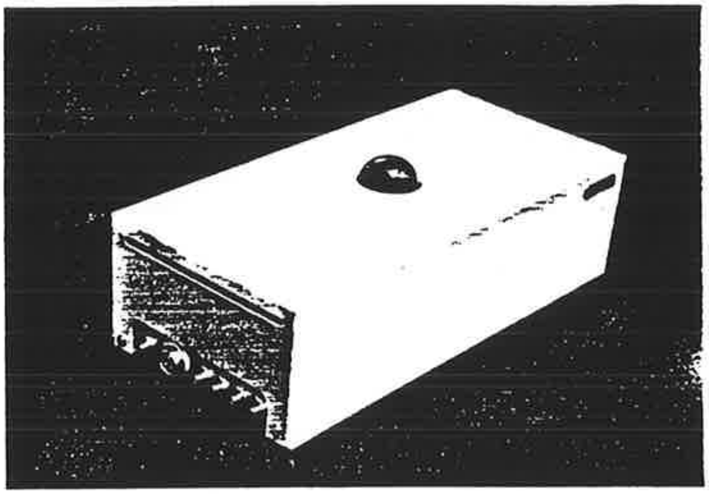

Figure 3 Prototype of Infrared Transceiver for Wireless Optical Networks

Biography

Kwang-Cheng Chen received B.S. from the National Taiwan University, Taipei, Taiwan in 1983, and M.S., Ph.D in 1987, 1989 from the University of Maryalnd at College Park, all in electrical engineering. He was an instructing official for military service during 1983-1985. He worked on satellite communications with the Satellite System Engineering Inc. and the COMSAT Corp. from 1987 to 1989. Since 1989, Dr. Chen has been with the IBM Thomas J. Watson Research Center to work on high speed wireless data networks. His research interests include communication theory, communication networks, and signal processing.

Peruvemba Balasubramanian joined IBM in 1966. Dr. Balasubramanian is currently the manager of Exploratory Workstation group at the IBM Thomas J. Watson Research Center.

Serafino Carri has been working in the diverse electronics field for 7 years such as industrial applications, medical electronics, and most recently in parallel computing, advanced notebook computers, and wireless communication projects with the IBM Thomas J. Watson Research Center.

Kenneth W. Case has been with IBM over 27 years. He is currently a Senior Associate Engineer at the Thomas J. Watson Research Center. Mr. Case designed control equipment utilized in research experimentation and assisted in the design and testing of the 801 machine and other digital devices. Previous to IBM, he worked for General Precision Inc. for 7 years on various aviation systems and air traffic control processing systems.

Colin G. Harrison studied Electrical Engineering at the Imperial College of Science and Technology at the University of London and at Ludwig Maximilians University, Munich. He obtained his Ph.D. in 1973 for studies of micromagnetic structures in thin single-crystals of nickel. He joined IBM General Products Division in 1979 in San Jose to work on detector problems for magnetic bubble memories and in 1981 began to lead a research project for IBM Instruments, Inc. in the area of medical imaging. He joined the Research division in 1988 in the ACE multiprocessor workstation project and has since been one of the instigators of the development of the notepad computer with handwriting input and wireless communications.

Peter D. Hortensius was born in Regina, Saskatchewan, Canada on June 24, 1960. He received the B.Sc.E.E., M.Sc., and Ph.D. degrees in 1982, 1985, and 1987 all from the University of Manitoba. He join the IBM T.J. Watson Research Center as a Research Staff Member in 1987. Dr. Hortensius is currently a member of the Workstation Design Group. His research interests include portable system design, wireless communication, system architecture, IC design and testing, interprocessor communication, and computer applications to the handicapped.

Scott Kirkpatrick received his A.B. degree from Princeton University and his Ph.D. degree from Harvard, both in physics. Since joining the IBM Research Division in 1971, he has been at the Thomas J. Watson Research Center, Yorktown Heights, NY. His research led to work on design automation for VLSI and optimization by simulated annealing, and subsequently to managing activities for advanced personal computers in the Computer Sciences Department. He is presently responsible for activities leading to prototypes of critical technologies for portable workstations with new functions, in the Computer Sciences Department. Dr. Kirkpatrick is a Fellow of the American Physical Society. In 1987, he received (jointly with Dan Gelatt) the American Physical Society's Prize for Industrial Applications of Physics. He is also a Fellow of the American Association for the Advancement of Science (1989).

William McGarry received a B.S in Physics '49 from Carnegie Mellon, joined Schlumberger Well Surveying Corp as an oil field geophysicist, and from '52 to '58 in their research laboratory in Richfield Ct. In that period, he attended Columbia University taking graduate courses in Mathematics and Control theory. In 1958, he joined Data Control Systems to develop fm data-acquisition equipment for the aerospace market. In '67, he coauthored the FM-Telemetry chapter of McGraw-Hill's Handbook of Telemetry and Remote Control. From '70 to '78, he worked as a consultant applying experience gained with VCOs,PLLs and signal-processing to the design of "PCM Bit-Synchronizers" while he designed Aydin Monitor Systems the bit-synchronizer for NASA's initial LANDSAT system and other computer-controlled communication NASA systems. In 1978, Mr. McGarry joined IBM Thomas J. Watson Research Center.

Kadathur S. Natarajan is Research Staff Member in the Computer Science Department at the IBM Watson Research Center, New York. He received his B.Tech from Indian Institute of Technology, Madras. M.E. from Indian Institute of Science, Bangalore and Ph.D. from Ohio State University, Columbus, OH. During 1981-83, he worked at ConTel/Network Analysis Corporation, Great Neck, NY, on design and development of analysis and optimization algorithms for voice and data communication networks. Since joining IBM in 1983, Natarajan has worked on design and performance evaluation of communication networks, videotext systems and parallel algorithms for optimization problems. His current research is developing new wireless communication network architectures and protocols for the support of mobile users. He is a member of IEEE Computer Society and IEEE Communication Society.

On-Off Keying Optical Transmission and Channel Capacity for Indoor High Rate Wireless Data Networks

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Abstract

High speed wireless data networking for portable and mobile facilities in indoor environments is an attractive task for information industry. In this paper, we consider high speed direct-detect optical on-off keying transmission in the physical layer of indoor wireless data networks and provide analytical tools to reveal the relationship among bit error rate, transmission rate, power, system and channel parameters, various noise sources and multi-path effects. Both direct-path and diffused propagations are possible for successful transmission. Further, practical design issues such as blocking, optical pulse duration, and timing jitter, are described. Typical numerical results are presented. Information theoretical capacity of indoor Gaussian channel with multi-path is also calculated to illustrate the fundamental limit to adopt this approach.

I. Introduction

Portable computing using 'laptops', 'notebooks', or 'palmtops' is becoming more pervasive and more computationally powerful. However, currently, when one uses a portable computer, the increasing vital communication link to computer networking still relies on tethered connection to common local area networks such as Token Ring and Ethernet. Flexibility and portability which are critical features of portable computing are restricted by such a communication environment. Reliable wireless networking to support portable computing and relevant functions becomes an important task to enhance portable computing. Multi-access wireless communication is typically accomplished using radio frequency (RF) communication techniques. An alternative for an indoor environment such as an office building which can potentially provide much higher data bandwidth and is immune to the regulatory problems of RF communication is optical transmission (most likely, infrared). Many earlier investigations have been conducted [1-3]. However, there still lacks analytical work in open literatures to evaluate the capability of this approach so that people can compare with its RF counterpart. In this piece of research, we would like to investigate the possibility to apply wide-beam free space optical transmission via both direct-path propagation and diffusion to achieve high data rate reliable communication. Due to the economic difficulties of coherent optical communication systems and associated severe multi-path fading in indoor environments, we intend to concentrate on direct detect on-off keying (OOK) modulation as the first step research in this topic.

Being similar to the pioneer investigation of indoor infrared data networks by Gfeller [1] at the IBM Zurich Research Laboratory, the proposed system design is shown in Figure 1. Here we have a base station which is typically (not necessarily) attached to the ceiling and is connected to an established wired local area network. Each computer or terminal has a transceiver which communicates with the base station via an optical (most likely infrared) channel. The primary propagation path is the direct path between the transceiver and base station. If such a direct path does not exist then a diffuse propagation path is also possible. For the indoor environment, the IR channel is adversely affected by sunlight, fluorescent lamps, other ambient light sources, and multipath dispersion due to the physical size of room. Here we extend this work using a mathematical model to analyze bit error rate performance in communication links between base station(s) and transceiver(s).

II. Basic Assumptions, Definitions, And Signal-To-Noise Ratio

Basic Assumptions

1. Point source.
2. Direct path is the primary propagation path. If the direct path is not available, diffuse channels may be available (see Figure 2).
3. Baseband OOK (On-Off Keying).
4. Direct detection receiver with an ideal photodiode that can convert every received photon to a corresponding unit of output current. This unit current which is correspondingly caused by 1 mW received optical power is the unit of all variables mentioned in this paper, unless specifically claimed. In this paper, power values are all normalized unless specified and all can be converted to real watts by appropriate calibration.
5. The source emits bits '1's and '0's independently and with equal probability.

Transmitter Parameters

P_t Isotropic optical transmission power.

G_t Optical transmitting antenna gain. Let Ω_t be the solid angle occupied by the constrained optical beam of the point source. Then,

$$G_t = \frac{4\pi}{\Omega_t} \quad (1)$$

Channel Parameters

R Distance between transmitter and receiver.

L_p Path loss.

$$L_p = 4\pi R^2 \quad (2)$$

Receiver Parameters

θ Angle between optical beam and tangential surface of receiver, where the transmitter has to be within the field of view (FOV) of the photodetector of the receiver.

L_{point} Pointing loss due to the misalignment of setting up the system.

A_r Effective area of optical detector.

G_r Optical receiving antenna gain.

L_s Synchronization loss. Denote T to be the bit period and τ to be the timing error. The average energy inaccuracy due to timing error for bit decision is $\frac{\tau}{2T}$. The worst case inaccuracy is $\frac{\tau}{T}$.

L_d Loss due to waveform distortion and system degradation.

G_a Amplifier gain.

η Optical-electrical conversion efficiency (quantum efficiency).

Noise Sources

N_0 Thermal noise.

N_I Interference power from other sources and multipath lambertian reflections.

N_b Background noise including dark current and ambient light coming from the side lobes of 60 Hz power sources.

N_s Shot noise.

1 This work was done when the author was with the IBM Thomas J. Watson Research Center.

Signal-To-Noise Ratio

The received power, P_r, is

$$P_r = \frac{P_t G_t}{L_p} A_r G_r \cos\theta \quad (3)$$

Define the net gain of the receiver, g, to be

$$g = \frac{\eta G_a}{L_s L_{point} L_d} \quad (4)$$

Because a wide optical beam (30° – 60° at least) is to be used, pointing loss should be small and can be ignored. $L_{point} \simeq 1$, and

$$g = \frac{\eta G_a}{L_s L_d} \quad (5)$$

The final signal-to-noise ratio before bit decision, $\frac{S}{N}$, is approximately

$$\frac{S}{N} \simeq \frac{g P_r}{N_0 + (N_i + N_b) g + N_s} \quad (6)$$

N_i is considered as a stochastic noise source in above equation. It may act as a dc offset and have contribute as a part of signal energy if the reflection delay is less than a bit period. (6) is useful in link budget calculations.

III. More Precise Link Analysis Including Multipath

(6) just provides a rough expression of signal-to-noise ratio. The exact situation is more complicated. Further, the signal-to-noise ratio does not represent the actual system performance since the bit error rate is what we really want to know. In this section, bit error rate is computed by considering a detailed mathematical model.

Background Noise

In addition to background Gaussian white noise which can be handled in term of N_0 in our model, dark current and ambient light are primary sources of background noise. Here the dark-current is (much) smaller than the ambient light and can be considered as a small DC offset which plays a minor role as a noise source. However, ambient light is a strong noise source to our link and has significant effect on bit decision process. Denote the power of ambient light to be N_{amb} and equivalent power of dark-current to be N_{dark}. If $N_{dark} \ll N_{amb}$,

$$N_b \simeq N_{amb}$$

Decompose N_b as

$$N_b = N_{b,d} + N_{b,s} \quad (7)$$

where $N_{b,d}$ denotes the deterministic part and $N_{b,s}$ denotes the zero-mean stochastic part of background noise. A practical way to decompose N_b is to define a narrow-band process as the deterministic part and a wide-band process as the stochastic part. Interference with extra propagation delay less than a bit period may be considered as a part of $N_{b,d}$.

Multipath Interference

We model multi-path effects as passing waveform to a channel filter whose impluse response is determined by the characteristics of certain room. Based on a computer program to simulate the impulse response of a room resulted from the reflections which was developed at the IBM Thomas J. Watson Research Center by Hortensius [4], the impulse response denoted by $h(\tau)$ has the following properties:

- $h(0)$ represents the power transmitted via direct-path. To simplify our equations, $h(0) \equiv 1$.
- $h(\tau) = 0,\ \tau < 0$.
- The physical meaning of $h(\tau)$ is that the fraction of reflected power through the path(s) with extra time delay τ compared to the direct-path. Except for very rare cases, $h(\tau) \leq 1,\ \tau > 0$.
- For a 10M bps system. (A more complicated consideration is required for data rates higher than 50M bps.) $\tau = 1$ (with the unit of bit period) means an extra propagation of 30 meters. Therefore, it is reasonable to assume that $h(\tau) = 0,\ \tau > 1$.

Since we are considering direct-detection IR links, the only interference concern is the detected energy. Since the unit time is considered in this paper, it is equivalent to received power. The situation here is different from that encountered in coherent communications.

The effect of the multipath spreading function (or the impulse response of a specific room), $h(\cdot)$, is equivalent to passing the signal waveform through a filter with impulse response $h(\cdot)$. Thus, the signal waveform at the receiver for bit "1" is

$$s_1(t) = w(t) \otimes d(t) \otimes h(t) \quad (8)$$

where $\otimes$ denotes the operation of convolution; $w(t)$ denotes the ideal rectangular waveform of OOK for bit "1", $d(t)$ denotes the impulse response of an equivalent filter with waveform distortion set to be $\delta(t)$ and its effect is counted in waveform distortion, L_d, and *vice versa*.

In this situation, $s_1(t)$ occupies the time duration from 0 to $2T$ and we define

$$f_{1b} = \frac{\int_T^{2T} s_1(t)\, dt}{S} = 1 - f_{1a} \quad (9)$$

where

$$S = \int_0^{2T} s_1(t)\, dt$$

$s_0(\cdot)$, the signal waveform at the receiver for bit "0", is always zero.

Multi-path effects which may increase the total received energy within one bit period are not completely destructive in direct-detection optical communication systems. Recall that P_r is actually the power due to direct path propagation. Let us define ρ as the power gain due to multi-path effects.

$$\rho = \frac{S}{P_r}$$

ρ is determined by $h(\cdot)$ if $d(\cdot) = \delta(\cdot)$.

Bit Error Rate

If the previous transmitted symbol is "1" then symbol immediately it will be affected since $s_1(\cdot)$ may occupy up to 2 bit periods, that is, the power may leak into the next bit period due to multipath and channel imperfections. Let us assume that a photodiode is used to transform optical power into electrical current via the mechanism shown in Figure 3. and denote I_r to be the output current.

Without any *a priori* statistical information of channel, the decision threshold, ξI_r, is chosen as $I_r/2$.

The net stochastic noise, $\tilde{N}$, is

$$\tilde{N} = N_0 + N_s + g N_{b,s} \quad (10)$$

where we assume N_0, N_s, and $N_{b,s}$ are independent each other and the voltage distributions

$$N_0 \sim G(0, \sigma_0^2) \quad N_s \sim G(0, \sigma_s^2) \quad N_{b,s} \sim G(0, \sigma_b^2)$$

The distribution function of $\tilde{N}$ is a zero mean Gaussian with variance $\sigma^2 = \sigma_0^2 + \sigma_s^2 + g^2\sigma_b^2$.

Let a_m be the $m$the transmitted symbol which is either "1" or "0". Denote r to be the input of optical OOK bit decision unit. For the mth bit,

$$r = g(a_m f_{1a} I_r + a_{m-1} f_{1b} I_r + N_{b,d}) + \tilde{N} \quad (11)$$

where $r \geq 0$. Let $v^2 = \sigma^2/g$. The bit error rate, P_e, is

$$P_e = \frac{1}{4}\left[Q\left(\frac{(1-\xi)I_r + N_{b,d}}{v}\right) + Q\left(\frac{(\xi - f_{1b})I_r - N_{b,d}}{v}\right) + Q\left(\frac{(f_{1a} - \xi)I_r + N_{b,d}}{v}\right) + Q\left(\frac{\xi I_r - N_{b,d}}{v}\right)\right] \tag{12}$$

Some typical numerical results of (12) are shown in Figure 4 and 5 to demonstrate the link performance of wireless infrared communications. Figure 4 is plotted according to the data that 1 W normalized power from the direct path effectively hits the photodiode. The stochastic noise, N, has the effect equivalent to that produced by 1/15 W; $N_{b,d}$ also has the effect equivalent to that produced by 1/15 W. Figure 5 is plotted according to assumptions that the same noises as those in Figure 4; the transceiver is in a typical position of a typical office room; $\eta = 1$. We assume that $\rho\eta = 1$ in both figures. Although electrical-to-optical efficiency at the transmitter and the waveform distortions other than multi-path fading are ignored here, they can be included by changing numerical results by an appropriate factor.

Actually, (12) can tell us a lot about how link parameters affect the system performance. Look at the stochastic noise term first.

$$\lim_{g \to \infty} \frac{\sigma^2}{g^2} = \sigma_b^2$$

The background noise plays an asymptotically important role in noise sources. However, the thermal noise from the amplifier and the shot noise are also increasing functions as the gain increases. Their effects cannot be ignored even in asymptotical cases. Second, P_r varies within a dynamic range in our system design, so is I_r. Without *a priori* information or estimation of ξ, the decision threshold, ξI_r cannot be properly chosen. Thus, multipath has a very adverse affect on the bit error rate even when f_{1b} (fraction of power leakage) is small.

IV. More On Analysis

Decision Threshold

If we treat ξ to be the only variable in (12), the optimal value of ξ can be solved by the typical optimization procedure. Let $\hat{\xi}$ be the value of P_e to achieve minimum.

It is straightforward to reach

$$\hat{\xi} V_r = \frac{V_r}{2} + N_{b,d} \tag{13}$$

, which is independent of f_{1a}, σ^2, and g. However, P_r (thus, V_r), ρ, and $N_{b,d}$, are actually unknown system parameters with large dynamic ranges in various environments. (13) partially solves the whole problem. An optimal robust decision scheme derived from incomplete *a priori* information of P_r, ρ, and $N_{b,d}$ or a dynamic decision algorithm which is capable of learning the communication link environments is necessary to build up a practical infrared wireless communication system with a power limit constraint [5].

Direct-Path Is Blocked

In practical operations, the direct-path may be blocked due to many possible reasons. In our proposed system design, certain diffuse channel is supposed to replace the direct-path as a primary propagation path. The bit error rate in such an environment is analyzed under the assumption that the perfect timing is available.

The effect of blocking the direct path is equivalent to multiplying a weighting function, $g(t)$, with the unblocked impulse response of room. The resulting impulse response of room is

$$\zeta(t) = h(t) \cdot g(t)$$

Generally speaking, $g(t) \leq 1$ but not necessarily to be so in every case. The resulting signal waveform at the receiver for bit "1" is

$$s_1(t) = w(t) \otimes d(t) \otimes \zeta(t) \tag{14}$$

The fraction of leakage power to next bit period is

$$f_{1b} = \frac{1}{S}\int_T^{2T} s_1(t)\, dt = 1 - f_{1a}$$

The bit error rate, P_e, has exactly the same expression as (12) with above modifications. Some typically numerical results are plotted in Figure 6 and Figure 7. The channel impulse response in Figure 6 represents typically slight multi-path effects in a room. The channel impulse response in Figrue 7 represents stong but not disastrous multi-path effects. Both cases that direct-path is unblocked and blocked are shown. The blocking of direct path can cause degradation of system performance. However, we may futher observe that multi-path effects are not always unwanted due to the power gain factor ρ which accounts for extra optical power brought in via multi-paths, although the multi-path effects do degrade the performance under the same lumination.

Narrow Pulses

Above numerical results proceed on the assumption that $w(t) = \Pi(0, T)$ which means a rectangular waveform with duration of T. A good way to yield better system performance is to apply pulses with short time duration (that is, narrow pulses in time domain). The rationale is to allocate more power into the same bit period and avoid power leakage to the next bit period. Denote the pulse duration to be τ_p which is less than T, the bit period. In (8), $w(t) = \Pi(0, \tau_p)$. Figure 8 shows the bit error rate of OOK with 20 nsec wide pulses at the beginning of each bit.

We can observe significant improvement by using narrow pulses. This will make higher data rate (20-30 Mbps or higher) systems more realizable. It also suggests us that PPM may be a good alternative because of multi-path consideration in addition to power efficiency.

Timing Error On Bit Error Rate

We can also consider the exact timing inaccuracy in this analysis by taking 3 bits into consideration and modifying the integration range of f_{1a} and f_{1b} with a time shift of τ. It is natural to confine $|\tau| < T/2$. Furthermore, τ follows a random variable in general. Define

$$\tau^+ = \max(\tau, 0) \qquad \tau^- = \min(\tau, 0)$$

(9) is modified as

$$f_{1a} = \frac{1}{S}\int_{\tau^+}^{T+\tau} s_1(t)\, dt \qquad f_{1b} = \frac{1}{S}\int_{T+\tau}^{2T+\tau^-} s_1(t)\, dt$$

$$f_{1c} = \frac{1}{S}\int_0^{\tau^+} s_1(t)\, dt \qquad f_{1d} = \frac{1}{S}\int_{2T+\tau}^{2T} s_1(t)\, dt \tag{15}$$

Therefore, (11) has to be modified as

$$r = g[(a_m f_{1a} + a_{m-1} f_{1b} + a_{m+1} f_{1c} + a_{m-2} f_{1d})V_r + N_{b,d}] + \tilde{N} \tag{16}$$

Since $\{a_m\}$ is an i.i.d. sequence of random variables, the bit error rate is

$$P_e = \frac{1}{2} E_\tau E_{a_{m-1}} E_{a_{m+1}} E_{a_{m-2}}$$

$$\{Q[\frac{(f_{1a} + a_{m-1} f_{1b} + a_{m+1} f_{1c} + a_{m-2} f_{1d} - \xi)V_r + N_{b,d}}{v}] + Q[\frac{(\xi - a_{m-1} f_{1b} - a_{m+1} f_{1c} - a_{m-2} f_{1d})V_r - N_{b,d}}{v}]\} \tag{17}$$

where the subscript of an expectation operator, E, means to take expectation with respect to the associated random variable denoted by that subscript. As earlier assumption, $Pr\{a_m = 1\} = Pr\{a_m = 0\} = 1/2$. We also can observe that $f_{1c} = 0$, $\tau < 0$ and $f_{1d} = 0$, $\tau > 0$ to simplify calculations.

To make, this analysis suitable for very high data rates (greater than 50M bps in a typical room) systems, equations (15) and (16) can be changed to consider more previously transmitted bits.

V. Capacity of Indoor Gaussian Channel

The net effect of all noises in above analysis is approximately as an additive white Gaussian noise. The channel capacity of such a band-limited channel is well known as

$$C = W \log_2(1 + \frac{S}{N}) \qquad (18)$$

where W is the available bandwidth.

However, since there is an extra channel filter $h(\tau)$ in modeling indoor optical channels, we are interested in knowing the channel capacity in this situation, and consequent transmission limit. Due to practical restrictions on devices and circuits in system design, this is a case of band-limited communication and only certain bandwidth, say W, is avialble. According to a well known result from information theory [6], the capacity at cost S of a channel with additive Gaussian noise of spectrum $N(f)$ and channel filter $H(f)$ can be given in terms of a parameter θ by

$$C(S) = \frac{1}{2}\int_{-\infty}^{\infty} \max[0, \log\frac{\theta}{N(f)\,|H(f)|^2}]\,df \qquad (19a)$$

$$S = \int_{-\infty}^{\infty} \max[0, \theta - \frac{N(f)}{|H(f)|^2}]\,df \qquad (19b)$$

We assume the channel filter has the impluse response $h(\tau)$ as

$$h(\tau) = e^{-\alpha\tau}[U(\tau) - U(\tau - T_0)] \qquad (20)$$

where $U(\cdot)$ is the unit step function, and α, T_0 are constants. The physical meaning of T_0 is that $h(\tau)\simeq 0$ when $\tau \geq T_0$. (20) is a good example to illustrate the capacity for such a channel.

We further assume an ideal low pass filter with cutoff frequency W. It is equivalent to finding the channel capacity over this band-limited Gaussian channel with bandwidth W. Denote the normalized Fourier transform of $h(t)$ to be

$$H(f) = \frac{1 - 2e^{-\alpha T_0}\cos 2\pi f T_0 + e^{-2\alpha T_0}}{1 + (\frac{2\pi}{\alpha})^2 f^2} \qquad (21)$$

The noise spectrum after low pass filtering can be represented by

$$N(f) = \begin{cases} N_0/2, & f \in [-W, W] \\ 0, & elsewhere \end{cases} \qquad (22)$$

Though a closed form representation of channel capacity is impossible, it can be calculated numerically. Figure 9 depicts the capacity of a typical indoor optical channel where $W = 20MHz$, $T_0 = 15$ nsec, and $\alpha T_0 = 3$.

VI. Remarks And Conclusions

This theoretical analysis takes all important noise sources and multi-path effects into considerations. For indoor wireless optical communications, multi-path may possibly affect link performance significantly. The effects increase when data rate becomes higher. With OOK modulation, multi-path fading can severely degrade system performance at mildly high data rates if there is no further coding and/or signal processing schemes available.

Our numerical examples do not count the degradations from waveform distortion due to filtering, synchronization loss, and so on. This implies that wireless indoor optical communications applying OOK require more efforts to make them suitable for higher data rate transmissions. In spite of these, as demonstrated, wireless optical communications are becoming a practical solution of future indoor (portable) communication systems/networks with large bandwidth requirement.

To reduce the disastrous effect of multipath, f_{ib}, $w(\cdot)$ should be pulse-like with duration shorter than T rather than a square waveform like $\Pi(0, T)$; $d(\cdot)$ which represents filtering distortion should also avoid side-lobes. For high data rates (e.g. 10M bps), these considerations, including how to decide ξV_m the decision threshold, are very critical.

For 10M bps OOK systems operating in typical environments, f_{ib} may range from 0.02 to 0.05 if all other reasons of waveform distortion are neglected. For 50M bps system in the same situation, f_{ib} is approximately 5 times larger than that of 10M bps system so that infrared communication link is severely degraded and not able to support reliable communication networks with reasonable power. If filtering effects and waveform distortion are all taken into consideration, power efficient reliable communications may not be achieved by OOK without other signal processing and/or coding schemes for data rate around 10-20M bps or higher.

Since our IR communication link is practically power-limited, the minimal transmission power, $P_{t,min}$ can be closely approximated as

$$P_{t,min} = \frac{4\pi R^2 D[\nu Q^{-1}(4P_{e,d}) + N_{b,d}]}{G_r A_r \eta(\xi - f_{ib})\cos\theta} \qquad (23)$$

where D is the transmission data rate; $P_{e,d}$ is the desired bit error rate; Q^{-1} is the inverse Gaussian tail (Q) function. If we choose $P_{t,min}$ the maximal transmission data rate D can be decided by the same equation. Another implication that we have to point out is that $P_{t,min} \propto R^2$ theoretically. Since R has a large dynamic range and the performance of OOK is so sensitive to lumination, the necessary transmission power is affected significantly by maximal operating distance between base station and transceiver.

Application of wireless infrared transmission in a small office room is shown to as effective as radio frequency transmission since multi-path will not produce severe power leakage and can help the transmission via diffuse propagation paths and can add lumination intensity when direct path comes to effect. Most importantly, multi-path may bring in more optical power and may be good for transmission once the extra time delay associated with such diffused transmission is constrainted within one bit period.

Without further coding and signal processing schemes, this kind of system design may require at least several hundreds miliwatt power and more to operate practically and successfully by taking into all possible impairments. The analysis also demonstrates that this kind of link is very power-limited in practical situations. Another encouraging side of this analysis is that optical transmission in a typical size office room via both direct-path and diffusion can reach most part of the room and has similar outcome of RF transmission.

Last but not the least, this paper demonstrates that 10-20M bps OOK (or similar direct-detect modulations) straightforward transmission systems are realizable for indoor wireless LANs. Multi-path will restrict practical applications of such straightforward approach at higher rates though a small percentage of channel capacity has been utilized. There exists a large room for researchers to explore more power and bandwidth efficient system designs in this situation.

Acknowledgement

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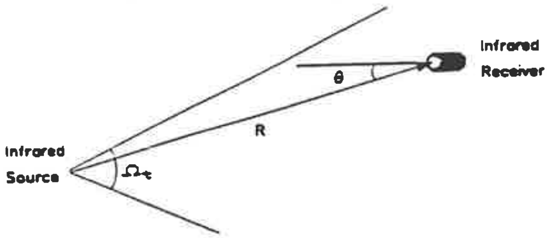

Figure 2 The Direct Path Optical Channel

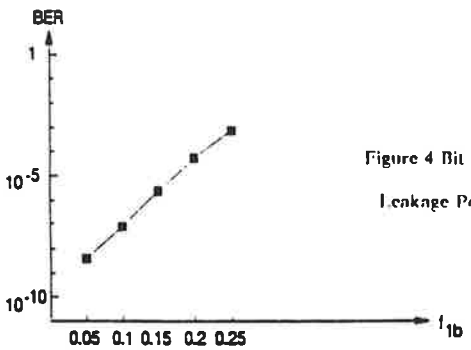

Figure 4 Bit Error Rate vs. Leakage Power Fraction

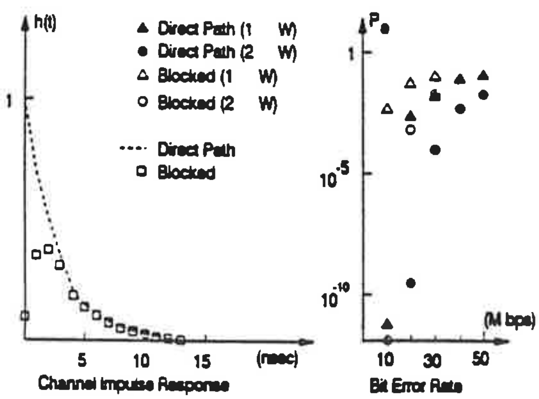

Figure 6 Slight Multi-path Effect

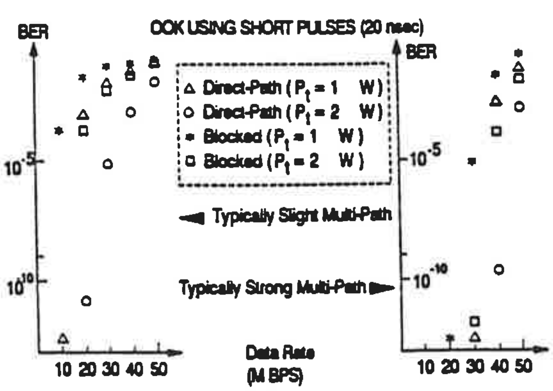

Figure 8 OOK Using 20 nsec Narrow Pulses

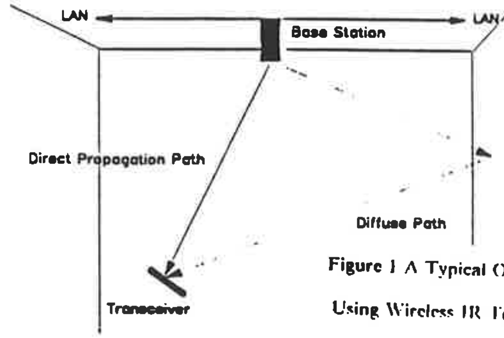

Figure 1 A Typical Office Network Using Wireless IR Transceivers

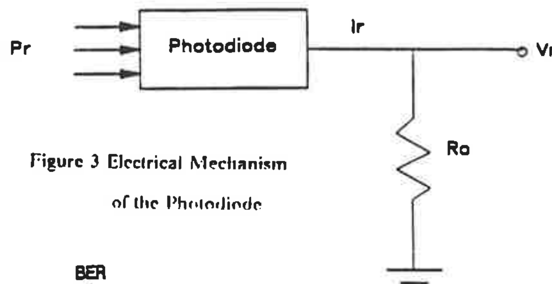

Figure 3 Electrical Mechanism of the Photodiode

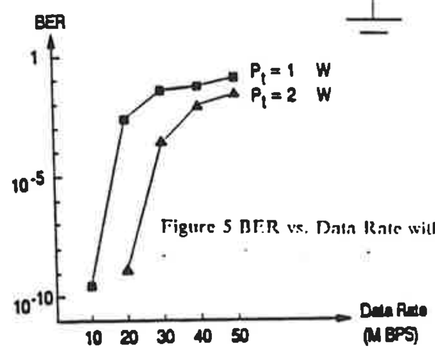

Figure 5 BER vs. Data Rate with Various Power

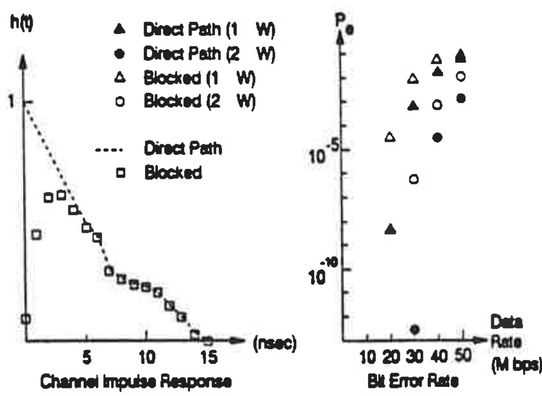

Figure 7 Strong Multi-path Effect

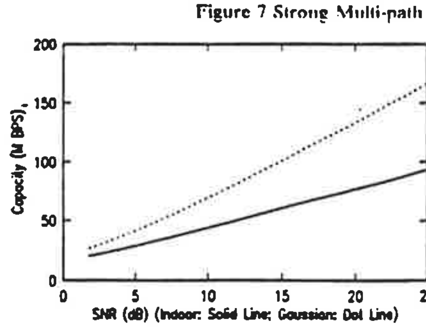

Figure 9 Capacity of Indoor Channel with 20M Hz Bandwidth