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Consideration of a Rate Adaptive MAC Protocol for Optical Wireless Communications

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I dedicate all that I achieve to my mother, may Allah keep her at rest.

I thank Allah for blessing me with the ability to learn and understand. And I pray that He provides me with more knowledge and wisdom.

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Abstract

Optical Wireless (OW) systems offer numerous advantages over their RF counterparts. Optical signals are contained within the communications environment which offers security at the physical layer level and reduces interference with users in adjacent rooms. The optical spectrum can support high data rates and there are no license requirements. OW systems suffer from a number of drawbacks including background noise (due to daylight and artificial light sources) and multipath propagation. The work presented in this thesis is concerned with design of a suitable MAC protocol for OW systems and with the design of adaptive rate receivers that can slow the MAC data transmission in order to cope with high levels of background noise. The receiver in an optical communication system is a key component in determining the overall system performance. This thesis considers an optical wireless receiver that mathematically integrates the incoming bits with respect to time in order to improve receiver sensitivity. This so-called Integrate-and-Dump methodology is not new in communication theory, but as far as the author is aware, it has not yet been adapted to optical wireless communications. The Integrate-and-Dump method was compared with traditional Threshold Detection techniques and found that the former performs better in areas of high noise. The proposed system is capable of providing an error rate of 10^{-9} at background noise levels less than $2.75\mu W$ when operated at 50 Mbs^{-1}. The system is also able to maintain this error rate at background noise powers of up to $279\mu W$ at 1 Mbs^{-1}. A design for a slotted MAC protocol for speech transmission is presented. It is suggested that this protocol be improved in order to include the adaptive rate functionality necessary to identify the required data rate for optimum throughput.

List of Acronyms

ACK	Acknowledge
AMPS	Advanced Mobile Phone Service
APD	Avalanche Photodiode
ARP	Address Resolution Protocol
ATM	Asynchronous Transfer Mode
BER	Bit-error-rate
B-ISDN	Broadband Integrated Services Digital Network
BN	Background noise
Bn	Bin Width
BRAN	Broadband Radio Access Network
BS	Base Station
CDMA	Code division multiple access
CEPT	European Conference of Postal and Telecommunications
Cf	Communication Floor
CRC	Cyclic Redundancy Check
CSMA/CA	Carrier-Sense Multiple Access With Collision Avoidance
CSMA/CD	Carrier-Sense Multiple Access With Collision Detection
Dc	Direct Current
DD	Direct detection
DECT	Digital Enhanced Cordless Telecommunications
DPIM	Differential pulse interval modulation
DS	Direct-Sequence
DTIRCS	Dielectric Totally Internally Reflecting Concentrators
EIA/TIA	Electronic Industry Association / Telecommunications Industry

	Association
EM	Electromagnetic
EOT	End Of Transmission
erf	Complimentary Error Function
FCC	Federal Communications Commission
FDD	Frequency Domain Duplex
FDMA	Frequency division multiple access
FET	Field Effect Transistor
FH	Frequency-Hopped
FM	Frequency modulation
FOV	Field-of-view
FSK	Frequency Shift Keying
GaAs	Gallium Arsenide
IEC	International electrotechnical commission
IEC	International Electrotechnical Commission
IM	Intensity modulation
IM/DD	Intensity modulation / direct detection
InGaAs	Indium Gallium Arsenide
IR	Infrared
IrDA	Infrared data association
IrLAP	Infrared link access protocol
ISI	Inter-symbol interference
ITU–T	International Telecommunications Union–Telecommunications
IWC	Infrared Wireless Cell
LAN	Local area networks

LED	Light emitting diode
LLC	Logical-Link Control
LOS	Line-of-sight
MAC	Medium access control
MPD	Multi-path dispersion
NACK	Negative Acknowledge
NBFM	Narrowband Frequency Modulation
ND LOS	Non-Directed Line-Of-Sight
Nrz	Non-Return-To-Zero
OOK	On-off keying
OSI	Open Standard international
OWC	Optical wireless communication
PCI	Protocol Control Information
PCN	Personal Communication Networks
PCS	Personal Communications Services
pdf	Probability Density Function
PDP	Packet Dropping Probability
PDU	Protocol Data Unit
PHY	Physical Layer
Pin	P-Intrinsic-N
Pll	Phase-Locked Loop
PN	Pseudonoise
PPM	Pulse position modulation
PRMA	Packet Reservation Multiple Access
PSK	Phase Shift Keying

QOS	Quality Of Service
R	Responsivity
R-ALOHA	Reservation ALOHA
RC	Resistance-Capacitance
RF	Radio frequency
RMS	Root Mean Square
RRC	Radio Resource Control
Rz	Return-To-Zero
S-ALOHA	Slotted ALOHA
SAP	Service Access Point
SDMA	Spatial Division Multiple Access
SDU	Service Data Unit
Si	Silicon
SIR	Serial infrared
SNR	Signal-to-noise ratio
TDD	Time Domain Duplex
TDMA	Time division multiple access
TIA	Telecommunications Industry Association
tt	Transmission Time
UMTS	Universal Mobile Telecommunications System
VAD	Voice Activity Detector
Vco	Voltage-Controlled Oscillator
Vp	Vulnerable Period
WATM	Wireless ATM
WLAN	Wireless local area network

Glossary of Symbols

A	Amplifier Open Loop Voltage Gain
Ar	Area Of The Received Point
ℓ	Average Arrival Rate Of Photons
D	Average Delay
P_0	Average incident power received at 0 transmission
P_1	Average incident power received at 1 transmission
P_{BN}	background noise power
B	Bandwidth
R_c	Channel Bit Rate
T_{cf}	Channel Frame Duration
J	Channel Reuse Factor
I_0	Current received at 0 transmission
I_1	Current received at 1 transmission
T_d	Downlink Timing Signals
q	Electron Charge
m	Expected Number Of Bits Per Packet
C_{Fb}	Feedback Capacitor
R_{Fb}	Feedback Resistor
gs	Guard Slots
P	Incident Power
R_L	Load Resistor
D_{max}	Maximum Delay
N	Number Of Information Slots In A Frame

Ps	Optical Power At Source
τ	Packet Duration
Pd	Power Received At Each Element
P_e	Probability Of Error
p	Probability Of Transmission
t_d	Propagation Delay
t_p	Propagation Time
N_{Rx}	Receiver noise current spectral density
ρ	Reflective Coefficient
σ_{BN}	RMS of Gaussian shot noise current
σ_{Rx}	RMS of receiver noise current
H	Size of an IWC
R_s	Source rate
$I_{\mathrm{threshold}}$	Threshold Current
T	Throughput
T_f	Uplink/Downlink Frame Duration
Vp	Vulnerable Period
λ	Wavelength

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Chapter 1

Introduction

"Rarely does it happen that any discovery or invention of importance is made by one man alone. The threads of inquiry are taken up and traced, one labourer succeeding another, each tracing it a little further, often without apparent result. This goes on sometimes for centuries, until at length some man seeking to fulfil the needs of his time, gathers the various threads together, treasures up the gain of past successes and failures, and uses them as a means for some solid achievement."

[Samuel Smiles]

The above sentiment is very true in the case of Optical Wireless Communication (OWC). To get to the concept of OWC many steps have been taken, some larger than others, and from the original concept many people have taken it a step further, but OWC has yet to achieve its full potential.

The transmission of information by means of pre-concerted signals has been practiced since the ancient times, the use of fire beacons at night and smoke signals by day. Among some nations, drums have long been, and still are, used to transmit messages over wide areas, in some cases with remarkable speed. But even the concept of communication using Electromagnetic (EM) waves has been in existence for more than a century. From when Maxwell published the first extensive account of his electromagnetic theory in 1867 [1], one person after another have been taking those "*threads of inquiry*", that little further. In 1887 Hertz proved the existence of EM waves (by demonstrating a spark transmitter generates a spark in a receiver several meters away) [2] and before the turn of the 19th century Guglielmo Marconi was awarded a patent for wireless telegraph, which heralded the birth of radio [3]. In the early 20th Century radio communication had become an area of vast interest and in 1935, Edwin Howard Armstrong unveiled his invention, Frequency Modulation (FM), to improve radio broadcasting [4]. This technology reduced the required bulk of radio equipment and improved transmission quality. The next 65 years saw the birth of mobile telephony and the progression to cellular mobile telephony.

As wireless communication was evolving, wired telecommunication was also going through its natural progression. It can be considered to have begun in 1825, when William Sturgeon exhibited a device that laid the foundations for large-scale electronic communications: the electromagnet [5]. Joseph Henry demonstrated the potential of Sturgeon's device for long distance communication five years later by sending an electronic current over one mile of wire to activate an electromagnet which caused a bell to strike. Thus the electric telegraph was born. Samuel Morse, William Crooke and Charles Wheatstone made further advances, and until 1877, all rapid long-distance communication depended upon the telegraph [6]. That year, a rival technology developed that would again change the face of communication - the telephone, which had been a concept of both Elisha Gray and Alexander Graham Bell but which Bell had managed to patent first (by only a matter of hours!). Communication networks have evolved during a century-long history of technological advances and social changes. The networks that once provided basic telephone service through a friendly local operator are now transmitting the equivalent of thousands of encyclopaedias per second. In the early 1980s, a revolution in telecommunications networks began that was spawned by the use of a relatively unassuming technology, fibre-optic cables [7, 8]. Since then, the tremendous cost savings and increased network quality has led to many advances in the technologies required for optical networks, the benefits of which are low attenuation, low cost and high bandwidth. But the wired connections restrict mobility and act as physical constraints during system set-up and network expansion. As an alternative a wireless network can be implemented.

Wireless networks have traditionally used radio frequency (RF) as the medium for data communication, but the RF spectrum has now become extremely congested and high bit-rate applications are very difficult to accommodate. The search for a new transmission medium has lead to the emergence of Optical Wireless Communication and more specifically infrared (IR) technology. The concept of IR as a medium for communication was introduced by Gfeller and Bapst over two decades ago [8]. Since then, IR equipment has evolved, and now state-of-the art IR technology offers major performance advantages over traditional cable or radio systems, especially for indoor applications, with huge available bandwidths in excess of 1.5Gbs [9]. Unlike radio and microwave technologies, infrared offers complete freedom from interference (between adjacent rooms) or radio licensing regulations. Components for IR communications are small, consume little power and so are inexpensive. As a result, IR communications has received much attention recently and will be considered in more detail in the following chapter.

An important consideration in an indoor OWC network, as with any other communication network, is the protocols to which it must conform. Moreover, these protocols are fundamental to the performance of the network as they govern the way in which data is transmitted, received and the manner in which the network resources are shared and allocated. Shared medium wired local area networks (LANs) require the use of a medium access control (MAC) method to implement the distributed access control algorithm such as Carrier Sense Multiple Access with Collision Detection (CSMA/CD), control token etc. Similarly infrared, as with radio, operates using a broadcast medium, where all receivers within a certain range from the transmitter will receive every transmission. So, to ensure that only one transmitter has access to the medium, a MAC protocol is also required for wireless LANs. There are several techniques that currently exist, most common of which are, frequency division multiple access (FDMA), time division multiple access (TDMA) and code division multiple access (CDMA) [10] and these will be further discussed in Chapter 4.

1.1 Primary Objectives

The objectives of the work undertaken and presented in this thesis are to:

- Review the Optical Wireless area of study and the MAC protocols used in wireless communications.

- Evaluate through simulations the performance of a slotted MAC Protocol that uses a fixed data rate. This MAC protocol was previously characterised only analytically in the group [11].

- Evaluate the influence of noise due to ambient infrared radiation arising from sunlight and artificial lights on the indoor infrared wireless communication system.

- Simulate impulse responses and multipath dispersion in an optical wireless channel, looking specifically at a diffuse network.

- To look into receiver technologies and consider an Integrated-and-Dump receiver

- Calculate the Signal-to-Noise Ratio and Bit Error Rates for the conceived receiver

- To identify what advantages an Integrate-and-Dump receiver would have over traditional threshold detection systems.

- Finally, Identify the maximum and minimum data rates that can be supported by the MAC protocol, in an adaptive manner, in a typical optical wireless indoor environment.

1.2 Thesis Layout

This thesis has been constructed such that the subsequent chapters consist of the following:

Chapter 2: Overview of Optical Wireless, describing the advantages and disadvantages of using Infrared as a medium for communications. Also discussing different methodologies used.

Chapter 3: Receiver Considerations looking at photo-detectors and various preamplifiers, including an Integrate-and-Dump receiver.

Chapter 4: Overview of MAC Protocols, gives an introduction to medium access control protocols that allow devices on a LAN to share their inter-connecting media.

Chapter 5: Slotted MAC for speech transmission. This chapter gives details of a MAC protocol simulated to provide efficient speech transmission in an optical wireless environment.

Chapter 6: Dispersion and Noise in Optical Wireless. This chapter demonstrates the noise distribution in a test room, which has eight halogen spotlights on the ceiling. Then using the room dimensions, a simulation of multipath impulse responses is performed.

Chapter 7: The Bit-Error-Rate (BER) and Signal-to-Noise Ratio (SNR) are calculated for both Threshold Detection and Integrate-and-Dump techniques.

Chapter 8: Conclusion and Summary of the thesis and Scope for further work.

1.3 Original Contributions

During this research study the author has:

- Contributed to the design of an optical wireless network MAC simulator with other members of the group [12, 13] to validate the results proposed by the theoretical model [11], thereby proving the efficiency of the MAC protocol designed.

- Developed C programmes to simulate the impulse responses and noise distribution of a test room with variable dimensions.

- Determined the equations to obtain mathematical results for SNR and BER of an Integrate-and-Dump receiver in an optical wireless environment. These results were used to suggest that the implementation of an Integrate-and-Dump receiver would be beneficial and would reduce the BER or maintain it at 10^{-9} in areas of high background noise by reducing the data rate of the optical wireless system.

1.4 Publications

- Qazi BR, Harikrishnan Y, Ahmed SB and Elmirghani JMH, *"Design and Simulation of a MAC protocol for Optical Wireless Communications"*, PostGraduate Networking Conference PGNet 2003.

- Qazi BR, Harikrishnan Y, Ahmed BS, Wells I and Elmighani JMH, *"Performance Analysis of a MAC Protocol for Speech transmission in Optical Wireless Communications"*, Proceedings of IEEE London Communications Symposium, vol.1, pp. 61-64, London September 2003.

Chapter 2

Review of Optical Wireless

2.1 Introduction

Optical communications, in its broad sense, date back over two centuries. In the midst of the French revolution engineer Claude Chappe invented the "optical telegraph" in the years 1790-1794 [6]. His system was a series of semaphores mounted on towers, where human operators relayed messages from one tower to the next. It was much more efficient than hand-carried messages, but the optical telegraph could not be used at night and it was dependant on the weather. During the mid-19th century it was replaced by the electric telegraph. Alexander Graham Bell, in 1880, patented an optical telephone system, which he called the Photophone, which transmitted telephone signals that were generated by an intensity modulated light beam [14]. But his earlier invention, the telephone, proved far more practical. Dreams of sending signals through the air waned, as the atmosphere didn't transmit light as reliably as wires carried electricity. In the decades that followed, light was used for a few special applications, such as signalling between ships, but otherwise optical communications, like the experimental Photophone Bell donated to the Smithsonian Institution, languished on the shelf.

In the intervening years, a new technology slowly took root that would ultimately solve the problem of optical transmission, although it was a long time before it was adapted for communications. It depended on the phenomenon of total internal reflection, which can confine light in a material surrounded by other materials with lower refractive index, such as glass in air. In the 1840s, Swiss physicist Daniel Collodon and French physicist Jacques Babinet showed that light could be guided along jets of water for fountain displays [15]. In 1854, British physicist John Tyndall demonstrated light guiding to the Royal Institution by showing light sent through a jet of water flowing from a tank was trapped in the spurt [16]. By the turn of the century, inventors realized that bent quartz rods could carry light, and patented them as dental illuminators. The concept that low-attenuation optical fibres could be an alternative to electric wires came about in the mid 1960s when Kao and Hockham published a paper in which the transmission of light through optical fibres was analysed [17]. Much research continued and in 1970, Corning Glass in the USA heralded a breakthrough in optical fibre communications by announcing that they could produce glass with attenuation as low as 20 dB/km [18]. This led to a revolution in wired communications. An alternative method for communications is the wireless network. Typically, radio frequency transmission has been used in wireless applications, but merging the advantages of optical communications with wireless communications, has lead to the emergence of OWC. In an optical wireless system, information is transmitted by sending a time varying optical signal between the transmitter and receiver. The information sent on this channel is not contained in the phase or frequency of the transmitted optical waveform, but rather in the *intensity* of the transmitted signal. Data is transmitted via Infrared using lasers or LEDs.

2.2 Advantages of Infrared

Observing the electromagnetic spectrum (Fig. 2.1), although the wavelengths occupied by RF are much longer than Infrared wavelengths (which makes RF ideal for long distance transmission), the frequency spectrum associated with Infrared is greater than that associated with RF. As a result, IR offers a much larger bandwidth. This, coupled with the fact that Infrared emitters and detectors capable of high-speed data transmission are available at relatively low cost, has attracted widespread attention over recent years for the use of IR as a carrier of data.

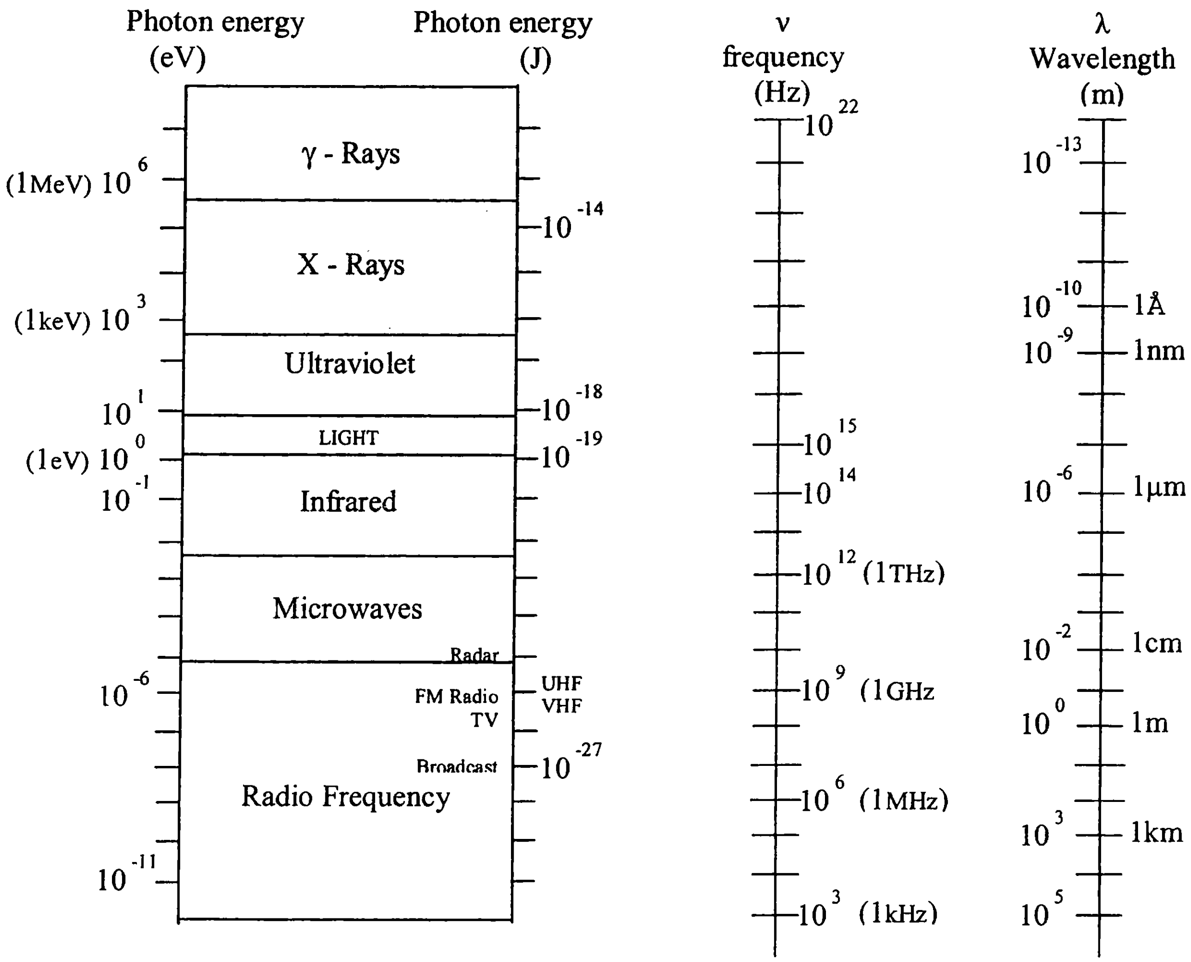

Figure 2.1: Electromagnetic Spectrum

In 1993 a group of leading companies founded the Infrared Data Association (IrDA), whose aim it is to promote the technology and set the standards. Early standards were released in 1993 and 1994, which set the serial infrared (SIR) physical layer specifications and introduced the infrared link access protocol (IrLAP) [19]. The IrDA teamed up with Microsoft in 1995, which soon after, announced the production of infrared peripheral devices that are compatible with MS Windows operating system. More recently, the IrDA have helped major mobile phone companies produce phones that are capable of transferring data over short distances using IrDA compatible communication ports. IR technology has become an appealing and promising technology in wireless local area networks (WLAN). This is because infrared signals do not penetrate through walls, thus virtually eliminating the problem of interference generated by neighbouring users and providing security at the physical level.

Another major advantage of using infrared is the fact that, unlike radio and microwave, it is unregulated and so free from license requirements. Semiconductor lasers with broad bandwidths and high launch powers were developed for optical fibre systems, but these features are equally attractive to optical wireless systems, more so for outdoor applications. Although, for indoor applications, lasers do pose a safety hazard since they are a point source emitter.

2.3 Safety Issues

A laser safety standard has been established by the International Electrotechnical Commission (IEC), in which optical sources are classified in accordance with their total emitted power [20]. Table 2.1 shows a summary of the principle classifications. The safety standard recommends that outdoor point-to-point systems, which use high power lasers operating in Class 3b, to be located in places such as rooftops where the beam cannot be interrupted or viewed inadvertently by a person.

	650 nm (visible)	880 nm (infrared)	1310 nm (infrared)	1550 nm (infrared)
Class 1	Up to 0.2mW	Up to 0.5mW	Up to 8.8mW	Up to 10mW
Class 2	0.2 - 1mW	N/A	N/A	N/A
Class 3a	1 – 5mW	0.5 - 2.5mW	8.8 - 45mW	10 - 50mW
Class 3b	5 - 500mW	2.5 - 500mw	45 - 500mW	50 - 500mW

Table 2.1: Power Classifications

For indoor systems, the safety standard recommends that they must be Class 1 eye safe under all conditions. Therefore, it is difficult to achieve a good power budget using lasers. However, LEDs allow a much higher launch power (especially if used in arrays) while still being Class 1 eye safe. Since LEDs are large area devices as opposed to point source devices, the power is diffused on the retina of the eye if viewed. It is for this reason that LED emitters are primarily used for indoor applications. Optical transceiver components are relatively cheap in comparison to their radio counterparts and enable simple intensity modulation / direct detection techniques (IM/DD) whilst consuming less power.

2.4 Disadvantages of Infrared

Optical Wireless Communications, with all its benefits, is not free from drawbacks. It is these drawbacks, and the failure to successfully counteract them, which has held back the progress of OWC over the past decade. In long distance outdoor systems, the problems lie in atmospheric loss and this includes clear air absorption, scattering, refraction, scintillation and free-space loss [21]. Clean air absorption (equivalent to absorption loss in optical fibres) is a wavelength dependent process that gives low-loss transmission windows centred on 850nm, 1300nm and 1550nm [22]. Scattering and Refraction is due to the attenuating effect of rain, fog mist and snow on the power reaching the receiver. Scintillation is the result of solar energy heating small packets of air to slightly different temperatures, thereby creating regions of varying refractive index along the propagation path [21]. Free space loss characterises the proportion of optical power arriving at the receiver that is usefully captured within the receiver's aperture (Fig. 2.2).

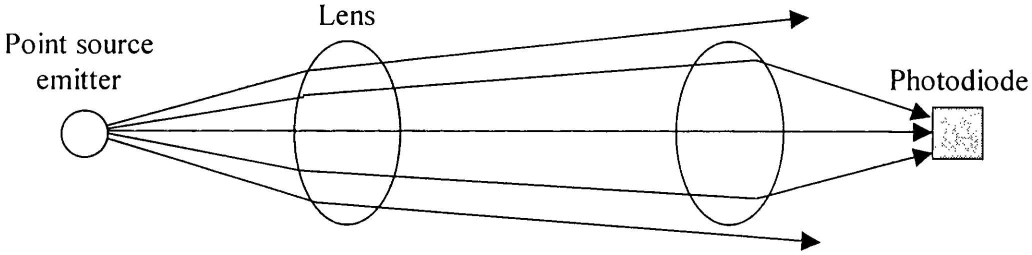

Figure 2.2: A diagrammatic example of free space loss [21]

Indoor OW systems, with the exception of free space loss, are not affected by atmospheric loss. Apart from free space loss, the only other considerations to determine the power budget are the transmitter launch power and the receiver sensitivity. But there are other drawbacks for indoor OW systems. As mentioned before, IR cannot penetrate through walls, confining transmission to a single room and although this is an advantage on the physical layer, as mentioned earlier, it is worth taking note that communication from one room to another will require the existence of a backbone of wired base stations. Another problem lies in the fact that various intense ambient light sources, arising from sunlight through windows, incandescent lighting and fluorescent lighting, corrupt the received data stream and induce background noise (BN) in an infrared receiver [23]. The effect of background noise induced by fluorescent lighting can be reduced by using optical filtering [23] or by spread spectrum techniques [24]. Infrared and visible light occupy adjacent wavelengths and exhibit similar behaviour. Both are absorbed by dark objects, diffusely reflected by light coloured objects and directionally reflected from shiny surfaces [25]. The diffuse reflection means that the transmitted data is able to reach the receiver through various paths of different length, a problem known as multi-path dispersion (MPD) which can, due to transmitted pulses being spread, lead to Inter-Symbol Interference (ISI). It is for this reason that the channel bandwidth contained within a room is typically only 25 - 30 MHz, although reducing ISI using channel equalisation can significantly increase this [26]. There are also various techniques to mitigate MPD, one of which is diversity detection. This employs a number of receivers, each with a narrow field-of-view (FOV), rather than a single receiver with a wide FOV. Furthermore these receivers reduce the amount of BN captured and so increase the received optical signal-to-noise power ratio [27]. But using this method requires the expense of greater complexity. Since IM/DD is the most common and practical transmission technique used for indoor OW systems, only a limited path loss can be tolerated, furthermore, the electrical signal-to-noise ratio (SNR) of a direct detection receiver is proportional to the square of the received optical power [25].

2.5 Categories of IR Links

It is convenient to classify IR Links into two categories, Line-of-Sight (LOS) and non-Line-of-Sight (non LOS). These classes can then be further sub divided into 3 more categories; Directed, Hybrid and Non-directed (Fig. 2.3). Directed links use transmitters and receivers that are aimed at each other in such a way that a link can be established. Non-directed links make use of the diffuse nature of IR. Diffuse networks use wide-angle sources and scatter from surfaces in the room to provide an optical 'ether' similar to that which would be obtained using a local radio transmitter. This produces coverage that is robust to blocking, but the multiple paths between source and receiver cause dispersion of the channel, thus limiting its bandwidth. The optical transmitters required are also extremely high power, and dynamic equalisation is required for high bandwidth. Also, hybrid links can be established by merging wide angled transceivers with directed ones. In the case of LOS systems, there is a requirement for an uninterrupted path between the transmitter and receiver. The advantage of this method is that MPD is minimised, and so allowing bit rates to exceed 100 Mb/s [28], and also the power efficiency is increased.

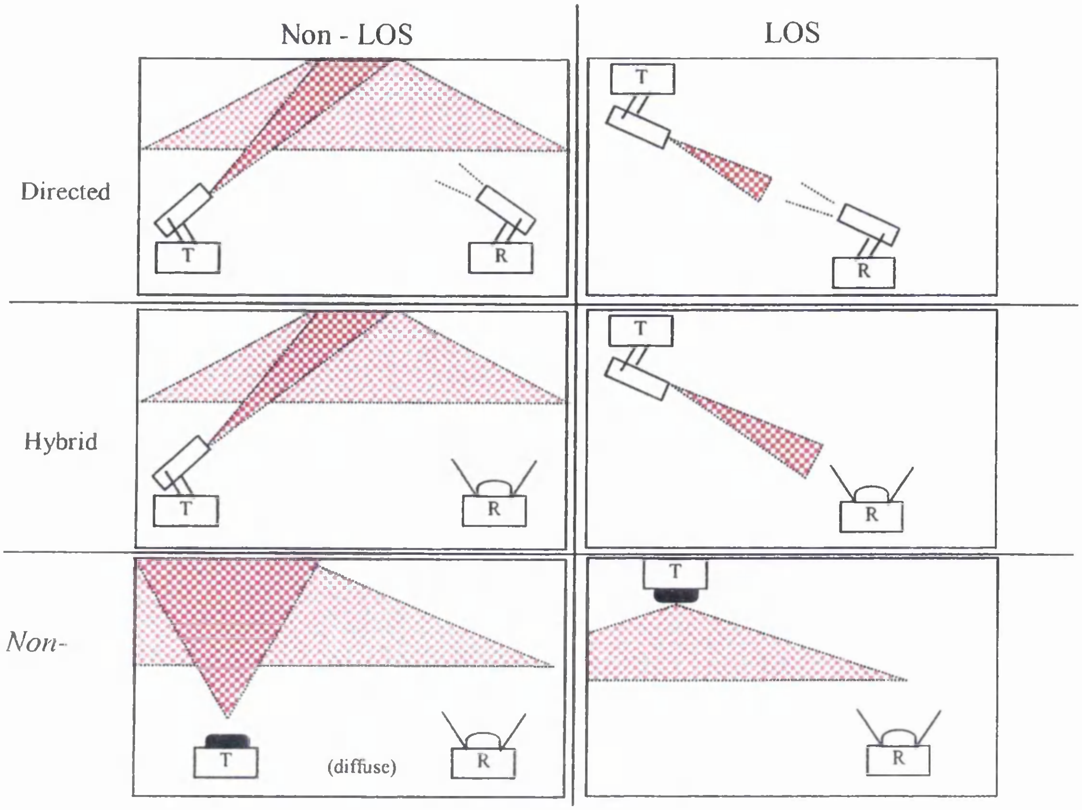

Figure 2.3: Categories of Infrared Links [25]

However, the coverage area provided by a single channel can be quite small, therefore, providing area coverage and the ability to roam presents the major challenge. LOS is particularly suited to applications where there is a dedicated link to a single user, but with multi-user applications, such as classrooms and offices, line of sight channels can be blocked or disrupted by persons moving around, as there are no alternative scattered path between transmitter and receiver. Also, barriers such as cubicle partitions can make it difficult to set up the path between the transmitter and receiver, and it is for this reason that non-LOS is preferred for multi-user utilisation. The non-directed non-LOS (often referred to as the 'diffuse link') offers the greatest robustness and ease of use. Several methods have been developed and used to reduce BN and MPD in LOS and non-LOS links [29]. One suggestion is to use an imaging light concentrator and a segmented photodetector, replacing the single element receiver, for non-directed non-

LOS links [29]. The same work proposed that a diffuse transmitter that projects multiple narrow beams can significantly reduce path loss and transmission power. Currently, most IR links are directed LOS or hybrid LOS, since the low path loss associated with these configurations means transmission power is less of a requirement, which consequently means that a simple (and so low-cost) receiver will suffice.

2.6 Modulation techniques

As mentioned earlier, IM/DD is the most widely used technique in OW communication. This is because intensity modulation (IM) can easily be implemented by simply varying the current passing through a laser diode or LED. The easiest way to recover IM signals is by Direct Detection (DD). DD is possible due to the photodiode, which can convert IR light energy into current. IM/DD can be implemented using different methods. Two of the most popular in OW are On-Off keying (OOK) and Pulse Position Modulation (PPM). OOK is a simple technique, which sends pulses of light for every '1' bit of the data stream (Fig. 2.4a). It is very simple to implement and offers a good bit rate. But the disadvantage of using OOK is that, at high bit rates, it is prone to ISI (Fig. 2.4b) and uses a higher average power compared to PPM. With Pulse Position Modulation, time slots are used within frames to represent the digital data. The number of slots required (and so the size of each frame) is determined by the number of data bits to be transmitted. So if three bits are to be conveyed we need $2^3 = 8$ time slots (8-PPM), and for four bits, 16 slots (16-PPM).

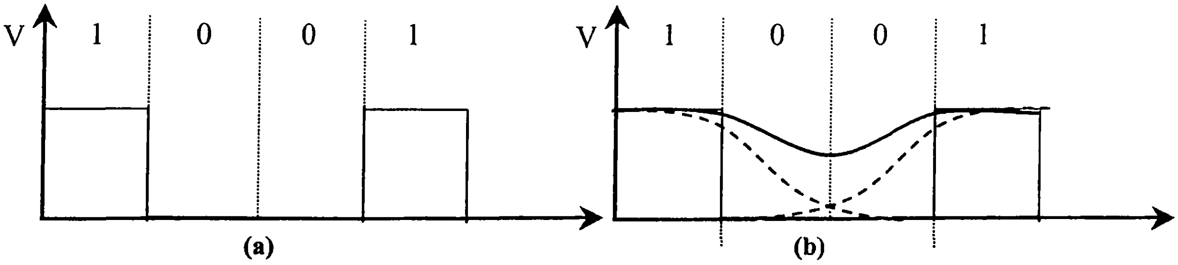

Figure 2.4: (a) On-Off keying pulses; (b) at high bit rates zeros becomes indistinguishable

Fig. 2.5 shows a 4-PPM scheme transmitting a data stream of 01101100. The first two bits of the datastream are represented by the relevant pulse in the first frame, the second two bits are represented in the second frame, and so on. PPM is more power efficient but does require a greater bandwidth. Fig. 2.6 also shows the inclusion of guard slots (gs) to prevent ISI between frames, which in this example show ISI prevention between frames 3 and 4. But the inclusion of guard slots is at the expense of even more bandwidth. Another scheme called Differential Pulse Interval Modulation (DPIM) uses the same basic principles of PPM but with variable frame lengths [30].

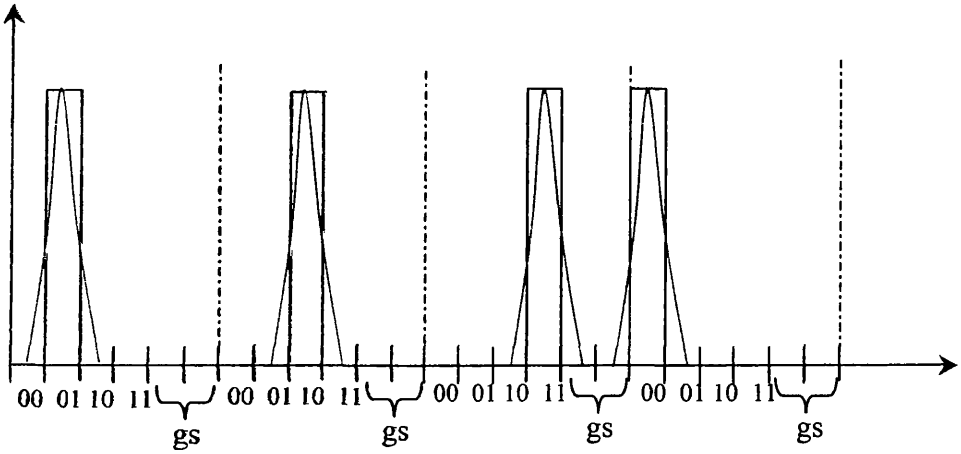

Figure 2.5: Example of a 4-PPM scheme

Pulses are always transmitted in the first time slot and the size of the frame is proportional to the binary value of the data word, since a new frame starts for every pulse. The transmission capacity is greater than PPM (which has wasted slots) and offers greater robustness to jitter. A study carried out on OOK and PPM [26] found that MPD affected the sensitivity of a PPM system more than a similar OOK scheme. But it was the opposite case whilst under the constraint of BN.

2.7 Cellular Concept

As with radio, OWC can be implemented using a cellular concept. Base stations placed on the ceiling consist of satellites that emit light, which is diffused in a beam covering a certain area known as a cell (Fig. 2.6). Small rooms will require only one satellite while larger rooms (or office spaces) may require several. A wired connection using optical fibre between the satellites make up the backbone mentioned earlier. The OWC cellular system, like the mobile phone cellular network, will require conforming to some protocol to allow users to share resources. Medium Access Control (MAC) Protocols in OWC are discussed in more detail in Chapter 4.

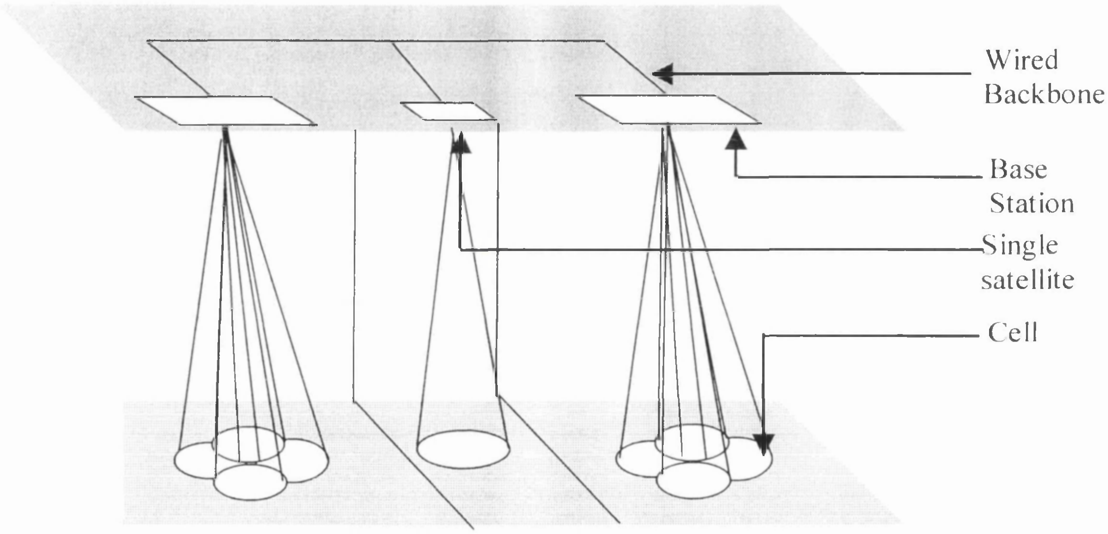

Figure 2.6: Cellular Concept

2.8 Ad-Hoc Networks

"One of the most vibrant and active new fields today is that of ad-hoc networks. Within the past few years the field has seen a rapid expansion of visibility and work due to the proliferation of inexpensive, widely available wireless devices and the network community's interest in mobile computing" [31]. An Ad-hoc network is exactly as it is labelled; it has no infrastructure and no pre-determined organisation of available links. Mobile communication devices (Nodes) converge into an area and become networked

Chapter 3

Receiver Considerations

3.1 Introduction

The function of an optical receiver is to convert the infrared signals captured by the photo-diode and transform it into electrical signals that can be processed electronically. In optical communications, the ones and zeros of binary data are typically represented by the presence and absence of light, also known as On-Off Keying (OOK). The two main constituents of an optical receiver are the photo-detector and preamplifier.

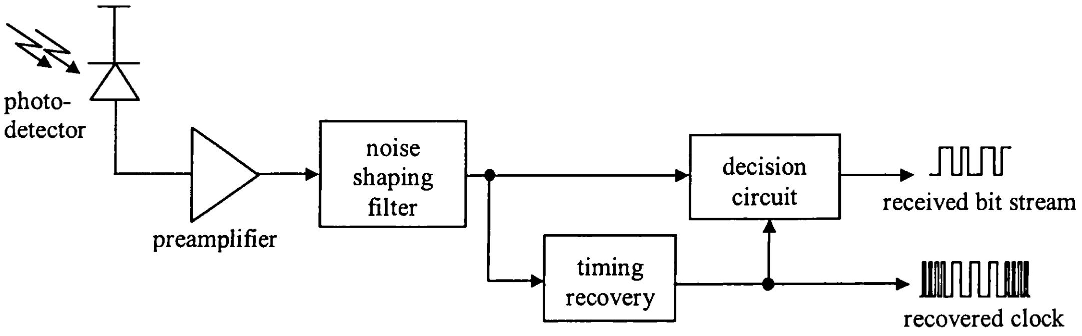

Figure 3.1: Optical receiver block diagram for OOK

Fig. 3.1 shows a block diagram of a receiver circuit [33]. Starting at the left of the diagram, a photo-detector is used to convert the OOK-modulated incident light into an electrical current. This current is amplified and converted to a voltage by the preamplifier. Its output is then filtered by a noise-shaping filter in order to achieve the best signal-to-noise ratio (SNR). The output of the noise-shaping filter is simultaneously fed to a timing recovery circuit and a decision circuit (usually a flip flop or comparator). The timing recovery circuit extracts a clock from the incoming bitstream and uses it to trigger the decision circuit at the optimum point in the bit time.

Both the timing recovery and decision circuits output voltages at standard logic levels. For synchronisation with the clock, the receiver should output a recovered clock that is synchronised with the received bitstream [34]. The digital bitstream should be accurate to some specified bit error rate (BER). Digital communication systems are typically accurate to one bit in 10^9 or one bit in 10^{12}. Chapter 7 shall discuss bit error rate and signal-to-noise ratio in more detail. This chapter shall focus on the receiver technologies required to convert the data transmitted in the infrared medium into electrical impulses in order for a computer to process the information received.

3.2 Photo-detectors

Photo-detector operation is based on the generation of photo-carriers by low-level injection into a semiconductor. An electric field across the semiconductor region causes the generated carriers to drift to the detector electrodes, thereby causing a signal current. Common types of photo-detectors include Avalanche Photodiode (APD) and p-intrinsic-n (PIN) photodiode. The PIN diode is operated under reverse bias. When a reverse bias of a few volts is applied, an electric field is formed across the junction depletion region. Light shined on this region generates electron-hole pairs and thus causes a photocurrent to flow through the diode. The purpose of the intrinsic layer is to increase the size of the depletion region, and thus increase the efficiency of the device. APDs can help to improve SNR since the thermal noise in the photodiode bias resistor and preamplifier circuitry stays unchanged. This is ensured by the Avalanche Multiplication Process [35], which amplifies the electronic signals. APDs are used if the main contributor to noise is the preamplifier. But PIN is preferred if OWC is prone to BN, since PINs are less complex and cheaper to manufacture. The photo-detector lies behind an optical filter, which is used to suppress ambient light (Fig. 3.2). This filter itself usually lies behind a hemispherical (or parabolic) concentrator, which collects the optical signals from the source and increases the radiant flux incident on the detector. The concentrator has been found to be able to offer the same optical gain over a large FOV [36]. But, dielectric totally internally reflecting concentrators (DTIRCs) have demonstrated higher optical gains when the FOV is narrowed [37].

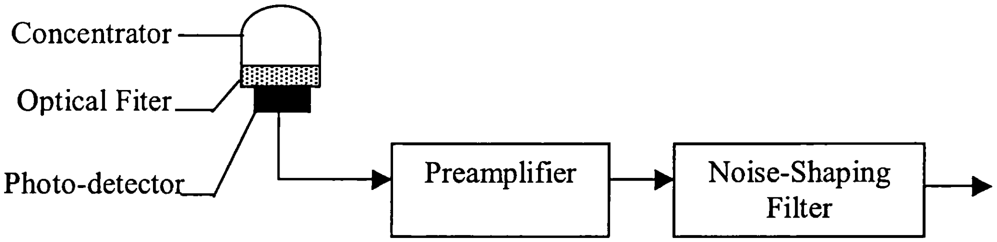

Figure 3.2: Block diagram of OW receiver

Photo-detectors are characterized by their ability to convert optical power (measured in watts) into electrical current (measured in amperes). The responsivity R of the photo-detector is the measure of this property in units of A/W. In the ideal case, each photon of light generates one electron-hole pair, giving:

$$R_{\text{ideal}} = \frac{q}{hv}$$

where q is the electron charge, and $hv = hc/\lambda$ is the wavelength-dependent energy of a single incident photon. In practice, the responsivity of a given semiconductor will also have a dependence on the band gap, and different materials such as Si, GaAs, and InGaAs will be sensitive to different parts of the optical spectrum.

3.3 Preamplifier

The purpose of the preamplifier is to provide a low-noise interface in order to receive the small detector photocurrent. Ideally, the preamplifier is a high-quality current-in/voltage out amplifier with high bandwidth to pass the desired bit rate. Unfortunately, most solid-state FET amplifiers are of the voltage-in/voltage-out or voltage-in/current-out variety. To overcome this problem, the photocurrent is converted into a voltage using a load resistor R_L and then amplified by a voltage amplifier. There are effectively three varieties of preamplifiers available, which are discussed in the following sub-sections.

3.3.1 Low Impedance Preamplifier

This is the simplest of the preamplifier considerations. A load resistor followed by a voltage amplifier terminates the photodiode.

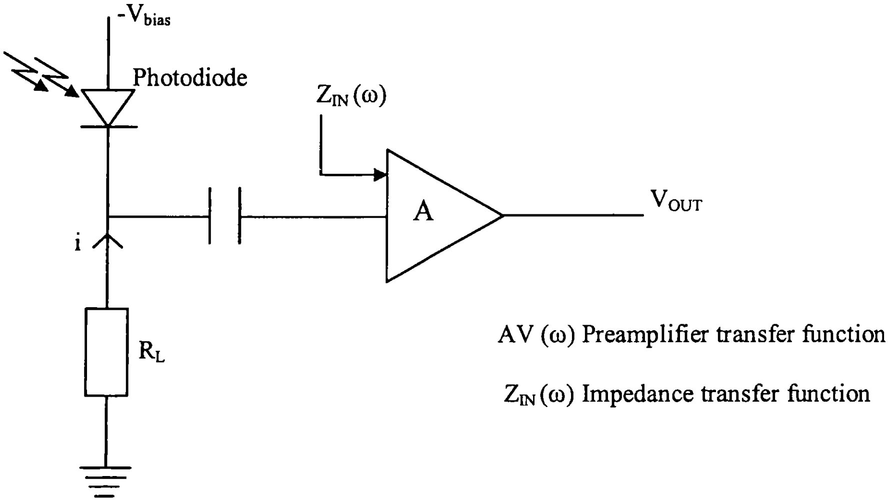

Figure 3.3: Low impedance preamplifier

The preamplifier bandwidth is determined by the resulting receiver time constant associated with the photodiode capacitance and terminating resistance. This configuration has good bandwidth but poor receiver sensitivity for direct detection systems. This is mainly due to the low terminating resistance giving rise to a high value of thermal noise. Due to the trade-off between bandwidth and sensitivity, This configuration tends to be impractical for wideband optical communication systems.

3.3.2 High Impedance Preamplifier

Increasing the input resistance can reduce the thermal noise produced by the low impedance preamplifier. But this leads to the reduction of the receiver bandwidth until eventually it behaves as an integrator. Due to this effect, this preamplifier is also known as an integrating front end. The signal shape is restored by an equaliser, which reverses the process by differentiating the output of the preamplifier (Fig. 3.4). The equalisation process results in the noise having a frequency squared spectral density that dominates in wideband high impedance receivers [34]. But the overall noise is still less than that for a low impedance receiver. These receivers suffer from poor dynamic range and have the added complexity of the differentiating equaliser. But, it is the most sensitive configuration and given its excellent low noise performance it has become a popular configuration.

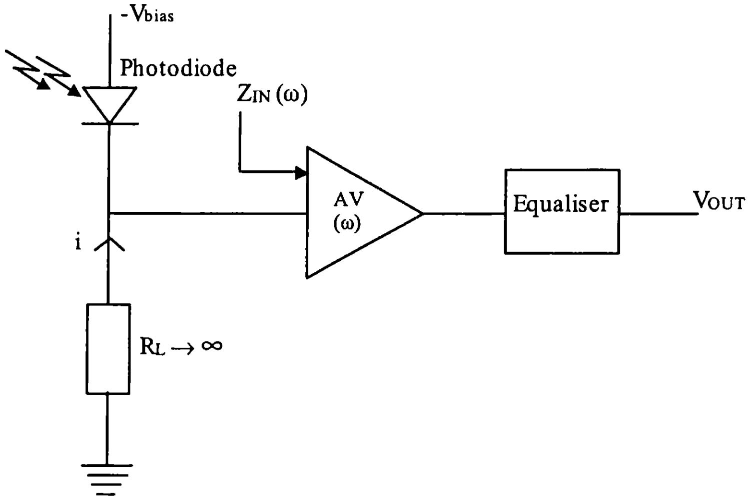

Figure 3.4: High impedance preamplifier

3.3.3 Transimpedance Preamplifier

This offers a compromise between the wide bandwidth of the low impedance design and the low noise of the high impedance design. Shunt negative feedback is used to reduce the effective input resistance of the amplifier (Fig. 3.5). The load resistor is incorporated in the feedback loop of the amplifier, and so its contribution to the input impedance is given by $\frac{R_{Fb}}{1+A}$. Provided gain is sufficiently large, the effective resistance is low, leading to wider bandwidths than high impedance designs. It has been shown that the noise of the feedback resistor may be referred directly to the input of the preamplifier and so the noise contribution is merely that associated with the thermal noise of the resistor [38]. This then becomes the dominant thermal noise source at the front-end of the preamplifier and since the value of the resistor is considerably higher than that of the low impedance design, superior performance is achieved. Ideally the feedback resistance would be the same as the resistance in a high impedance design in order to achieve the same noise performance. But, this would require an extremely large amplifier gain in order to achieve the desired bandwidth. The minimum open loop gain is constrained by stability considerations and therefore this configuration is not as sensitive as the high impedance design but is superior to the low impedance design.

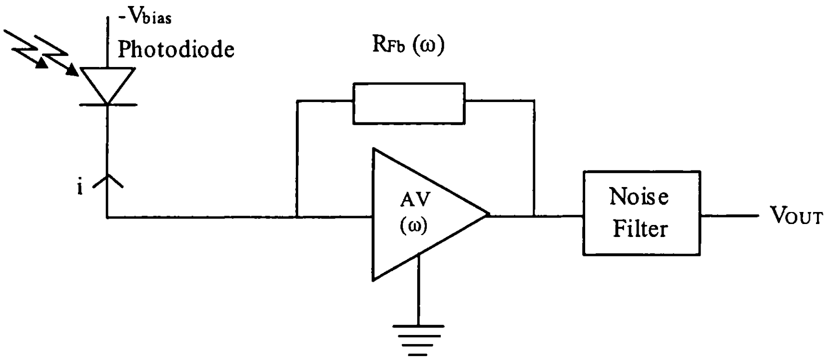

Figure 3.5: Transimpedance preamplifier

Optical preamplifiers based on the transimpedance design are suited to most infrared link applications, because they achieve the wide dynamic range and wide bandwidth without the need for equalisation. In a transimpedance amplifier the resistor R_{Fb} can be made large because the negative feedback reduces the effective resistance seen by the photodiode by a factor of (1+A) where A is the open loop voltage gain of the amplifier.

As a result, the thermal noise contribution of the feedback resistor is minimised and the bandwidth can be matched to that of the signal.

In the design of a transimpedance preamplifier, a wide dynamic range, ambient light rejection and low voltage operation are primary considerations. The dynamic range measures the variation of signal strength that the receiver can tolerate while still meeting performance requirements such as bit error rate. There are two techniques of rejecting ambient light at the preamplifier [39]. First, is to place a high pass resistance-capacitance (RC) network at the input of the amplifier. This allows high-frequency signal current to pass through, blocking the DC component generated by the almost invariant background noise. The second method uses optical filters in front of the photo-detector. A common signal detection technique is to use average level (threshold) detection. For mobile applications, the two main important factors are system integration and lower power consumption. Hence, low voltage operations have become a design requirement at present.

3.4 Integrate and Dump

Following the preamplifier, signal decisions have to be made. These can be made using a threshold detection device, where one and zero decisions are made using a sample of the signal and an appropriate threshold. This method is simple to implement, however it ignores the majority of the signal and bases decisions on one sample. A more efficient approach that yields better sensitivity and makes use of the full signal energy is the integrate and dump decision approach. The signal from the preamplifier is integrated, thus summing up the signal energy as shown in Fig. 3.6. A decision switch is closed every bit period, T, and the accumulated signal energy is then compared to a threshold. This approach improves signal detection and receiver sensitivity. Furthermore, it offers flexibility in dealing with variable noise scenarios such as those encountered in optical wireless systems influenced by directional background noise that varies spatially in the environment. In high noise spatial regions, signal transmission can be slowed. This results in a longer bit period T and higher signal energy per bit, which can restore the signal-to-noise ratio. The main drawback of the integrate and dump receiver is the added complexity associated with the integration circuit and switch.

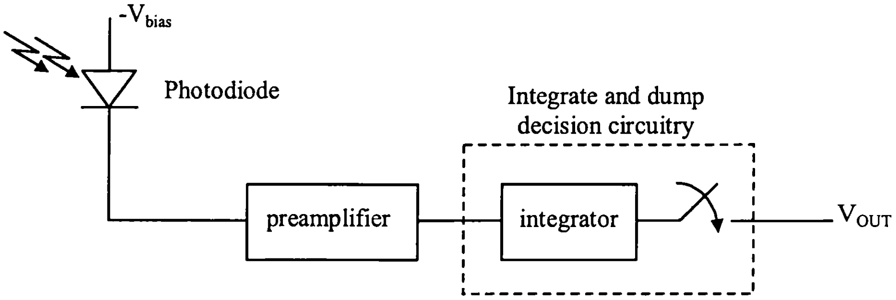

Figure 3.6: Integrate and Dump Receiver

3.5 Noise Shaping Filter

The purpose of the noise-shaping filter (shown in Fig. 3.1) is to reduce the wideband circuit noise without significantly altering the signal waveform. Typically, the noise shaper is a lowpass filter, which simply bandlimits the noise while at the same time removing the high-frequency components of the bit waveform. Thus, transmitted bits that are rectangular will have their edges rounded by the filter, and in the extreme case, will become sine-like in appearance. The bit rounding may also cause inter-symbol interference when a given bit is smeared into the timeslot of an adjacent bit. In order to choose the proper noise-shaping filter, it is first necessary to determine the noise response of the preamplifier.

3.6 Timing recovery and Decision Circuit

The recovery of a clock from the received bitstream is necessary in order to synchronize the bits to the local equipment. In addition, in the case of the integrate-and-dump receiver, the recovered clock is used in the receiver itself to operate the reset switch. There are two common methods used to recover the clock: open-loop synchronizers and closed-loop synchronizers. In the open-loop case, a spectral line at the bit rate is extracted directly from the incoming bit stream. For example, in certain cases such as return-to-zero (RZ) line coding, the frequency spectrum of the bit stream will have a component at the bit rate, and a linear bandpass filter is used to isolate and amplify that component. In other cases, such as non-return-to-zero (NRZ) line coding, there is no spectral component at the bit rate. In these cases, the bit stream is first "filtered" with a nonlinear function such as square law or absolute value in order to create a spectral line at the bit rate [40]. Then, a bandpass filter is used as in the RZ case (Fig. 3.7a). The main drawback to open-loop synchronizers is that the clock recovery will be highly dependent on the signal-to-noise ratio (SNR) of the received bit stream. For the smallest received signals, the recovered clock will contain a significant jitter component due to the noise in the bit stream [40]. This will seriously degrade performance at low signal-to-noise levels, i.e. low incident light levels. In closed-loop synchronizers, a local variable-frequency oscillator is locked onto the received bit stream by using a phase-locked loop (PLL). This is achieved through traditional PLL methods [42, 43] by using a phase detector, loop filter, and voltage-controlled oscillator (VCO) as shown in Fig. 3.7b.

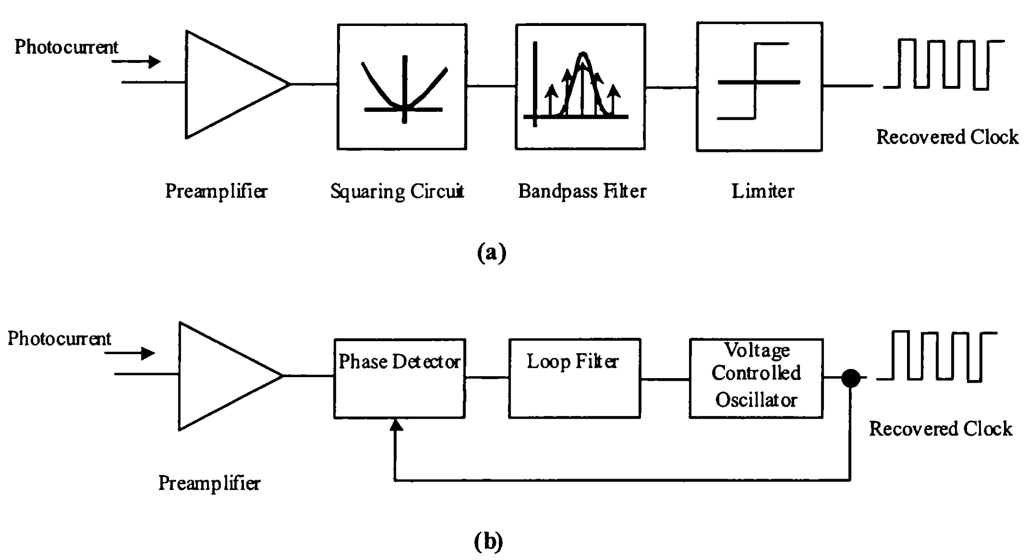

Figure 3.7: Two methods of clock recovery: (a) an open-loop synchronizer, the preamplifier output is squared and then bandpass-filtered to recover the spectral component at the bit rate (b) a closed-loop synchronizer, a phase-locked loop is used to recover the clock.

The PLL has a long enough time constant such that it remains locked to the incoming bitstream even with the occasional absence of bit transitions (as in the case of long strings of "ones" or "zeros"). However, in the case of an integrate-and-dump receiver, a problem arises in how the bitstream is recovered in order to extract the clock since the recovered clock is necessary to operate the receiver (in order to close the reset switch) and receive the bitstream. In this case, an early-late gate synchronizer loop may be used as described in [44].

3.7 Summary

The receiver in an optical communication system is a key component in determining the overall system performance. The major issues that govern the design of a receiver front end are wide bandwidth, large dynamic range, low power dissipation, high bit rate, sensitivity and the ability to reject background noise. This chapter has discussed the main constituents of an optical receiver and has reviewed the low, high and trans-impedance preamplifiers as well as the integrate and dump configuration.

Chapter 4

MAC Protocols for Wireless LANs

4.1 Introduction

In order to serve mobile users, a new type of local area network is emerging – the wireless LAN (WLAN), which uses radio or infrared light for physical layer transmission. Rather than being a competitor for wired Ethernet or Fibre Optic LANs, WLANs today primarily supplement wired LANs. The IEEE published a set of standards for wireless LANs in 1999 [45]. The IEEE 802.11 standard is designed to fit into the structure of the suite of 802 LAN standards. Hence, it determines the physical layer (PHY) and medium-access control layer (MAC) leaving the logical-link control (LLC) to 802.2. The MAC layer uses a form of carrier-sense multiple access with collision avoidance (CSMA/CA), which shall be discussed later in the chapter.

The MAC is part of the Data Link layer of the OSI seven-layer model. The Data Link layer is divided into two sub-layers (Fig. 4.1), the upper sub-layer consists of the LLC, while the MAC makes up the lower sub-layer. The MAC is an effective methodology that allows devices on a LAN to share their inter-connecting media. Two or more devices may send data simultaneously due to the shared nature of the media. As a result the MAC has to:

- Decide when to send data
- What to do if its data collides with another's
- How long to wait before re-transmitting

The MAC layer provides the interface between a node's logical link layer and the network's physical layer. The MAC differs for different kinds of physical media. This study is concerned with Optical WLANs. The MAC rides on every transmission of user data into the air and defines how the components of a WLAN have to behave to permit a data communication.

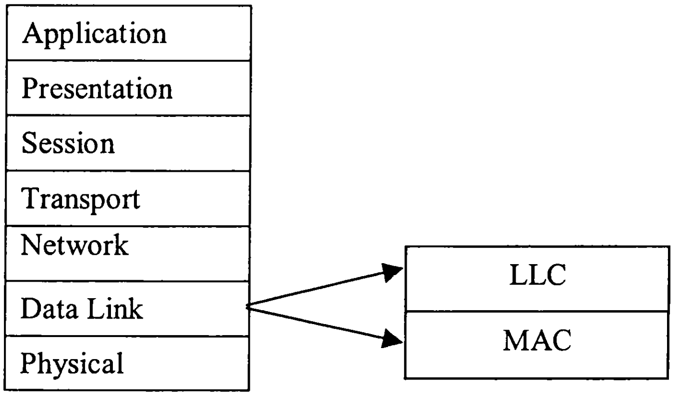

Figure 4.1: The OSI 7 Layer Model

A standard MAC Protocol encapsulates the Service Data Unit (SDU), which is the information passed to it from the preceding layer, by adding a 14 byte header (Protocol Control Information (PCI)) [46]. The combined PCI and SDU is known as the Protocol Data Unit (PDU) belonging to that layer. This then becomes SDU of the following layer. Data is then added before a 4-byte (32-bit) Cyclic Redundancy Check (CRC) is appended to the end of the frame (Fig 4.2).

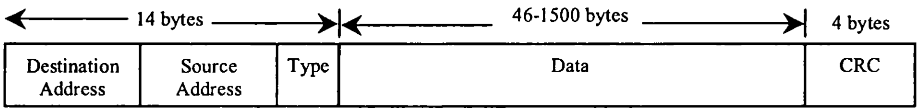

Figure 4.2: MAC encapsulation of a packet of data

The header consists of three parts:

- A 6-byte destination address, which specifies either a single recipient node (unicast mode), a group of recipient nodes (multicast mode), or the set of all recipient nodes (broadcast mode).

- A 6-byte source address, which is set to the sender's globally unique node address. This may be used by the network layer protocol to identify the sender, although usually other mechanisms are used (e.g. Address Resolution Protocol (arp)). Its main function is to allow address learning, which may be used to configure filter tables used in a bridge, which allows the joining of two LAN segments in order to create a larger LAN [47].
- A 2-byte type field, which provides a Service Access Point (SAP) to identify the type of protocol being carried.

The 32-bit CRC added at the end of the frame provides error detection in the case where line errors (or transmission collisions) result in corruption of the MAC frame. The MAC receiver discards any frame with an invalid CRC without further processing. The MAC protocol does not provide any indication that a frame has been discarded due to an invalid CRC

4.2 TCP/IP Model

The acronym TCP/IP (Transmission Control Protocol/Internet Protocol) is a four-layer model used to describe a group of network protocols. Its name is derived from two of the most important protocols that make up this model: Transfer Control Protocol (TCP) and Internet Protocol (IP). The MAC in this model would reside in the lowest level, the Network Access layer, which groups the Physical and Data Link layers of the OSI model together. Also, the Session, Presentation and Application layers of the OSI model are combined into one layer in the TCP/IP model (Fig. 4.3). The principle is the same as that of the OSI model in that each layer controls a specific part of the communication process and the ultimate goal is to represent data in a way that a different host is able to read it. TCP/IP is the primary model used on the global Internet, and is implemented on LANs when using an Internet style Intranet.

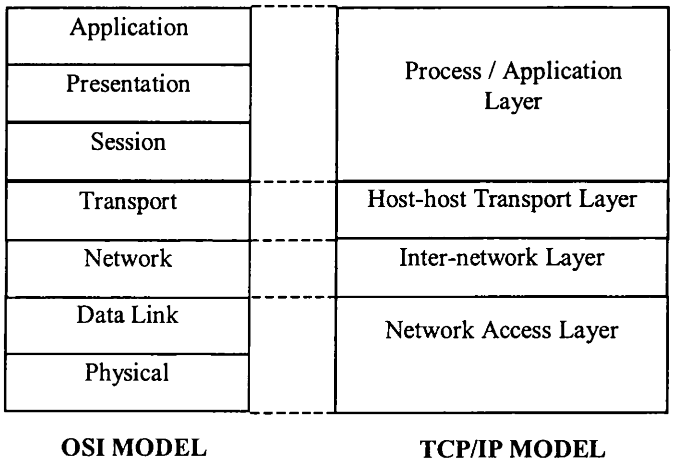

Figure 4. 3 Comparison of 4-layer TCP/IP model with 7-layer OSI model

In radio WLANs, the limited bandwidth of the radio frequency, requires multiple users to share the available spectrum simultaneously, which lead to the development of *multiple access techniques*. The most widespread techniques that emerged for sharing resources are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA) and Spatial Division Multiple Access (SDMA) [48-51]. Duplex configurations are used within multiple access schemes to provide simultaneous transmission of uplink and downlink information.

4.3 Frequency Division Multiple Access (FDMA)

In FDMA, the available frequency band is divided and provided to different users (Fig. 4.4). FDMA is perhaps the simplest technique to provide multiple access. Each user is given a specific carrier frequency and an associated frequency band within which to operate. Each frequency channel may carry a voice conversation or digital data. FDMA is the basic technology used in the analogue Advanced Mobile Phone Service (AMPS), the first widely installed cellular phone system in North America.

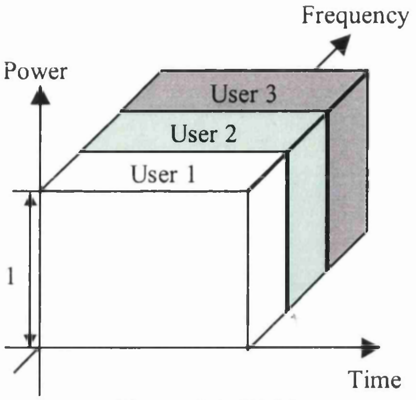

Figure 4.4: FDMA

No one else in the same cell or a neighboring cell can use the frequency channel while it is assigned to a user. This reduces interference, but severely limits the number of users. A single user can be identified using bandpass filters. FDMA is the principle technique used in analogue cellular systems. The concept of FDMA is quite simple; the available bandwidth is segmented equally into bands (or channels). A small guard band is used to ensure that none of the bands overlap and also reduce interference from neighbouring channels (Fig. 4.5).

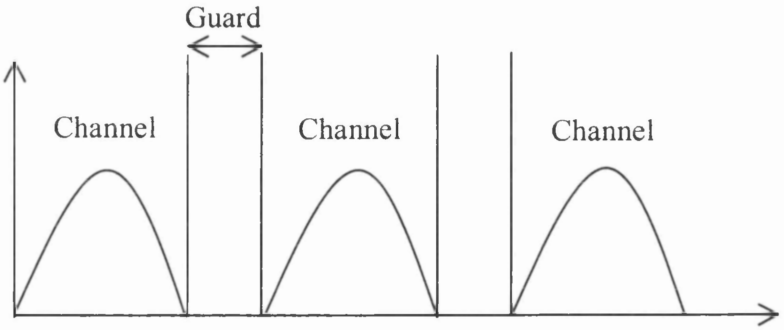

Figure 4.5: Principle of frequency division multiple access

A basestation provides a caller an unused channel. This channel is specific to that caller until the call is terminated or the caller moves to a different cell, in which case, a new channel will be given to the user for that cell. A common duplexing technique for

FDMA is frequency domain duplex (FDD) which divides a channel in two, using one half for the forward channel and the other half for the reverse channel

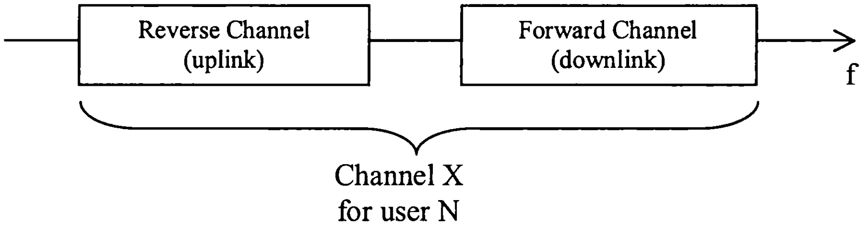

Figure 4.6: Frequency Domain Duplex

The AMPS system uses FDMA/FDD. In AMPS, analogue narrowband frequency modulation (NBFM) is used to modulate the carrier. The number of channels that an FDMA system can simultaneously support is given by [51]:

$$N = \frac{B_t - 2B_{guard}}{B_C} \tag{4.1}$$

Where: B_t = total spectrum allocation

B_{guard} = guard band allocated at the edge of spectrum band

B_C = channel bandwidth

The advantage of FDMA is its simple hardware design, synchronisation is not required, and fading is practically flat since each channel has very little bandwidth. The disadvantages are that a lot of bandwidth may go wasted due to channels sitting idle. Also, although guard slots reduce interference, they do not prevent it from occurring in the event of a neighbouring channel having an instable carrier frequency, and this leads to crosstalk. One major drawback of FDMA is that it cannot be used for variable rate transmission, which is required for combined voice and data transmission.

4.4 Time Division Multiple Access (TDMA)

TDMA divides the available spectrum into multiple time slots. The whole bandwidth is accessible, but is allocated on a time basis (Fig. 4.7). Each user is given a cyclically repeating time slot in which to occupy the complete bandwidth. So each user in a cell obtains a unique time slot within a frame. If there are N users, then N time slots will be required. When all available time slots in a given frequency band are used, the next user must be assigned a time slot on another frequency band. So if there are four users, each having a conversation (simultaneously), then four time slots will be required.

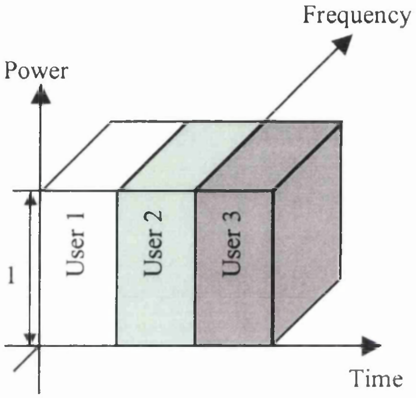

Figure 4.7: TDMA

But its far more efficient to use a single channel, which can accommodate all four conversations providing, each conversation is divided into small segments, assigned a time slot and transmitted in synchronised timed bursts on a rotational basis. This allows the user to carry on with the conversation (or transmission of information) continuously. Only one person is actually using the channel at any given moment, but he/she only uses it for short bursts. Then the user gives up the channel momentarily to allow the other users to have their turn. An analogy can be made with how a PC carries out multitasking using a single processor to run multiple applications seemingly simultaneously. Using this method, the base station ensures that there are no collisions for calls being handled within the cell. The main limiting impairment is multiple access interference from users in other cells, which is typically far above the background noise level. This is typically dealt with by limiting the reuse of frequencies. TDMA was first specified as an Interim Standard by the Electronic Industry Association / Telecommunications Industry Association (EIA/TIA) (IS-54). IS-136, an evolved version of IS-54, is the United States standard for TDMA for both the cellular (850 MHz) and personal communications services (1.9 GHz) spectrums. TDMA is also used for Digital Enhanced Cordless Telecommunications (DECT). Unlike FDMA, which accommodates analogue FM, TDMA requires digital data and digital modulation. The structure of a TDMA frame is shown in Fig. 4.8. Each frame consists of a preamble, information message and trial bits. The preamble contains the address and synchronisation information that both the base station and the subscribers can use for identification [52].

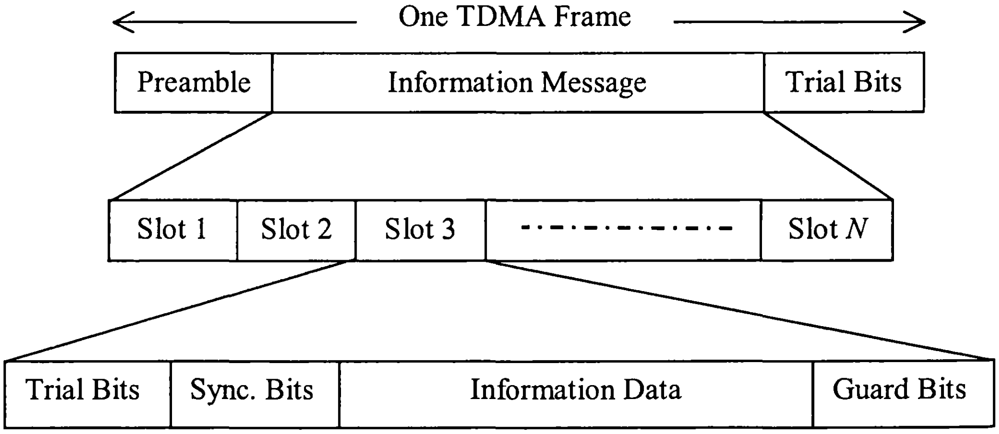

Figure 4.8: TDMA frame structure [51]

The number of channels in a TDMA system can be found by multiplying the number of TDMA slots per channel by the number of channels available and is given by [51]:

$$N = \frac{m(B_t - 2B_{guard})}{B_C} \tag{4.2}$$

where m is the maximum number of TDMA users supported on each radio channel.

IS–54 and IS–136 implementations of TDMA effectively tripled the capacity of cellular frequencies by dividing a 30–kHz channel into three time slots, enabling three different users to occupy it at the same time. Currently, there are systems in place that can allow six times capacity and in the near future, with the utilisation of hierarchical cells, intelligent antennas and adaptive channel allocation, the capacity should approach 40 times analogue capacity [52]. The advantage of TDMA is that users can be given different amounts of bandwidth, mobiles can use the idle times to determine the best station and switching off when there is no transmission can save power. The drawbacks are the added overhead resulting from the requirement of synchronisation and the higher risk of multipath interference on wireless links.

Time division multiple access/frequency division multiple access (TDMA/FDMA) is a hybrid technique combining both TDMA and FDMA to divide the system bandwidth by both frequency and time. Instead of using the full bandwidth (frequency) of a system to transmit digital signals, as in TDMA, the bandwidth is divided via FDMA into a number of frequencies, each supporting a channel. Then TDMA uses time slot sharing to increase the number of conversations per frequency channel by multiplexing the encoded signals.

4.5 Code Division Multiplexing (CDMA)

Digital-American Mobile Phone Service (D-AMPS), the European standard, Global System for Mobile communications (GSM) and Personal Digital Cellular (PDC) all use TDMA. However, each of these systems implements TDMA in a somewhat different and incompatible way. An alternative multiplexing scheme to FDMA with TDMA is CDMA (code division multiple access), which takes the entire allocated frequency range for a given service and multiplexes information for all users across the spectrum range at the same time (Fig. 4.9). CDMA uses the complete bandwidth, which is shared by all and uses codes to distinguish between the terminal users (TU).

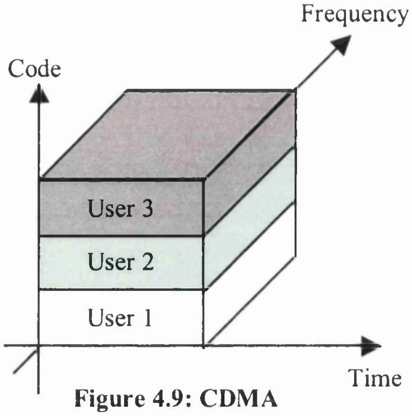

Figure 4.9: CDMA

CDMA users share a common frequency channel. All users are on the same frequency at the same time. However, each pair of users is assigned a special code that reduces interference while increasing privacy. CDMA is a *spread-spectrum* (SS) approach to user multiplexing used mostly in wireless broadcast channels (cellular, satellite, etc). The Telecommunications Industry Association (TIA) adopted CDMA in 1993. CDMA allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal"). So a large number of users can occupy the same bandwidth at all times providing each user is assigned a pseudorandom or pseudonoise (PN) binary valued sequence code [27]. Phase Shift Keying (PSK) and Frequency Shift Keying (FSK) are the two modulation schemes that spread spectrum systems generally use. If the PN sequence is used with PSK, phases of 0 and π will be generated pseudorandomly in accordance with the code. This results in direct-sequence systems (DS-CDMA) [53]. Alternatively, if FSK is used, the frequency of the transmitted signal is selected pseudorandomly. The result is a frequency-hopped direct sequence system (FH-CDMA) [54]. The advantages of CDMA are that it is immune to narrowband noise and multipath interference, it is more secure with a strong multiple access capability, there is no need for all stations to be synchronised and all cells can use all frequencies. But, CDMA requires a greater amount of complexity and a large contiguous frequency band (for direct sequencing) and is not very bandwidth efficient if used by a single user.

4.6 Spatial Division Multiple Access (SDMA)

SDMA, which reuses a certain resource (channel capacity) in spatially separated areas is commonly implemented in the satellite communications field, which optimises the use of radio spectrum and minimises system cost by taking advantage of the directional properties of dish antennas. In SDMA, satellite dish antennas transmit signals to the numerous zones on the earth's surface. The antennas are highly directional, allowing duplicate frequencies to be used for multiple surface zones. If for example, signals had to be transmitted simultaneously by one satellite to mobile or wireless receivers in twenty different surface zones, twenty channels and twenty antennas would be necessary to maintain channel separation in a conventional system. In SDMA however, there can be far fewer channels than zones. If duplicate channel zones are sufficiently separated, the twenty signals can be transmitted to earth using four or five channels. The narrow signal beams from the satellite antennas ensure that interference will not occur between zones using the same frequency.

SDMA requires careful choice of zones for each transmitter, and also requires precise antenna alignment. A small error can result in failure of one or more channels, interference among channels, and or confusion between surface coverage zones. Sectored antennas are increasingly being used in wireless LANs and cellular systems to achieve spatial multiplexing gain.

FDMA, TDMA, CDMA and SDMA are known as Channel Partitioning Circuit-switched multiple access protocols. They all dedicate a fixed resource for the duration of the connection. This is inefficient for bursts of data. Random Partitioning Packet-switched multiple access protocols such as ALOHA and CSMA are very flexible and are more suitable for dynamic and bursty wireless packet data networks and so are predominantly used in WLANs. But these protocols suffer form low throughput under heavy loading due to frequent collisions and cannot dedicate bandwidth. The following sub-sections will examine these protocols.

4.7 ALOHA

The ALOHA protocol was developed in the late 1970s by the University of Hawaii so that computers across a number of small islands could be connected via a radio communication system. Early satellite systems also adopted ALOHA which involved contention techniques to transmit on a common channel. Each user is allowed to transmit whenever they have data. The transmitting subscribers listen out for an acknowledge (ACK) or negative acknowledge (NACK) signal, which is broadcast by the base station to determine whether or not the transmission was successful. In the case of a collision, the transmitting nodes wait for some random time and then re-transmit the packets. Using packet contention a large number of subscribers can be accommodated with very little overhead. Throughput (T) is used to evaluate the performance of contention techniques and is defined as the average number of messages successfully transmitted per unit time, and the average delay (D) of a typical message burst is also used to characterise these protocols. The vulnerable period (Vp), which is the period that packets are most susceptible to collisions, needs to be determined in order to find throughput. Fig. 4.10 shows the vulnerable period for a packet using ALOHA [51]. Packet A will collide with packets B and C due to the overlap in transmission time.

The pure ALOHA protocol is a random access protocol used for data transfer. A user transmits on a channel and then waits for acknowledgement on either the same channel or a separate feedback channel. Since the probability of collisions increases with the number of users, the size of delay also increases. The vulnerable period (as shown in Fig. 4.10) is twice the packet duration.

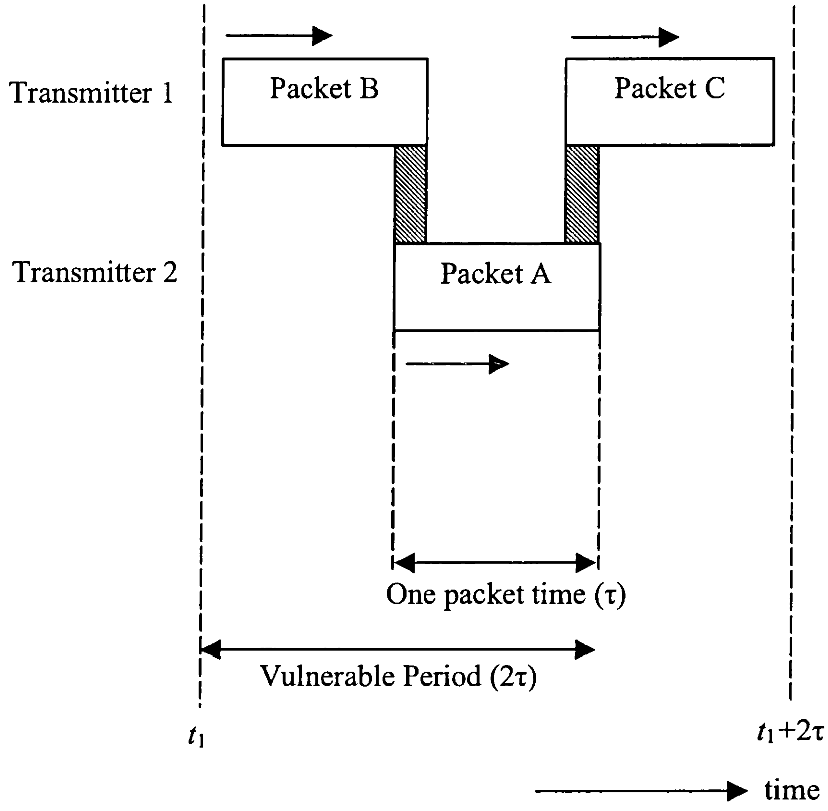

Figure 4.10: Vulnerable Period for a packet using ALOHA protocol [51]

Therefore, the probability that no other packet will be generated during the interval 2τ (where τ is the packet duration in seconds) is found by evaluating Pr(n) [51]:

$$\mathrm{Pr(n)} = \frac{(2R)^{\mathrm{n}} e^{-2R}}{\mathrm{n!}} \quad \text{at n} = 0 \qquad (4.3)$$

where R is the throughput of a packet radio network generated by the user population, n is the number of packets. This assumes that packet transmissions occur with Poisson distribution. So, the probability of no collisions Pr(0) is e^{-2R}. Therefore, since the normalized throughput of a packet radio (given as total offered load times and the probability of successful transmission) is T = R.Pr[no collision], the throughput of the ALOHA protocol is:

$$T = R.e^{-2R} \tag{4.4}$$

Slotted ALOHA (S-ALOHA) is a synchronous protocol using equal time slots that have a length greater than the packet duration τ. Users can only transmit a message at the beginning of a new time slot. This eliminates partial collisions but complete collisions still cause delay as the number of users increases. On collision, the transmitter waits for some random time, but then also has to wait for the beginning of the next available time slot, which adds to the delay. The Vp of S-ALOHA is only one packet duration and so the probability of no collisions is e^{-R}. Therefore, the throughput of S-ALOHA is given by [52]:

$$T = R.e^{-R} \tag{4.5}$$

There is therefore a tradeoff between ALOHA and S-ALOHA packet radio protocols. While ALOHA provides its maximum throughput with less delay than S-ALOHA, the maximum throughput achieved is significantly less than S-ALOHA. But S-ALOHA has double the normalised delay before achieving its maximum throughput.

Reservation ALOHA (R-ALOHA) is a protocol that contains both elements of contention and reservation, combining S-ALOHA and TDMA. It was originally designed by Crowther *et al* [55] to improve the throughput of a satellite channel beyond that of S-ALOHA, which is purely a contention protocol. R-ALOHA is based on Time Division Multiplexing and allows users to reserve slots, permanently or on request, for the transmission of packets. The channel is slotted in time, and the slots are divided into frames with N-slots in each frame just like TDMA. Each slot is large enough to contain a packet of data. The frame duration is assumed to be greater than the maximum channel propagation delay in the broadcast network. Therefore, each user knows the usage status of time slots one frame ago. If a time slot in the previous frame was unused, it may have been simply empty, or two or more packets attempted to use it (causing a collision) and so none could be received quickly. On the other hand, a used time slot in the previous frame indicates that exactly one packet was transmitted into it and the packet was successfully received. One method of R-ALOHA allows a terminal to reserve a slot permanently until it completes transmission, although a time-out sequence will interrupt very large duration transmissions. Tanenbaum [56] describes another method, which is to allow a request in a sub-slot (reserved in each frame) to be transmitted. On receipt of a successful transmission, the next regular slot in the frame is allocated to the terminal for data transmission.

4.8 Carrier Sense Multiple Access (CSMA)

The basic approach of CSMA protocols is that a terminal wishing to transmit will first listen for a carrier signal on the transmission channel. If no such carrier is detected, then a packet can be transmitted. On the other hand, if it is detected that another station is actively transmitting data, then the transmission will be postponed for a random time. There are two important parameters in CSMA protocols, detection delay and propagation delay. Detection delay is a measure of how fast a packet travels from base station to a mobile terminal. Propagation delay influences the time needed to sense whether or not a channel is idle and is a measure of how fast a packet travels from base station to a mobile terminal. Propagation delay influences the performance of CSMA protocols because if the delay is small, then a terminal may transmit a packet thinking the channel is idle whilst another terminal just begins transmitting at the same time. This results with a collision of the packets causing both to be corrupted. The propagation delay (t_d) can be expressed as:

$$t_d = \frac{t_p R_b}{m} \tag{4.6}$$

where: t_p = propagation time in seconds

R_b = channel bit rate

m = expected number of bits per packet

There are several methods of resolving contention within CSMA. All of them use the 'listen before you talk' technique, but then alter in how the contention resolution is specifically adopted. Short descriptions of some of these techniques follow.

P-persistent CSMA: Time slots are used for transmitting data. So if the channel is idle, a terminal may transmit at each time slot with a probability of p. If the probability of 1.0 is used to gain access to a channel, then a terminal will transmit as soon as it finds the channel idle and the probability of a collision occurring is 1 (this is known as 1-persistent CSMA). However, if the probability of transmitting is reduced, then the probability of collisions will reduce. For example, if only two stations wish to gain access and the probability is reduced from 1 to 0.5, then the probability of collisions is $0.5^2 = 0.25$. If the channel is busy then the terminal will persistently sense the channel until it becomes idle. Fig. 4.11 shows the difference between different settings of p [57]. Again there is a tradeoff with throughput and delay. The average delay is determined by:

$$\frac{1-p}{p} \text{ slot times} \tag{4.7}$$

Non-persistent CSMA is a popular technique for Wireless LAN applications. On receipt of a negative acknowledgement, a terminal waits for a random time before re-transmitting a packet. The packet transmission interval is greater than the propagation delay to the farthermost user.

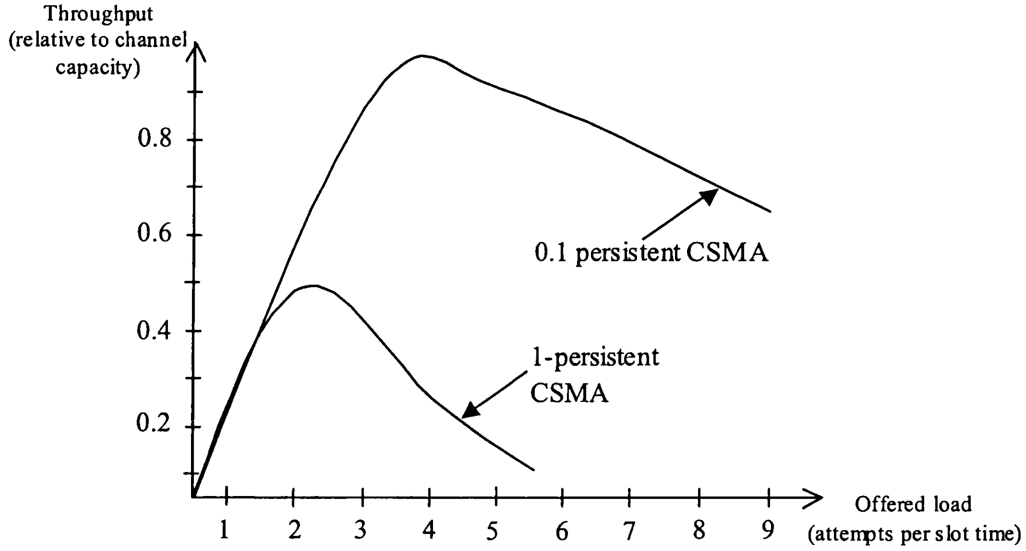

Figure 4.11: CSMA Analytical Performance [57]

CSMA/CD (collision detection) works on the "*listen while you talk*" principle, which, unlike the p-persistent CSMA protocol, ceases transmission if a collision occurs. If two terminals, A and B are considered at either end of the transmission medium and A begins to transmit, then B may also begin to transmit since, due to some propagation delay, it is unaware of A's transmission and so think the channel is idle, resulting in a collision. The first station to detect the collision will abort transmission and send a jamming signal to notify the other stations (within its collision domain) that a collision has occurred. Otherwise the channel would remain occupied without any useful signal being recoverable. This enhances the throughput, compared to a system that only acknowledges reception after transmission of the full message or packet. A and B will then initiate a back-off algorithm before re-transmitting. Fig. 4.12 describes the steps taken by means of a flow chart [47]. To ensure successful collision detection there is a size limit on the medium and a minimum packet size for a given transmission speed.

This is because it is possible for A to complete its transmission before receiving the jamming signal from B. Therefore the rate of data transmission must be greater than twice the propagation delay from one end of the medium to the other. CSMA/CA (collision avoidance) is very similar to p-persistent and in fact many approaches use p-persistent schemes as a collision avoidance technique. The idea is to prevent collisions at the moment they are most likely to occur. CSMA/CA is often used in wireless LANs and works on the *"listen before you talk"* principle as a means of avoiding (but not eliminating) collisions. The most important differences between the wireless LAN and the MAC protocol of most wired networking applications is the impossibility to detect collisions. With the receiving and sending antennas immediately next to each other, a station may be unable to see any signal but its own. As a result, the complete packet will be sent before the incorrect checksum reveals that a collision has happened. It is therefore of utmost importance that the number of collisions be limited to the absolute minimum and this is achieved by CSMA/CA. To describe the process let us consider a data station 'A' for example, that intends to transmit. A will first broadcast a jamming signal, after waiting a sufficient time for all stations to receive the jamming signal, A transmits a frame, and while transmitting, if A detects a jamming signal from another station, it stops transmitting for a random time and then tries again. The jamming signal, in the case of CSMA/CA, indicates that the sending station intends to transmit as opposed to notifying the stations that a collision has occurred, which is the case described earlier with CSMA/CD.

4.9 Packet Reservation Multiple Access (PRMA)

Goodman et al. [58] in 1989 originally proposed Packet Reservation Multiple Access (PRMA), a terminal-to-base transmission protocol for wireless local area networks as a statistical multiplexer to improve the capacity of Time Division Multiple Access (TDMA) for conversational speech.

1. Host wants to transmit
2. Is carrier sensed?
3. Assemble frame
4. Start transmitting
5. Is a collision detected?
6. Keep transmitting
7. Is transmission complete?
8. Transmission Completed
9. Broadcast jamming signal
10. Attempts = attempts + 1
11. Attempts > too many?
12. Too many collisions; abort transmission
13. Algorithm calculates backoff
14. Wait for t seconds

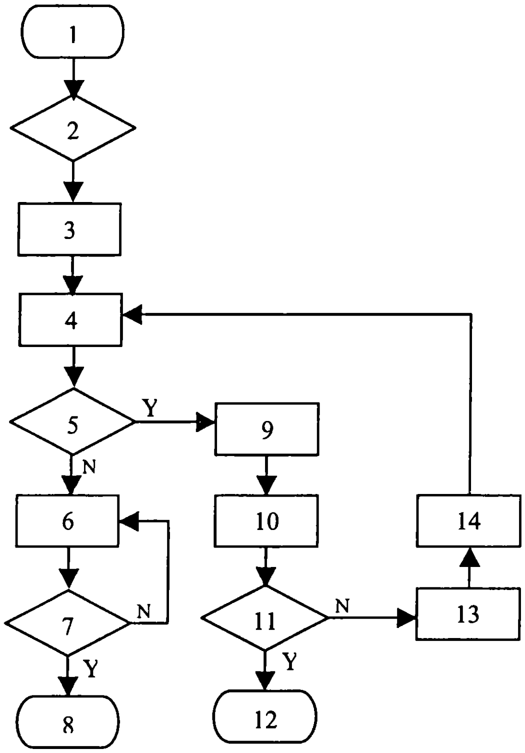

Figure 4.12: Decision flow of CSMA/CD protocol [47]

Speech can be separated into two parts, talkspurt and silence by using a voice activity detector (VAD). For efficient use of transmission links, only talkspurts are put into packets for transmission. PRMA is a TDM based protocol, and has been specifically designed to handle multiple access over wireless links combining the best features of circuit-switched and packet-switched multiple access protocols. PRMA is related to R-ALOHA contrived for conveying speech signals on a flexible demand basis via TDMA systems [59]. To reduce collisions and minimise transmission delay, there is a dedicated bandwidth for delay sensitive services such as real time voice and video. Like TDMA, the channel is divided into time slots, which are classified as either reserved or available and grouped into fixed-sized frames. The frame duration is chosen so that a voice terminal transmits a single packet per frame. Terminals use the S-ALOHA protocol to contend for available slots. After successfully contending for a time slot, a terminal is able to reserve it for the duration of the time it has data to send. Other terminals are now prohibited from transmitting while the slot is reserved. Reserved slots are surrendered when the terminal has no more data to send making it available for contention again.

There are drawbacks to PRMA, such as a reduction of throughput and increase in delay as a result of increased collisions while contending for available slots; Permission probability must be managed so that terminals with time sensitive data may access the channel quickly. Moreover, PRMA has an inability to recover quickly from corrupted packets. A terminal must wait an entire frame duration before re-transmitting a corrupted packet in next reserved slot. Failure to receive a valid packet in a reserved time slot may cause the base station to think that a terminal has finished transmitting, and to release the slot for contention.

4.10 Summary

This chapter has provided an overview of why a MAC protocol is required in a network, specifically in the wireless domain. The MAC layer resides in the lower sub-section of the Data Link layer of the OSI model. Protocols derived for this layer allow the sharing of a communication channel for multiple users. Duplex configurations and traditional multiple access schemes FDMA, TDMA, CDMA and SDMA have been described as well as recent protocols such as CSMA and PRMA.

Chapter 5

Slotted MAC Protocol for OW Transmission

5.1 Introduction

Recently mobile communications have taken huge leaps; the increase in availability, production and purchase of mobile phones and PDAs are evidence of this. The emergence of Optical Wireless Communication (OWC) and more specifically infrared (IR) technology is a move towards that direction. Infrared technology offers major performance advantages over traditional cable or radio systems, with huge achievable bit rates in excess of 1.5 Gbs^{-1} [25]. Unlike radio and microwave technologies, infrared offers complete freedom from interference and radio licensing regulations. As extensive research continues in OWC, the requirement for a MAC protocol designed specifically for IR transmission has become essential. This chapter discusses such a design, which provides mobile-to-mobile communication and evaluates system performance through simulation comparing the results to the analytical model in [60].

5.2 Real World Model

The cellular network structure envisaged for the proposed protocol is as shown in Fig. 5.1. Consider an example of a company building, each office may contain a number of cells, smaller rooms may only consist of one or two cells. Each node within a cell then transmits to a satellite point on the ceiling using the infrared medium, by means of transceivers fitted to the mobile nodes. The satellites communicate with a base station, which corresponds with each satellite about the availability of slots on the respective protocol. The base stations are inter-connected via optical fibre links, which provide the backbone of the network and allow the whole building to become interlinked. Each satellite consists of an array of LEDs or lasers, which satisfy the eye safety standard recommendations established by the International Electrotechnical Commission (IEC) [20]. Lasers have been deemed a safety hazard for indoor applications, as they are a point source emitter. Ways of extending or diffusing the laser source to comply with IEC825 were discussed in Chapter 2. To achieve maximum throughput, the rate at which a mobile node transmits should adapt according to its position within the cell.

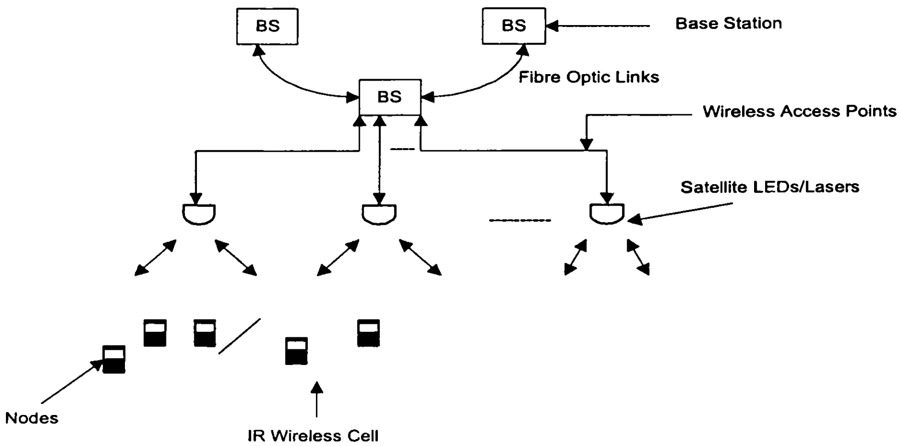

Figure 5.1: Optical Wireless Network Structure

5.3 Design of MAC Protocol

The MAC Protocol is based on Packet Reservation Multiple Access (PRMA), a terminal-to-terminal transmission protocol (through base station) for wireless local area networks. PRMA is a TDM based protocol, and uses CSMA/CA techniques to avoid collisions when users try to reserve a slot.

The time organisation of Uplink and Downlink frame of the MAC protocol can be seen in Fig. 5.2 [60]. Each frame is divided in to J channel frames. The uplink frame consists of a reservation (R) slot and N information slots. The downlink frame consists of an acknowledgement (ACK) slot and N information slots. A node needs to reserve a slot before it can actually transmit the data.

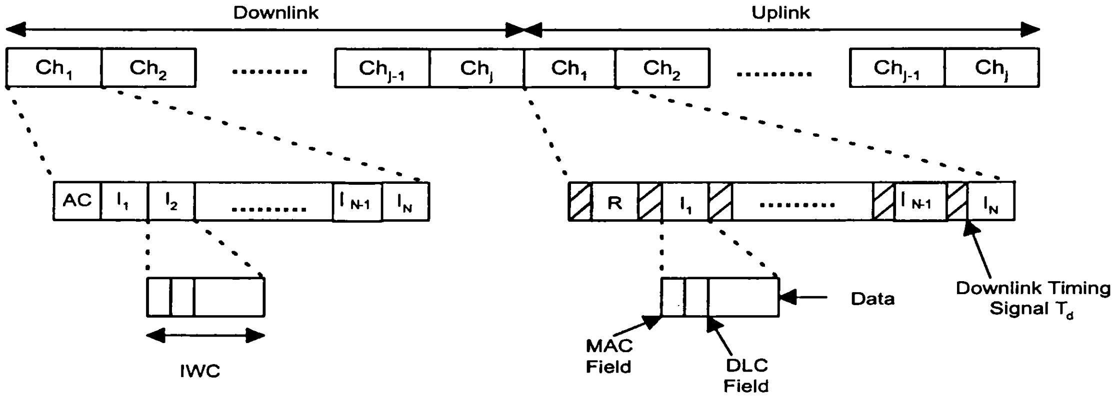

Figure 5.2: Timing Organisation of the MAC Protocol [60]

The nodes request the reservation by transmitting their source and destination addresses through the R slot. The duration of the I slot is the transmission time of an IR wireless cell. The base station uses the ACK slot to broadcast messages for each downlink slot as well as reservation messages for each node that requested a slot. Nodes start to transmit in their own time slots by means of short downlink timing signals (T_d).

When an acknowledgement is received, the transmitting node will know which slot (in the uplink frame) is allocated to it, and the receiving node will identify the corresponding slot in the downlink frame from which it is to extract the data. The receiving node will continue to read data from this slot until it encounters an end of transmission (EOT) value, upon which the slot is released for contention.

If there are no free slots, when nodes try to reserve a slot, a delivery delay occurs for the packets waiting to be transmitted. For real time services like voice, this delay should not exceed a maximum delay of D_{max}. For speech, packet-dropping probability at which speech quality degradation is unapparent must be less than 1%. The MAC protocol allocates fixed number of slots in each channel frame.

5.4 Theoretical Model

To investigate the performance of this MAC protocol, a theoretical model was developed [61]. In this analysis, a finite number (M) of homogenous voice users are considered. Each user has a speech activity detector with talkspurts and silences that follow a negative exponential distribution. Talkspurt duration (t1) is equivalent to the message length or service time [62] and gap duration (t2) is equivalent to the interarrival time of messages.

The MAC protocol is designed so that the uplink channel frame rate is identical to the arrival rate of periodic (voice) packets. The analysis considers only the statistical allocation of the time slots. It also ignores the co-channel interference and ISI in the physical layer by using a large channel re-use factor and a channel bit rate no greater than 10 Mb/s. The system performance depends on the packet arrival pattern and MAC structure. The packets arrival rate conforms to a Poisson distribution and so the inter-arrival times of the packets follow a negative exponential distribution. A mathematical model for the MAC protocol under these features based on an M/M/N/∞/M queuing model was developed. It consists of exponentially distributed durations (M) of all talk spurts and gaps exponential service (M), N parallel servers, infinite storage and M users [63]. The number of time slots (servers) N per channel frame is given by [63]:

$$N = \text{int}\left[\frac{R_C T_{cf}}{2JT_{cf}R_S + H}\right] \tag{5.1}$$

where int [x] is the largest integer smaller than or equal to x, R_c is the channel bit rate, R_s is the source rate, H is the header of the infrared wireless cell (IWC) and J is the channel reuse factor. T_{cf} is the channel frame duration and is given $T_{cf} = (T_f / J)-(ACK / R_c)$, where T_f is the uplink/downlink frame duration. Transmission delays between nodes and satellite points are negligible. The number of voice users in the system at a given time, can be obtained by using birth-death theory for finite source queues.

5.5 Simulator Design

The software to simulate the above-described MAC protocol was developed by the author together with two colleagues in the group [64, 65] and the results were jointly published [12, 13]. The simulator employs event driven simulation and is programmed in Java using object-oriented concepts. As Java is a machine independent language, the simulator can be run on any operating system or platform/environment. The full program is provided in Appendix A.

The simulator uses Poisson process to generate traffic for each node. Even though, statistically self-similar process generates more realistic traffic as compared to a Poisson process [66, 67], Poisson models are still used to generate traffic for simulations because they can be modelled easier than self-similar processes [68]. Poisson models have another advantage; they can be defined by just a single parameter (in this case, inter-arrival mean time). Packet inter-arrivals are generated using an inverse transformation [69]. Using the simulation, the performance of the system in terms of throughput, access delay and packet dropping probability is evaluated.

5.6 Performance Analysis

In this section, an analysis is carried out on the performance of the system using a fixed number of voice sources. The performance of the system for the parameters given in Table 5.1 will depend on the packet arrival pattern and MAC structure. The system performance in terms of throughput, average access delay, and packet dropping probability is evaluated for a range of system parameters.

Variable	Notation	Value
Channel bit rate	R_c	10 Mb/s
Speech peak bit rate	R_s	64 kb/s
Uplink/downlink frame duration	T_f	3.1 ms
Downlink timing signal	T_d	4 bits
Speech mean ON duration	t_1	1 s
Speech mean OFF duration	t_2	1.35 s
Speech maximum time delay	D_{max}	20 ms
Channel reuse factor	J	7
Size of an IWC	H	53 bytes

Table 5.1: System Parameters

Fig. 5.3 illustrates the accuracy of the simulator with respect to the analytical model [60, 61, 63]. The graph is that of the system throughput versus the number of terminal users (M). The system throughput gradually increases as M increases (i.e. as offered load increases) until a saturation point is reached (full statistical utilisation of MAC slots) where it remains constant even if the number of users increases. The transmission delay considers all packets transmitted from a source node to its destination node and the subsequent delay incurred. Fig. 5.4 illustrates the transmission delay of the system, which increases significantly after M exceeds 10 (available number of slots) due to the wait and contention of available slots. Again the theoretical results agree with the simulated results. Nodes that wish to transmit when slots are unavailable are susceptible to dropping packets if the access delay exceeds a maximum value. As the number of active nodes in the cell increases, so does the probability of packets being dropped. Fig. 5.5 shows the packet dropping probability (PDP) against the number of active nodes, which are all transmitting at single speech rate.

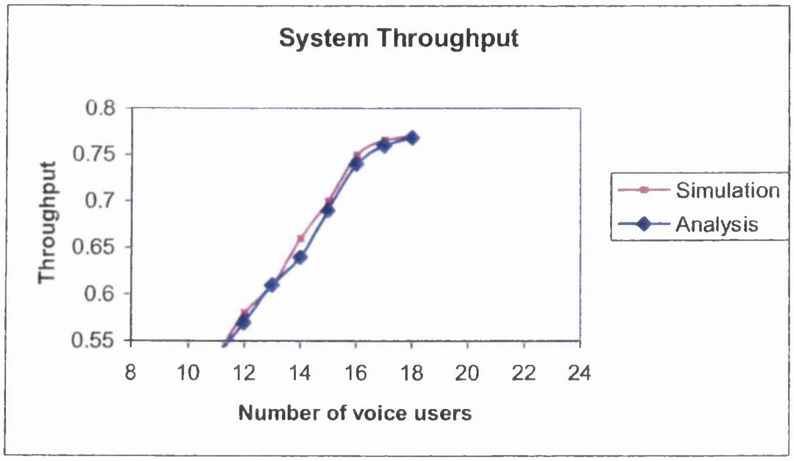

Figure 5.3: System Throughput vs. Voice Nodes

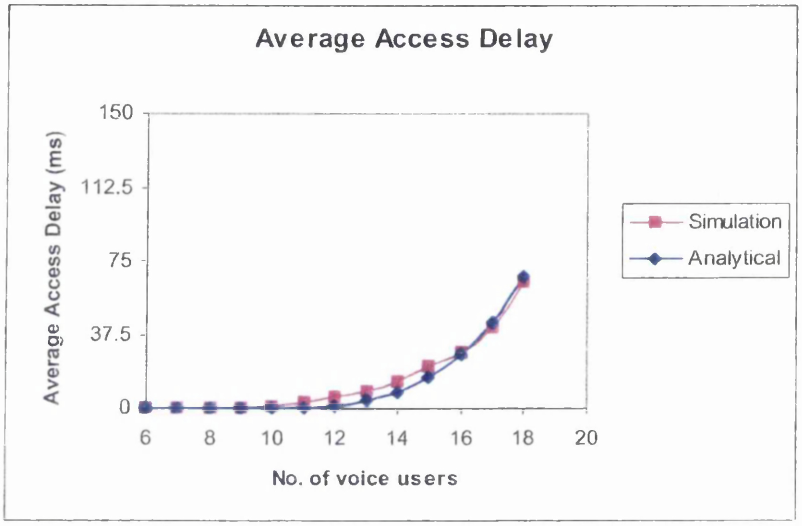

Figure 5.4: Average delay vs. number of voice nodes

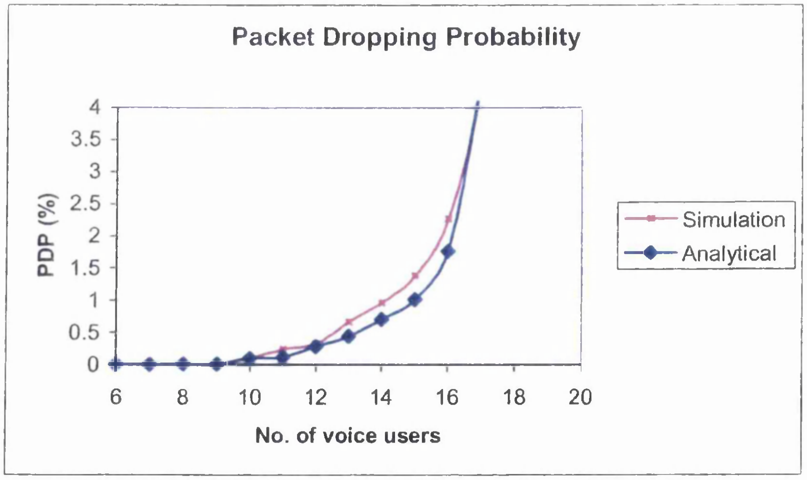

Figure 5.5: Packet Dropping Probability vs. Active Nodes

The difference between the theoretical and simulation results in Figs. 5.3, 5.4 and 5.5 may be attributed to the statistical nature of the simulations. According to [58], to prevent speech quality from becoming indiscernible, PDP must be lower than 1 percent. Since each node only requests one slot, the first nine nodes are easily accommodated, as there are nine available slots. The following nodes then have to wait for a slot to become available, which leads to PDP. At 1 percent, a maximum of ten nodes can be supported. Beyond ten nodes, the quality of service (QoS) is deemed unsatisfactory. The access delay correlates significantly with PDP.

5.7 Summary

This Chapter has considered a MAC protocol and a simulator for the protocol used for indoor optical wireless LANs employing IR technology and with a wireline optic backbone network. A proposed scenario for such a LAN was presented and the MAC protocol was simulated. The system performance for fixed number of voice sources in a cell over a range of system parameters was evaluated. Computer simulations of the results agreed with theoretical results. The performance of the protocol was determined by collating the PDP, system throughput and average access and transmission delays. The system has good stability and potential for further work.

Chapter 6

Dispersion and Noise in OWC

6.1 Introduction

A diffuse indoor OW network takes advantage of the efficient infrared reflective properties of a common room or office space. Typical plaster wall and acoustical ceiling tiles have been found in a study [70] to have diffuse reflectivities in the range of 0.6-0.9, while other materials such as carpets exhibit lower values. The same study found that plaster walls and ceilings are almost ideal Lambertian reflectors. Therefore, the transmitted infrared signal may experience a number of reflections on transit to the receiver. But, these reflections cause multipath dispersion similar to radio signals, which is a major impediment in communication systems as it leads to inter-symbol interference (ISI). Another factor to be considered, which impairs OWC systems is the shot noise resulting from background light via sunlight, incandescent and fluorescent lighting. These shot noise sources cause variation in the received photocurrent that is unrelated to the transmitted signal, resulting in an additive noise component at the receiver. Fig. 6.1 shows the optical power spectra of some common infrared sources [25]. Most wireless infrared communications systems can be modeled as having an output signal Y(t) and an input signal X(t) which are related by:

$$Y(t) = X(t) \otimes c(t) + N(t) \qquad (6.1)$$

where ⊗ denotes convolution, c(t) is the impulse response of the channel and N(t) is white Gaussian additive noise. Most systems use intensity modulation with direct detection (IM/DD) to achieve optical modulation and demodulation since the photodetector current is proportional to the received optical signal intensity, which for intensity modulation is also the original modulating signal. The photocurrent at the receiver can be written as:

$$Y(t) = X(t) \otimes R \bullet h(t) + N(t) \qquad (6.2)$$

where R is the responsivity of the receiving photodiode (A/W). Note that the electrical impulse response $c(t)$ is simply R times the optical impulse response $h(t)$ [71]. This chapter concentrates on the system as represented by the above model.

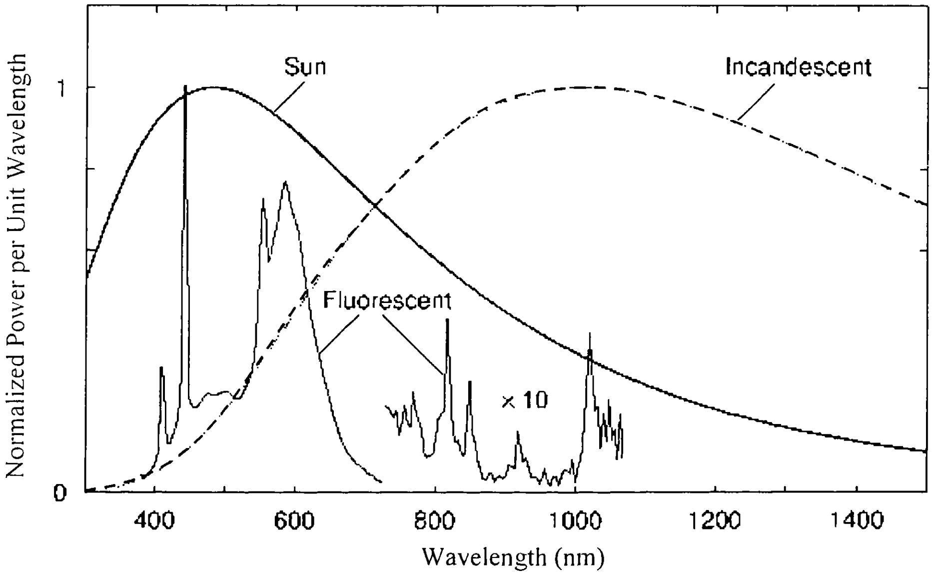

Figure 6.1: Spectral power densities of common ambient light sources [25]

A method for calculating the background noise and impulse response in a room with a fixed transmitter and mobile receiver will be presented. The results will allow the determination of signal-to-noise ratio (SNR), which shall be discussed in the next chapter.

6.2 Noise Distribution

As mentioned, the ambient noise sources of an optical wireless link are critical factors in determining performance. To simulate the noise distribution of a set of spotlights, a test room is set up (Fig. 6.2(a)). The room is 8m x 4m x 3m and eight spotlights or lamps (L) were considered at the following Cartesian coordinates:

L1 (1,1,3)	L2 (3,1,3)	L3 (5,1,3)	L4 (7,1,3)
L5 (1,3,3)	L6 (3,3,3)	L7 (5,3,3)	L8 (7,3,3)

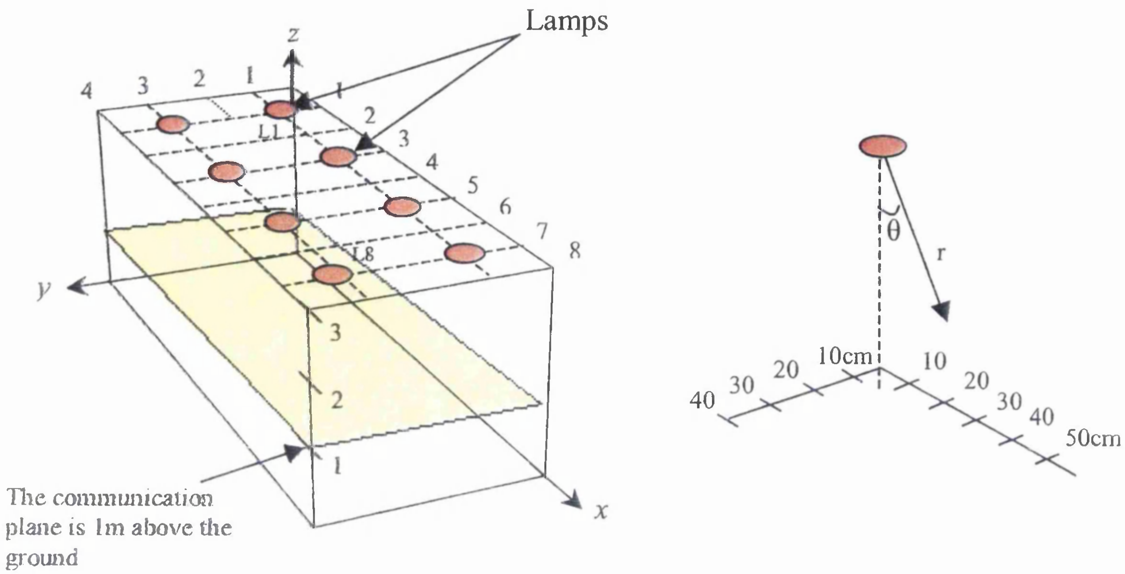

Figure 6.2: a) Test room set up **b) Angle between emitted ray and normal**

Incandescent lamps can be modelled as Lambertian sources [72]. Therefore, the angular intensity distribution follows the equation:

$$I(\theta) = Ps\frac{n+1}{2\pi}\cos^{n}\theta \tag{6.3}$$

where Ps is the emitted power from the source, n is the mode number, which specifies the directionality of the source (a mode of $n = 1$ corresponds to a traditional Lambertian source) and θ is the angle between the emitted ray (r), and the normal of the lamp (Fig. 6.2(b)). The coefficient $\frac{n+1}{2\pi}$ ensures that integrating $I(\theta)$ over the surface of a hemisphere will result in the original source power Ps. The optical power emitted by each lamp was determined by dividing the angular intensity distribution by r^2.

To measure the optical power received, the bespoke simulator, took measurements along the communication floor (Cf) at 10cm intervals along both the x and y axis. So effectively, Cf was divided into 80 x 40 centimetre squares (elements), with the power calculated at the centre of each element.

To calculate the individual power at each element *Pd*, the distance r between the lamp and the receiving photodiode has to be considered (r_1):

$$r_1 = \sqrt{\left((x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2\right)} \qquad (6.4)$$

where, (x_1, y_1, z_1) are the coordinates of the lamp (or transmitter) and (x_2, y_2, z_2) are the coordinates of the receiver. *Pd* can then be given as:

$$Pd = Ps \cdot \frac{n+1}{2\pi} \cdot \frac{\cos^n \theta \cdot \cos\Phi \cdot Ar}{r_1^{\,2}} \qquad (6.5)$$

Since the photodiodes are placed on the floor, the emitting and incident angles θ and Φ are equal as they are alternate angles. Therefore equation 6.5 can be written as:

$$Pd = Ps \cdot \frac{n+1}{2\pi} \cdot \frac{\cos^{(n+1)} \theta \cdot Ar}{r1^2} \qquad (6.6)$$

Considering a Philips PAR38 spotlight (Appendix B), which has Ps = 75W and was found to have $n = 36.1$ [26], with a photodiode of 1cm^2 *Ar*, the distribution of the noise from the spotlights was simulated (Fig. 6.3). The results indicate that the maximum noise power received is 10.8mW and the minimum power level is 7.62µW.