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Adaptive signal processing for infrared wireless CDMA systems

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Adaptive Signal Processing for Infrared Wireless CDMA Systems

by

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Abstract

Infrared system provides a feasible alternative to radio system for indoor wireless communication. Direct spread CDMA format is a promising candidate for infrared transmission system. In indoor systems, transmission is severely impaired by noise and interference produced by artificial light. In this thesis, the performance of the DS CDMA indoor wireless infrared system on diffuse channels is analyzed by taking the effects of inter symbol interference (ISI) and electronic ballast florescent light interference into account. Moreover, to mitigate the effects of ISI and electronic ballast florescent light interference, an adaptive filter technique is proposed for noise cancellation and equalization. This is done by considering a ceiling bounce model for the channel and electronic ballast florescent light for noise. Analytical and simulation results show 7dB improvement in SINR and 10-15 times improvement in BER.

Acknowledgments

The completion of this thesis report would not have been possible without the valuable advice, continual guidance and technical expertise of my supervisor, Prof. Xavier. N. Fernando.

I am graceful to my fellow graduate students in the Wireless Networks and COmmunications REsearch(WINCORE) group for their stimulating discussions, companionship and for creating a fruitful and pleasant work atmosphere.

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Chapter 1

Infrared for Wireless Communications

1.1 Introduction

It is well known that a technology becomes ubiquitous when it is incorporated seamlessly within many products entering our homes, when it is invisible and yet used daily in devices we depend on, without us even realizing the presence of the underlying specific technology. It is not an exaggeration to say that to some extent optical wireless links are also ubiquitous. There are two or three infrared (IR) remote controls in our homes, so they already influence our daily habits. We can all imagine the frustration of most people living a day without IR controls and struggling to deal with the TV, DVD, or music center manually.

The history of optical wireless communications (free space optical links) predates that of fiber optics. Optical wireless communication is in use today in many applications, offering very-high-speed wireless links cost effectively. Wireless communications based on IR technology is one of the most growing areas in telecommunications.

Application user models dictate the product specification, and the design and engineering of optical links which is uniquely tailored to the product. The product variants of optical wireless links range from very long distance inter satellite links to very short distance optical interconnects.

In common with other systems, the technology growth depends on the user problems it successfully solves, techno-economic issues, and developments/breakthroughs in constituent component technologies. The requirements for high-volume applications are low-cost, short-

Property of Medium	Radio	IM/DD infrared	Implication for IR
Bandwidth regulated	Yes	No	- Approval not required, - Worldwide compatibility
Passes through walls	Yes	No	- Less coverage, - More secure, - Independent links in different rooms
Multipath fading	Yes	No	- Simple link design
Multipath distortion	Yes	Yes	- Simple equalization
Path Loss	High	High	
Dominant Noise	Other User	Background noise	- Limited range, - Difficult to operate outdoors - High transmitter power requirement

Table 1.1: Comparison of Radio and Infrared Systems

range, high-dynamic-range, and robustness to ambient noise and interference.

1.1.1 Infrared Vs Radio

Wireless networks offer increased mobility and flexibility to the user, allowing information to be accessed anywhere, without the need of a physical network. Two technologies are currently available for short range wireless communications: Blue tooth and infrared devices. Both have their advantages and disadvantages, but both approaches can also provide complementary solutions for wireless data transfer between devices. Blue tooth is a radio frequency (RF) technology operating in the unlicensed 2.4 GHz industrial scientific medical(ISM) band. These technology specifications include omni-directional voice and data transfer within a distance of 10 to 100 meters at maximum transfer rate of 1 Mbps. However, due to higher implementation cost, RF interference, electromagnetic (EM) interference and difficulty in handling a huge flow of data communication during periods of heavy traffic, this technology becomes inefficient.

As a medium for short range, indoor communications, infrared radiation offers several significant advantages over radio. In general infrared region includes wavelength between about 780 nm and 100 μm. Nowadays infrared emitters and detectors capable of high speed operation are available at low cost. Radio and infrared are complementary transmission media, and different applications favor the use of one medium or other. Radio is favored in applications where user mobility must be maximized, or transmission through walls over long range is required, and may be favored when transmitter power consumption must be minimized. Infrared is favored for short range applications in which per link bit rate and aggregate system capacity should be maximized, cost should be minimized, international compatibility is required, or receiver signal processing complexity should be minimized.

Early wireless products operated in certain bands and bandwidth are limited to same frequency and usually shared with other systems. However, in infrared (IR) system the optical signal carrier considered for wireless communication does not fall under FCC regulations and there is no interference with electro-magnetic spectrum. This means IR transmission does not disturb any other electronic devices and the reception of IR signals is not interfered by electro magnetic fields. Since modern offices are crowded by several kinds of electronic devices, this is certainly an advantage. It offers potentially huge bandwidth unregulated world wide, and is capable of providing high data rates for future multimedia applications.

IR has a similar behavior to that of visible light. It is absorbed by dark objects and diffuses due to reflections on surfaces. It can penetrate through glass but not through walls. This makes the IR secure against casual eavesdropping. This means that the same optical carrier can be reused in adjacent room without interference.

Infrared links use intensity modulation and direct detection technique for transmission and reception respectively. Therefore carrier wavelength is very short. Large area, square law detectors lead to efficient spatial diversity that combats multipath fading. However, in radio links, there is a large fluctuation in received signal magnitude and phase. Since the square law photo detector is many times larger than the infrared wavelength, multipath propagation does not produce fading in a direct detection system. Freedom from multipath fading greatly simplifies the design of infrared links.

Advantages	Disadvantages
Low cost	Short range
Fairly reliable	Line of sight
Little interference	Device must remain stationary while synchronizing
Point-to-Point	One-to-one
	Total capacity up to 4Mbps

Table 1.2: Performance Comparison of IrDA standard

Advantages	Disadvantages
Fast (11 Mbps)	Expensive
Can use an access point or Point-to Point	Speed fluctuations
Long range (up to 1000 ft)	
Very reliable due to scalability	

Table 1.3: Performance Comparison of IEEE 802.11 standard

1.1.2 IR standards and Scenarios

Over number of years the computer industry has developed the IrDA standards for wireless data links. The main purpose of those standards is to offer low-cost reliable connectivity between devices. IrDA has specified standards for 115.2 Kb/s, 4 Mb/s, and 16 Mb/s optical wireless links. It is a point-to-point, narrow angle (30degree cone) and ad-hoc data transmission standard. IEEE 802.11 has also specified a wireless LAN specification for optical wireless physical layer (PHY). The IEEE 802.11 standard [30] defines a vendor- independent ethernet-like hardware technology for the 2.4 GHz licence free frequency band. It provides a scalable radio access capacity varying 1 to 11 Mbits/s within a few tens of meters of distance.

Tables 1.2 and 1.3 compare IrDA standard and IEEE 802.11 standard respectively.

IEEE is continuously revising their 802.11 standards to provide faster speeds, more efficient data transmission, increased distance, and high security.

Indoor remote control and inter-device connectivity has proven to be a fertile market for optical wireless communication. Optical wireless products must comply not only with cost and usability constraints, but also with eye safety constraints. Short-range optical wireless links are usually power-budget-limited due to eye safety constraints. The maturing of optical transmitter, receiver, optics technologies and understanding of free space channel intricacies have been invaluable to overall system development. In indoors, for example, the ambient light noise intensity at the receiver fluctuates significantly depending on the proximity of the noise source to the detector. This noise could arise mainly from tungsten lamp sources, fluorescent lights, or diffuse sunlight. Interference could occur from other products radiating IR such as TV remote controls or IR music headphones, or neighboring users, if there is inadequate medium access control.

Outdoor terrestrial links are subjected to different challenges since the channel is subject to weather fluctuations affecting the power budget, and, depending on location, could perhaps be influenced by the sun. Eye safety is very important in all situations, and operating within the safety margins as specified by IEC and other regulations is a part of the system design; this can be a frustrating and often costly consideration. There are three user scenarios in infrared environments: IrDA short-range indoor, diffuse IR-LAN, and outdoors free space links with range on the order of 2 km. Each scenario has its own intricacies and is unique in its own right. For the IrDA user model, the challenges are low cost, low hardware real estate, high data rate, very high dynamic range, low power consumption, and low bit error rate (BER). The diffuse IR LAN user model designs rely on the emitted radiation being diffused by reflections in a uniform manner from walls and ceilings. This is not easily achieved considering reflection losses. There are number of future proposals for multi-beam diffusers and receiver diversity techniques for improving the performance of such systems without sacrificing too much bandwidth. The cost of such systems is higher and is an important consideration.

The outdoor free space links are a few kilometers long and require high receiver sensitivity, the use of lasers instead of LEDs for transmitters, telescopic optics for creating and aligning/focusing the beam, and means of compensating for channel variation due to weather conditions such as rain, fog, and snow. The biggest challenge for outdoor links is offering cost-effective link availability under all weather conditions. This issue begins with an interesting comprehensive low-level comparison of RF with IR since it helps clarify the differences between the two technologies. The recent growth of Bluetooth and 802.11 products with RF transceivers at the physical layer makes this comparison useful in positioning IR and RF technologies.

The modulation scheme is critical for efficient operation of IR links. Apart from bandwidth and power efficiency, short-range IrDA links must operate from contact to 1 meter, which requires a dynamic range in the order of 50 dB. The receivers must cope with intersymbol interference and large variations of DC optical power via diffuse lights. There are other modulated optical sources causing high frequency interference in the signal band. Careful choice of encoding schemes is very important in helping to alleviate those problems and at the same time facilitate the clock extraction process. In indoor optical LAN model, where many users can be connected to each other without the need for alignment. A transmission from a user can be received by any other user with multiple reflections from the room walls and ceiling, thus emulating optical ether. This is a more difficult challenge; one of the issues is uniform distribution of the optical power across the room while maintaining a system capacity advantage over RF.

1.2 Architecture

Infrared links may employ two different designs. They are directed links and non directed links. Directed links employ directional transmitters and receivers, while non directed links employ wide angle transmitters and receivers. In directed links, links relies on the uninterrupted line of sight (LOS) path between the transmitter and receiver. LOS link design maximizes power efficiency and minimizes multipath distortion. Non-LOS links are generally referred to a diffuse link. The major advantages of using diffuse approach are that, there is no need for an accurate alignment between transmitter and receiver. This is especially important in portable applications. The main drawback of diffuse approach is the temporal dispersion caused by reflections from ceiling and walls, which effectively limits the rate of transmission. Since the infrared cannot penetrate walls, communication from one room to another requires the installation of access points interconnected with wired backbone. For practical transmission, IM/DD is the only available transmission technique. With the intensity modulation, the transmitted signal can never be negative, unlike conventional electrical signals. The input signal is a current used to drive a laser. Since the laser has intensity modulation characteristic, it can be closely approximated by an output optical intensity proportional to the laser input current. This intensity is propagated over the channel, which is characterized by a multipath impulse response that relates input and output intensities [28].

1.3 Issues in IR System

The important issue facing the development of optical wireless system is safety. Radiation can cause hazards to human eye and skin. The primary drawback is eye safety; the light can pass through the human cornea and be focused by the lens into the retina, where it can potentially induce thermal damage. The cornea is opaque to radiation at wavelengths beyond about 1400 nm, considerably reducing potential ocular hazards, so that it has been suggested that 1550 nm band may be better suited for IR links. Due to the safety issue, the maximum power can be transmitted in IR system is limited. Therefore, the safety issue can be met more easily with use of the low optical power density diffuse techniques [29]. Limiting the maximum optical power can be further aided by the use of a modulation format that offers high sensitivity at the detection stage.

Indoor wireless infrared transmission is affected by number of different impairments such as shot noise due to ambient light, interference produced by ambient artificial light, and multipath dispersion. Typically, natural and artificial ambient light produce high levels of shot noise in a photo detector that limits the performance of a given transmission system [2] including spread spectrum systems. For incandescent lamps the interference spectrum typically extends up to 2 KHz while for fluorescent lamps driven by conventional ballasts it may extends up to 20 KHz. However, for fluorescent lamps driven by electronic ballasts the interference spectrum extends up to 1 MHz. Therefore this one poses a more serious problem to infrared transmission systems.

One of the major problems faced by most of the modulation schemes employed in wireless

IR communications is multipath dispersion. When the LED transmits the IR signal, it travels through many different optical paths in the channel. For instance , it can reflect off the walls or ceiling of a room or it can travel the line of sight path to the receiver. Since these optical paths have different lengths, the signal reach the receiver at different times. Each path that the signal travel has also a different path gain, amongst which the line of sight path is the highest. The path gain decreases with distance dependent on the reflectivity of nearby surfaces, as well as other factors. Each user will thus receive numerous delayed versions of the same signal at different optical signal strengths and add them together. This multipath propagation delay introduces inter symbol interferences to the system.

There are various methods to combat multipath dispersion. They are angular and imaging diversity [26], parallel transmission using multiple subcarrier [27] and adaptive equalization techniques. Each of the solutions has its advantages and disadvantages and their effectiveness depends on the modulation scheme used. Direct sequence spread spectrum(DSSS) techniques have been investigated to combat multipath dispersion without relying on the use of complex signals processing and excessive optical components.

Although time division multiple access (TDMA) and wavelength division multiple access (WDMA) are well established multiplexing techniques in fiber optic communication, they are rarely used in infrared environments due to varies reasons.

TDMA: This is a synchronous technique, where a common timing should be provided for communications. Users cannot communicate independently and concurrently. Therefore TDMA is not a desirable technique for infrared wireless systems.

WDMA: This technique calls for each user to have N independent wavelength together with a tunable optical reception filter. Such a complex and expensive system is also not desirable in IR systems.

CDMA: This technique is used to transmit multiple users' data simultaneously using coding, ideally orthogonal, to add dimensionality to the transmit space. Therefore, CDMA with class of optical sequence provides a better solution for IR applications. In optical CDMA (OCDMA), every transmitter get its own minimal interfering code sequence to others, enabling a very easy channel allocation and separation, without having too complex hardware demands.

1.4 Infrared Transmitters and Detectors

The two more commonly used sources of IR transmitters are: light emitting diodes (LEDs) and laser diodes (LDs). LEDs are usually cheaper and reliable than laser diodes that makes them the preferred choice for different manufacturers. Laser diodes, on the other hand, can be used at higher modulation rates than LEDs. Operation of these devices is in the near infrared region, utilizing the wavelengths of relevance of 850 nm, 950 nm, 1300 nm, 1480 nm and 1550 nm, where suitable devices are commonly available.

The *pin* photo-detectors and avalanche photo diodes are the most commonly used detector types in IR wireless system. The *pin* detector is preferred in most of the systems, because of its low bias voltage requirement and its tolerance to temperature fluctuations. However, *pin* detectors are about 10 to 15 dB less sensitive than avalanche photo diodes [14][15]. Avalanche photo diodes on the other hand, provide a more robust communication link due to their increased power margin. This reduces the problem of accurate alignment of lenses and allows for reduction of preamplifier noise, laser power and other losses. Other than transmitter and receiver, there are optical concentrators which are used to improve the collection efficiency of the receptors by transforming light rays incident over a large area into a set of rays that emerge from a smaller area [18]. This implies that smaller photo diodes can be used, which decreases the capacitance, the cost, and improves receiver sensitivity. Also the transmitted power level can be reduced, which avoids the problems related to optical safety considerations and reduces power consumption. The truncated spherical lens is widely used as concentrators.

Research on wireless IR communication in indoor environments has recently focused on noise interference spectrum typically extends up to 1 MHz. This poses a serious noise effect on infrared transmission system. Infrared receivers typically employ either longpass or bandpass optical filters to attenuate ambient light interference. Longpass filters can be

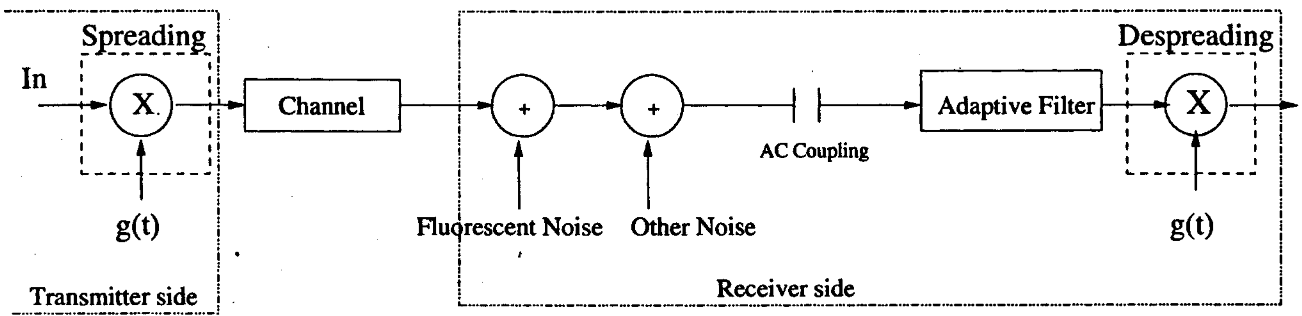

Figure 1.1: Proposed infrared wireless system to mitigate the interferences

Characteristics	LED	Laser Diode
Spectral width	25-100nm(10-50THZ)	< 5nm
Modulation width	Tens of KHz to tens of MHz	Tens of MHz to tens of GHz
E/O conversion efficiency	10-20	30-70
Eye safety	Generally considered eye safe	Must be rendered eye safe especially for λ <1400nm
Cost	Low	Moderate to high

Table 1.4: Characteristics of LEDs and Laser diodes

thought of as essentially passing light at all wavelengths beyond the cutoff wavelength. They are usually constructed of colored glass or plastic, so that their transmission characteristics are substantially independent of the angle of incidence. Longpass filters are used in almost all present commercial infrared systems [14]. Bandpass filters are usually constructed of multiple thin dielectric layers, and rely upon the phenomenon of optical interference. These filters can achieve narrow bandwidths, leading to superior ambient light rejection.

Since incandescent lights and conventional ballast fluorescent light are operated at power line frequencies and carry most of their energy at first harmonic frequencies, high pass electrical filters also can be used to eliminate those interference without much signal degradation. However in the case of electronic ballast fluorescent lights with 1 MHz interference frequency, their harmonics are overlapped with signal spectrum. Sophisticated digital signal processing techniques need to be developed in this case.

1.5 Adaptive Filters

Adaptive techniques are emerging rapidly in communication systems because the hardware devices used to implement modern communication systems are very well suited to realize those adaptive algorithms. In recent years, many sophisticated and robust adaptive signal processing techniques are developed. The original hurdle is formed by the complexity of the system. This hurdle is being lowered by a better understanding of underlying theories in communication, the introduction of the efficient computational methods for solving the set of equations that yields the parameters and the wide spread availability of large scale integration implementations of complex signal processing devices. These adaptive filters consist of two distinct parts: an adaptive filter with adjustable coefficients, and an adaptive filter algorithm to adjust or modify the coefficients. The Adaptive filters are most widely used in noise cancellation. However, they can be used for many other purposes such as an adaptive self tuning filter, adaptive line enhancer, system modelling, etc. The adaptive filers are used in communications when,

- the system characteristics are variable or

- there is spectral overlap between the desired signal and noise or
- the band occupied by the noise is unknown or varies with time or
- there is multipath and multiuser interference such as in digital communication systems.

Signal processing involves the preparation of the signal for transmission as well as reception. The processing aims either at the preparation of the signal for transmission or at recovery of the signal and feature extraction from it after reception. Adaptive signal processing can be used to optimize the way of achieving this.

If the transmission channel and noise variations are known and fixed and if the signals to be transmitted or received are well defined and stationary, then this priori knowledge can be used to determine the optimal signal processing method to achieve a given goal. This method can be implemented in a fixed system and used all the times. However in practice, the characteristics of the transmission channel and noise variations are not very well known or even vary with time. The signals to be dealt with are mostly non-stationary. In such circumstances there are only two ways left to design the system.

- Design a compromise system that is one whose parameters are determined beforehand and fixed based on the 'average' channel. Here for average signal the optimum result is obtained.
- Design the system such that it can adapt itself to particular transmission channel and or the particular signal it encounters. The adaptivity makes the system better matched to the transmission channel and the received signal than a compromise system and therefore, adaptive systems can lead to a better performance.

Adaptive filtering concept is shown in Figures. 1.2 and 1.3. The purpose of adaptive noise canceller is to subtract the noise from a received signal in an adaptively controlled manner so as to improve the signal to noise ratio. The adaptive equalizer is used to operate on channel output such that the cascade connection of the channel and the equalizer provides an approximation to an ideal transmission medium [33]. In these systems, filters are generally fed

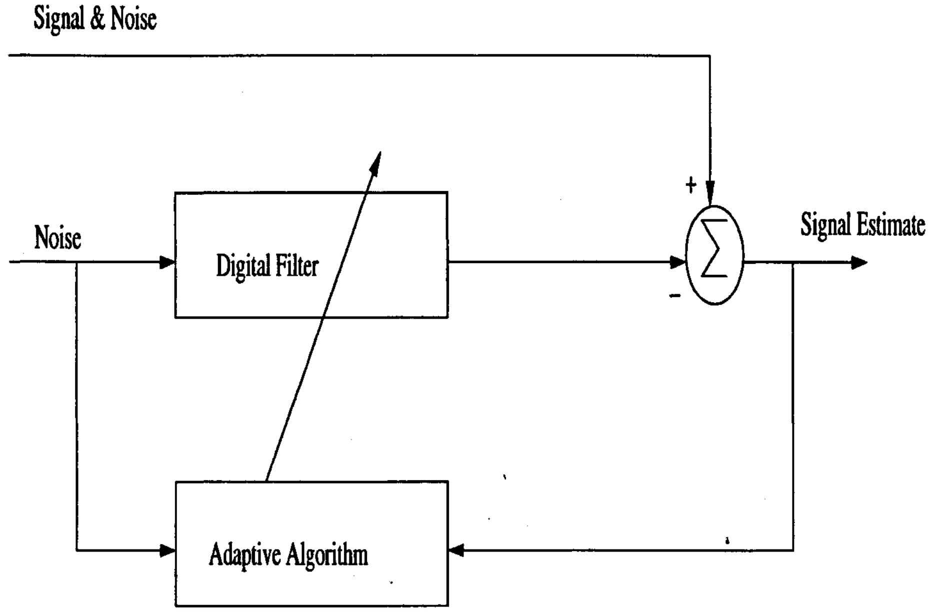

Figure 1.2: Adaptive Interference Cancellation [33]

with a short training sequence to which they have to adapt prior to receiving data. To maximize the efficiency of the system, training sequence need to be as short as possible requiring that adaptation occurs in as few iterations as possible. Also, as bit rates of communication systems increase, the time available to complete one iteration decreases.

In our system, the fluorescent spectrum is overlapping with signal spectrum and the channel behavior is not exactly known in a practical situation. For slowly varying channels, the coherence time is around 1000-2000 sample periods. However, the typical training time for adaptive filter is much less than the coherence time of a slowly varying channel. Therefore an adaptive filter will be a better solution to our system. Most algorithms are based on a mean square error criterion. They determine the coefficients on the basis of minimizing the mean value of a squared error signal. There are different types of adaptive filters, among those we selected RLS filter for its faster convergence. This arises from the fact that time averaging is very accurate and can predicate very precise results.

The main difference, when compared to the family of LMS algorithms is the inherent statistical conception. Here the time-based averages are calculated from different samples of the same random process. In contrary, in LMS algorithms, averaging (ensemble averaging)

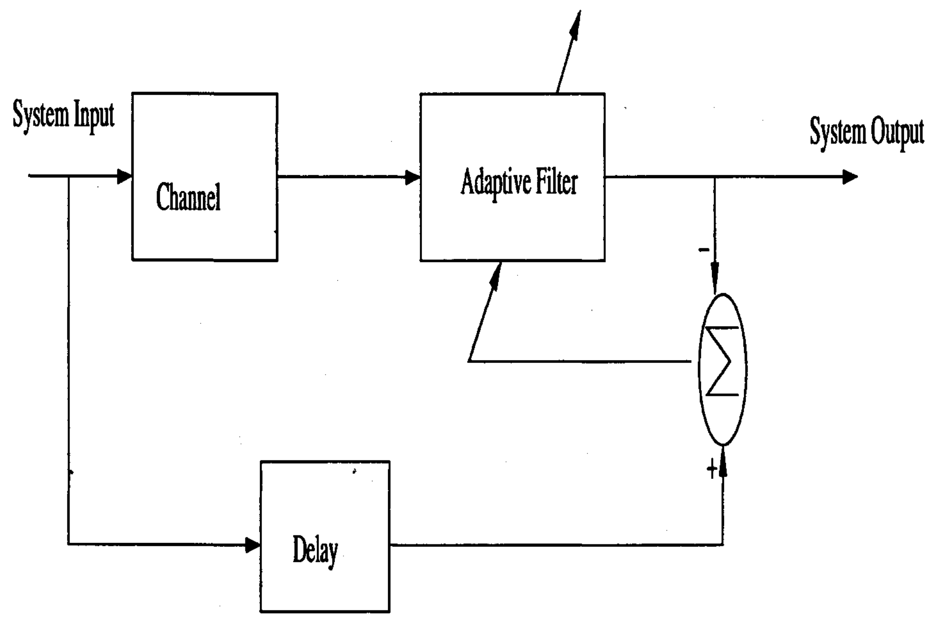

Figure 1.3: Adaptive Inverse Modelling [33]

involves values acquired from certain time but from different realizations of one random process. Furthermore RLS filter exploit more of information available from the input signal and can provide better tracking.

1.6 Our Approach

The system under consideration is shown in Fig. 1.1. At the transmitter side information sequence is multiplied with signature waveforms to spread the signal and transmitted through a diffuse channel. In a closed room the transmitter and the receiver are kept at the same level(eg. table hight). The transmitted signal is reflected back from the ceiling and walls of that room. At the receiver side, the photo diode not only receives the reflected signal but also receives the fluorescent light signal. Due to the electronics in the receiver circuitry, the receiver has other type of noises such as thermal noise, shot noise and dark current noise. AC coupling is used to eliminate the dc components in the received signal. After eliminating/reducing the dc component, the received signal is sampled at chip rate and sent through the adaptive filter to cancel out the interference due to fluorescent light and multipath effect.

The filtered signal is despreaded by the replica of the same signature waveform. We assume that the synchronization is achieved. In this analysis, we take fluorescent interference and multipath interference as major impairments to the system. To simplify the analysis, the noise due to other sources is considered as negligible.

1.7 Research Objective

Achieving a high electrical signal to noise and interference ratios (SINR) is the single greatest problem facing the designer of an infrared wireless system. To obtain a significantly high SINR, the effects due to interference and noise need to be minimized or eliminated.

Currently, in most work environments, fluorescent lights are used for illumination to enhance the lighting efficiency and to reduce the operating cost. Our studies suggest that the fluorescent lights create the greatest interference to the IR system. In the research described here, we propose an adaptive filtering technique on the diffuse environment of the spread spectrum CDMA indoor IR system to eliminate or reduce the interference due to fluorescent lights and multipaths.

1.8 Methodology

This report focuses on improving the performance of IR wireless system in the presence of multipath and fluorescent interference. Previous researchers analyzed the IR system either with noise effects or with interference independently, using other modulation schemes. In this report we introduce an adaptive filter to the existing spread spectrum CDMA system in a diffuse channel environment. In our method, we focus on the cancellation of fluorescent interference effect and multipath dispersion using discrete FIR adaptive filters. For fluorescent interference we use Moreira's measurements and calculate the power at the receiver. In addition, we consider the fraction of fluorescent power actually received by the photo diode. This is less than total noise radiated because of the spectral mismatch. Also we consider actually received power level at the receiver by considering the spatial effect in the physical environment.

In our simulation, chip period is varied to get different number of paths and bit rates. In addition, the effect of fluorescent interference is varied by varying the number of fluorescent lights in an office room. With the adaptive filter, the system is more robust against fluorescent interference even under a number of fluorescent lights. The filter coefficients are modified during the experiment by training the system frequently to reduce the interferences created at different conditions.

The closest work was done by T.O'Farrel and M.Kiatweerasakul in [1]. They investigated the performance of an IR system by using sequence inverse keying (SIK) spread spectrum format. However, in that research, the authors [1] simply compared the performance of on-off keying (OOK) and SIK spread spectrum formats. In our analysis, we introduce an adaptive filter for the performance improvement in a CDMA spread spectrum system.

1.9 Thesis Organization

The rest of the thesis is organized as follows. Chapter 2 briefly describes most of the previous work in Infrared wireless system and reviews some of the results. This Chapter builds up the background from previous works. System components used in the current study is described in Chapter 3. All mathematical derivations related to the evaluation of the system model are described in Chapter 4. Theoretical analysis of signal to noise interference ratio of the system is presented at different points in the network and finally those results are compared in tabular form. Simulink model used in this analysis is described and the simulation results obtained are discussed in Chapter 5. The report is concluded with a summary of my research work in Chapter 6, along with suggestions for future work.

Chapter 2

Previous work in Infrared Systems

First, let us briefly review some previous works in infrared wireless system. These previous works explicitly identify the transmission methods, channel models, effects of noise and interference, receiver design, signal to noise ratio and signal to interference noise ratio.

Many researchers tried to improve the performance in infrared wireless system by using different modulation schemes. They consider different modulation schemes to achieve different goals such as ISI cancellation, multi-user application, fluorescent interference cancellation, etc. In the noise analysis, these researchers assumed Gaussian noise for simplicity. Although the infrared system is a quasi-stationary system, everybody in this field treated the system as stationary for simplicity. However in actual situations these systems have pedestrian users and other moving components, that make the channel quasi-stationary.

2.1 Wireless Data Communication via Diffuse Infrared Radiation

Gfeller [7] was the first person to successfully demonstrate that diffused propagation of optical beams could transmit data between base station and transceivers. In his work, a novel wireless broadcast/multi access channel was described for flexibly interconnecting a cluster of data terminals located within the same room to a common cluster controller. The transmission medium is diffusely scattered infrared radiation at 950 nm wavelength. Transmission is low- to- medium speed and the range up to 50 meters. Theoretical analysis indicated that the transmission speed was below 1 Mbits/s. However, the practical maximum transmission speed was around 100 Kbit/s due to the limited modulation capacity of the LED.

In principle, each terminal was equipped with a light emitting diode(LED) for converting electronic signal to an optical signal and a photodiode for converting the optical signal to electronic signal, and corresponding driver and receiver circuits. Similarly, a central optical satellite station served as an interface to the common cluster controller which was local or remotely connected via a conventional wire link.

Optical radiation from satellite is diffusely scattered from filling the room with the optical signal carrier. The photodiodes receive the radiation from a wide field of view (FOV). Hence, there is no line of sight required between transmitter and receiver.

An experimental PCM baseband link and PSK link, operating at 125 Kbit/s and 64 Kbits/s respectively, have been built. The channel is suitable for low to medium speed transmission at low error rate and free from EMI.

In that period, the low- cost state of the art LEDs were too slow. The maximum transmission speed was around 100 Kbits/s due to the limited modulation capability of the LED. Higher transmission speeds up to one Mbits/s appeared feasible if increased optical power raises no objection. Whereas current trends indicate a decrease of hardware costs for optical components and circuitry.

2.2 High speed Wireless Networks via Optical Transmission

Wireless communication is most commonly accomplished by radio frequency (RF) communication techniques. However, limited spectrum availability may constrain the development of high speed (10 Mbits or above) wireless networks. In addition the indoor RF channel is a difficult channel for coherent communication since it suffers from fast, deep, frequency selective fades, rapid time varying, and very unpredictable characteristics. Low cost, high speed, RF transceivers for the indoor channel will require much innovation and will be difficult to develop. Previous investigations have primarily considered systems with modest rates usually in the range of 0.1- 1 Mbits/s.

Kwang-Cheng Chen's research [11] results indicated a way to provide high speed (10 Mbps and above) wireless LAN using optical transmission. This author's network architecture also similar to Gfeller's original network. Here, he made use of both the direct path and diffused path optical propagation. It is important to provide diffused path capability since blocking of the direct path may occur in practical situations. Hence, a wide optical beam was broadcasted by the transmitter and a wide field of view at the receiver was used. Two types of base stations were provided. The first was simply a repeater base station which was used to extend the coverage area of a cell by repeating the transmission at higher power or by directly communication over a wired connection to other repeaters which simply rebroadcast the transmission. Hence the coverage was extended to include all interconnected repeaters. Therefore, the available bandwidth was extended over the combined coverage area of all repeaters.

The second type of base station provided store and forward capability. The available wireless bandwidth was not shared across all interconnected base stations as in the case with repeaters. Thus, spatial reuse of wireless bandwidth in cells is possible.

For a repeater based system, all the data bandwidth of the wireless network was shared by all offices through the interconnecting wired extension. However, in the case of base stations each office was separated and hence could utilize the entire wireless date bandwidth, provided the interconnecting wired network could handle the extra capacity.

Based on his work, this author observed the followings

1. Indoor lighting, florescent and tungsten created electrical power in the receiver at frequencies up to 300 KHz.

2. Received power falls off rapidly with distance and angle from the transmitting source.

3. Infrared wavelength bandpass filter could effectively reduce the indoor lightening interference.

He further analyzed for physical layer transmission employing OOK modulation. He reached the following conclusions.

1. Utilization of low cost device technology constrains the channel to be band limited.

2. Utilization of the diffuse propagation path at 10 Mbps is difficult but possible.

3. Short duration of pulses could resist and even take advantage of multipath effects and hence improve bit error rate.

4. Only around 10 percent channel capacity was used even for a 10 Mbps system using low cost devices.

For physical layer transmission system design, pulse position modulation(PPM) is another possibility. Since OOK is the most straight forward choice, this author use direct detection modulation technique with OOK system. However, it suffers the following difficulties

1. The necessity of an equalizer to alleviate multipath effects above 10 Mbps.

2. Difficulties in determining the optical detection threshold due to the dynamic range of the received power and background noise.

3. Difficulties in timing recovery for runs of 1's and 0's.

2.3 Performance Analysis of Indoor IR Systems

2.3.1 OOK CDMA

There are number of modulation techniques that used to evaluate the performance of IR systems. OOK code division multiple access (CDMA) is proposed in [12], where the BER performance of indoor infrared systems is analyzed on diffuse channels by taking the effects of intersymbol interference (ISI) over several chips. This author adopted the ceiling bounce florescent model to obtain the channel impulse response in evaluating the effect of multipath distortion on ISI.

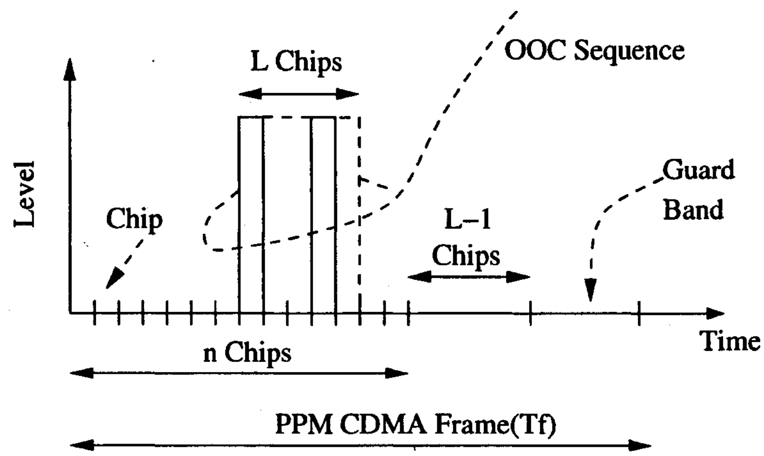

Figure 2.1: Proposed PPM structure in [25]

2.3.2 PPM CDMA

This technique provides asynchronous multiple access where each user is assigned a signature code belonging to the class of optical orthogonal code (OOC). Compared to OOK CDMA, PPM CDMA provides an improvement in bit rate by using the OOC sequences. It is demonstrated that there exists an optimum PPM order, at a given number of errors. It has been shown from Fig. 2.1 that PPM-CDMA offers more than five times the bit rate achievable using OOK CDMA for the same bandwidth requirements over the range of parameters considered. According to the authors of [25], the algorithm could be considered as a strong candidate for application in the multi-user indoor wireless network.

2.3.3 Biorthogonal Direct Sequence Spread Spectrum System

A set of M biorthogonal signals can be constructed from $\frac{1}{2}$M orthogonal signals by simply including the negatives of the orthogonal signals.

One of the major problems in indoor optical wireless transmission is the ISI due to multipath propagation, which greatly degrades the quality of the transmission. Different equalization techniques have been employed in several modulation schemes to mitigate the effect of multipath dispersion [14, 15, 16]. However, the use of equalizers substantially increases the receiver complexity. In earlier researches, a sequence inverse keying (SIK) direct sequence spread spectrum modulation was proposed to combat the impact of multipath dispersion. Although the processing gain of the spread spectrum technique attenuates the multipath dispersion effects without the need for extra circuitry such as equalizers, SIK was mainly limited by its processing gain which reduces the system bandwidth efficiency.

A method for improving bandwidth efficiency is the use of an M-ary signalling technique, which requires multiple-bit observation at the receiver. The use of random M-ary orthogonal codes over non fading and fading radio channel also were discussed in [17] and [18]. With this symbol-by-symbol detection, the interference was effectively reduced compared to bit-by-bit detection. These authors proposed a direct sequence (DS) spread spectrum system using M biorthogonal sequences instead of M orthogonal scheme. One advantage of a biorthogonal scheme over an M array orthogonal scheme is that it has a less complex receiver structure than the latter for the same transmission bandwidth. Hence a biorthogonal scheme combines the capabilities of spread spectrum techniques with the bandwidth efficiency of M-array orthogonal schemes, but with less complexity.

This proposed method [13] has the interference rejection capabilities of spread spectrum techniques and at the same time more bandwidth efficient than a binary system. The performance of the system using biorthogonal Walse codes and biorthogonal random codes have been evaluated through computer simulations and theoretical analysis. Results of this investigation showed that a biorthogonal DS system is able to withstand multipath dispersion since only small power penalties are incurred. The simulation results showed that, biorthogonal Walse codes and biorthogonal random codes have similar performance, with the former outperforming the later at higher bit rates. However, comparison with the simulation results showed that the Gaussian approximation analysis is reasonably accurate for systems with sequence length $N \geq 16$, but for $N=8$, it is not very accurate, as the assumption that multipath interference has Gaussian distribution is weakly valid in this region. I.e. Gaussian approximation becomes more accurate in less dispersive channels and when the length of code sequence is large.

2.3.4 Sequence Inverse Keying (SIK) Direct Sequence Spread Spectrum Modulation

The performance of an IR wireless spread spectrum system under multipath dispersion and artificial light interference has been investigated in [19]. Results indicate that a spread spectrum system experiences small power penalties due to dispersion. SIK spread spectrum technique is less sensitive to interference produced by electronic ballast driven lamps due to the noise rejection property inherent to CDMA [19], whereas OOK without spreading is very sensitive to this type of interference. Although optical filtering and electrical highpass filtering may be used to mitigate florescent light interference, the former is costly while latter introduces some inter symbol interference (ISI). It is important to choose the highpass filter cutoff so that ISI is minimized, in which case it is not possible to optimally suppress the interference.

The advantage of the spread spectrum technique is its inherent ability to mitigate multipath ISI, and yet it is less complex than other mitigation techniques such as equalization. The spread spectrum technique is mainly limited by its spreading factor that reduces the system bandwidth efficiency. At higher bit rates or in non-LOS links, shorter spreading sequences may be used to reduce the effects of multipath dispersion. I.e. the processing gain of spread spectrum technique may be fixed according to the severity of multipath.

The author [19] used a sequence inverse keying (SIK) direct sequence spread spectrum modulation technique to combat the impact of multipath dispersion and artificial light interference. While the additional bandwidth requirement of a spread spectrum modulation scheme reduces the system bandwidth efficiency, the processing gain of the spread spectrum technique helps to combat multipath dispersion and artificial interference effects without need for extra circuitry such as equalizers.

2.3.5 M-ary CDMA

One of the main concerns in indoor optical wireless networks is limitation in the transmitted power due to eye-safety considerations. Each base station should produce minimum power while keeping SINR in an acceptable level for reliable detection. In reference [20], it has been shown that infrared CDMA using OOC spreading can establish communication with power level well below ambient light power levels and therefore is a suitable candidate for infrared wireless systems. However, a large bandwidth is required in these systems because of the sparse nature of OOC and the need for a high value of code length or processing gain to guarantee reliable multiple access system. Considering the fact that the indoor channel is a bandlimited channel due to multipath distortion, the use of infrared CDMA depends on the design of channel equalizers and a power penalty should be considered to compensate for the effect of multipath distortion.

These authors of [21] proposed the use of M-ary CDMA for the downlink of indoor wireless infrared systems. They compared the performance of the proposed M-ary system and the ordinary on-off keying infrared CDMA technique. This analysis was based on photon counting technique and all the major noise sources, such as ambient noise, dark-current noise, and receiver thermal noise and multi-user interference were considered. They showed that M-ary infrared CDMA system performance is better than ordinary infrared CDMA system for a given bit rate. In addition, M-ary systems use the available bandwidth much more efficiently than ordinary infrared CDMA systems. This method offers flexibility in system design and parameter selection.

The process of obtaining the optimum threshold at on-off keying Infrared CDMA systems can become quite difficult to implement and the threshold value should be adaptively changed in order to adjust to the optimum value when channel parameters change. Although the structure of M-ary CDMA receiver was much more complicated than ordinary IR CDMA receivers, it could be easily implemented using VLSI technology since it was the repetition of a simple structure. Also it is shown that the M-ary Infrared CDMA receivers were more feasible in estimating and setting of threshold value than ordinary infrared CDMA receivers which use extra circuitry.

2.4 Modelling of Artificial Light Interference

The performance of wireless IR systems is limited by several factors. The most important factors are the speed limitations of the optoelectronic devices, the significant path loss which leads to the use of considerably high optical power levels, multipath dispersion, the receiver noise and the shot noise induced by natural and artificial light. J.C.Moreira presented a characterization of the interference produced by artificial light and proposed a simple model to describe it. The measurements show that florescent lamps driven by solid state ballasts produce the wider band interfering signals, and are then expected to be more important than other source of degradation in optical wireless system.

These authors [5] presented a characterization of the noise and interference that natural and artificial light source induce in wireless indoor optical communication systems. Florescent lamps geared by electronic ballasts that produce lower amplitude interference but whose spectra is very broad, extending to more than 1Mhz. The presented results suggest that performance re-evaluation of the modulation and encoding schemes being used for optical wireless system be required.

2.5 Advanced Technologies to Minimize the SNR Fluctuation Effects

Antonio Tavares, Rue. L. Aguiar, R.Valadas and A.Oliveira Duarte [22] , discussed several advanced techniques to the design of non-directed wireless IR communication systems, in order to minimize the SNR fluctuation effects.

The first technique, angle diversity, makes use of the directional nature of the SNR at the receiver. The second technique adapts system data rates to environment conditions. Three different strategies were analyzed. The first one produces an effective reduction of the transmission rate in the communication channel, reducing both receiver bandwidth and ambient noise through adaptive filtering. This presents three major implementation problems:

- DC levels at the receiver will change with different bit-rates

- The receiver cannot be optimally designed for a specific bit rate and thus will always have sub-optimal performance

- Receiver bandwidth will have to be modified in a controlled way.

The second strategy is based on the introduction of coding redundancy through the utilization of repetition coding. The effective bit rate over the communication channel is maintained.

The third strategy results to convolutional coding, and also maintains the channel effective bit rate. This technique differs from the previous ones because it allows error correction at the receiver.

2.6 Performance Evaluation of IR System with Electronic Ballast Florescent Interference

The impact of fluorescent light interference can potentially be reduced by highpass electrical filtering, but such filtering introduces ISI. Therefore, in this analysis the system was tested with fluorescent light interference but no high pass filtering was used.

The authors [23] evaluated the performance of OOK and L-PPM infrared links in the presence of electronic ballast interference. For their evaluation, they presented expressions for the bit error rate (BER) of systems using on-off keying (OOK) and pulse position modulation (PPM) in the presence of both fluorescent interference and ISI. Among the modulation techniques investigated, L-PPM is less susceptible than OOK to degradation from florescent lighting, particularly at high bit rates. They have shown that in the absence of line coding or active base line restoration, a first order high pass filter is not effective in mitigating the impairment of OOK systems. Such a filter is useful in improving the performance of L-PPM schemes, particularly at high bit rates and when the florescent light signal is strong. According to the authors' evaluation, 16 PPM yields the highest average power efficiency among all schemes evaluated.

2.7 Modelling of Non Directed IR Wireless Channel

Non directed infrared light transmission with IM/DD is a candidate for high speed wireless communication within buildings. Characterization of this IR channel has been performed using experimental measurements, and simulation through ray-tracing techniques. The results of experimental studies of the channel are highly dependent on the rooms selected for the measurement study.

There were two physical processes that produce multipath dispersion observed in diffuse IM/DD channels. The first one was multiple reflections and the second one was due to diffuse reflection from a single infinite plane. These two physical processes made these authors [3] to consider the functional forms for channel model and they are exponential decay model and ceiling bounce model.

These authors [3] showed that non directed IM/DD channels can be characterized solely by their path loss and delay spread. This was due to the strong correlation between multipath power requirement and delay spread for baseband modulation schemes (OOK and PPM). This correlation was very well reproduced by a ceiling bounce model for the impulse response. Rather than evaluating the candidate modulation scheme based on its performance on an ensemble of measured channels, one can instead use the uniform and reproducible method to evaluate performance of the ceiling bounce impulse response. Using this ceiling bounce model, the authors gave a simple method to predict power requirements given simple parameters of the room and the locations of the transmitter and receiver.

2.8 Optical Parallel Transmission with Multi Wavelength for High Speed Communications

In indoor optical transmission, the inter symbol interference due to multipath propagation greatly degrades the quality of transmission, and its effects become more severe in case of diffuse links. To mitigate ISI effects, various equalizers have been investigated. These equalizers have good performance, whereas the system structure becomes more complex.

For this strategy, the authors [24] use wavelength division multiplexing(WDM).

On indoor optical channels, ISI effects degrade the performance of communication. The authors [24] proposed and analyzed a multi wavelength modulation scheme. In this system, the bits of one user are divided into several channels and transmitted simultaneously. This parallel transmission lowers the rate per channel and degrades the effects of ISI due to multipath propagation without decreasing the total data rate. In addition, parallel coding, which permits the application of channel coding without degradation in the date rate, can be used. This makes it possible to transmit without changing bit duration and improve the quality of transmission without degradation of the net data rate. A combination of these two strategies permits high quality and high speed transmission. As a result of computer simulations, it has been shown that multi wavelength modulation scheme permits high quality transmission on indoor multipath channel and parallel coding permits error correction without changing the total data rate.

Although the above researchers used different techniques with different modulation schemes to improve the IR system performance, none of them considered the effect of fluorescent interference in terms of spectral effects and spatial effects. Also in this research, in addition to spread spectrum technology, we consider an adaptive cancellation technique to improve the performance in the presence of fluorescent interference.

Chapter 3

Noise and Channel Model of an Infrared System

IR wireless system can be analyzed with different channel models, noise models and configurations. This chapter covers a detailed description of the system components used in the analysis. The rationale for selecting the models is also described.

Fig. 3.1 shows the simplified block diagram of a wireless infrared spread spectrum CDMA system. At the transmitter side, the information sequence I_n is spreaded by multiplying the signature waveforms $g(t)$.

$$g(t) = \sum_{i=o}^{N-1} a(i).p(t - iT_c) \qquad a(i)..\varepsilon(1,0) \tag{3.1}$$

where $a(i)$ is the pseudo-noise(PN) code sequence, $p(t)$ is the pulse shape and T_c is the chip

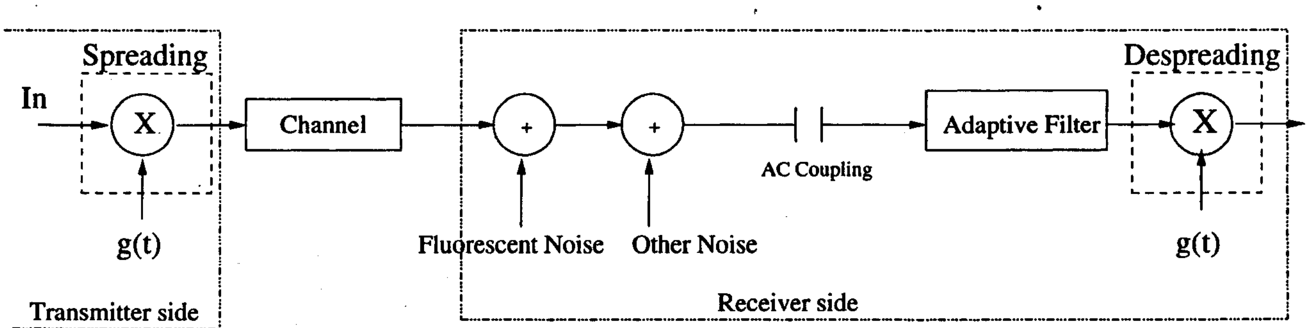

Figure 3.1: Proposed infrared wireless system to mitigate the interferences

period. N is the code length, so that each pulse bit has N chips.($NT_c = T$)

3.1 Channel Model

In the literature, two multipath channel models are widely used, an exponentially decaying line of sight model and a ceiling bounce model. The ceiling bounce model is more appropriate for diffused infrared wireless systems [3]. Therefore, the ceiling bounce model is adopted in this research work to obtain the multipath dispersion. With this model, for a fixed transmitter and receiver locations, the multipath dispersion can be characterized by its impulse response $h(t, a)$ as given by (3.2) [3].

$$h(t) = G_0.\frac{6a^6}{(t+a)^7}.u(t) \tag{3.2}$$

where

$$a = \frac{2H}{C} \qquad and \qquad G_0 = \frac{\rho.A_r}{3\pi.H^2} \tag{3.3}$$

where $u(t)$ is the unit step response, H is the height of the ceiling above the transmitter and receiver, ρ is the reflectivity of the reflecting surface. A_r is the receiver photo diode area and C is velocity of light.

3.2 Fluorescent Light Periodic Interference Model

As we discussed earlier, there are two types of ballasts used in fluorescent lights. One is conventional ballast and the other one is electronically driven ballast. Generally the conventional one operates on power line frequency and makes interference in harmonics. This is deterministic and periodic. Therefore it can be eliminated by careful design of filters. However, nowadays electronic ballasts are widely used to reduce the size and to increase the efficiency. In these electronic ballasts, power transistors are used for switching operations. Therefore these switching operations modulate the power at very high frequencies and this harmonics extend up to MHz range. This will spectrally overlap to our frequency of interest.

The model used for the interference from the artificial light in this thesis is based on the measurements and model presented by Moreira et al in [5]. This model presents the fluorescent lamps driven by electronic ballasts. The noise spectrum produced by these lamps consists of low and high frequency components. The low frequency components resemble the spectrum of a conventional fluorescent lamp and the high frequency component is attributable to the electronic ballast. A mathematical expression for the interfering noise due to artificial light signal as given in [5],

$$m(t) = RP_m + \frac{RP_m}{K_1}\sum_{i=1}^{20}[b_i cos(2\pi(100i - 20)t + \xi_i) + c_i cos(2\pi 100i + \varphi_i)]$$

$$+\frac{RP_m}{K_2}[d_0 cos(2\pi f_h t + \theta_0) + \sum_{j=1}^{11} cos(2\pi 2j f_h t + \theta_j)] \tag{3.4}$$

Where $K_1 = 5.9$ and $K_2 = 2.1$, R is the responsivity of the photo diode and P_m is the average optical power of the interfering signal. The constants K_1 and K_2 relate the interference amplitude to P_m. $f_h = 37.5KHz$ is the fundamental frequency of the electronic ballast. The first, second and third terms of the (3.4) represents the photo currents due to the mean interference, the low frequency interference and high frequency interference respectively. The parameters b_i and c_i are estimated in [5].

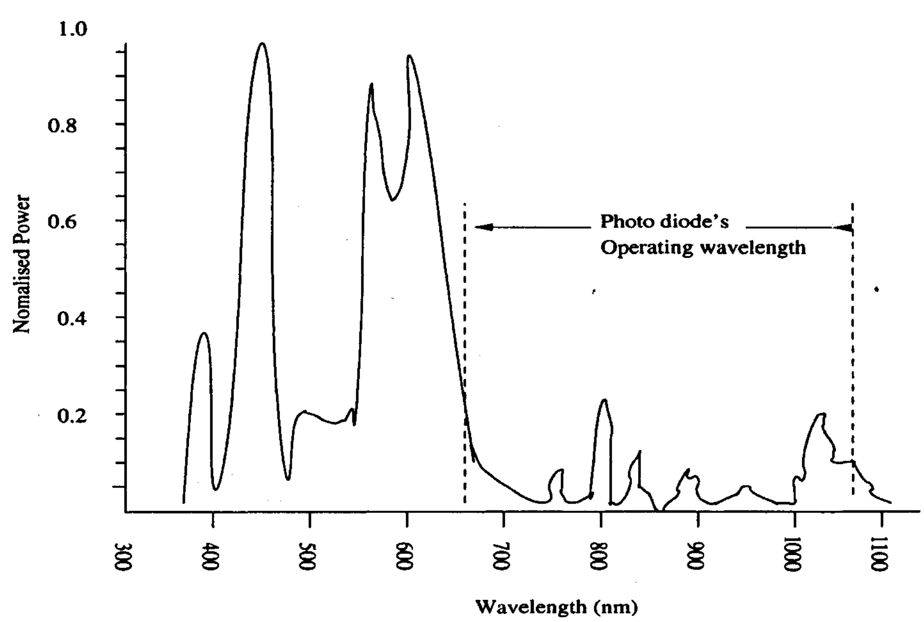

Figure 3.2: Fluorescent spectrum

Fig. 3.2 shows the spectrum of light emitted from fluorescent lights. It shows that the spectrum interferes with receiver photo diode's wavelength range. Only a fraction of the power is actually received due to this mismatch in spectrum. In this research work we use two considerations namely: spectral consideration and spatial consideration to reduce these mismatch limitations. This graph is created by using the measurements in [14].

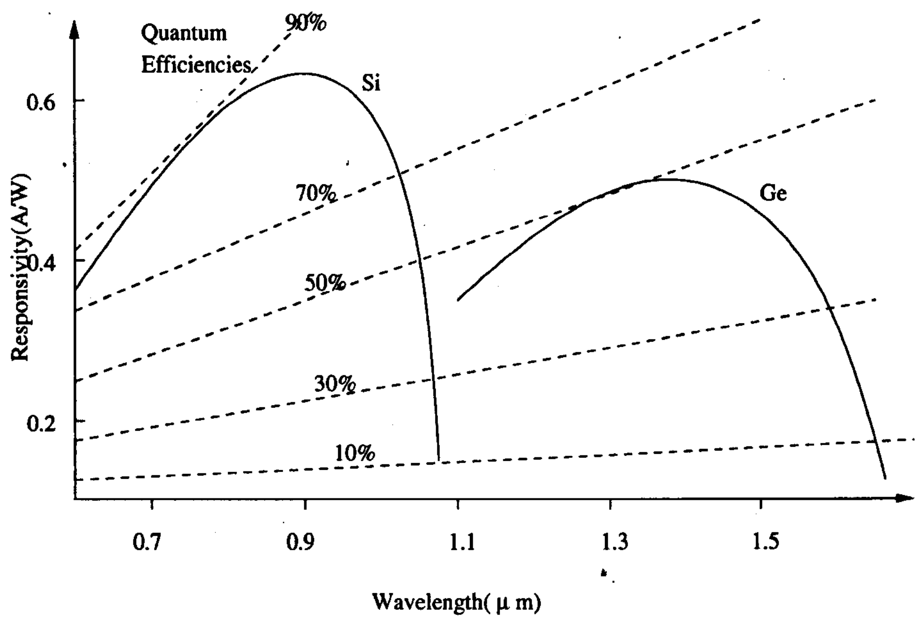

Figure 3.3: Comparison of Responsivity for Si and Ge Photo Diodes [8]

3.2.1 Spectral Consideration

In this section, the spectrum of the electronic ballast fluorescent light and the characteristic of a Silicon photo diode are taken into consideration. Fig. 3.3 shows the resposivity characteristics of Silicon and Germanium type photo diodes. For a Silicon type photo diode , the responsivity is fallen between 680 nm to 1080 nm [8]. As shown Fig. 3.2, the fluorescent spectrum overlaps the photo diode's operating wavelength. From the graph most of the emitted power falls out of the operating wavelength of the photo detector. To account for this phenomenon, we calculate the fraction of the optical power that will fall within the operating wavelength of the photo detector.

From Fig. 3.2, total power emitted by the fluorescent is the total area under the spectrum. The total power absorbed by the photo diode is the area under spectrum between 680 nm to 1080 nm. Using these power values, the percentage optical power absorbed by photo diode is calculated. It is around 10 percentage of the total power.

3.2.2 Spatial Consideration

Not all the power from the fluorescent light is received by the photo diode. As shown in Fig. 3.4 power level at the receiver is calculated according to the physical locations of the fluorescent lights and receiver. The received power depends on field of view(FOV) of the receiver, area of the fluorescent light(A), area of photo diode(A_r), fluorescent lamp's output power(P_s) and the distance between fluorescent light and photo diode(D). In perspective views, FOV is an angle which defines how far the view will be generated to each side of the line of sight. We derived the equation (3.7) to calculate the received power. We assumed that the surface of fluorescent light is an ideal Lambertion reflector and the power emitted per surface area is constant over the entire fluorescent bulb area A.

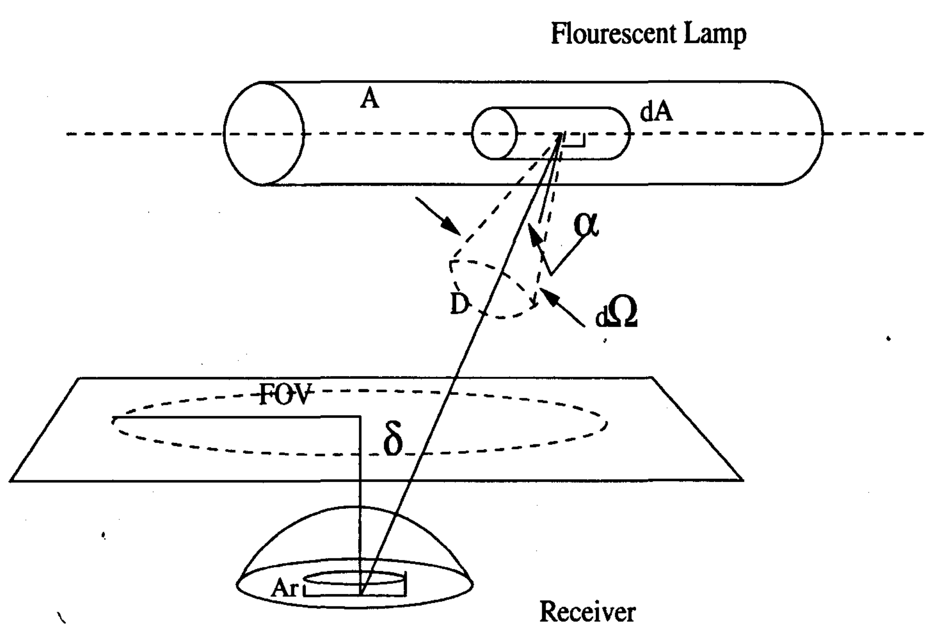

Figure 3.4: Spatial consideration for fluorescent power calculation

From Fig. 3.4, the optical power incident on the photosensitive area A_r of the receiver from the surface element dA can be given as

$$dP_m = \frac{P_s}{A} cos\alpha.dA.d\Omega \tag{3.5}$$

where

$$d\Omega = \frac{A_r}{D^2} cos\delta \qquad if A_r \ll D^2$$

Ω is the solid angle that covers the receiver area A_r. Therefore

$$dP_m = \frac{P_s.A_r}{A.D^2} cos\alpha.cos\delta.dA \tag{3.6}$$

The total power incident on A_r is obtained by integrating (3.6) over the entire FOV, which is given by (3.7).

$$P_m = \frac{2P_sAA_r sin(FOV)}{\pi D^2} \tag{3.7}$$

3.3 Other Noise Processes

In a typical PIN diode receiver, other than the artificial light interference, there are three major noise mechanisms [8]. Namely shot noise, thermal noise and dark current noise. All these noise mechanisms are unavoidable. The photo diode dark current is the current that continues to flow through the bias circuit of the device when no light is incident on the photo diode. Typically dark current noise is very small and negligible. Thermal noise has a constant variance and depends on the receiver resistance. Shot noise arises in electronic devices because of the discrete nature of the current flow in the device. Variance of shot noise depends on the mean received signal power and mean fluorescent power.

In an infrared wireless receiver, the shot noise due to ambient light is the predominant noise. This consists of two components, the static noise due to mean optical power and the periodic interference due to varying optical power. The static noise power can be written as

$$P_{static\ noise} = 2qRP_mB \tag{3.8}$$

where q is the charge of an electron and B is the bandwidth of interest.

3.4 Multi User Interference

Interference in communication channels are contributed by sources other than noise. Multi-user interference is one type of interference. Spread spectrum technology allows many users to access the same communication channel by encoding each users signal with an orthogonal spreading code and then using the same code to decode the signal at the receiver. Unfortunately, strict orthogonality between spreading codes is often unachievable, leading to the undesirable problem of multi-user interference. The correlation process spreads its spectrum exactly like DS SS transmission process and making like wide band interference prior to integration. This integration decreases the average AC power. Therefore the overall interference power become low and thus increases the SINR. Adaptive implementations of multi user (interference-mitigating) receivers are particularly attractive since, in practice, both the mobile terminal and the base-station operate in a random environment which must be acquired and tracked.

Chapter 4

Signal Processing for Performance Improvement

In this chapter, the system performance is evaluated at different points in the network Using the system components defined in Chapter 3. To compare the effect of adaptive filtering in this network, a spread spectrum system without adaptive filter was taken into consideration. Later in the investigation, the same system was analyzed with the use of an adaptive filter. For comparison, the evaluated signal powers, fluorescent interference powers and multiuser interference powers are tabulated in Tables 4.1, 4.2, 4.3 and 4.4. The theoretical BER curves for the systems in comparison are obtained by using Gaussian approximations.

4.1 Signal to Noise and Interference Ratio of an Infrared CDMA System

Consider the system with spreading and despreading without the adaptive filter. Assume the system has K users, the k^{th} user signal can be written as,

$$s_k(t) = \sum_{i=-\infty}^{\infty} \sqrt{\varepsilon_k}.I_k.g(t - iT_c) \tag{4.1}$$

Therefore, total input signal can be written as,

$$s(t) = \sum_{k=1}^{K} s_k(t)$$

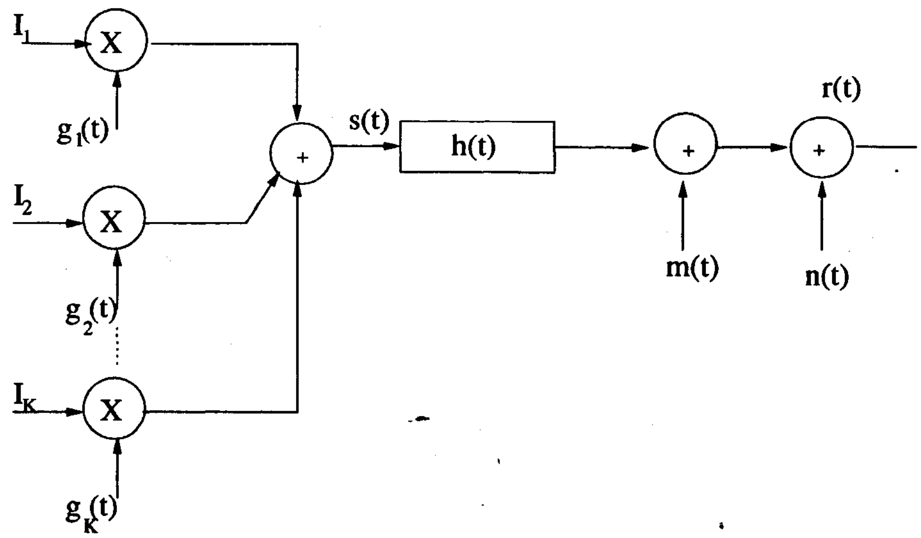

Figure 4.1: Simplified block diagram of an infrared CDMA system with noise and interference

Assume I_k is wide sense stationary with mean μ, and ε_k is the energy of the k^{th} pulse and $g(t)$ is the signature waveform of user with chip period T_c ($NT_c = T$). Autocorrelation of the information sequence I_k is defined as

$$\phi_{ii}(m) = \frac{1}{2}E[I_k I_{k+m}] \qquad m = ... -1, 0, 1... \tag{4.2}$$

where m is the shift value by which samples are separated.

Power spectral density of the signal $s(t)$, $\Phi_{ss}(f)$ is given as in (4.3) [4].

$$\Phi_{ss}(f) = \sum_{k=1}^{K} \frac{1}{T}|G(f)|^2.\Phi_{ii}(f) \tag{4.3}$$

where $G(f)$ is the fourier transform of $g(t)$ and $\Phi_{ii}(f)$ is the power spectral density of the information sequence. From Fig. 4.1, the signal received at the receiver before despreading is

$$r(t) = \sum_{k=1}^{K} s_k(t) * h_k(t) + n(t) + m(t)$$

$$r(t) = s(t) * h(t) + n(t) + m(t) \tag{4.4}$$

where $h(t)$ is impulse response of the channel, $m(t)$ is the periodic interference of the electronic ballast fluorescent lights and $n(t)$ is the Gaussian noise. The asterisk denotes the convolution operation. The same $h(t)$ is considered for all users, assuming the same H, A_r and ρ.

Power spectral density of the output signal $r(t)$ is ,

$$\Phi_{rr}(f) = \Phi_{ss}(f).|H(f)|^2 + \Phi_{nn}(f) + \Phi_{mm}(f) \tag{4.5}$$

where $H(f)$ is the fourier transform of the channel impulse response $h(t)$, $\Phi_{nn}(f)$ is the power spectral density of the Gaussian noise and $\Phi_{mm}(f)$ is the power spectral density of the fluorescent interference.

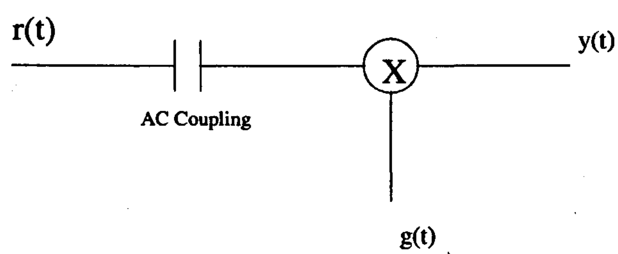

Figure 4.2: Despreading in Infrared wireless system

From Fig. 4.2, the output after the despreaded is given as $y(t)$. Therefore the power spectral density of the output signal $y(t)$ is given as,

$$\Phi_{yy}(f) = \frac{1}{T}|G(f)|^2.\Phi_{rr}(f)$$

$$\Phi_{yy}(f) = \frac{1}{T}|G(f)|^2.\{\Phi_{ss}(f).|H(f)|^2 + \Phi_{nn}(f) + \Phi_{mm}(f)\} \tag{4.6}$$

The k^{th} user is our desired user, therefore in a multi-user environment, the power spectral density of signal $s(t)$ can be written as follows

$$\Phi_{ss}(f) = [\Phi_{ss}(f)]_{k^{th}\ user} + [\Phi_{ss}(f)]_{other\ users} \tag{4.7}$$

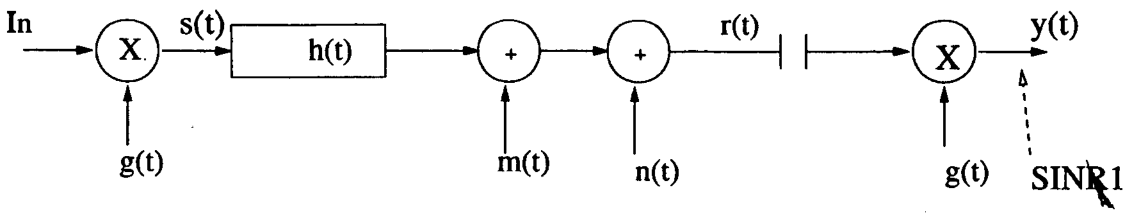

Figure 4.3: Block diagram representation of an IR system without adaptive filter

This first and second component in the (4.7) are due to the desired user's signal and other users' signal respectively.

$$\Phi_{ss}(f) = \frac{1}{T}\{|G_k(f)|^2.\Phi_{i_k i_k}(f) + \sum_{n \neq k} .|G_n(f)|^2.\Phi_{i_n i_n}(f)\} \qquad n, k \; \epsilon[1, K] \tag{4.8}$$

where $\Phi_{i_k i_k}(f)$ is the power spectral density of the k^{th} user's information sequence and $\Phi_{i_n i_n}(f)$is the power spectral density of other user's information sequence. $G_k(f)$ and $G_n(f)$ are the fourier transforms of the signature waveforms of k^{th} and n^{th} users respectively. In (4.8), the first and second components are due to the desired transmitted signal and other transmitted signals respectively.

Substituting (4.8) into (4.6) the power spectral density of the interference signal can be written as,

$$\begin{aligned}\Phi_{interfernce}(f) &= \frac{1}{T}|G_k(f)|^2|H(f)|^2.\{\frac{1}{T}\sum_{n \neq k}|G_n(f)|^2\Phi_{i_n i_n}(f)\} \\ &= \sum_{n \neq k}\frac{1}{T^2}|G_k(f)|^2.|G_n(f)|^2.\Phi_{i_n i_n}(f).|H(f)|^2 \end{aligned} \tag{4.9}$$

Therefore the interference power is

$$\begin{aligned}P_{interference} &= \{R^2 \int \Phi_{interference}(f)df\}\Big|_{f=0} \\ &= \{\int \sum_{n \neq k}\frac{R^2}{T^2}|G_k(f)|^2.|G_n(f)|^2.\Phi_{i_n i_n}(f).|H(f)|^2 df\}\Big|_{f=0}\end{aligned} \tag{4.10}$$

where R is the responsivity of the photo diode. Fluorescent interference power

$$P_{fluorescent} = R^2\{\int \frac{1}{T}|G(f)|^2.\Phi_{mm}(f)df\}\Big|_{f=0}$$

$P_{fluorescent}$=Variance of the fluorescent noise

According to Moreira's fluorescent light model, the fluorescent interference power can be given as in (4.11). The parameters a_i, b_i and d_j are estimated in [5].

$$P_{fluorescent} = \frac{1}{N^2}R^2.P_m^2\{\frac{1}{2K_1^2}\sum_{i=1}^{20}(a_i^2+b_i^2)+\frac{1}{2K_2^2}(\sum_{j=1}^{11}d_j^2+d_0^2)\} \tag{4.11}$$

This can be further simplified by using the numerical values for the parameters estimated in [5] as follows.

$$P_{fluorescent} = \frac{R^2P_m^2}{N^2}.(0.3593)^2$$

where P_m is the average optical power of the interference signal and N is the spreading gain of the CDMA system. The required user's power can be calculated as in (4.12).

$$P_{signal} = \frac{R^2}{T^2}\{|G_k(f)|^4.|H(f)|^2.\Phi_{i_k i_k}(f)df\}\Big|_{f=0} \tag{4.12}$$

Finally, the system performance is determined by $SINR$ as

$$SINR = \frac{P_{signal}}{P_{interference}+P_{fluorescent}}$$

4.2 Signal to Noise and Interference Ratio with an Adaptive Filter

Adaptive filters have the advantage that they can be easily updated and track the variations in the noise/interference in the system. Consider the system with spreading, despreading and an adaptive filter. In IR CDMA systems, the noise and time varying multipath dispersion can be mitigated by adaptive filters. Therefore, we include a discrete time adaptive filter just before despreading as shown in Fig. 4.4. In this analysis, RLS adaptive algorithm is used to keep the training sequence as short as possible.

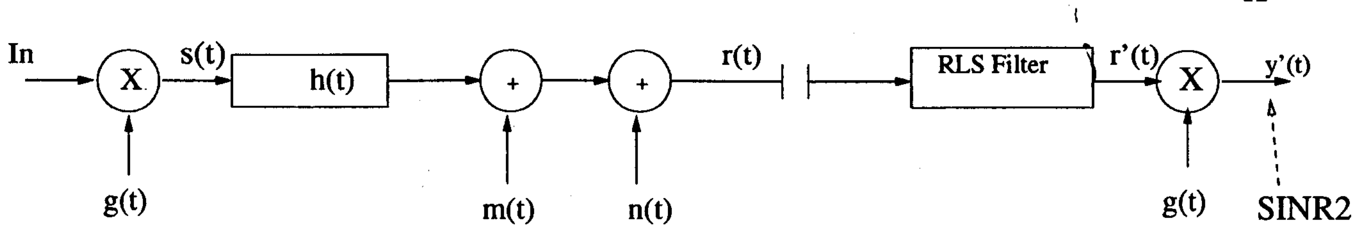

Figure 4.4: Infrared wireless system with Adaptive Filter

After convergence, the tap weights of this filter would formulate a higher order function, which is the inverse of the channel and noise combination function. The objective of the adaptive filter is to update the tap coefficients $\mathbf{W(n)}$ on a sample by sample basis so that the estimation error between desired output and estimated output is minimized in the mean square sense. The optimum value of the tap weight for RLS filter can be determined using Wiener-Hopf normal equation that is given in (4.13).

$$\phi(\mathbf{n}).\mathbf{W}(\mathbf{n}) = \theta(\mathbf{n}) \tag{4.13}$$

$$\text{Therefore} \qquad \mathbf{W}(\mathbf{n}) = \phi^{-\mathbf{1}}(\mathbf{n}).\theta(\mathbf{n})$$

where $\phi(\mathbf{n})$ is the $m \times m$ time averaged correlation matrix of the input to the adaptive filter and $\theta(\mathbf{n})$ is the $m \times 1$ time averaged cross correlation matrix between desired response and input.

From Fig. 4.4, the input to the adaptive filter is $r(t)$.

$$\phi(\mathbf{n}) = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{r}(\mathbf{i}).\mathbf{r}^{\mathbf{T}}(\mathbf{i})$$

$$\theta(\mathbf{n}) = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{r}(\mathbf{i}).\mathbf{d}(\mathbf{i})$$

where $\mathbf{d(i)} = \mathbf{r(i)} + \mathbf{m(i)}$ and $m(i)$ is discrete fluorescent interference.

$$\theta(\mathbf{n}) = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{r}(\mathbf{i}).\{\mathbf{r}(\mathbf{i}) + \mathbf{m}(\mathbf{i})\}$$

$$\theta(\mathbf{n}) = \phi(\mathbf{n}) + \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{r(i).m(i)} \tag{4.14}$$

By substituting (4.14) into (4.13), the optimal $W(n)$ can be evaluated as follows.

$$\mathbf{W_{optimal}(n)} = \mathbf{I} + \phi^{-1}(\mathbf{n}).\sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{r(i).m(i)}$$

where $\mathbf{I}$ is the identity matrix. Therefore, when there is a fluorescent noise the $\mathbf{W_{optimal}}$ depends on the cross correlation between noise and the input.

Assume, Fourier transform of adaptive filter coefficients, transmitted signal and fluorescent interference as $W(f)$, $S(f)$ and $M(f)$ respectively. Here the adaptive filter is used to mitigate the effect of the channel impulse response and the fluorescent interference in the system. Therefore,

$$(H(f) + S^{-1}(f).M(f)).W(f) = \mathbf{I} \tag{4.15}$$

The (4.15) is the ideal requirement within the bandwidth of interest. In Fig. 4.4, the output of the system after the adaptive filter is given as $r'(t)$. The power spectral density of that signal is given as in (4.16),

$$\Phi'_{rr}(f) = \Phi_{rr}(f).|W(f)|^2 \tag{4.16}$$

Assume the received signal after despreading is $y'(t)$. The power spectral density of the received signal is given as,

$$\Phi'_{yy}(f) = \frac{1}{T}.\Phi'_{rr}(f).|G(f)|^2$$

$$\Phi'_{yy}(f) = \frac{1}{T}.|W(f)|^2.\Phi_{rr}(f).|G(f)|^2$$

$$\Phi'_{yy}(f) = \frac{1}{T}.|W(f)|^2.\{\Phi_{ss}(f).|H(f)|^2 + \Phi_{nn}(f) + \Phi_{mm}(f)\}.|G(f)|^2$$

$$\Phi'_{yy}(f) = \frac{1}{T}.\Phi_{ss}(f).|G(f)|^2.|W(f)|^2.|H(f)|^2 + \frac{1}{T}.|W(f)|^2.|G(f)|^2.\Phi_{nn}(f) + \frac{1}{T}.|W(f)|^2.|G(f)|^2.\Phi_{mm}(f) \tag{4.17}$$

In this configuration, the required user's received power, other users' interference and fluorescent interference power can be written as follows,

$$P_{signal} = \frac{R^2}{T^2}\{\int |G_k(f)|^4.\Phi_{i_k i_k}(f).|W(f)|^2.|H(f)|^2 df\}\Big|_{f=0}$$

$$P_{interference} = \frac{R^2}{T^2}\{\int_{n\neq k} |G_k(f)|^2.|G_n(f)|^2.\Phi_{i_n i_n}(f).|W(f)|^2.|H(f)|^2 df\}\Big|_{f=0}$$

$$P_{fluorescent} = \frac{R^2}{T}\{\int |G_k(f)|^2.|W(f)|^2.\Phi_{mm}(f)df\}\Big|_{f=0}$$

4.2.1 Power Levels before the Adaptive Filter

Considering behavior of the system before the adaptive filter.

From Fig. 4.4, $r(t)$ is the signal received at the beginning of the adaptive filter. The power spectral density of the signal $r(t)$ is given as,

$$\Phi_{rr}(f) = \Phi_{ss}(f).|H(f)|^2 + \Phi_{nn}(f) + \Phi_{mm}(f)$$

$$\Phi_{rr}(f) = |H(f)|^2.\{\frac{1}{T}\Phi_{i_k i_k}(f).|G_k(f)|^2\} + \{\frac{1}{T}\sum_{n\neq k}.\Phi_{i_n i_n}(f).|G_n(f)|^2 + \Phi_{nn}(f) + \Phi_{mm}(f)\} \tag{4.18}$$

From the power spectral density (4.18), the required power, other users' interference and fluorescent interference power can be calculated as follows,

$$P_{required} = \frac{R^2}{T}\{\int |H(f)|^2.|G_k(f)|^2.\Phi_{i_k i_k}(f)df\}\Big|_{f=0}$$

$$P_{interference} = \sum_{n\neq k}\frac{R^2}{T}\{\int |H(f)|^2.|G_n(f)|^2.\Phi_{i_n i_n}(f)df\}\Big|_{f=0}$$

$$P_{fluorescent} = \{\int \Phi_{mm}(f)df\}\Big|_{f=0}$$

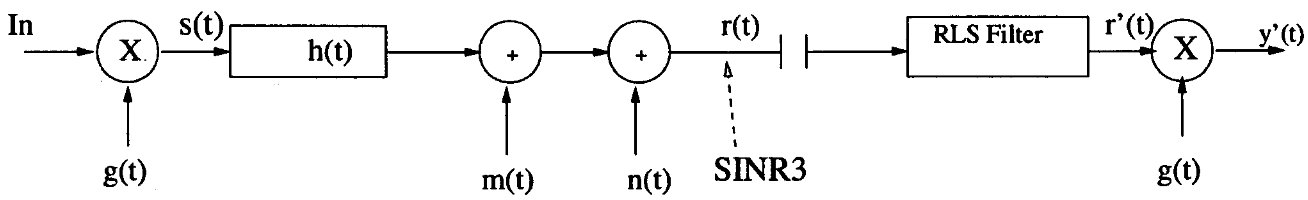

Figure 4.5: Evaluation of SINR before adaptive filter

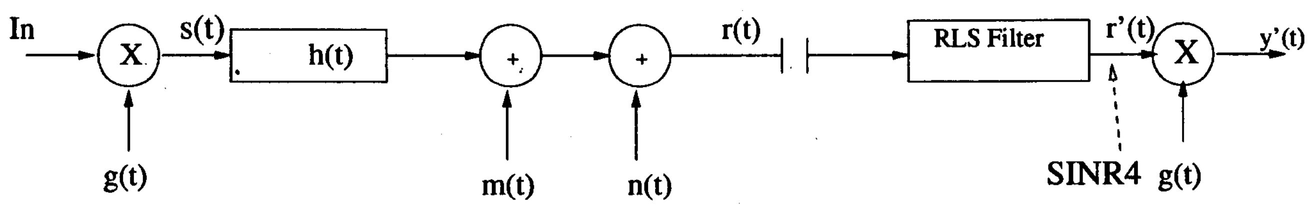

Figure 4.6: Evaluation of SINR after adaptive filter before despreading

4.2.2 Power Levels after Adaptive Filter and before Despreading

Considering behavior of the system before despreading and after adaptive filter. From Fig. 4.6, $r'(t)$ is the signal received at the output of the adaptive filter and the power spectral density of that signal can be written as follows,

$$\Phi'_{rr}(f) = \Phi_{rr}(f).|W(f)|^2$$

$$\Phi'_{rr}(f) = |W(f)|^2.\{\Phi_{ss}(f).|H(f)|^2 + \Phi_{nn}(f) + \Phi_{mm}(f)\}$$

$$\Phi'_{rr}(f) = \Phi_{ss}(f) + \Phi_{nn}(f).|W(f)|^2 + \Phi_{mm}(f).|W(f)|^2$$

$$\Phi'_{rr}(f) = \frac{1}{T}\{\Phi_{i_k i_k}(f).|G_k(f)|^2 + \sum_{n\neq k}|G_n(f)|^2.\Phi_{i_n i_n}(f)\} + \Phi_{nn}(f).|W(f)|^2 + \Phi_{mm}(f).|W(f)|^2 \tag{4.19}$$

Finally, the power levels of the required user,other user and fluorescent noise can be written as follows,

$$P_{required} = \frac{R^2}{T}\{\int |G_k(f)|^2.\Phi_{i_k i_k}(f)df\}\Big|_{f=0}$$

	$SINR_1$
P_{signal}	$\frac{R^2}{T^2}\{\lvert G_k(f)\rvert^4.\lvert H(f)\rvert^2.\Phi_{i_k i_k}(f)df\}\Big\rvert_{f=0}$
$P_{interference}$	$\{\int\sum_{n\neq k}\frac{R^2}{T^2}\lvert G_k(f)\rvert^2.\lvert G_n(f)\rvert^2.\Phi_{i_n i_n}(f).\lvert H(f)\rvert^2\}\Big\rvert_{f=0}$
$P_{fluorescent}$	$\frac{R^2 P_m^2}{N2}.(0.3593)^2$

Table 4.1: Power Levels of IR system

	$SINR_2$
P_{signal}	$\frac{R^2}{T^2}\{\int\lvert G_k(f)\rvert^4.\Phi_{i_k i_k}(f).\lvert W(f)\rvert^2.\lvert H(f)\rvert^2 df\}\Big\rvert_{f=0}$
$P_{interference}$	$\frac{R^2}{T^2}\{\int_{n\neq k}\lvert G_k(f)\rvert^2.\lvert G_n(f)\rvert^2.\Phi_{i_n i_n}(f).\lvert W(f)\rvert^2.\lvert H(f)\rvert^2 df\}\Big\rvert_{f=0}$
$P_{fluorescent}$	$\frac{R^2}{T}\{\int\lvert G_k(f)\rvert^2.\lvert W(f)\rvert^2.\Phi_{mm}(f)df\}\Big\rvert_{f=0}$

Table 4.2: Power Levels of IR System with Adaptive Filter

$$P_{interference} = \sum_{n\neq k}\frac{R^2}{T}\{\int |G_n(f)|^2.\Phi_{i_n i_n}(f)df\}\Big|_{f=0}$$

$$P_{fluorescent} = \{\int |W(f)|^2.\Phi_{mm}(f)df\}\Big|_{f=0}$$

Note that after the adaptive filter and before despreading , the required user's power and other users power are equal.

Using the power equations derived in Tables 4.1, 4.2, 4.3 and 4.4, $SINR$ can be calculated for each case. Finally the bit error rate(BER) of the system can be attained using the (4.20) as where, 'erfc' is the complementary error function [31]. In the theoretical analysis, the simulated adaptive weights are used for tap coefficient values.

$$BER = \frac{1}{2}erfc\{\sqrt{\frac{SINR}{2}}\} \tag{4.20}$$

	$SINR_3$
P_{signal}	$\frac{R^2}{T}\{\int \lvert H(f)\rvert^2.\lvert G_k(f)\rvert^2.\Phi_{i_k i_k}(f)df\}\Big\rvert_{f=0}$
$P_{interference} SINR_2$	$\sum_{n\neq k}\frac{R^2}{T}\{\int \lvert H(f)\rvert^2.\lvert G_n(f)\rvert^2.\Phi_{i_n i_n}(f)df\}\Big\rvert_{f=0}$
$P_{fluorescent} SINR_3$	$\{\int \Phi_{mm}(f)df\}\Big\rvert_{f=0}$

Table 4.3: Power Levels of IR System before Adaptive Filter

	$SINR_4$
P_{signal}	$\frac{R^2}{T}\{\int \lvert G_k(f)\rvert^2.\Phi_{i_k i_k}(f)df\}\Big\rvert_{f=0}$
$P_{interference}$	$\sum_{n\neq k}\frac{R^2}{T}\{\int \lvert G_n(f)\rvert^2.\Phi_{i_n i_n}(f)df\}\Big\rvert_{f=0}$
$P_{fluorescent}$	$\{\int \lvert W(f)\rvert^2.\Phi_{mm}(f)df\}\Big\rvert_{f=0}$

Table 4.4: Power Levels of IR System after Adaptive Filter and before Despreading

4.3 Analytical Results

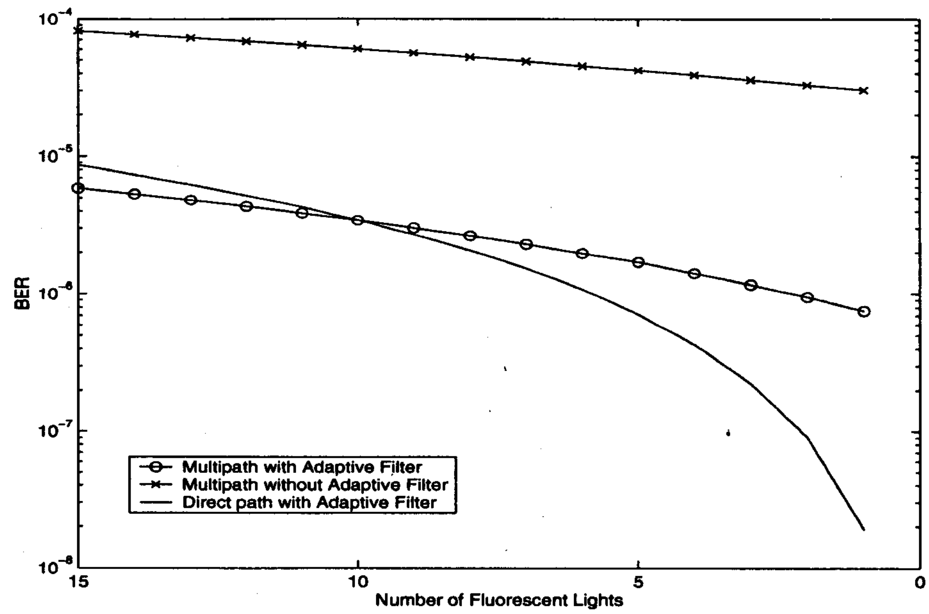

Figure 4.7: BER curve of the IR wireless system, N=127 with simulated Adaptive Filter weights, using ERFC tables

Figures 4.7 and 4.8 illustrates the BER against number of fluorescent lights. The BER was computed using the expressions shown in section 4.2.2. The figures compare the performance of the IR system with multipath, direct path and multi users. Variation of SNR with number of fluorescent lights is given in Fig. 4.9.

Fig. 4.7 shows the theoretical BER curves for a single user IR system. The direct path curve indicates the effect of fluorescent light in the system with adaptive filter. Then multipath effect is added to the system and find the BER with fluorescent and multipath interferences.

From Fig. 4.7, with direct path, adaptive filter is able to significantly decrease the BER. The SNR required for the $BER \leq 10^{-6}$ is 21.5 dB. In the same figure multipath effect is analyzed with and without adaptive filter. The adaptive filter improves the BER by ten fold with multipath. Similar behavior can be seen in simulation results which is shown in Fig. 5.17.

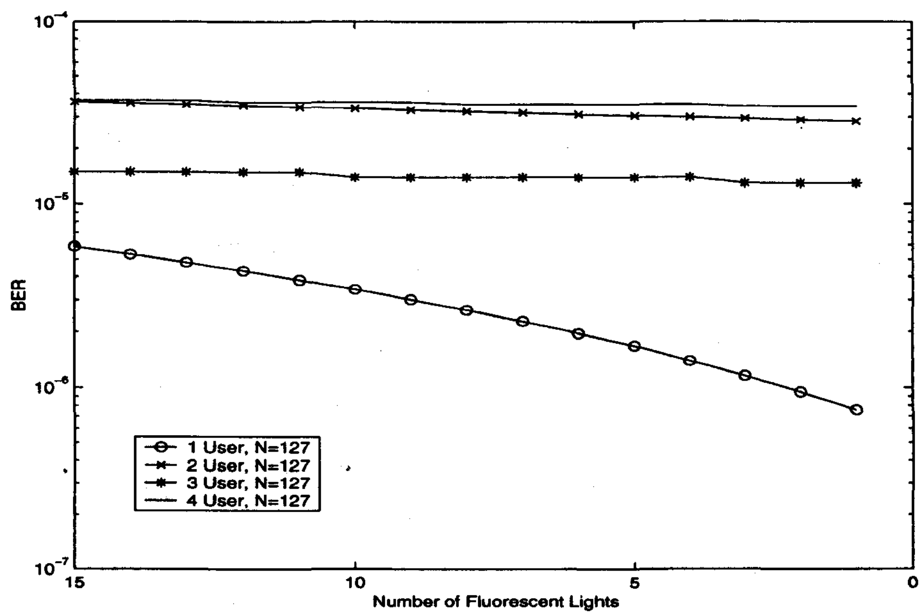

Figure 4.8: Comparison BER curves of the Multi User IR system with Adaptive Filter

Fig. 4.8 shows the theoretical BER of the IR system with 1 or more users. As the number of users increase, the BER increases significantly. With two or more users, the BER is independent of the fluorescent noise. There is a significant jump in BER from 1 user to 2 users and 2 users to 3,4 users. This implies that the adaptive filter can cancel out part of the multi-user interference for 1 or 2 users. As the number of users increases, this adaptive filter become inadequate to cancel out the multiuser effects.

Fig. 4.10 compares the BER curves with and without adaptive filter. This illustrates the BER improvement due to adaptive filter in a multiuser environment. In multiple user case, the improvement in BER is less significant compared to that in single user case.

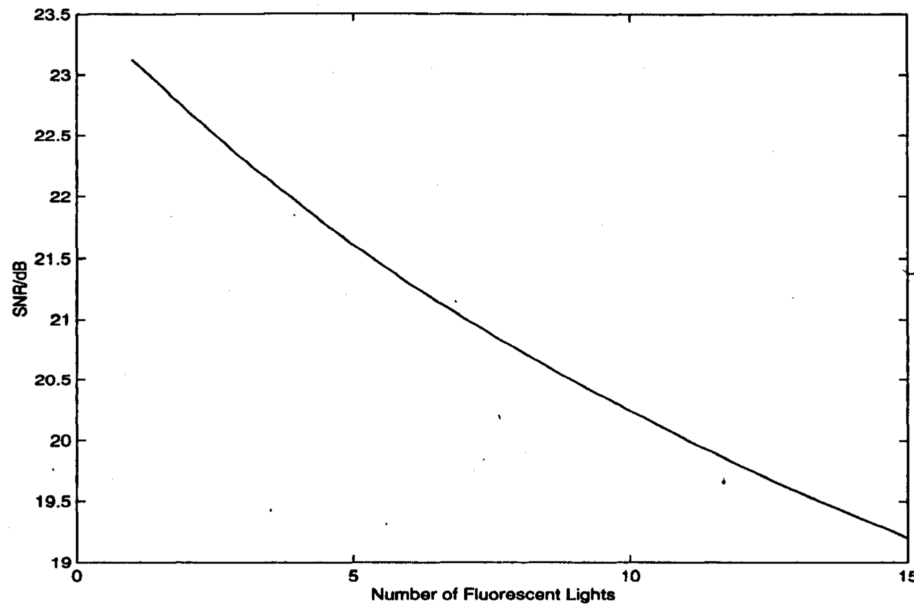

Figure 4.9: Variation of SNR with Number of fluorescent Lights

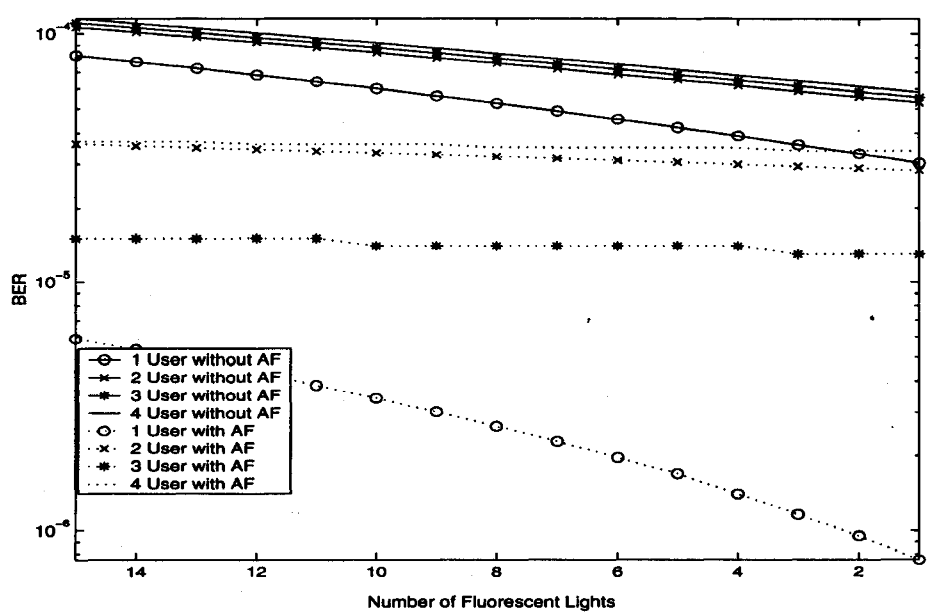

Figure 4.10: Comparison BER curves of the Multi-user IR system

Chapter 5

Simulation and Verification of Results

In this chapter, simulation models are described and the reason for obtaining the various parameters are explained.

5.1 Simulink Models

In practical digital communication systems the channel is not ideal. Signal transmitted at a bit rate equal to or exceeding the channel bandwidth results in intersymbol interference among a number of adjacent received symbols. Specially, the adaptive filter or signal processing algorithm for handling the interferences at the receiver contains a number of parameters which are adaptively adjusted on the basis of measurements of the channel characteristics.

In our simulation model, the IR system is trained using LMS and RLS algorithm. The simulink model of the proposed scheme is shown in Fig. 5.1. The random integer generator data are uncorrelated and have values either 1 or 0. These data pass through the multipath channel. In this model, channel is selected with direct path and other two delayed paths. There is a unity gain block in the direct path. The delayed gains of the paths were taken by sampling the ceiling bounce model's impulse response at the appropriate time. Delay time is specified in the integer delay blocks. The fluorescent light interference is generated in discrete levels using the matlab function block and counter block. The Malab Function block implements the noise (3.4). The counter block generates the sampling times for fluorescent noise with respect to random data generation.

Channel output and fluorescent interference are added together and connected to the input terminal of the adaptive filter. Adaptive filter output and random data generater output are compared at the comparator block. The training of the adaptive filter is done by sending the error/difference of the comparator block to the error terminal of the adaptive filter. Tap terminal of the adaptive filter is connected to the scope block through flip block to see the convergence of the tap weights. Also to get the learning curve, the error is squared using squared function block and mean value is estimated using mean block. Display block displays the mean squared error values.

The adaptive filter is trained until the mean squared error reaches a reasonable minimum. The learning curves Fig. 5.11 show that the adaptive filter reasonably converges within 500 iterations for multipath interference. However, It converges reasonably within 600 iterations for both multipath and fluorescent interferences. The tap weights after convergence are the optimal tap weights of the filter and are shown in Fig. 5.5 for multipath interference only. In this analysis, learning curves are obtained with LMS and RLS algorithms. From the figures obtained under different conditions, RLS filter is selected due to its faster convergence than the LMS counter part. Fig. 5.11 indicates the learning curves converge only with number of samples for multipath interference. Similarly, Fig. 5.12 shows how the different algorithms work with fluorescent and multipath interferences. Fig. 5.13 compares the learning curves of the RLS filter with and without fluorescent light interference.

Fig.5.2 shows the simulink model of IR system where the adaptive filter is replaced with frozen weights. The filter weights are obtained by training a RLS filter with multipath and fluorescent interferences. As shown in Fig.5.2, the random integer generator's output is sent through a Unipolar to Bipolar converter. This converts the ones and zeros into -1s and 1s. Matlab Function blocks are used to convert those -1s and 1s to unit positive values. Output of the Matlab Function block corresponds to '1' of the random generator is multiplied with PN sequence to spread the signal. Similarly, the output corresponds to '0' is multiplied by inverted PN sequence for spreading. A Logical operator is used to invert the PN sequences. The spreaded signal is sent through the multipath channel. At the

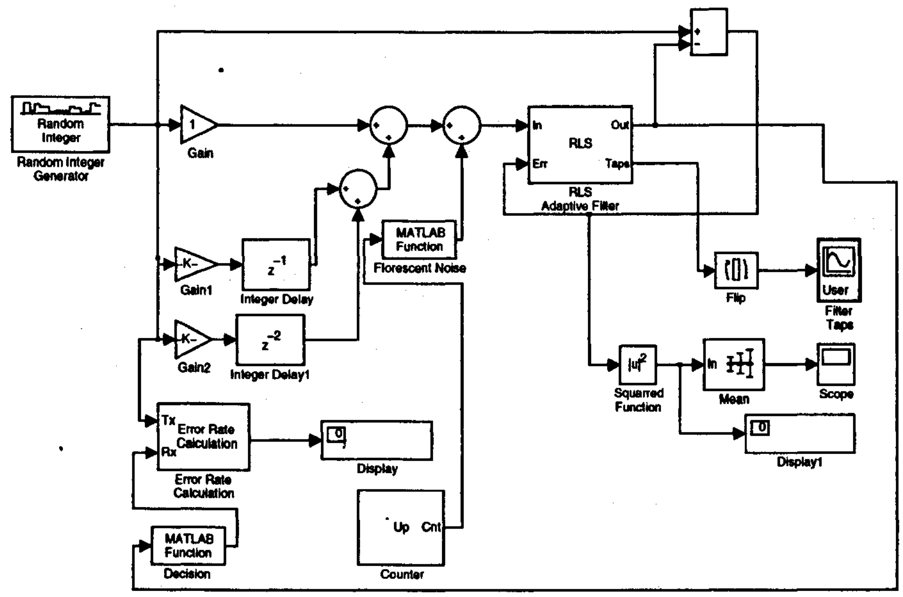

Figure 5.1: Simulink model of IR system for RLS training

receiver front end fluorescent interference is added to the system using an adder block. The fluorescent light power is adjusted for each SNR.

The effect of these interferences are eliminated/minimized by a fifteen coefficient filter. Output of this filter is multiplied again with same PN sequence for despreading. The despreaded spectrum is integrated over the bit period and compared with the threshold value before dumping at the Integration and dump block. This block output is sent through the matlab function block for decision making. The decided data is compared with the original data for bit error rate calculation. Finally the bit error rate is displayed in the display block. To find the multi user effect in the IR system, a similar architecture is used with multiple users. Fig. 5.3 shows the two user architecture of the IR system.

5.2 Setup of Simulation

Since the fluorescent interference is the dominant, the effects due to other noise are not considered. The fluorescent interference is generated from Moreira's [5] equation that is given in (3.4). This noise is sampled periodically.

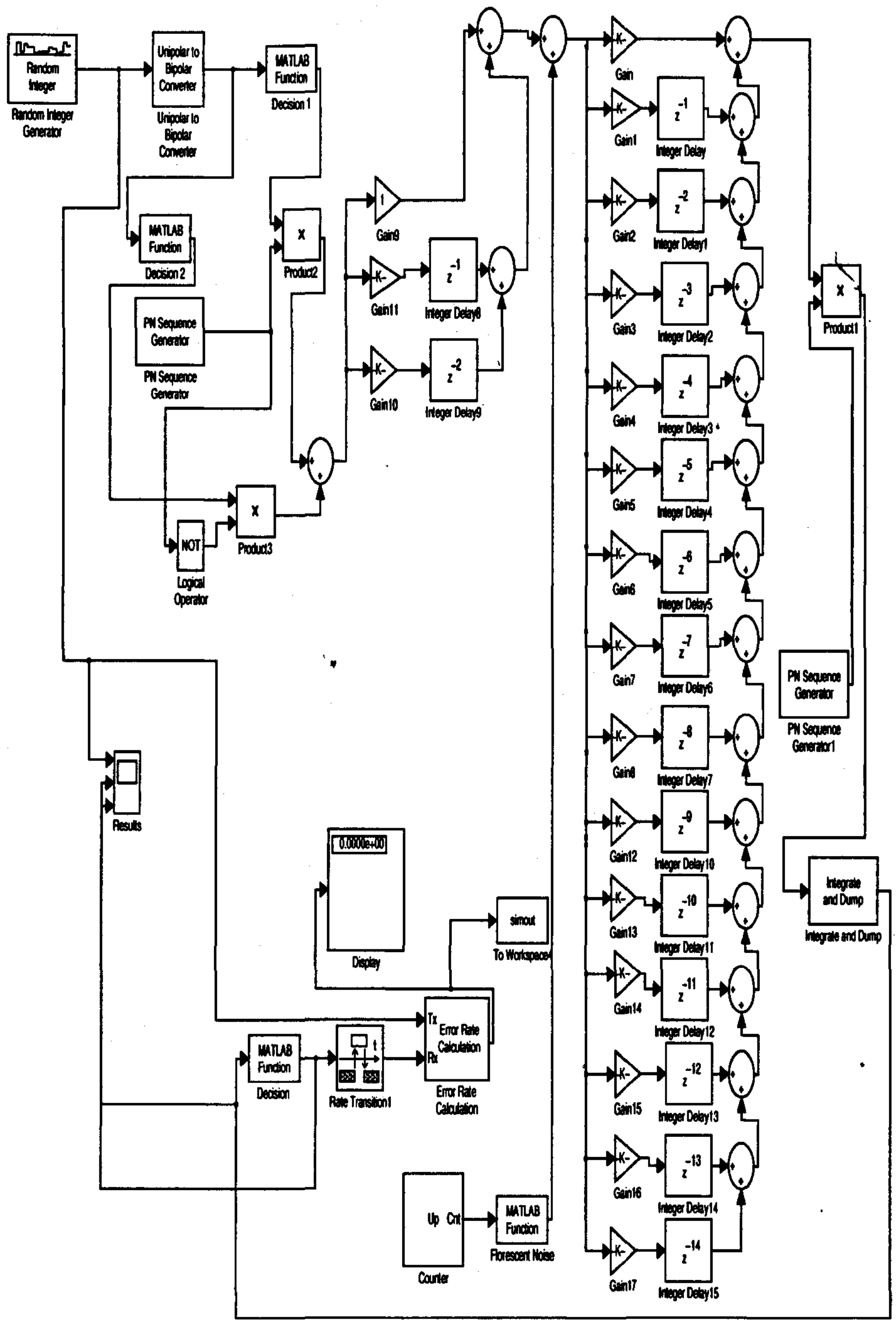

Figure 5.2: Simulink model of IR system with fixed(trained) filter

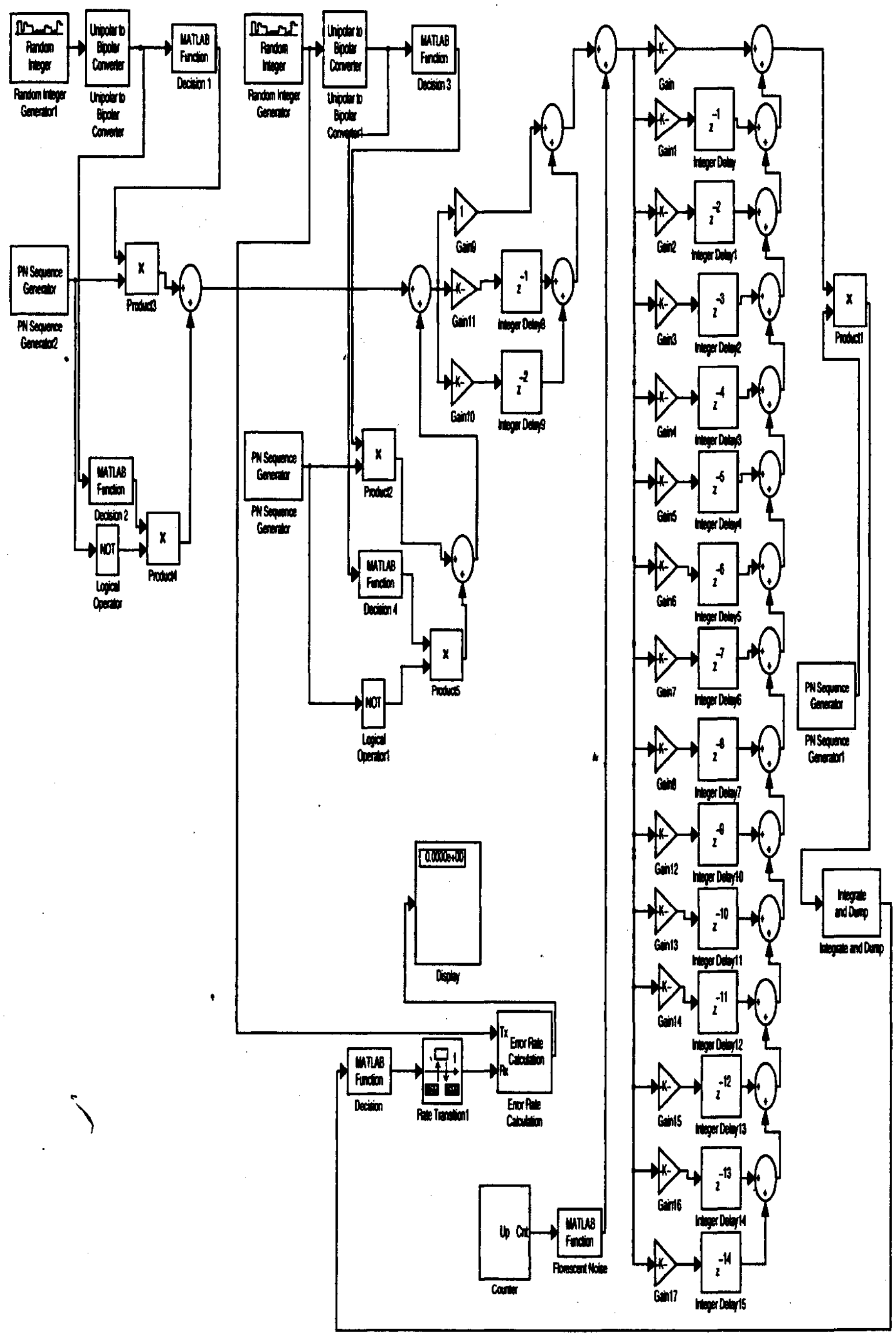

Figure 5.3: Simulink model of IR system with Two Users

Parameter	Values
Responsivity R	0.62 A/W
Receiver area	$1cm^2$
Distance between Tx and Rx	3.5m
Fluorescent output power	34W
Fluorescent tube length	4Foot
Fluorescent tube diameter	1.5inch
User power	1mW
System symbol period T_s	0.635 μs

Table 5.1: Simulation Parameters

$$m(nT_c) = RP_m + \frac{RP_m}{K_1}\sum_{i=1}^{20}[b_i cos(2\pi(100i-20)nT_c+\xi_i)+c_i cos(2\pi 100i+\varphi_i)]$$

$$+\frac{RP_m}{K_2}[d_0 cos(2\pi f_h nT_c+\theta_0)+\sum_{j=1}^{11} cos(2\pi 2j f_h nT_c+\theta_j)] \quad (5.1)$$

By considering the channel impulse response, the sampling times were selected as $5nS$ and $10nS$ to obtain the significant multipath gains. Information sequence is generated with

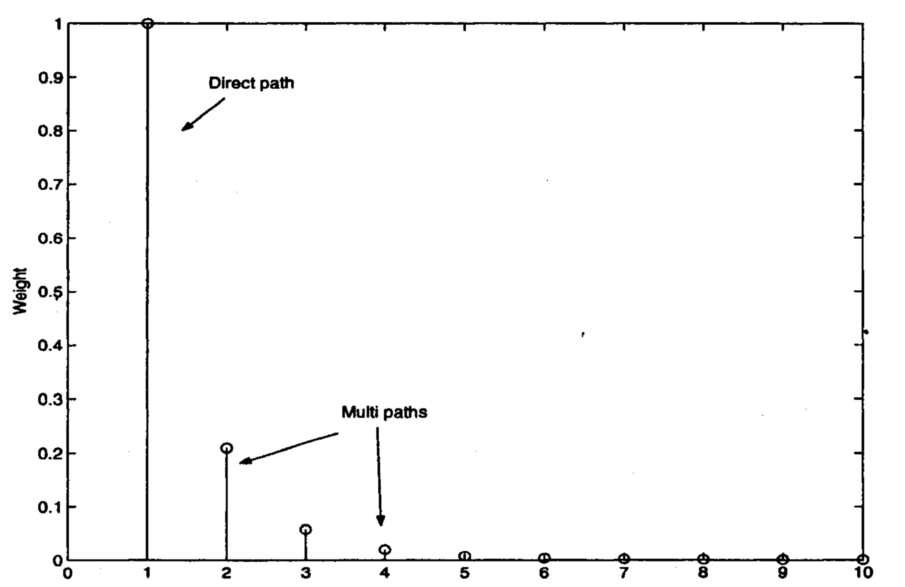

Figure 5.4: Discrete impulse response of the Ceiling bounce channel model

a random integer generator. PN sequence is generated using a PN sequence generator for spreading and despreading. Discrete time domain response of the ceiling bounce channel model is obtained using (5.2).

$$h(nT_c) = G_0 . \frac{6a^6}{(nT_c + a)^7} \qquad n = 1, 2, 3... \qquad for \quad T_c = 5ns, 10ns \tag{5.2}$$

From this response the multipath gains are selected at different time instants. Fig. 5.4 describes the discrete impulse response of the ceiling bounce model for $T_c = 5nS$ seconds.

To eliminate the effect of interference, LMS or RLS algorithms can be used. However, the RLS algorithm is selected because of the fast convergence. These algorithms are executed with filter orders of 3, 5, 7, 12 and 15 to find an optimal filter order for the best interference cancellation. Once the adaptive filter is trained using the filter coefficients and delay values, the weights are frozen.

Output of this filter is despreaded by a PN sequence to obtain the information sequence back. Correlation of the incoming signal is achieved by multiplying the exact replica of the PN sequence. To find the exact form of the received information sequence, the despreaded signal integrated over the bit period in step of chip period and the value for each bit period is stored. After sampling these outputs at each bit period, the sampled values are compared against an essentially non-zero threshold level in the decision block to verify whether they are ones or zeros. This threshold value is strongly dependent on background interference power and mean interference power and should be automatically tuned at each condition to achieve the best possible performance. The detected ones and zeros are compared with the original transmitted sequence at bit error rate calculation block.

The simulation model is executed under two different conditions.

$$T_s = NT_c = \frac{1}{Bit\, rate}$$

In the first case, the bit rate is kept constant at 1.6 Mbps by varying the chip period T_c, so that path coefficients and number of path are varied at different N values. This means, by varying N and T_c values, bit rate is kept constant. In the second case, the chip period is kept at $5ns$ and the N values are varied, so that the bit rate is different.

The simulation model described in Fig. 5.1 has been adapted for use with different number of users, different bit rates, different PN sequence gains. The bit error rate is recorded in each case. The average bit error rate for different cases is given in the Section 5.3.

To find the effect of the interferences in the IR system, different types of interferences are tested independently and in combination. The system is initially analyzed with multipath effect and fluorescent interference separately. Then it is tested with both the multipath and fluorescent light interferences.

5.3 Simulation Results

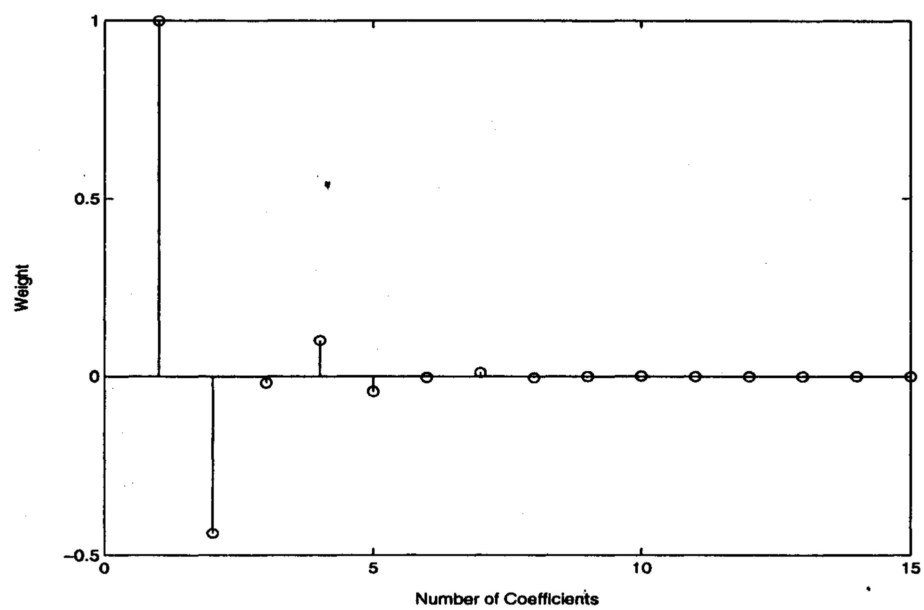

Figure 5.5: Tap weights of RLS filter for Multipath interference Only

Fig. 5.5 shows the tap weights of the RLS filter with multipath interference. From the figure it is evident that 5 tap weights are sufficient for cancelling the multipath interference. The frequency response of the adaptive filter tap weights is shown in Fig. 5.6. This shows that the filter behaves like a high pass filter while equalizing the multipath interference.

When the fluorescent interference is introduced to the system, the filter order to mitigate

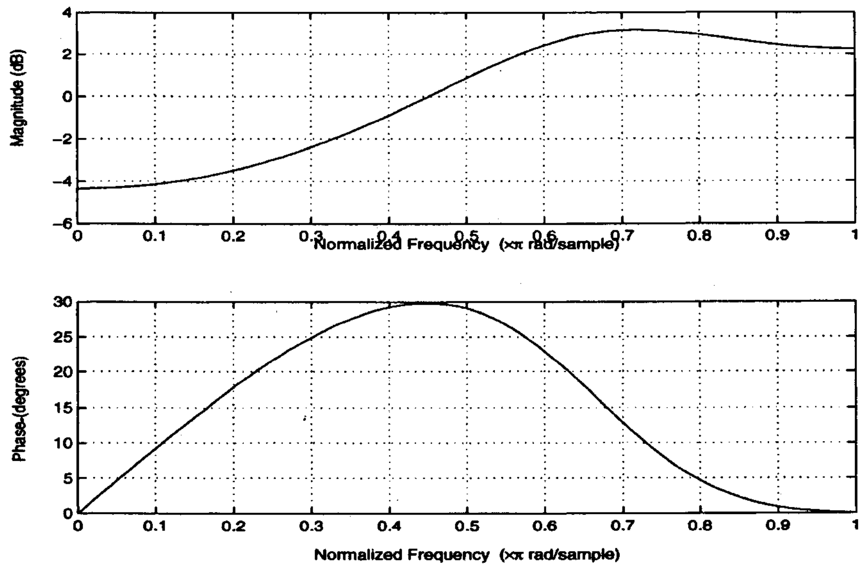

Figure 5.6: Frequency spectrum of RLS filter for Multipath interference Only

this interference become high. As shown in Fig. 5.7, the tap weights are significant up to filter order 15. The higher the filter order, the more the complexity. Therefore, to reduce the complexity, a filter order of 15 is selected in the simulation. Frequency spectrum in Fig. 5.8 of the filter taps in this case looks like a notch filter. This notch filter essentially removes 300 KHz, which is the strongest frequency from the fluorescent light.

Figures. 5.9 and 5.10 show that the effect of both multipath and fluorescent interference in the adaptive filter. Since the tap weights are significant up to order 15, an adaptive RLS filter of order 15 is selected in this simulation. The frequency spectrum clearly indicates, how this filter mitigate both of these effects. The frequency response of the filter looks like the combination of the two frequency responses as shown in Fig. 5.6 and Fig. 5.8.

Fig. 5.13 compares the learning curves of the RLS filter in the presence of multipath interference with and without fluorescent light interference. Although the filter converge as seen in both cases, the minimum achievable error is much higher with fluorescent interference as compared to the multipath interference. This also proves that the fluorescent interference makes much more impairment to IR system.

Fig. 5.14 shows graphs of BER versus number of fluorescent lights with PN sequence

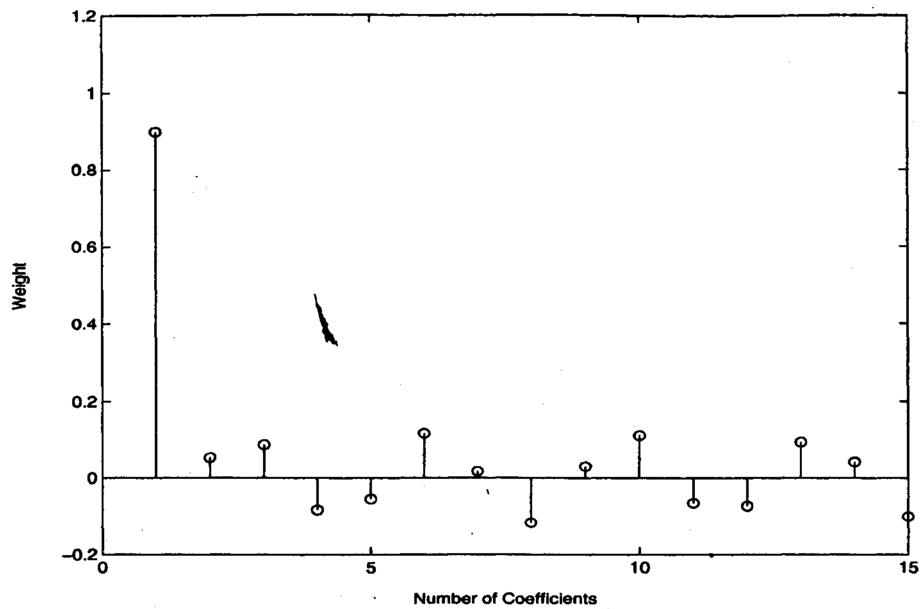

Figure 5.7: Tap weights of RLS filter for Fluorescent interference Only

length N=127 and $T_c = 5ns$. Curves are plotted for users 1 to 4. The simulation results shown in Fig. 5.14 agree with the theoretical concept that the BER increases gradually with the number of users. The result is obtained by simulating a spread spectrum CDMA system for the data rate of 1.6 Mbps. In addition, results presented in Fig. 5.14 is obtained by fixing the values of each user's input power and neglecting the noise from other sources while changing the fluorescent interference power using varying number of fluorescent lights.

Similarly, Fig. 5.15 was obtained with N=63 and $T_c = 5ns$. Fig. 5.16 compares the BER for N=127 and N=63 when $T_c = 5ns$. When N changes from 127 to 63, the bit rate is increased by almost two times for a constant T_c. As shown in Fig. 5.16, curves for N=127 and N=63 resemble to each other but are simply shifted up for higher bit rates.

Fig. 5.16 illustrates the effect of N with different number of users. The result confirms the general concept of spread spectrum CDMA technology that as the spreading gain for N increases, the effect of interferences decreases so that BER decreases.

Fig. 5.17 shows the variation of BER for different conditions with number of fluorescent lights when there is only one user. Based on the result obtained in simulations, the adaptive filter significantly improves the BER of an IR system. In the direct path case the

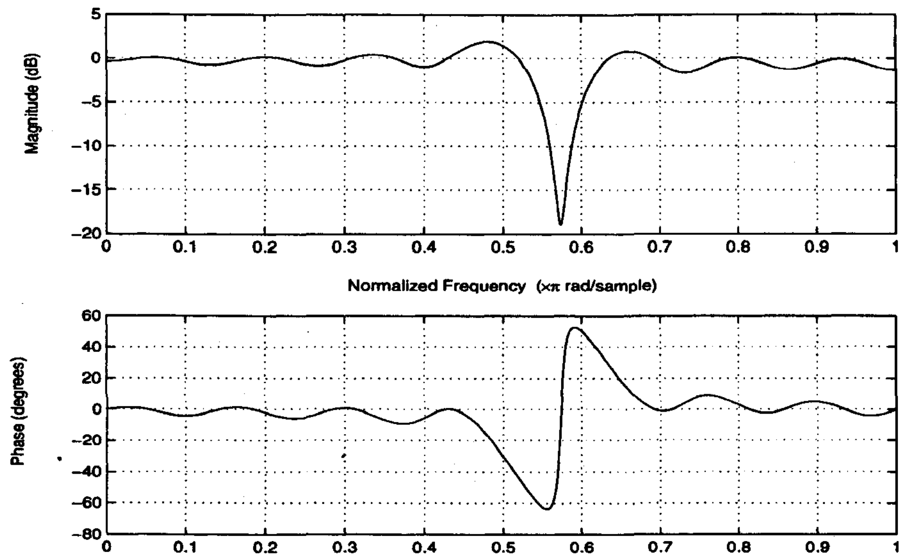

Figure 5.8: Frequency spectrum of RLS filter for Fluorescent interference Only

improvement due to the adaptive filter is even better. As in the analytical results, simulation results also show that the adaptive filter improves the BER around ten times with multipath interference. However, the achievable BER is much higher in the simulation results.

Since $T_s = NT_c$, as N changes, T_c changes.

$$h(nT_c) = G_0 \cdot \frac{6a^6}{(nT_c + a)^7}$$

Now for n=1,2 and 3, $h(nT_c)$ is significant.

The final simulation is performed to investigate the effect of varying the code sequence length N, for the same bit rate. Since $T_s = NT_c$, as N changes, the T_c also change for a constant bit rate. This is done with the same system parameters using three paths per user while the number of users varying from one to four. Path gains are obtained from the discrete channel model given in (5.2 according to the T_c values. Two different values of N are used: 127 and 63. The corresponding chip rates are $5ns$ and $10ns$ respectively. The resulting curves for the simulation is shown in Fig. 5.18. The curves for N=63 much resemble the curves for N=127 but are simply shifted up. This figure also confirm the concept of spread spectrum

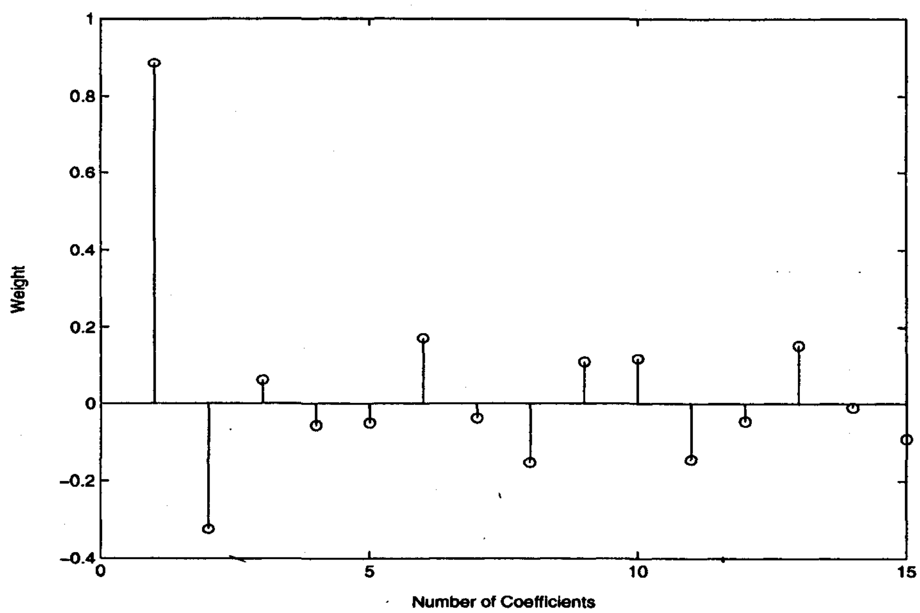

Figure 5.9: Tap weights of RLS filter for Multipath and Fluorescent interference

CDMA technology. Fig. 5.19 shows the variation of BER with number of fluorescent light when N=63 and $T_c = 10ns$.

5.4 Conclusions

Initially, the proposed IR system was analyzed mathematically and subsequently the technique was tested in a simulation model using the mathematically derived equations. The conclusions reported below are based on the results obtained from the simulation studies and the analytical studies.

1. By comparing the convergence of the learning curves, the RLS filter was selected for its faster convergence. The learning curves of the RLS filter with and without fluorescent interferences confirm that the fluorescent interference makes much more impairment to the IR system. i.e. The minimum achievable mean squared error is much higher with fluorescent interference.

2. The frequency spectrums of the adaptive filter show the effect of interferences by the multipath and fluorescent light independently as well as due to combination of the

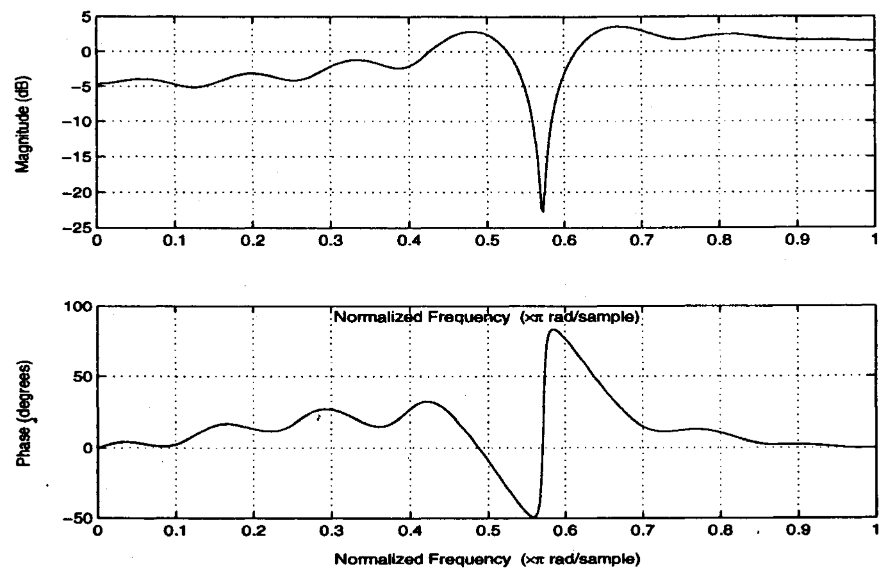

Figure 5.10: Frequency spectrum of RLS filter for Multipath and Fluorescent interference

both. The filter cancels out the frequencies at 75 KHz, 125 KHz, 195 KHz, 300 KHz, 375 kHz, and 446 KHz. However, it essentially removes the frequency at 300 KHz which is the strongest frequency from the fluorescent light.

3. Simulation models are investigated with 1.6 Mbps and 3.2 Mbps. As bit rate increases, the BER also increases. This result confirms the general concept of spread spectrum technology; that is as spreading gain N increases, the effect of interference decreases so that the BER decreases.

4. Adaptive filter improve the BER of the IR system by ten fold. In the direct path condition, the improvement is even better.

5. As the number of users increases, the BER also increases.

   - In the noise limited region(13 or more bulbs), the BER is independent of the multi user interference.

   - In the interference limited region(10 or less bulbs), the BER is independent of the fluorescent interference.

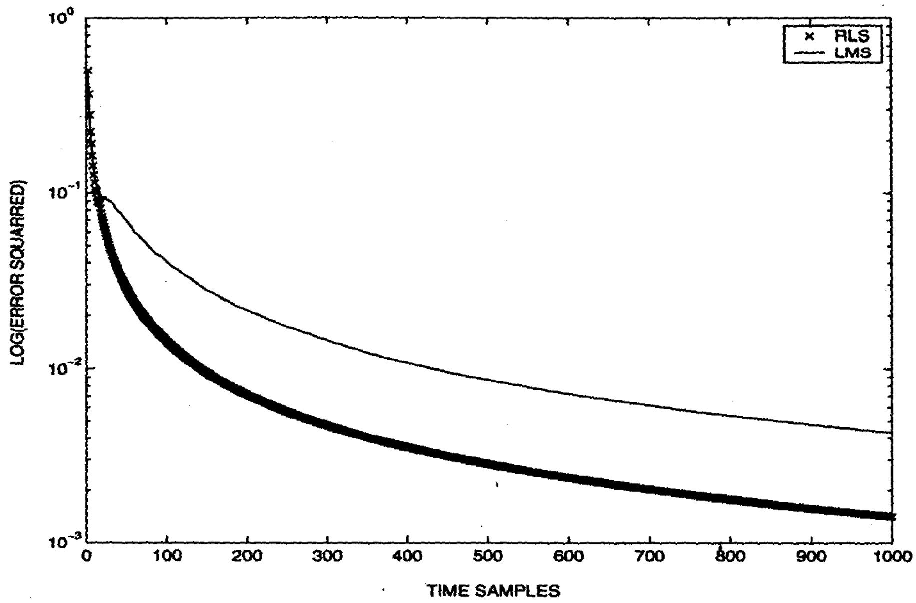

Figure 5.11: Comparison of Learning curves of different Adaptive Algorithms with Multipath Interference Only

6. Generally the proposed technique achieves a good performance in terms of interference cancellation. The SNR required for $BER \leq 10^{-6}$ is around 20 dB. The SNR obtained is almost closer to our analytical results.

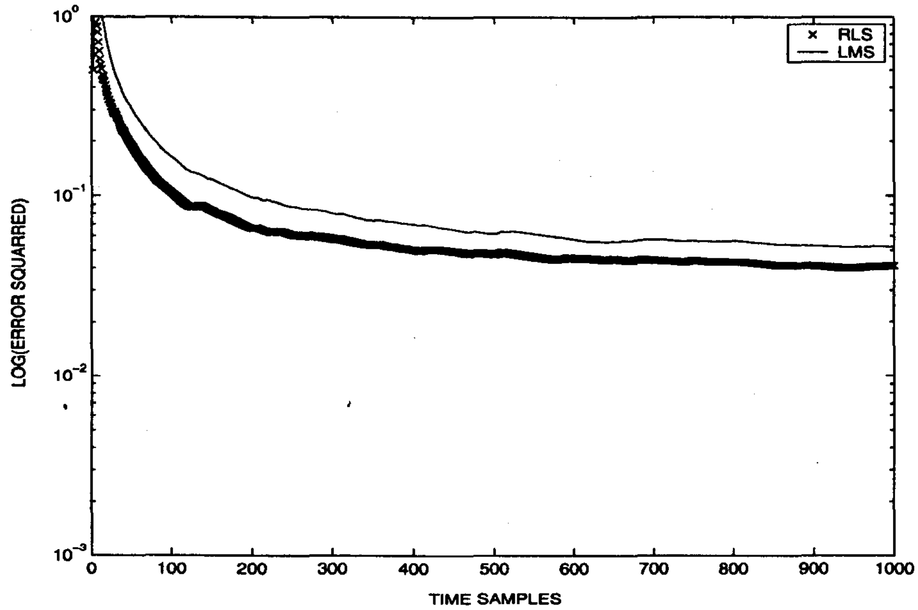

Figure 5.12: Comparison of Learning curves of the Adaptive Filters for both Fluorescent and Multipath Interferences

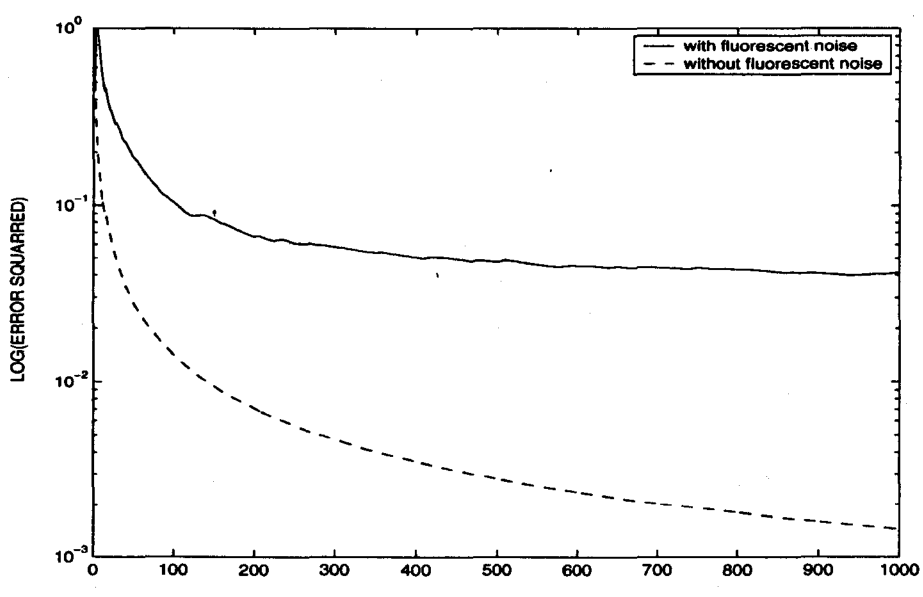

Figure 5.13: Comparison of Learning curves for RLS Filter

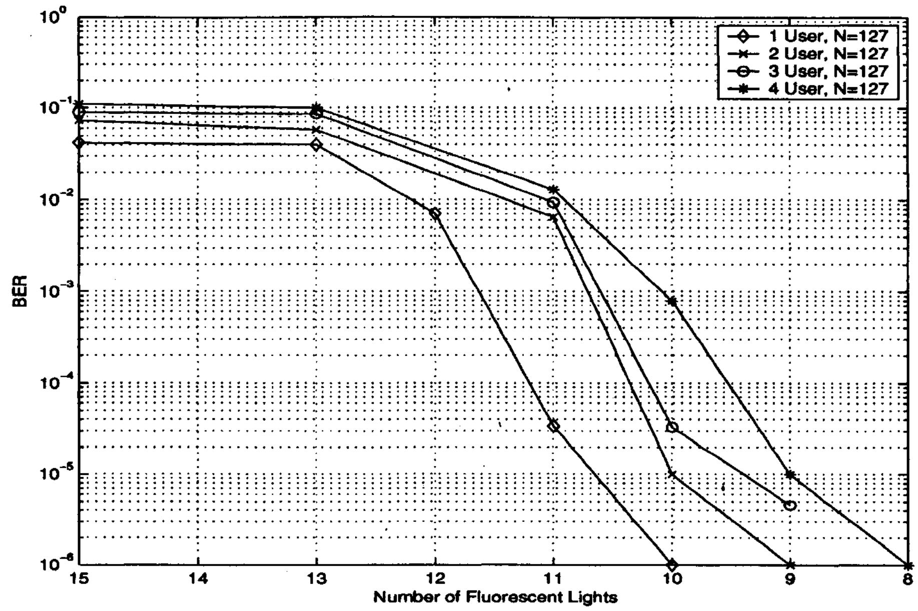

Figure 5.14: BER curve of the IR system with Adaptive Filter, when N=127

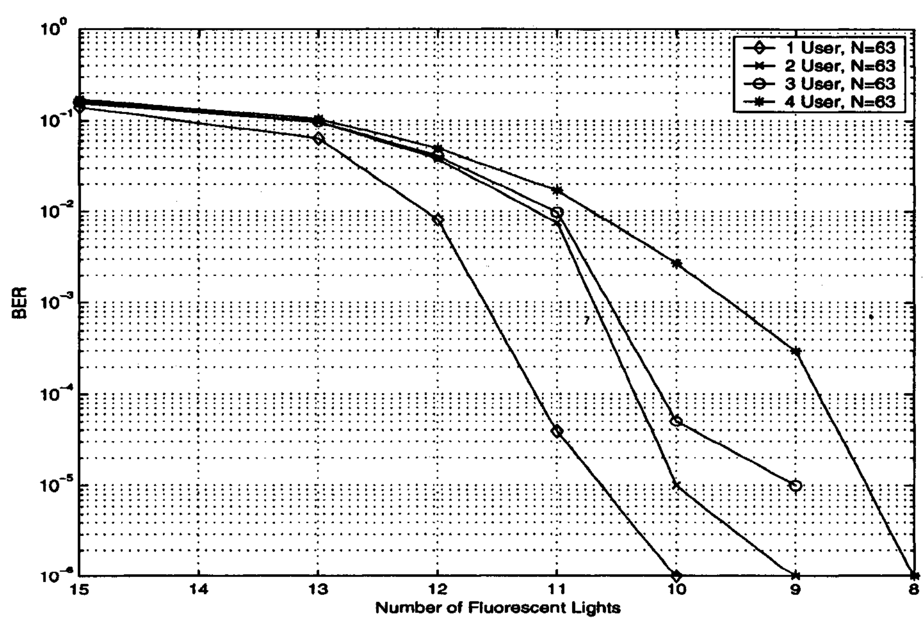

Figure 5.15: BER curve of the IR system with Adaptive Filter, when N=63

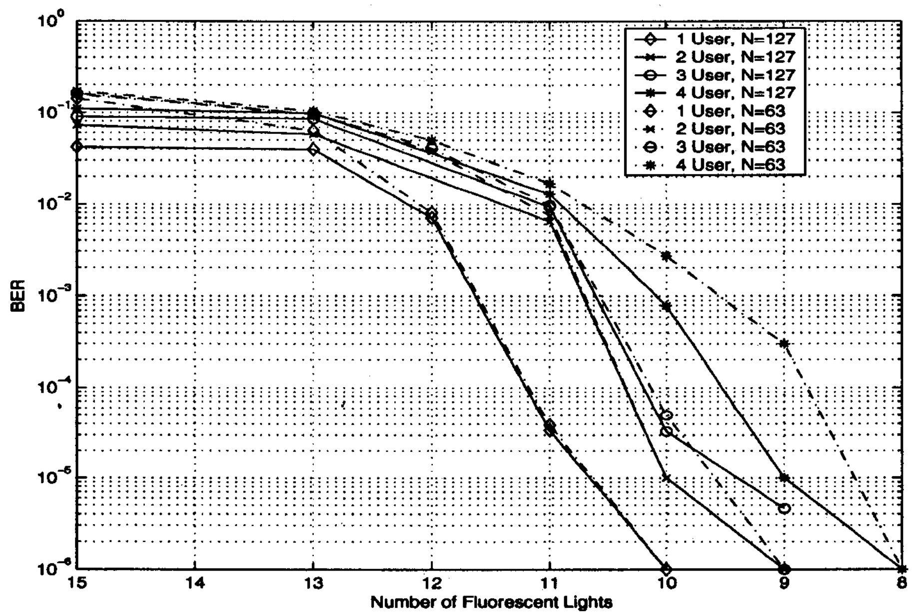

Figure 5.16: Comparison BER curves of the IR system with Adaptive Filter, when N=127 and N=63, $T_c = 5ns$

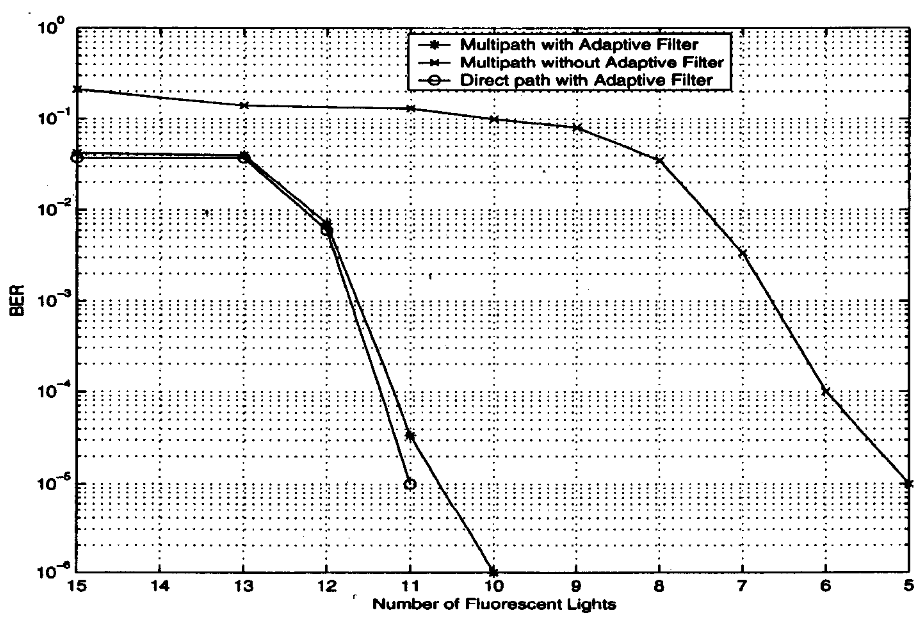

Figure 5.17: BER curve of the IR system ,when N=127

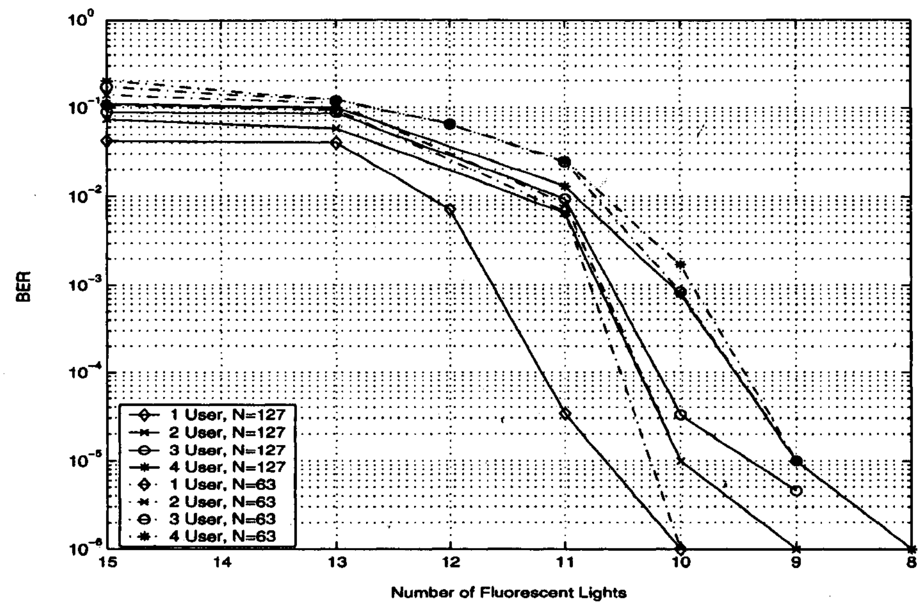

Figure 5.18: Comparison of BER curves of the IR system at equal bit rates

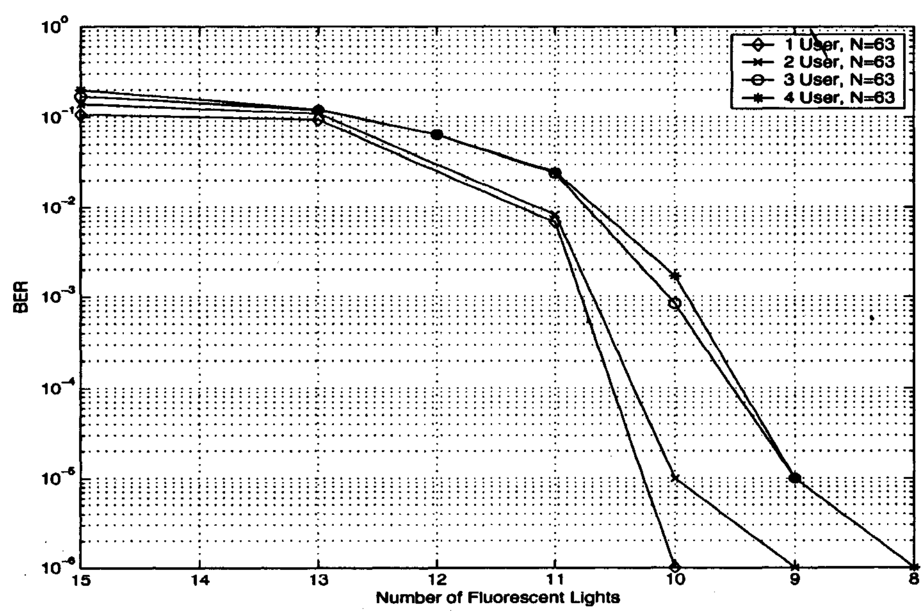

Figure 5.19: BER curve of the IR system ,when N=63, $T_c = 10ns$

Chapter 6

Summary and Future work

6.1 Summary

Wireless communications based on IR technology become one of the actively expanding area in telecommunications due to rapidly growing demand for high data rate services in indoor environments. Although it has high demand, it's utilization is affected by a number of different impairments such as shot noise due to ambient light, interference caused by ambient light and other users, and multipath dispersion. Hence the problem studied in this thesis facilitates in improving the weakness of the existing system. This thesis illustrates a simulation model of an IR wireless system using MATLAB/SIMULINK software and provides a feasible solution to improve the performance of IR wireless system in the presence of multipath and fluorescent light interferences.

In our work, we have discussed the method for multipath and fluorescent interference cancellation. Chapter 1 explains the motivation for investigating the IR system in detail and the importance for the improvement in the system. Chapter 2 reviews some of the results in IR system. Chapter 3 gives a brief description about system components and how they are taken into account in our analysis. Although different noise components are discussed in this chapter, in this thesis more emphasis is given to multipath and fluorescent interference because they introduce more impairments to the system. In this report we introduced an RLS adaptive filter to the spread spectrum CDMA system in diffuse channel environment. Major focus of this method is to cancel the fluorescent interference that affects the IR wireless system. In the fluorescent interference case, we have introduced two considerations called spectral and spatial for more accurate analysis. Chapter 4 considers the development of equations that represent the performance evaluation at different points in the system. RLS adaptive filter to the spread spectrum CDMA system in diffuse channel environment is utilized to test the simulation model and for mathematical prediction of BER curves at various points in the system. To simply the analysis and for prediction of the BER curves, the Gaussian approximation method was used. This chapter conclude with theoretical BER curves with a number of fluorescent lights. Simulink models and the results are described in Chapter 5. First, the system was analyzed mathematically and found that the BER curves under different conditions using Gaussian approximations. Later the technique was tested in a simulation model and found the BER curves for the same conditions applied in the theoretical analysis. The modelling process has yielded information about the system which helps to define the major constraints and provides better understanding of the interaction between its different elements and environment. The proposed technique in this thesis provides evidence for better performance in terms of cancelling the interference caused by multipath and fluorescent lights.

6.2 Future Work

From the simulation results, We found that the BER was very high with multiple users. In order to mitigate these multi-user interference with less complexity, we need further test the simulation with different adaptive algorithms. Since these IR systems are quasi stationary systems, rather than analyzing the system with stationary adaptive algorithms, analyzing it with non-stationary algorithm might give better results. In addition, we can consider some front end receiver circuits to reduce the effects of those interference. According to our design, the algorithm used for training purposes is RLS. However, in high speed infrared wireless systems the training period should be kept as low as possible in order to improve the performance of the system . Since the Kalman filters are highly applicable to processing via a microprocessor thus it offers advantages to real-time applications. In future analysis we can consider Kalman filters for the interference cancellations. Therefore, more subjective tests and objective measurements need to be done to further improve the performance.

In future work we can consider a single filter which can do both despreading and adaptive filtering at the same time, rather than keeping separate blocks/circuits.

Since the IR system is based on intensity modulation, for spreading and despreading we can use Spatial CDMA in future work. Spatial CDMA is a spread-space processing in CDMA where spatial diversity utilized for spreading/despreading. In a spread space technique, the energy of the information signal is spread over a much larger spatial domain as opposed to spread spectrum technique. In this method, rather than using PN sequence generator in the circuits, we can use two-dimensional code mask consist of pattern for ones and zeros for spreading. The processing gain here is defined as the number of pixels in the mask [32]. Another option to increase the capacity and network flexibility is to use multi wavelength communication technique. Fixed and tunable semiconductor lasers or laser arrays are critical components for the multi wavelength networks. However, this technique increases the complexity in circuit designs and raise the overall cost.

Appendix A

Abbreviations and Acronyms

BER	Bit Error Rate
CDMA	Code Division Multiple Access
DS	Direct Sequence
DSSS	Direct Sequence Spread Spectrum
E/O	Electrical to Optical
EMI	Electro Magnetic Interference
FCC	Federal Commission for Communications
FOV	Field Of View
FIR	Finite Impulse Respone
IEC	International Electrotechnical Commission
IM/DD	Intensity Modulation/ Direct Detection
IR	Infra Red
ISI	Inter Symbol Interference
ISM	Industrial Scientific Medical
IrDA	Infrared Data Association
LAN	Local Area Network
LD	Laser Diode
LED	Light Emitting Diode
LMS	Least Mean Square

LOS	Line Of Sight
OCDMA	Optical Code Division Multiple Access
OOC	Optical Orthogonal Code
OOK	On-Off Keying
PCM	Pulse Code Modulation
PHY	PHYsical Layer
PN	Pseudo-Noise
PPM	Pulse Position Modulation
PSK	Phase Shift Keying
RF	Radio Frequency
RLS	Recursive Least Square
SIK	Sequence Inverse Keying
SINR	Signal to Interference and Noise ratio
SNR	Signal to Noise Ratio
SS	Spread Spectrum
TDMA	Time Division Multiple Access
WDMA	Wavelength Division Multiple Access

Bibliography

[1] Tmothy O'Farrell and Montep kiatweerasakul, " Performance of a spread spectrum infrared transmission system under ambient light interference," *The ninth IEEE international symbosium on indoor and radio communications*, pp. 703-707, 1998.

[2] Xavier N Fernando, "An investigation of indoor wireless infrared CDMA networks," *Master's thesis*, AIT, Thailand 1994.

[3] Jeffery B.Carruthers and Joseph M khan, "Modeling of nondirected wireless infrared channels," *IEEE Transactions on communications*, pp. 1260-1267, October, 1997.

[4] John G Proakis, "Digital communications "4th edition, *Chapters 4 and 5.*

[5] Moreira A.J.C Valadas R.T and De Oliveira Duarte A.M, "Optical interference produced by artificial light," *Wireless networks*, pp. 131-140, Vol. 3, 1997.

[6] Barry J.R, Khan J.M, Audeh M.D, Carruthers, "Non directed infrared links for high capacity wireless LANs," *IEEE personal communications*, pp. 12-25, 2nd quarter, 1994.

[7] Gfeller F.R, and Bapst URS, "Wireless in-house data communication via diffuse infrared radiation," *Proc IEEE*, pp. 1474-1486, November, 1979.

[8] Gerd Keiser, "Optical Fiber Communications "3rd edition, *Chapters 6 and 7.*

[9] Chan H.H, Elmirghani.J.M.H, Cryan.R.A, "Performance Analysis of indoor Infrared wireless networks utilising PPM CDMA," *1996 IEEE International conference on communications*, pp. 1467-1471, 1996.

[10] Sridhar Krishnan, Xavier N Fernando and K Hongbo Sun, "Non-stationary noise cancellation in infrared wireless receivers," *IEEE CCECE'2003, Canadian conference on Electrical and computer Engineering*, Montreal, Canada, pp. 1945-1949, May 5-7 2003.

[11] Kwang-Cheng Chen, "Indoor high speed wireless networks via optical transmission," *IBM Thomas J. Watson Research Center*, pp. 211-215, 1994.

[12] Ryoko Matsuo, Michihito Matsuo, Tomoaki Ohtsuki and Iwao Sasase, "Performance analysis of indoor infrared wireless systems using OOK CDMA on diffuse channels," *1999 IEEE Pacific Rim conference on computers and signal processing*, pp. 30-33, August, 1999.

[13] K.K.Wong and T. O'Farrell, "Biorthogonal Direct-sequence spread spectrum system for Infrared wireless communications," *Proc IEEE*, pp. 933-938, 2000.

[14] J.R.Barry and J.M. Kahn, "Wireless infrared communication," *Kluwer Academic Press, Boston, 1st edition*, pp. 933-938, 1994.

[15] G.W.Marsh and J.M.Kahn, "Performance evaluation of experimental 50-Mb/s diffuse infrared wireless link using on-off keying with decision feedback equalisation," *IEEE Transactions on communications*, pp. 1496-1504, Vol. 44, 1996.

[16] H.Park and J.R.Barry, "Performance of multiple pulse position modulation on multipath channels," *IEE Proceedings-Optoelectronics*, pp. 360-364, Vol. 143, 1996.

[17] P.K.Enge and D.V.Sarwate, "Spread spectrum multiple access performance of orthogonal codes:Linear receivers," *IEEE Transactions on communications*, pp. 1309-1319, Vol. 35, 1987.

[18] M.Chase and K.Pahlavan, "Performance of DS-CDMA over measured indoor radio channels using Random orthogonal codes," *IEEE Trans. Vehicular Tech.*, pp. 617-624, Vol. 42, 1993.

[19] K.K.Wong, T.O'Farrel and M.Kiatweerasakul, "Infrared wireless communication using spread spectrum techniques," *IEE Proceedings-Optoelectronics*, pp. 308-314, Vol. 147, August, 2000.

[20] S.Zahedi, J.A.Salehi and M.Nasiri-Kenari, "A Photon-counting Approach to the Performance Analysis of indoors infrared CDMA Networks," *Proceedings of PIMRC 2000, London, UK.*, pp. 18-21, September, 2000.

[21] S.Zahedi, J.A.Salehi and M.Nasiri-Kenari, "M-ary infrared CDMA for indoors wireless communications," *2001 12th IEEE International symbosium on Indoor and mobile radio communications*, pp. E6-E10, 2001.

[22] Antonio Tavares, R.L.Aguiar, R.Valadas A.Oliveira Duarte, "Advanced Technologies for infrared wireless local area networks," *Third National Telecommunication conference*, Portugal, 2001.

[23] R.Narasimhan, M.D.Audeh and J.M.Kahn, "Effect of electronic-ballast fluorescent lighting on wireless infrared links," *IEE Proc. Optoelectronics*, Vol. 143, December, 1996.

[24] Yuichi Tanaka and Masao Nakagawa, "Optical Parallel transmission with multi-wavelength for high speed communications on indoor channels," *IEICE Trans.Commun*, Vol. E81-B, April, 1998.

[25] J.M.H. Elmirghani and R.A. Cryan, "Indoor Infrared wireless networks utilising PPM CDMA," *Conference Proceeding Singapore ICCS'94*, pp. 334-337, 1994.

[26] Tang A.P, Kahn J.M and Ho K.P, "Wireless infrared communication links using multi-beam transmitters and imaging receivers," *1996 IEEE International conference on communications*, pp. 180-186, June, 1996.

[27] Carruthers J.B and Kahn J.M, "Multiple subcarrier modulation for non-directed wireless infrared communications," *IEEE Journel on Sel. Areas in communications*, pp. 538-546, Vol. 14, 1996.

[28] Malik D. Audeh and Joseph M. Kahn, "Performance Evaluation of Baseband OOK for wireless indoor infrared LAN's operating at 100Mb/s," *IEEE Transactions on communications*, pp. 2085-2094, Vol. 43, June, 1995.

[29] P.P.Smyth et al, "Optical wireless local area networks- enabling technologies," *Bt Technol*, pp. 56-64, Vol. 11, 1993.

[30] "IEEE, IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications," *Institute of Electrical and Electronics Engineers, inc., New York*, November, 1997.

[31] Theodore S. Rappaport, "Wireless Communications," *Prentice Hall,Appendix E, Gausion approximations for spread spectrum CDMA* , 2002.

[32] Mohammad Abtahi and Jawad A. Salehi, "Spread-Space Holographic CDMA Technique: Basic analysis and applications," *IEEE Transactions on wireless communications* , pp. 311-321, Vol. 1, 2002.

[33] Simon Haykin, "Adaptive Fliter Theory Fourth Edition," *Prentice Hall, Backgound and Preview I* , 2002.