

## A Photon Counting Approach to the Performance Analysis of Indoors Wireless Infrared CDMA Networks

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### ABSTRACT

Indoors wireless infrared transmission is severely impaired by ambient noise. In addition, in a multiple user network, since many users share the same physical channel, considerable amount of multi-user interference will also be introduced. In this paper, Infrared CDMA techniques are proposed to combat the effect of ambient and multi-user interference. Our analysis is based on Photon-Counting approach and Bit Error Rate is given versus signal power. The results show that using infrared CDMA techniques, transmission can be performed well below ambient noise power with transmission power that satisfies eye-safety power regulations.

### I. Introduction

There is a general trend towards indoors wireless communication system to replace wired communication systems. This is generally because of growing use of wireless access that allows mobile users to remain in contact with fixed networks. Proposed techniques for this application are both in radio and infrared spectrum. The advantage of radio techniques are due to safe low-power radiation transmission and using coherent detection techniques to maximize the receiver SNR. On the other hand, Infrared techniques are favored when security, cost-effective transmitters and receivers, and vast unregulated frequency band are of concern. However, the single most important issue about the use of infrared in wireless applications is the eye-safety considerations that limits the transmitted power. The severity of power problem is that communication should be operational under quite strong ambient light produced by background sun and skylight, incandescent and fluorescent lamps and other artificial thermal lights. In addition, in a network with multiple users in a room a significant source of interference are other users' signals which can be received with powers comparable to the power of desired signal.

In this paper, the bit error rate performance of an Infrared CDMA wireless system is investigated taking into account the effects of signal's shot noise, ambient light, multi-user interference, photodetector dark current and receiver thermal noise. We assume the use of Optical Orthogonal Codes (OOC) as spreading signature. We also consider only the downlink problem for network analysis, i.e., transmission from base station to receiver. Results of BER versus received signal power or received irradiance are presented. Our analysis is based on photon-counting method that gives the best predictions for BER of an optical communication systems and we avoid the usual Gaussian approximation model of the received signal. However, since evaluating exact probability density function of received signal is quite intractable; we have used the Saddle-Point approximation technique that numerically evaluates BER using characteristic function of the received signals.

Section 2 of this paper describes the signaling format of infrared CDMA techniques and the receiver structure used for our evaluation. Section 3 gives a description of multi-user networking scheme and also presents a modeling for power propagation in diffuse links. In section 4, we present the analysis of BER using Saddle-Point approximation techniques. In section 5, we study a typical example of system performance under typical office conditions. In section 6 advanced ideas on how to increase the bit rate of each user without increasing the bandwidth of the system is briefly discussed. Section 7 concludes this paper.

### II. Infrared CDMA Signaling

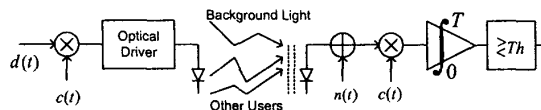


Figure 1: Infrared CDMA Architecture

Figure 1 shows a diagram of a typical wireless, infrared CDMA link. In the transmitter, data bits modulate unipolar bit stream  $d(t)$  with a rate  $R=1/T$  bps. Unipolar OOC signature sequence  $c(t)$  are used to encode the user's bit stream. Each code sequence has a duration  $T$  seconds, which is divided into  $F$  chips each with a duration  $T_c=T/F$ , where  $F$  is defined as the code length or the processing gain of the system. Only  $K$  out of these  $F$  chip positions are marked on, i.e., contain pulses. OOC codes have desirable auto-correlation and cross-correlation properties [1]. Number of available OOC codes with minimum auto and cross-correlation equal to one is limited to  $(F-1)/K(K-1)$ . The output of the multiplier then intensity modulates the instantaneous power of an LED or LD. At the receiver, the desired user's infrared signal as well as multi-user interference and background noise is detected using a photodetector and will be converted into an electrical current signal. Dark current noise of the photodetector as well as Gaussian circuit noise will be added to the output current of the photodetector. Correlation of the incoming signal is achieved by multiplying the received signal with the exact replica of the unipolar signature sequence  $c(t)$ , and then integrating over a bit period. After sampling the output of the correlator at  $t=T$ , the sampled value will be compared against an essentially non-zero threshold level and decision is made on the transmitted bit. This threshold value, as will be seen, is strongly dependent on background ambient noise power and mean interference power and should be automatically tuned at each condition to achieve the best possible performance. Receiver can measure the required parameters at chip positions where no OOC pulse is expected to estimate the required threshold.

### III. Multi-User Networking Scheme

Like many other studies of multiple-access problem, we only investigate high-speed downlink problem and we assume that uplink operation of links produce no interference on received signal [2]. For example, downlink and uplink are time division duplexed or uplink operations are performed on another wavelength out of the range of receiver's optical band pass filter.

It is usually desired to perform all communications in a room using only a single base station. However, since there is a high path loss in diffuse infrared channels, a single base station may not be sufficient for the coverage of an entire area of a large room. Under such a condition, we partition the area of a room to theoretically non-overlapping cells, and then service to the receivers in each cell will be assigned to the base station in that specific cell site. Figure 2 shows such a cellular scheme in which every cluster has 3 cells. We assign to each of these base stations a signature sequence, i.e. an OOC code, that will be used to transmit bits to the intended user.

Multiple user interference problem arises from the fact that a receiver not only receives signal from its intended base station, but also from other base stations which send signal to the receivers in their corresponding geographical areas. The power level of interference could be quite high. For example, assume a receiver is placed at the vertex of a cell namely cell zero. It can be easily seen that the average received power from intended base station and two adjacent interfering base stations are the same. Vertex of a cell is considered to be the worst location in each cell regarding signal to interference ratio, since received signal is at its weakest where received interference is at its strongest level.

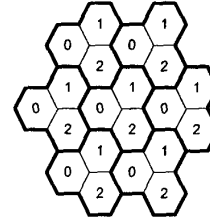


Figure 2: Cellular Structure. Ideally, each base station supports only one user.

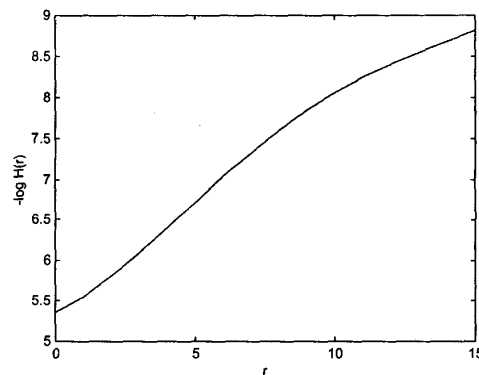


Figure 3: Optical Path loss versus horizontal distance of transmitter and receiver

The model for power loss in a diffuse infrared link is in general a function of horizontal distance between the transmitter and the receiver pair and has been shown in Figure 3 [2]. For our purpose, we have obtained a polynomial approximation to the model given in [2] and it is as follows:

$$\begin{aligned}
 -10 \log_{10} H(r) = & \\
 & 5.3555 + 0.15595r + 0.041271256r^2 \\
 & - 0.00408814r^3 + 0.000112978r^4 \quad r \leq 15m \quad (1)
 \end{aligned}$$

where  $r$  is the horizontal separation of transmitter and receiver and  $H(r)$  is optical path gain of the link.

#### IV. BER Performance Analysis

Ambient light sources are the main noise sources in an indoor infrared communication. Modeling of various ambient light sources is presented in [3]. The main effects of ambient light induced current noise is a shot noise associated with a steady background irradiance and a deterministic signal associated with time variations of irradiance of artificial illuminating devices. The latter is usually a modulating signal with frequency components ranging from 50Hz-1MHz depending on the type of illuminating devices. In practical implementations, this signal is usually filtered out using electrical high-pass filtering and there is no power penalty associated with this type of interference. The main noise source is then therefore shot-noise induced background light and in this paper, we will consider it as an optical signal with irradiance  $I_b(W/Cm^2)$ . We also assume the use of a photodetector with area  $A_d(Cm^2)$  and quantum efficiency  $\eta$ . Therefore, photodetector responsivity can be expressed as  $R = \eta e / hf (A/W)$  where  $e$  is electronic charge,  $h = 6.6 \times 10^{-34} \text{ Jule/Hz}$  is Plank's constant and  $f$  is the center frequency of optical carrier. Hence, a background light associated mean photon count  $m_b = RA_d I_b T_c / e$  in photodetector will be produced.

We denote by  $I_s(W/Cm^2)$  to be the irradiance of the signal per mark chip. Therefore, signal associated mean photon count per mark chip can be expressed by  $m_s = RA_d I_s T_c / e$ . In the proposed Infrared CDMA system,  $I_s$  can be related to the average optical received power using:

$$P_r = \frac{KI_s A_d}{2F} = \frac{KR_b m_s e}{2R} \quad (W) \quad (2)$$

Dark current noise of the photodetector can be modeled as a Poisson process with mean count  $m_d$  per chip time. If mean dark current of the photodetector is  $i_d(A)$ , then  $m_d = i_d T_c / e$ . We also assume that circuit Gaussian noise has a power spectrum density  $N_0(A^2/Hz)$ . Therefore, variance of the electron count, noise samples can be expressed as  $\sigma_v^2 = N_0 T_c / e^2$ .

We assume there are  $N$  interfering base stations in the system and we denote by  $\rho_i$  to be the horizontal distance of base station  $i, 0 \leq i \leq N$ . We reserve notation  $i=0$  for main base station and therefore base stations  $i \neq 0$  are interfering base stations  $A(\rho_i) = H(\rho_i) / H(\rho_0)$ .

Photon count of the photodetector at each chip time due to signal and background noise is a Laguerre process [4]. However, number of received modes in such systems (temporal and spatial) is much greater than one. In addition, average number of photons associated with each diffraction-limited mode can be shown to be much less than one even for strong ambient lights like direct sun. In fact,

this number can be shown to be  $\eta / (\exp(hf / \kappa T) - 1)$  where  $\kappa$  is Boltzman's constant and  $T$  is temperature in Kelvin. This is well below one even when sun radiation with temperature  $6000^\circ K$  is in field of view of the receiver. Therefore, Laguerre distribution can be well approximated with a Poisson distribution. Mean of this Poisson process when a mark chip is sent is  $m_s + m_b$ , and when no mark chip is sent is  $m_b$ .

Output random variable of the integrator is the summation of a Poisson process with mean  $K(d_0 m_s + m_b + m_d)$ , a Gaussian random variable with variance  $\kappa \sigma_v^2$ , and  $N$  other random variables each associated with photon count interference of the interfering base stations.  $d_0$  is the transmitted data bit by main base station and it can take on two values namely 1 or 0 for OOK with equal probability. Each interfering base station, contributes an interfering pulse with probability  $K^2 / 2F$  [1]. If the interfering base station  $i$  has contributed an interfering pulse, then photon count associated with it, is a Poisson random variable with mean  $m_s A(\rho_i)$ . All these random variables are independent. Probability density function of the output criteria is the convolution of the probability density functions of these random variables and is quite intractable. However, since it is the summation of a series of independent random variables, its characteristic function is the product of the characteristic functions of the contributing random variables. Therefore, characteristic function of the output criteria assuming bit  $d_0 \in \{0,1\}$  is transmitted can be written as:

$$\Phi_d(s) = \exp \left\{ K(d_0 m_s + m_b + m_d)(e^s - 1) + \frac{\kappa s^2 \sigma_v^2}{2} \right\} \prod_{i=1}^N \left( 1 - \frac{K^2}{2F} + \frac{K^2}{2F} \exp(m_s A(\rho_i)(e^s - 1)) \right) \quad (3)$$

In formula (3), we have assumed that other user's signal are chip-synchronous with the desired base station. Although this case can not be implemented in real conditions, but this pessimistic model puts an upper bound on the BER of the actual chip-asynchronous systems. Bit Error Probability assuming a threshold value  $Th$  can be expressed as:

$$P_e = \frac{1}{2} \{q_+(Th) + q_-(Th)\}$$

where  $q_+(Th) = \Pr(r > Th | a = 0)$ ,  $q_-(Th) = \Pr(r < Th | a = 1)$ . We define a new function  $\psi_d(s) = \ln(\Phi_d(s)e^{-sTh}/s)$ . We denote positive root of  $\psi'_0(s) = 0$  as  $s_0$  and negative root of  $\psi'_1(s) = 0$  as  $s_1$ . Saddle-Point approximation techniques [5] states that,

$$q_+(Th) \approx \frac{\exp[\psi_0(s_0)]}{\sqrt{2\pi\psi''_0(s_0)}}, \quad q_-(Th) \approx \frac{\exp[\psi_1(s_1)]}{\sqrt{2\pi\psi''_1(s_1)}}$$

### V. A Typical Example

In this section we present an example with typical values and show the efficiency of CDMA Infrared techniques. In the cellular scheme presented, the minimum number of cells per cluster is three and therefore we need at least three codes. We choose optical orthogonal codes with weight  $K=9$  and therefore minimum acceptable value of code length is  $F=217$  [2]. Suppose that bit rate of each base station is  $2Mbps$ . We assume the use of a photodetector with  $A_d=0.1Cm^2$  and quantum efficiency  $\eta=0.77$ . At wavelength  $\lambda=850nm$ , photodetector responsivity  $R$  becomes  $0.53\mu A/\mu W$ . We also assume that dark current of photodetector is  $160nA$ . Using a developed unexposed film as a long-pass filter can greatly reduce the background noise induced in the system, however our analysis does not depend on the use of such a filter. We assume the use of a low-noise transimpedance receiver with equivalent input current noise density of  $0.793pA/\sqrt{Hz}$ . In Figure 4, we have drawn the BER versus received irradiance for several values of background irradiance. Direct sunlight without optical long-pass filtering produces irradiance about  $I_b=10000\mu W/Cm^2$  ( $\approx 4.3\times 10^{16}$  Photons/ $Cm^2.sec$ ) and about 5 times weaker with optical filtering. Indirect sunlight in a room with two windows produces a background ambient irradiance up to  $I_b=2000\mu W/Cm^2$  without optical filter and about 4 times weaker with optical filtering. A  $60W$  incandescent lamp in 1m will produce an irradiance of only about  $I_b=200\mu W/Cm^2$  and a  $36W$  Fluorescent lamp will produce irradiance about  $I_b=100\mu W/Cm^2$  without optical filtering and about 20 times weaker with optical filtering. (See for example [3] for background light measurements). IrDA standards states that receivers should operate in background irradiance of about  $490\mu W/Cm^2$ . It can be seen that at background irradiance level of  $490\mu W/Cm^2$  ( $\approx 2.1\times 10^{15}$  Photons/ $Cm^2.sec$ ), received irradiance of  $4\mu W/Cm^2$  ( $\approx 1.7\times 10^{13}$  Photons/ $Cm^2.sec$ ) is adequate to maintain BER below  $10^{-9}$ . Figure 5 also shows BER versus transmitted power. In background light of  $490\mu W/Cm^2$ , transmitter power of  $25mW$  which in terms of photon emission rate is equivalent to approximately  $1.1\times 10^{17}$  Photons/sec and transmits  $1.2\times 10^{10}$  photons per "On" chip, is adequate to maintain BER below  $10^{-9}$ .

It can be seen that required power to achieve a reasonable BER is below  $250mW$  and therefore the diffuse sources considered for this application satisfy eye-safety power criteria set by IrDA[2]. We have assumed cells with radius 4m and the receiver is placed at the vertex of a cell. It should be noted that BER in figures 4 and 5 is obtained based on optimum threshold setting in each background condition, therefore the system should tune its threshold value depending on the position of transmitter and background power it receives. We have mentioned an alternative in section 6 that removes the need for threshold adjustment in addition to higher bit rate.

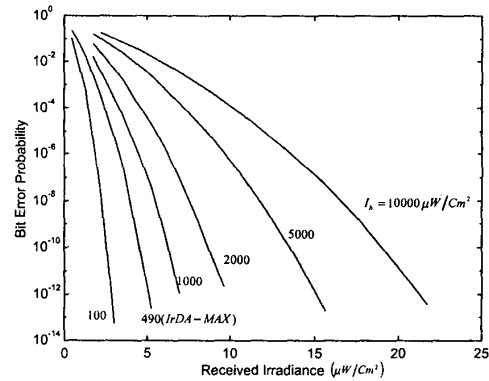


Figure 4: Dependence of BER on received Irradiance for several values of background irradiance  $I_b$ . Note that  $I_b=490\mu W/Cm^2$  corresponds to IrDA Standards [6].

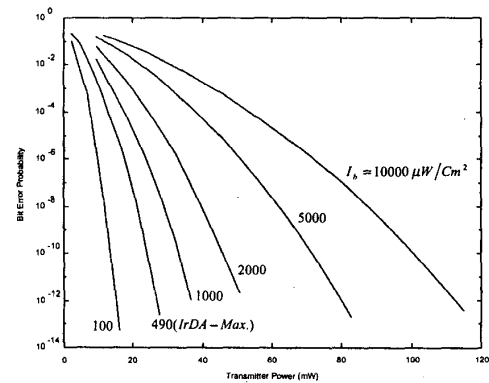


Figure 5: Dependence of BER on transmitted power for several values of background irradiance  $I_b$ .

### VI. M-Ary Infrared CDMA

Cyclic properties of optical orthogonal codes make it possible to present some desirable properties. We know that the cyclic shift of an OOC has cross-correlation properties of another code. Therefore, an OOC has minimum cross-correlation with its  $F-1$  cyclic shifts [7][1]. Therefore, as in Figure 6, receiver can consist of up to  $F-1$  correlators matched to the cyclic shifts of OOC assigned to the base station and in each time slot,  $\lfloor \log_2 F \rfloor$  bits can be received. This improvement is achieved while transmitter and receiver bandwidths have been kept fixed. The other advantage of this technique is that there is no need to adjust a threshold value for best performance and optimum receiver should only compare the output of the correlators and decides which sequence of bits has been transmitted. This system is also resistant to low frequency changes in background noise.

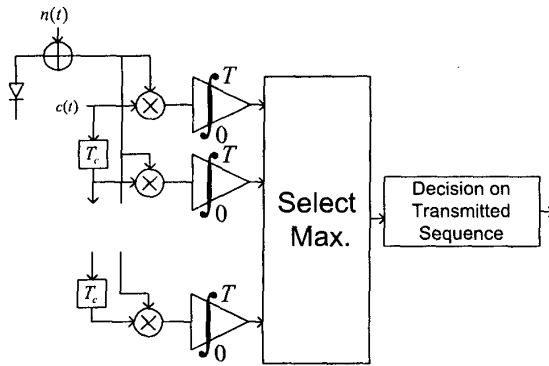


Figure 6: Structure of M-Ary Infrared CDMA Receiver

## VII. Conclusions

In this paper we have investigated the performance of Infrared CDMA techniques under ambient noise. It was shown that Infrared CDMA could achieve acceptable bit error rates under strong ambient noise. Also the effects of dark current and circuit Gaussian noise were considered and it was shown that Infrared CDMA technique with OOC can operate below noise level and can operate with a typical receiver design parameters. We also have suggested the use of M-ary Infrared CDMA to increase throughput of the system and to get rid of threshold adjustment.

## VIII. Acknowledgments

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