M-Ary Infrared CDMA for Indoors Wireless Communications

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***Abstract*-In this paper, we investigate the use of M-Ary Infrared CDMA technique in wireless Infrared networks. It is shown that this method is highly capable in providing the multiple access facility for downlinks of Infrared wireless networks. The results show that the M-Ary CDMA technique, which fully utilizes the properties of Optical Orthogonal Codes, achieves better BER performance in comparison with ordinary Infrared CDMA networks. The main advantages are the reduction in bandwidth, power, and the elimination of threshold-setting at the receiver.**

I. INTRODUCTION

Indoors wireless communication systems have gained a lot of interest because of the mobility option it provides for the network users while providing them with high bit rate. Transmission at both radio and optical frequencies have been proposed for these systems in order to establish wireless links between mobile users and fixed base stations. Several multiple access techniques are presently considered to establish networks of mobile users with access facility to network resources through fixed base stations. The multiple access technique should make it possible for a receiver to detect the signal transmitted by its intended base station among signals transmitted by interfering base stations operating at adjacent coverage areas.

One of the main concerns in indoors wireless networks that incorporate optical links is the transmitted power due to eye-safety considerations. Each base station should produce minimum power while keeping signal to noise and signal to interference ratios in an acceptable level for reliable detection. In reference [1], it has been shown that Infrared CDMA using OOC as spreading sequence can establish communication with power levels 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 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 the effect of multipath distortion.

In this paper, we propose the use of M-Ary CDMA for the downlink of indoors wireless infrared systems. We obtain the performance of the proposed M-Ary system and compare it with the ordinary On-Off Keying Infrared CDMA technique as described in [1]. We will show that using M-Ary CDMA, communication can be performed at higher bit rates while keeping the bandwidth fixed or at lower power levels while keeping the bit rate fixed. Analysis is based on photon counting techniques and all major noise sources, i.e., ambient induced noise, dark-current noise and receiver thermal noise and multi-user interference are considered. We use Saddle-Point approximation method to evaluate numerically the BER using characteristic function of the received signals.

Section 2 of this paper describes the multi-user networking problem and presents a simplified modeling for power propagation. Section 3 gives a description of Infrared CDMA and M-Ary CDMA signaling formats. In section 4, we present the BER analysis and section 5 concludes the results by a numerical example.

II. DOWN-LINK MULTI USER NETWORKING

Diffuse infrared links are the most robust link configuration in wireless infrared networks [2]. However, it has the most severe path loss among optical link configurations. A particular model for the path loss of diffuse infrared links is given by measurement in [3] and a polynomial approximation to the model is presented in [1] and is as follows:

$$\begin{aligned} -10\log H(\rho) = 5.3555 + .15595\rho + .04127\rho^2 \\ - .004088\rho^3 + .00011129\rho^4 \end{aligned} \tag{1}$$

where ρ is the horizontal separation of transmitter and receiver and $H(\rho)$ is the power gain of the optical link (inverse of power loss).

It is usually desirable to perform all communication tasks in a room by a single base station. However, because of the high path loss of the system, the required power to provide signal coverage to the entire area of a large room may become much greater than the maximum allowed power level. Marsh and Kahn have suggested the use of a cellular scheme to provide coverage to the entire area of large rooms with the use of multiple base stations [3]. Theoretically, the area of a large room is divided into non-overlapping cell areas and each cell area is served by a base station located at the

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center of the cell, and coverage to receivers in that cell is provided through diffuse infrared links. However, because of Lambertian like pattern of diffuse sources, each receiver not only receives signal from its intended base station, but also from all other base stations in that room. The received interference can be quite strong and the total interference power can even be stronger than the original signal power. For example, consider a receiver that is placed at the vertex of a cell, i.e., the common point between three cells. The amount of received interference is at least twice the original signal power for such a receiver. Therefore, the receiver should be able to operate on signal to interference ratio levels of less than one.

From the signal to interference point of view the worst location in each cell is the vertex of the cell, i.e., the place where the weakest signal and the strongest interference is received. Therefore, BER for the receiver placed in the vertex will place an upper bound on the BER of the system. We denote by R the radius of the cell and will assume that the receiver is placed at the vertex of the cell and denote by ρ_i the horizontal distance of i'th interferer to the receiver and will indicate their associated path losses with $H(\rho_i)$. We also denote $A(\rho_i) = H(\rho_i)/H(R)$ the relative interference power.

III. INFRARED CDMA SIGNALING SCHEMES

In this paper, we have used OOC as spreading sequence. Unipolar OOC signature sequence $c(t)$ is a periodic sequence with period $T = T_c F$ where F is the code length or the processing gain and T_c is the chip time. Only K out of these F chip positions of each OOC are occupied by pulses. Each set of OOC sequences satisfy two properties, i.e., auto-correlation property that means each cyclic shifted version of a code has at most one .overlapping pulse position with original code, and the second, cross-correlation property that means each code and its cyclic shifted versions have at most one overlapping pulse position with a given code [4].

The block diagram of an ordinary Infrared CDMA receiver is shown in Fig.1. The structure uses the cross-correlation property to distinguish its signal from the received interference [1]. However, using both Auto-Correlation and Cross-Correlation properties simultaneously can have great advantages over ordinary Infrared CDMA systems. Fig.2. shows the block diagram of an M-Ary infrared CDMA receiver that uses both properties of OOC. The transmitter sends the original OOC or one of its $F'-1$ cyclic shifted versions where $\log_2 F' = \lfloor \log_2 F \rfloor$. The receiver is formed of F' correlators matched to different cyclic shifts of the given OOC. The most important advantage of this signaling method is that by transmission of each cyclically shifted OOC sequence, $\log_2 F'$ bits can be transmitted and therefore the systemís bit rate can be increased while keeping the chip rate fixed or the systemís chip rate can be decreased while keeping the bit rate fixed in comparison with ordinary Infrared CDMA system. The second most important advantage of this method in comparison with ordinary Infrared CDMA system is that it doesnít need a threshold setting mechanism at the receiver. 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, for example when the position of the receiver changes. Although the structure of M-Ary CDMA receiver is much more complicated than ordinary Infrared CDMA receivers, but since it is the repetition of a simple structure, it can be easily implemented using VLSI technology. Considering the extra circuitry required to estimate the optimum threshold value in ordinary Infrared CDMA receiver, M-Ary Infrared CDMA receiver may prove to become more feasible.

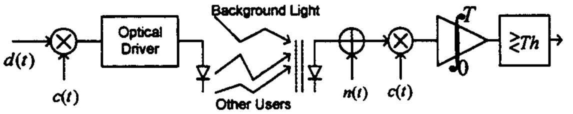

Fig.1. Infrared CDMA Architecture (Ordinary On-Off Keying)

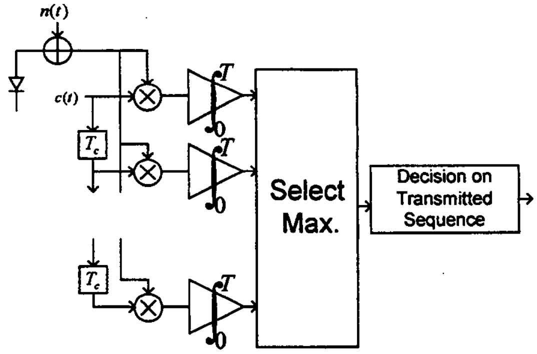

Fig.2. M-Ary Infrared CDMA Receiver Structure

IV. PERFORMANCE ANALYSIS

The main source of noise in Infrared systems is ambient-light induced shot noise. The irradiance of background light is denoted here by $I_b(W/Cm^2)$. We assume the use of a photodetector with area $A_d(Cm^2)$ and quantum efficiency η and responsivity $R = \eta e/hf\,(A/W)$ where e is electronic charge, $h = 6.6\times10^{-34}(Jule/Hz)$ and f is the center frequency of optical carrier which is usually on the order of $3.3\times10^{14}Hz$ for infrared frequencies. An ambient light photon counter will enumerate an average number of $m_b = RA_d I_b T_c/e$ in a T_c counting interval and the exact number of enumerated photons is a Poisson random variable.

We assume that the irradiance of the received signal is $I_r(W/Cm^2)$ for an ìOnî chip time. Therefore, mean photoelectron count in the receiver would be $m_r = RA_d I_r T_c / e$ and again the enumerated photons have a Poisson distribution. If the mean of dark current of the photodetector is $i_d(A)$, then $m_d = i_d T_c / e$ and it will again have a Poisson distribution. 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 $\sigma_n^2 = N_0 T_c / e^2$.

A. *Ordinary Infrared CDMA Method Using OOC*

In an ordinary Infrared CDMA system, receiver forms a random variable U and compares it against a threshold value and decides about the transmitted bit. Random variable U can be expressed as:

$$U = n_r + n_b + n_d + n_t + \sum_{i=1}^{M} n_i \tag{2}$$

where n_r is the signal dependent photon count with a Poisson distribution and mean Km_r if the transmitted bit is *one* or mean zero if the transmitted bit is *zero*, n_b is the background light induced photon count with a Poisson distribution with mean Km_b and, n_d is the dark current electron count with Poisson distribution and mean Km_d and n_t is a Gaussian random variable with zero mean and variance $K\sigma_n^2$. M is the total number of interfering base stations and n_i is the amount of interference from the i'th base station and is a conditionally Poisson random variable. Due to properties of OOC, an interfering base station can interfere at most in one pulse position with probability $K^2/2F$ where in such a case n_i will be a Poisson random variable with mean $m_r A(\rho_i)$, otherwise, it will be a zero mean Poisson random variable. It should be noted that we have assumed the system to be under chip-synchronous assumption which places an upper bound on the performance of the On-Off Keying Infrared CDMA system [4].

If transmitted bit is denoted by d_0, the characteristic function of the random variable U can be expressed as:

$$\Phi_U(s) = \exp\left\{K(d_0 m_r + m_b + m_d)(e^s - 1) + \frac{Ks^2\sigma_n^2}{2}\right\}$$
$$\prod_{i=1}^{M}\left(1 - \frac{K^2}{2F} + \frac{K^2}{2F}\exp\left(m_r A(\rho_i)(e^s - 1)\right)\right) \tag{3}$$

B. *M-Ary Infrared CDMA System Using OOC*

This receiver forms F' random variables where U_j is the output of j'th correlator and can be expressed as:

$$U_j = n_{rj} + n_{bj} + n_{dj} + n_{tj} + \sum_{i=0}^{M} n_{ij} \tag{4}$$

Note that starting index of i is set at ìzeroî contrary to (2) where starting index of i is set at ìoneî. Statistical properties of random variables n_{rj}, n_{bj}, n_{dj} and n_{tj} is the same as for ordinary Infrared CDMA system. However, the statistical properties of random variables n_{ij} vary greatly. First, note that the intended base station may produce interference to the output of correlators not matched to the specific shifted version of OOC transmitted in that special sequence period. This interference is limited to one pulse and therefore, random variable n_{0j} has a characteristic function,

$$\Phi_{0j}(s) = 1 - \frac{K^2}{2F} + \frac{K^2}{2F}\exp\left(m_r A(R)(e^s - 1)\right) \tag{5}$$

In contrast with ordinary Infrared CDMA systems using OOC where number of interference pulses of each user is limited to ìoneî, interference of each interfering base station is limited to ìtwoî pulses in M-Ary CDMA systems. Each sequence period may overlap with two sequences of an interfering base station and each of these sequences may produce up to one interfering pulse at the correlator. (See Fig.3) Therefore, characteristic function of random variables n_{ij} for $i \neq 0$ can be shown to be as,

$$\Phi_{ij}(s) = p + q\exp\left(m_r A(\rho_i)(e^s - 1)\right) + r\exp\left(2m_r A(\rho_i)(e^s - 1)\right) \tag{6}$$

In order to calculate the probabilities p, q and r, i.e., the probability that i'th interferer produce ìzeroî, ìoneî or ìtwoî interfering pulses we first note that $p + q + r = 1$. Fig. 3 helps to give an idea on how to calculate the values of p, q and r. We assume that there is a time mismatch of X_i between received signal of original and interfering base stations and assume it has a uniform distribution over a sequence period. Again let us assume that system is chip-synchronous and therefore X_i can take on values of $0, 1, \ldots, F-1$ with equal probabilities.

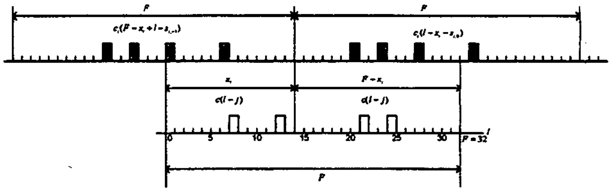

Fig. 3. Interference parameters in M-Ary CDMA

Assuming a time mismatch of x_i, the event of two hits occurs when each part of the code overlaps with one of the consecutive sequences. The probability of overlap of one pulse of the first part of the code with the first interfering sequence can be expressed as $(Kx_i/F)^2/x_i$ assuming that pulses are uniformly distributed in the OOC sequence [4][6]. The probability of the overlap of the second part can be similarly expressed as $(K(F - x_i)/F)^2/(F - x_i)$. Therefore, averaging over x_i, r can be expressed as below,

$$r = \sum_{x_i=0}^{F-1}\frac{1}{F}\left[\left(\frac{Kx_i}{F}\right)^2\frac{1}{x_i}\times\left(\frac{K(F - x_i)}{F}\right)^2\frac{1}{F - x_i}\right] = \frac{K^4(F^2 - 1)}{6F^4} \tag{7}$$

Now the probability of one hit, i.e., q can be expressed as,

$$q=\sum_{x_i=0}^{F-1}\frac{1}{F}\left[\left(\frac{Kx_i}{F}\right)^2\frac{1}{x_i}+\left(\frac{K(F-x_i)}{F}\right)^2\frac{1}{F-x_i}\right]-r=\frac{K^2}{F}-r \qquad (8)$$

and therefore $p=1-K^2/F$. Using these values, characteristic function of random variable n_{ij} can be calculated using (6).

We now calculate the bit error probability of M-Ary Infrared CDMA system using (6). First, we note that if P_{se} is the sequence error probability, i.e., the probability that a sequence is incorrectly detected, it can be related to bit error probability by $P_e = F'P_{se}/2(F'-1)$. We first calculate symbol correct probability P_{sc} and then relate that to symbol error probability by $P_{sc}=1-P_{se}$. If we denote k as the index of the transmitted sequence and s_{im} as the index of m'th symbol of i'th base station, the probability that symbol k is correctly detected can be expressed as,

$$P_{sc}=\Pr\{\forall j\neq k, U_j<U_k \mid s_{00}=k\}\cong\left[\Pr(U_j<U_k \mid s_{00}=k)\right]^{F'-1} \qquad (9)$$

where,

$$\Pr(U_j<U_k \mid s_{00}=k)=1-\Pr\{Z<0\} \qquad (10)$$

and random variable Z can be expressed as,

$$Z=\left(n_{rk}+n_{bk}+n_{dk}+n_{tk}+\sum_{i=1}^{M}n_{ik}\right)-\left(n_{bj}+n_{dj}+n_{tj}+\sum_{i=0}^{M}n_{ij}\right) \qquad (11)$$

Characteristic function of random variable Z can be obtained and is as follows;

$$\begin{aligned}\Phi_Z(s)=\exp\{&Km_r(e^s-1)+2K(m_b+m_d)(\cosh s-1)+Ks^2\sigma_n^2\}\\&\times\prod_{i=1}^{M}\Phi_{ik}(s)\prod_{i=0}^{M}\Phi_{ij}(-s)\end{aligned} \qquad (12)$$

C. *Saddle-Point Approximation Technique*

In order to numerically evaluate the BER we use Saddle-Point Approximation technique and define two new functions $\psi_0(s)$ and $\psi_1(s)$ as follows,

$$\psi_0(s)=\ln\left(\Phi_{U|d=0}(s)e^{-s.Th}/s\right), \psi_1(s)=\ln\left(\Phi_{U|d=1}(s)e^{-s.Th}/s\right) \qquad (13)$$

We denote positive root of $\psi_0'(s)=0$ as s_0 and negative root of $\psi_1'(s)=0$ as s_1. Using Saddle-Point Approximation technique, BER can be evaluated using the following equations [5]:

$$\begin{aligned}\Pr(U>Th \mid d_0=0)&\approx\frac{\exp[\psi_0(s_0)]}{\sqrt{2\pi\psi_0(s_0)}}\\ \Pr(U<Th \mid d_0=1)&\approx\frac{\exp[\psi_1(s_1)]}{\sqrt{2\pi\psi_1(s_1)}}\end{aligned} \qquad (14)$$

V. NUMERICAL RESULTS AND CONCLUSIONS

In this section, we present an example with typical values and compare the aforementioned systems. We assume the use of OOC with code length $F=217$ and weight $K=9$. The code weight $K=9$ is a reasonable value to establish multiple access and the code length $F=217$ is the minimum required code length to be able to generate three OOCs [4]. Three codes are the minimum required number of codes in a cellular CDMA network [3].

We assume the use of a photodetector with quantum efficiency $\eta=0.77$ and area $A_d=0.1Cm^2$ working at wavelength $\lambda=850nm$ with responsivity $R=0.53\mu A/\mu W$ and dark current $i_d=160nA$ [1]. We assume that receiver circuitry add a white Gaussian noise with input equivalent density $0.793\,pA/\sqrt{Hz}$ due to thermal effects.

Although, background light irradiance can be as strong as $I_b=10000\mu W/Cm^2$ (equivalently 4.3×10^{16} Photons$/Cm^2$.sec) due to direct sunlight without optical filtering in the field of view of the receiver, but the IrDA standard places the limit of $I_b=490\mu W/Cm^2$ (equivalently 2.1×10^{15} Photons$/Cm^2$.sec) on the background light for the operation of an infrared receiver. This amount of background light is the equivalent of direct sun in the field of view of the receiver with a developed unexposed film as a long-pass optical filter.

We assume a cellular structure with radius $R=4m$ and assume that receiver is placed at the vertex of the cell. We also assume that bit rate of each transmitter is $R_b=2Mbps$. We assume that interference is only received from six nearest neighbors and received interference power from other transmitters is negligible. BER for such a set of parameters is shown in Fig. 4. IrDA standard restricts the average power level of diffuse infrared transmitters to $250mW$ [3], therefore, both methods can operate at acceptable and eye-safe power levels. It can be seen that M-Ary Infrared CDMA system performance is better than ordinary Infrared CDMA system for a given bit rate while using a bandwidth of seven times less than ordinary Infrared CDMA system.

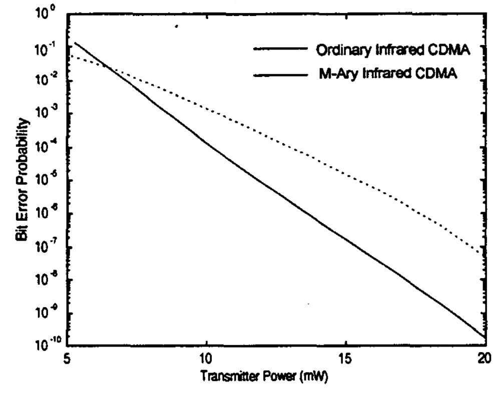

Fig.4. BER comparison vs. transmitter average power

In Fig. 5, we compare the two systems while using a fixed bandwidth of $300MHz$ which is equivalent to the inverse of time duration of the shortest pulse that can be used in the system. However, we have removed the restrictions on code length and at each bit rate, each system uses the highest possible code length so that it could fully utilize the available bandwidth. It can be easily seen that M-Ary Infrared CDMA method uses the available bandwidth much more efficient ly than ordinary (On-Off) Infrared CDMA.

These two figures indicate that M-Ary Infrared CDMA method has a superior performance over ordinary Infrared CDMA systems. This method offers flexibility in design of system and system parameters. Also there is no need to set and adjust a threshold value and therefore the receiver structure could prove to be much simpler than ordinary Infrared CDMA receiver.

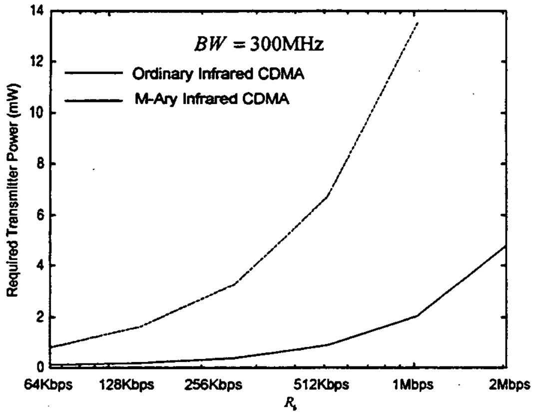

Fig.5. Transmitter Power Required to Achieve BER 10^{-9}, $M = 6, K = 9$

However, there are several considerations on the use of M-Ary Infrared CDMA for practical indoor systems. The most important problem arises from the fact that indoor channel is a multi-path channel.

It can be intuitively said that the system performance will be acceptable when the maximum delay spread of the system is much less than chip time of the system. Impulse response of the channel will also produce imperfections to the system performance by injecting part of the power of the transmitted sequence to the output of adjacent correlators matched to nearby shifts of the code. Therefore, it is recommended to use only the shifted versions of the original code with a minimum distance greater than Root-Mean-Square delay spread of the channel.

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