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Performance Enhancement of Indoor Wireless Infrared CDMA System Based on ZCC Code and Multiple Cell Configurations

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Abstract

Objectives: The aim of this paper is to develop an indoor wireless infrared CDMA system based on Zero Cross Correlation (ZCC) code to minimize the effect of noises, and thus improves the overall performance. **Methods/ analysis**: Two different configurations of 1-cell and 4-cell are investigated. A mathematical framework to calculate the SNR and the BER under the effect of total noise such as LED shot noise, ambient light shot noise and thermal noise, is derived. The system performance is analysed in terms of SNR and BER, versus the width and length of the room, and number of users, respectively, and then compared with the system based on a Flexible Cross Correlation (FCC) code. **Findings**: The indoor infrared CDMA based on 4-cell configuration using the ZCC code showed better performance than the system based on 1-cell configuration or using the FCC code. As results, the 4-cell configuration based on ZCC could accommodate a larger number of users rate at the corners and edges of the room. It offered 42% and 150% larger cardinality at the edges, and the corners of the room respectively, compared to the 1-cell configuration. In addition, this system also offered 55%, 47%, 51% larger cardinality at the centre, the edges, and the corners of the room, respectively, in contrast to the FCC code. **Application/Improvement:** The proposed 4-cell configuration based on ZCC code for indoor wireless infrared CDMA system enhances the cardinality, and offers an excellent degree of mobility.

Keywords: FCC Code, Indoor Wireless, Infrared, Multiple Cell Configuratuions, OCDMA, ZCC Code

1. Introduction

Wireless communication systems have been considered as an attractive and alternative method that offers mobility and flexibility for users. Wireless systems can be implemented by using both method Radio Frequency (RF) and Infrared (Ir) radiation. RF is used in most of the current wireless communication systems. This has made the RF spectrum crowded and limited its capacity to accommodate new high bit rate[1]. At the same time, the need for significant bandwidth, high speed links, low price components, has led to the development of Infrared Wireless Communication (IrWC) systems. In fact, within the radio range, limited bandwidth up to tens of MHz can be provided by the carriers, whereas infrared signals can be extended to several orders of magnitude[2].

Infrared light that hits opaque objects such as walls cannot travel through it and therefore, prevents adjacent rooms from mutual interference. This permits numerous IrWC systems, operate in various rooms of a substantial building without any interference. Moreover, IrWC systems are not sensitive to induced Electromagnetic Interference (EMI), and therefore they are a most excellent choice for environments that experience EMI, for example, factories and health care centres[3]. In addition, IrWC receivers are also impregnable to interference resulting from radio-waves devices which include electrical and radio wave communication devices. However,

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cost-effective and energy-efficient are always an attractive area for researchers, thus LED-based communication was widely attracted attention in constructing such system[4].

Regardless of the advantages, infrared systems are subjected to several interferences, such as shadowing, background noise, multi-path dispersion and Inter-Symbol Interference (ISI)[5,6]. Furthermore, systems employing simultaneous multiple users are suffering from Multiple Access Interference (MAI) and Phase-Induced Intensity Noise (PIIN), which significantly deteriorate the Bit Error Rate (BER) performance[7]. Thus, Optical Code Division Multiple Access (OCDMA) technology has attracted much attention in infrared wireless networks, due to its fairness, flexibility, cost-effective nature, simplified network control and management, service differentiation, and increased inherent security[8,9]. Moreover, it permits multiple users to share the same the infrared medium simultaneously, by assigning unique code to each user. Whereas a unique code set is defined as it possesses minimum length, maximum weight, high autocorrelation and low cross-correlation function.

There are a lot of codes, have been constructed based on the above criteria. For instance, Modified Double Weight (MDW) codes have been generated based on double weight code, in order to minimize the effect of PIIN and improve the performance of BER[10]. However, MDW codes require very long code sequences, to accommodate a large number of users with hamming weight greater than four. Flexible Cross Correlation (FCC) codes are considered to reduce the code length, suppress the effect of phase intensity noise, and then enhance the Signal-to-Noise Ratio (SNR)[11]. Most of the existing codes considered the PIIN noise, in addition to shot noise and thermal noise, but Zero Cross Correlation (ZCC) codes are designed with no overlapping of bit ‘1’ between users; therefore, they eliminate PIIN, thus minimize MAI due to its ZCC properties[12].

In this paper, we develop an indoor IrWC system with 1-cell and 4-cell configurations[13], based on CDMA technology, and using ZCC code. The SNR and BER analysis for the proposed system with multiple users in an indoor Ir channel was performed and compared with FCC code. The effects of the parameters such as ambient light, room configuration and receiver position were considered.

This paper is structured as follows. In Section 2, the IrWC system configuration and channel model is described. Section 3 describes the performance analysis and Section 4 shows the results and discussion. Finally, the conclusion is given in the Section 5.

2. System Description

2.1 IrWC System Configuration

IrWC links can be classified into different link schemes according to two criteria: (a) the existence of an immediate direction connecting the transmitter and receiver, and (b) the receiver’s Field Of View (FOV) and transmitter’s beam directionality[14,15]. The focus of this paper is on Non-Directed Line Of Sight (NdLOS) links. NdLOS link does not need an exact alignment between the transmitter and receiver. Because it presents a larger coverage area and an extremely good mobility, which allows users simply roam within the covered zone without losing connection. Additionally, it provides a higher transmission bandwidth, a lesser path loss, and a lower ISI.

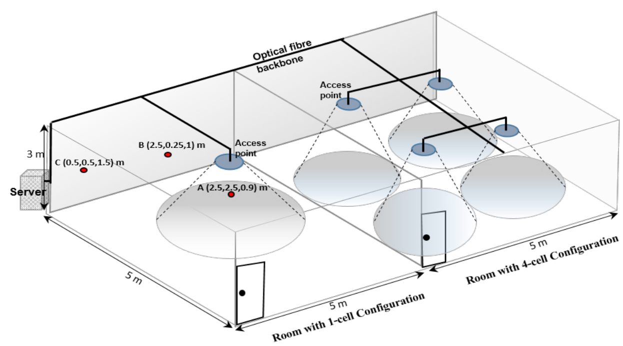

Figure 1. Indoor IrWC system 1-cell and 4-cell configurations.

Two types of cell configurations such as 1-cell and 4-cell of indoor NdLOS - IrWC systems are proposed in this research. The performance of the system is characterized by referring to the SNR and BER for both cell configurations and different receiver’s positions. Figure 1 depicts the proposed typical room having a width of 5 m, a length of 5 m and a height of 3 m. The ceiling is divided according to the number of the proposed cells where all cells have equal dimensions in that particular ceiling. However, the transmitter is located in the centre of ceiling for 1-cell configuration and on the centre of each cell for 4-cell configurations, with FOV directed downward to the ground while the receiver is located at different positions on the floor. Assuming that, the divergence angles and the transmitted optical power are the same for all cells in that particular configuration.

2.2 Infrared Channel Model

The length of an NdLOS link is comparatively short, and therefore, has very low attenuation due to the absorption and scattering. LED emission is mathematically modelled using a generalized Lambertian radiant intensity. The indoor NdLOS link represents the NdLOS path between the transmitter and receiver; and the channel DC gain for a receiver, located at a distance of *D and* angle φ with respect to the transmitter, is given by[2,16,17]:

$$h_{NdLOS} = \begin{cases} \dfrac{m+1}{2\pi D^2} A_R \cos^m(\varphi)\cos(\psi), & 0 \le \psi \le \psi_c \\ 0 & \psi > \psi_c \end{cases} \quad (1)$$

Where D is the direct distance between the transmitter and receiver, A_R is the physical area of the photo-detector, m is the order of Lambertian emission, related to the LED semi-angle at half power, ψ is the reception angle, ψ_c is the width of the receiver's FOV. The total received power resulted from the NdLOS path of the multi-transmitter system can be computed as:

$$P_R = \left(\sum_{l=1}^{\text{LEDnum}} P_t \bullet h_{NdLOS} \right) \bullet T_c(\psi) \bullet T_F(\psi) \quad (2)$$

Where P_t is the optical transmitted power, $T_F(\psi)$ is the transmission coefficient of the optical filter, and $T_C(\psi)$ is the gain of the optical concentrator. The parameters of the room, the transmitter, and the receivers, are listed in Table 1.

Table 1. Simulation parameters I

Parameter		Value
Room dimensions *(x,y,z)*		5x5x3 m^3
Reflection coefficient *(ρ)*		0.8
Position of receiver, *Rx* (*x*, *y*, *z*)		A(2.5,2.5,0.9) B(2.5,0.25,1) C(0.5,0.5,1.5)
Physical area of a photo detector (A_R)		1.0 *cm2*
Field of view (*FOV*)		70 [*deg.*]
Pixel size (Δ*x*, Δ*y*)		0.11x0.11 *m*
Gain of an optical filter (T_F)		1.0
Refractive index of a lens at a photo detector (*n*)		1.5
Elevation		90 [*deg.*]
Azimuth		0.0 [*deg.*]
Cell configurations	Cell size (m)	Launched power per cell (W)
1 -cell	5.0x5.0	1.00
4-cell	2.5x2.5	0.25

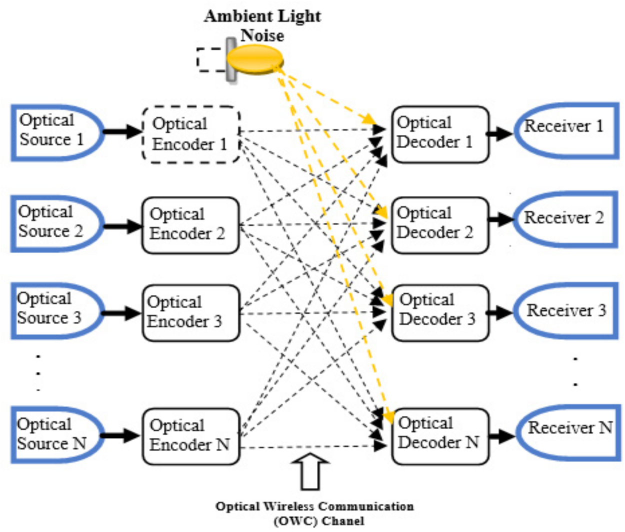

Figure 2. Optical wireless CDMA block diagram.

3. Performance Analysis

As shown in Figure 2, the system comprises of N transmitters and N receivers. An optical ZCC code is first used to encode the information bit for each user, so that many users can share the same LED spectrum. Subsequently, all user signals are multiplexed and wirelessly transmitted at the same time[18]. In order to reduce the ambient light noise in the indoor atmosphere, an optical filter is placed in front of the Photo-Diode (PD) at the receiver side. The transmitted signal will be decoded using the corresponding ZCC code, and then detected by the PD. The data bits will be carried by the ZCC code assigned to each user. These data bits consist of 1 and 0, which respectively represent the availability and absence of the optical pulse. For direct detection technique, the Power Spectral Density (PSD) at the photodiode is given by[19]:

$$P_{rx}(v) = \frac{P_R}{\Delta v} \sum_{k=1}^{K} d_k \sum_{i=1}^{L} c_k(i)\, rect(i) \quad (3)$$

Where P_R is the total received power resulting from the NdLOS channel, Δv is the bandwidth of the broadband source, d_k is a data bit of Kth user, L is the code length, and K is the number of users. The *rect (i)* is equal to u[$\Delta v/L$][20]. So, the *PSD* is given by[12,21]:

$$\int_0^\infty P_{rx}(v)\,dv = \int_0^\infty \left[\frac{P_R}{\Delta v} \sum_{k=1}^{K} d_k \sum_{i=1}^{L} c_x(i)\, c_y(i). \left\{ u\left[\frac{\Delta v}{L} \right] \right\} \right] dv$$

$$= \underbrace{\left(\frac{P_R}{\Delta v}.1.w.\frac{\Delta v}{L} \right)}_{auto-correlation} + \underbrace{\left(\frac{P_R}{\Delta v}.1.0.\frac{\Delta v}{L} \right)}_{cross-correlation}$$

$$= \frac{P_R}{L}.\,w \tag{4}$$

Where c_x and c_y are the two code sequences. Since ZCC code has no cross correlation among users, we will only consider the autocorrelation part. Thus, the total power incident on the photodiode is given by:

$$\left\langle i_{sig}^2 \right\rangle = \Re^2 \int_0^\infty P_{rx}^2(v)\,dv = .\frac{\Re^2 P_R^{\ 2}}{L^2} w^2 \tag{5}$$

where $\Re$ is the photo detector responsively and is calculated as $\Re = \eta q / hv$, with η, q, *and* hv as the quantum efficiency, the electron charge, and the photon energy, respectively.

The total noise power (variance) σ^2_{tot} is given by summing the noise contributions such as thermal noise ($\sigma^2_{thermal}$) and shot noise (σ^2_{shot}). The shot noise variance includes signal-induced noise $\sigma^2_{sig\text{-}shot}$, and background light-induced noise $\sigma^2_{bg\text{-}shot,}$ is given as follows[12,16,22]:

$$\left\langle \sigma_{shot}^2 \right\rangle = \left\langle \sigma_{sig-shot}^2 \right\rangle + \left\langle \sigma_{bg-shot}^2 \right\rangle$$

$$= (2\,q\,G^2 Fe\,B\,i_{sig}) + (2\,q\,G^2 Fe\,I_{bg} I_2 B)$$

$$= (2\,q\,B\,G^2 Fe \frac{\Re\,P_R\,w}{L}) + (2\,q\,G^2 Fe\,I_{bg} I_2 B)$$

$$= 2\,q\,B\,G^2 Fe\,(\frac{\Re\,P_R}{L} w + I_{bg} I_2) \tag{6}$$

In which *Fe* represents the APD excess noise factor, and is given by:

$$Fe = k_{eff} G + (1 - k_{eff})(2 - \frac{1}{G}) \tag{7}$$

where k_{eff} is the APD effective ionization ratio. The total power of the thermal noise is given by:

$$\left\langle \sigma_{thermal}^2 \right\rangle = \frac{4 K_b T B}{R_L} \tag{8}$$

The *SNR* compares an average level of signal power versus an average level of noise power, as given by:

$$SNR = \frac{\left\langle i_{sig}^2 \right\rangle}{\left\langle \sigma_{shot}^2 \right\rangle + \left\langle \sigma_{thermal}^2 \right\rangle}$$

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$$= \frac{G^2 \cdot \left(\dfrac{\Re^2 P_R^{\ 2} w^2}{L^2} \right)}{2\,q\,B\,G^2 Fe(\dfrac{\Re P_R}{L} w + I_{bg} I_2) + \dfrac{4 K_b T B}{R_L}} \tag{9}$$

Since, P_R is as illustrated in Eq. 2, then the final mathematical framework derivation of the *SNR* is summarized by:

$$SNR = \frac{\dfrac{\Re^2 \cdot G^2 \cdot w^2 \left[\left(\sum_{l=1}^{LEDnum} P_t \bullet h_{NdLOS} \right) \bullet T_c(\psi) \bullet T_F(\psi) \right]^2}{L^2}}{2\,q \cdot B \cdot G^2 \cdot Fe \cdot \left(\dfrac{\Re \cdot w \cdot \left[\left(\sum_{l=1}^{LEDnum} P_t \bullet h_{NdLOS} \right) \bullet T_c(\psi) \bullet T_F(\psi) \right]}{L} + I_{bg} I_2 \right) + \dfrac{4 K_b \cdot T \cdot B}{R_L}} \tag{10}$$

where w is the code weight, G is the APD internal gain, B is the electrical bandwidth, K_b is the Boltzmann's constant, I_2 is the noise bandwidth factors, R_L is the load resistor, and I_{bg} is the photocurrent due to background radiation (e.g. fluorescent lamps). The parameters listed in Table 2 are used in the numerical analysis.

$$BER = 0.5 * erfc\left(\sqrt{\frac{SNR}{8}} \right) \tag{11}$$

where $erfc(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$

4. Results and Discussion

This section provides the numerical analysis of the IrWC system based on SAC-OCDMA and ZCC code in comparison with the FCC code for 1-cell and 4-cell configurations of the proposed room using MATLAB software. The quality of the signal can be expressed by

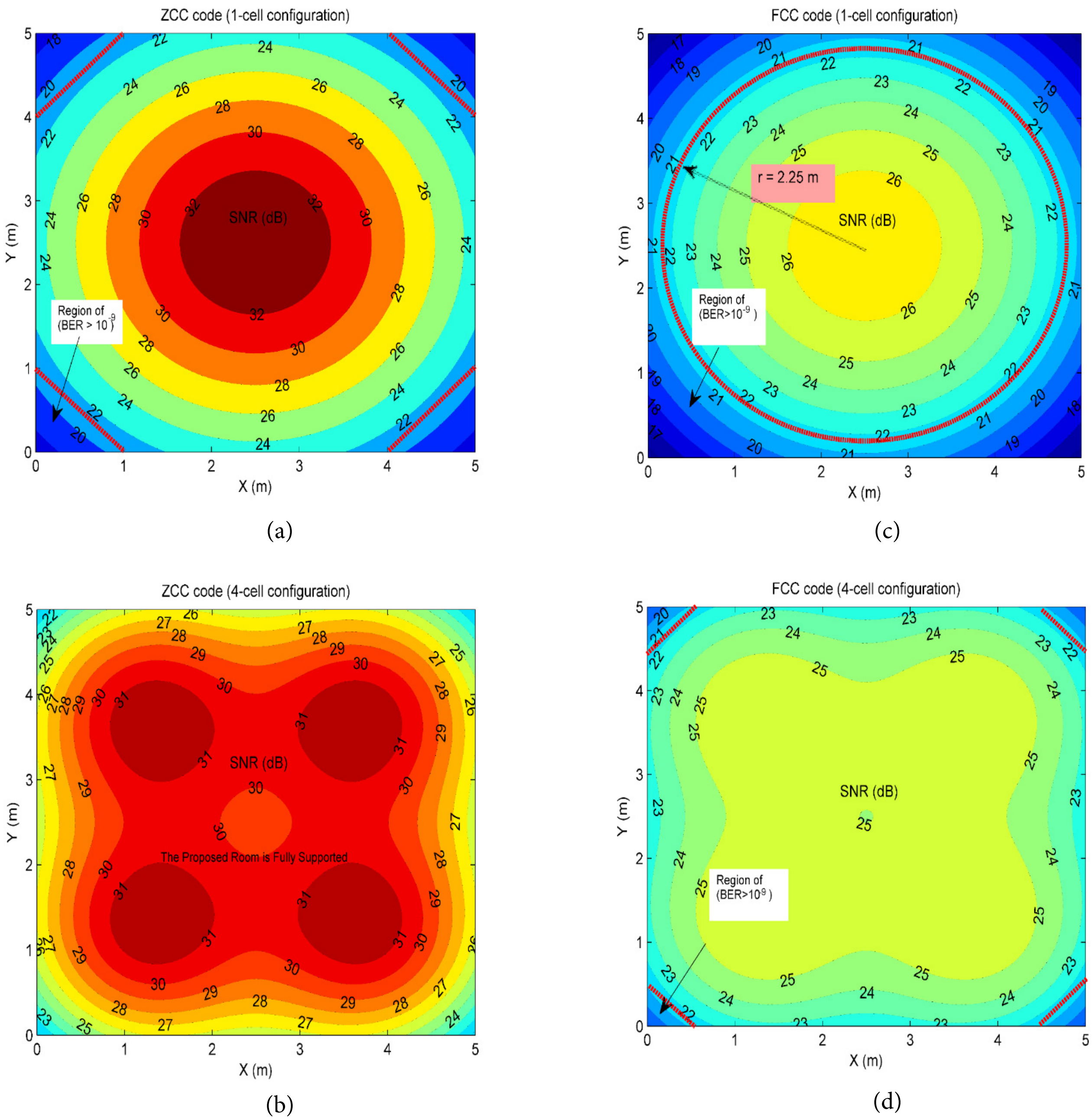

Figure 3. SNR distribution versus width and length of the room for 1-cell and 4-cell configurations, the receiving plane's height is 0.9 m.

SNR, which is interrelated with the Bit-Error Rate (BER). These two parameters are employed to evaluate the overall performance of the system.

4.1 SNR Distribution of 1-Cell and 4-Cell Configurations

The SNR distribution over the receiving plane for 1-cell and 4-cell configurations using ZCC code is illustrated in Figure 3(a) and Figure 3(b) while Figure 3(c) and Figure 3(d) depict the FCC code. It is shown from these figures, that a significant improvement in performance can be achieved when a 4-cell configuration is utilized compared to the 1-cell. This due to the uniformity of the received power distribution. The SNR of ZCC and FCC codes for the entire receiving plane when 1-cell configuration is employed are 18 dB and 17 dB respectively, which are smaller than the SNR of 21.58 dB, which is required for transmission with a BER < 10^{-9}. In contrast, the 4-cell configuration enhances the SNR performance for the entire receiving plane where the minimum SNR achieved is 22 dB and 20 dB for ZCC and FCC, respectively. In sum, the SNR of the 4-cell configuration using the ZCC code is greater than the required SNR. Therefore, the 4-cell configuration is proven to improve the performance of the indoor OW system. The region that consists of BER > 10^{-9}, is illustrated in Figure 3.

Table 2. Simulation parameters II

Parameters		Values
Operating wavelength (λ_0)		1550 *nm*
Line width broadband source (Δv)		3.75 *THz*
Photo detector quantum efficiency (η)		0.6
Date bit rate (R_b)		622 *Mbps*
Electrical bandwidth (B)		311 *MHz*
Receiver noise temperature (T)		300 *K*
Receiver load resistor (R_L)		1030 Ω
Electron charge (q)		$1.6\text{x}10^{-19}$ *C*
Planck's constant (h)		$6.66\text{x}10^{-34}$ *J.s*
Boltzmann's constant (K)		$1.38\text{x}10^{-23}$ *J/K*
Noise-bandwidth factor (I_2)		0.562
Fluorescent light noise (I_{bg})		2 μA
Detector Type	**Effective Ionization Ratio (*keff*)**	**Typical Gain (*G*)**
APD (InGaAs)	0.45	10

4.2 Variation of BER as a Function of Number of Users for Different Receiver's Positions and Cell Configurations

The BER of 1-cell and 4-cell configurations for the three positions as illustrated in Figure 1, is investigated to evaluate the overall performance of the system. These positions are selected to represent the entire room, whereas position A (2.5, 2.5, 0.9) represents the location of the centre; B (2.5, 0.25, 1) represents the point at the edge; C (0.5, 0.5, 1.5) represents the point at the corner. However, different positions within the room can support different number of users. As shown in Figure 4, a significant improvement in the performance is observed at position B and C when the 4-cell configuration based on the ZCC code is utilized, compared to the 1-cell. The improvement obtained is about 42.4%, 150% at B and C, respectively. The results differ for position A where the 1-cell configuration can support a higher number of users compared to the 4-cell configurations. Because for 1-cell configuration, the distribution of power is concentrated in the centre where position A is located. It is observed that the use of multi-call configurations yields a significant increment in number of users, particularly at the corner, and at the area between the centre and the corner of the room, compared with the case of 1-cell configuration. In other words, the increments in number of users are proportional to the increment in number of cells.

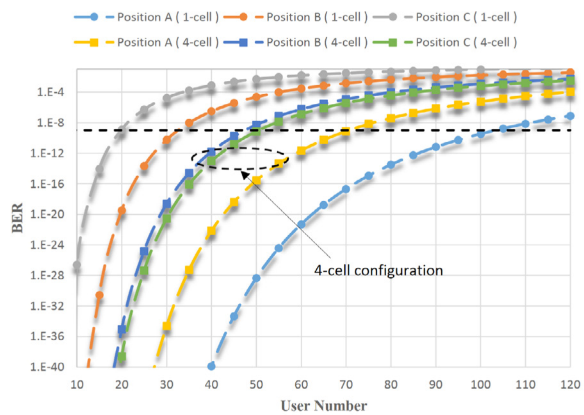

Figure 4. BER versus number of users for 1-cell and 4-cell configurations at different receiver's positions of: A (2.5, 2.5, 0.9), B (2.5, 0.25, 1), C (0.5, 0.5, 1.5). The weight is 4.

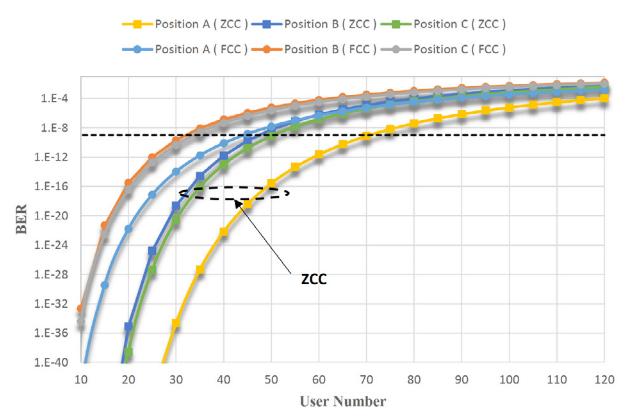

Figure 5. BER versus number of users for 4-cell configuration at different receiver's positions at: A (2.5, 2.5, 0.9), B (2.5, 0.25, 1), C (0.5, 0.5, 1.5). The weight is 4.

In contrast, Figure 5 depicts the variation of BER against the number of active users for the ZCC and FCC codes with the OW-CDMA system when 4-cell configuration is utilized. It can be observed that the performance of the ZCC code for all positions is better compared to the FCC code. The maximum acceptable BER of 10^{-9} is achieved using the ZCC code with 71, 48 and 50 active users compared to 45, 32 and 33 active users achieved by FCC, for position A, B and C respectively. The results show that the ZCC code can accommodate a large number of active users compared to when the FCC code is used.

5. Conclusion

This study has investigated an indoor infrared wireless communication (IrWC) system based on CDMA technology, and using ZCC code. The 1-cell and 4-cell configurations of the room were studied and their performances were compared. The performance degradation is observed in the 1-cell configuration system, due to the non-uniformity of the optical transmitted power. Whereas the maximum and minimum received power are concentrated at the centre and edges of the room, respectively. The SNR and BER analysis for the proposed system based on ZCC code were performed, and then compared with the system based on FCC code. The indoor infrared CDMA based on 4-cell configuration using the ZCC code achieved better performance than the system based on 1-cell configuration or using the FCC code. The effect of various parameters such as ambient light, room configuration and receiver position, were considered.

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