Mobile MC-CDMA Optical wireless System Employing an Adaptive Multibeam Transmitter and Diversity Receivers in a Real Indoor Environment

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Abstract—Multicarrier Code Division Multiple Access (MC-CDMA) combines some of the desirable feature of Orthogonal Frequency Division Multiplexing (OFDM) and CDMA in that it offers multiple access facilities at a reduced channel rate. In this paper, the channel characteristics of mobile infrared links have been modelled in a highly impaired environment in the presence of windows, office cubicles, bookshelves, and shadowing. We introduce an adaptive line strip multibeam system (ALSMS) in conjunction with diversity detection and show that it dramatically improves the SNR performance of infrared links in the presence of very directive noise and shadowing. Our results indicate that, the mobile MC-CDMA ALSMS system with an angle diversity receiver offers a significant performance improvement including a reduction in the background noise (BN) effect, a strong received power, reduction in delay spread, and improvement in the SNR over the mobile MC-CDMA LSMS system in the poor communication environment considered. Furthermore, the OW MC-CDMA system operates at a channel rate lower than that associated with OW CDMA systems and we demonstrate the performance improvement obtained in a real OW environment in the presence of transmitter and receiver mobility.

Keywords—optical wireless; MC-CDMA; bit error rate (BER); adaptive multibeam transmitter; diversity detection

I. INTRODUCTION

In the last decade, the rapid growth of portable wireless devices has created a need for faster communication links [1]-[4]. Optical wireless (OW) transmission offers several potential advantages over radio frequency (RF), including large unregulated bandwidth, immunity to interference caused by other RF wireless devices, possibility of frequency reuse where infrared (IR) does not penetrate walls or opaque objects, and the use of inexpensive optoelectronic devices, such as light-emitting diodes (LEDs) and silicon detectors [1] which are small and consume little power. However, OW communication links have several drawbacks, which include shot noise induced by intense ambient light, transmission power restricted by eye and skin safety regulation, multipath dispersion associated with non-direct line of sight (NLOS), and the need for a backbone network to interconnect OW access points in different rooms since optical signals do not pass through walls [2]-[4]. Furthermore, the need for mobile computing and mobile multimedia communication in general has focused interest on OW where a large bandwidth is potentially available [5].

High data rate in multi-user wireless access is demanded by multimedia applications, which require very high bandwidth with mobility [6], [7]. Code Division Multiple Access (CDMA) is a strong candidate to support multimedia services because it has the ability to cope with the asynchronous nature of multimedia traffic. On off keying-CDMA (OOK-CDMA) offers advantages over OOK with an increased number of channels, but at the cost of reduced data throughput under limited bandwidth [8]. Orthogonal Frequency Division Multiplexing (OFDM) is able to support high data rates without needing channel equalizers as the aggregate throughput is distributed over the set of subcarriers and the symbol rate is reduced. OFDM is a parallel data transmission scheme in which high data rates can be achieved by transmitting N orthogonal subcarriers [9]. Therefore this work proposes for the first time an optical wireless system that combines OFDM signaling with CDMA multi-user capabilities. The application of MC-CDMA in optical wireless is mainly motivated by the need to support high data rate services in a multi-user wireless environment characterized by harsh indoor optical channels. MC-CDMA signals can be efficiently generated and demodulated using Fast Fourier Transform (FFT) devices without substantially increasing the receiver’s complexity. MC-CDMA systems combine the robustness of orthogonal modulation with the flexibility of CDMA schemes [10], [11]. MC-CDMA schemes are categorized into two groups; MC-Direct Sequence-CDMA (MC-DS-CDMA) which spread the signal in the time domain and MC-CDMA which perform the operation in the frequency domain. In both schemes, the different users share the same bandwidth at the same time and separate the data by applying different user specific spreading codes, i.e., the separation of the user’s signals is carried out in the code domain. Moreover, both schemes apply multicarrier modulation to reduce the symbol rate and, thus, the amount of ISI per subchannel. This ISI reduction is significant in spread spectrum systems where high chip rates occur. In [12], Hara and Prasad have shown
that MC-CDMA outperforms MC-DS-CDMA in terms of downlink BER performance. Therefore, the high spectral efficiency and the low receiver complexity of MC-CDMA make it a good candidate for the downlink of a wireless system. In this paper, we consider the mobility of OW MC-CDMA systems and introduce a new adaptive technique (for multibeam transmit power adjustment) and diversity detection in a harsh environment, which is typically encountered in real office configurations where optical signal blockage (owing to cubicles), windows, doors, furniture, ambient light noise, and multipath propagation all exist. Mobile users experience a time varying channel which results in weak coverage in certain zones/parts of the room as the user moves. The most important issue that an OW MC-CDMA system designer must take into account is the amount of received power which varies with the distance between the transmitter and the receiver. Due to this fact, an adaptive multibeam transmitter is employed to increase the amount of received power at a given receiver location as well as reducing the performance degradation due to user mobility. In effect the transmitter in an adaptive multi-beam system assigns higher powers to beams nearest to the receiver, so as to maximize the receiver SNR. Therefore, we model a mobile adaptive OW MC-CDMA system; an adaptive line strip spot-diffusing (ALSMS) system in conjunction with an angle diversity receiver of seven branches, for a real office environment that consists of windows, a door, minicubicles, bookshelves, and other objects. For comparison purposes a mobile LSMS MC-CDMA system with an angle diversity receiver of seven branches is considered for two room scenarios: an empty room, and a real office environment. Moreover, consideration is also given to the other elements of the real indoor environment namely ambient light noise and multipath dispersion, and the performance is evaluated. The rest of the paper is organized as follows: Section II gives a description of the mobile OW system model. Mobile adaptive multibeam transmitter system configuration; ALSMS is discussed in details in Section III. Section IV describes the OW MC-CDMA system model. Performance analysis of OW MC-CDMA system is carried out in Section V. Theoretical and simulation results are given in Section VI. Finally, conclusions are drawn in Section VII.

II. OW SYSTEM MODEL

For OW links, the most viable method is to employ intensity modulation (IM), in which the instantaneous power of the optical carrier is modulated by the signal. The receiver makes use of direct detection (DD), where a photodetector generates a current, which is proportional to the instantaneous received optical power. The OW channel using IM/DD may be modeled as a baseband linear system which can be characterized by

\[ I(t, Az, El) = \sum_{l=1}^{L} R s(t) \otimes h(l, Az, El) + \sum_{l=1}^{L} n_l(t, Az, El) \]  

where \( I(t, Az, El) \) is the received instantaneous current in the photodetector at certain position due to \( l \) reflection elements, \( t \) is the absolute time, \( Az \) and \( El \) are the directions of arrival in azimuth and elevation (angle), \( L \) is the total number of receiving elements, \( s(t) \) is the transmitted instantaneous optical power, \( \otimes \) denotes convolution, \( R = 0.5 A/W \) is the photodetector responsivity, and \( n(t) \) is the background noise, which is modeled as white and Gaussian, and independent of the received signal. The major sources of background noise in an indoor environment include daylight, incandescent light (for example, halogen and tungsten filament lamps), and fluorescent light sources. These sources emit a substantial amount of power within the wavelength range of silicon photodetectors, as well as introducing shot noise, and can saturate the photodetector when their intensity is high [13]. Although ambient light can be much stronger than the transmitted data signal, certain measures (such as optical filters) can be used to minimize its influence. In order to investigate the effects of diffuse transmission on indoor mobile OW systems, simulations were developed using an example 8 m × 4 m room having a ceiling of 3 m for two different room configurations denoted as A and B. Figure 1 shows Room B that has three large glass windows, a door, a number of rectangular-shaped cubicles with surfaces parallel to the room walls, and other furniture such as bookshelves and filing cabinets. The walls and ceiling, in Room A, have a diffuse reflectivity of 0.8, while the floor has a 0.3 diffuse reflectivity. The glass widows and door in Room B are expected not to reflect any signal hence their diffuse reflectivities are set to zero. In Room B, the walls surrounding widows and the ceiling have a diffuse reflectivity of about 0.8, while floor has a 0.3 diffuse reflectivity, two walls (except the door) of Room B are covered with bookshelves and filing cabinets with a diffuse reflectivity of 0.4. It is assumed that signals, which reach the cubical office partitions, are either absorbed or blocked. Furthermore, several tables and chairs within the CF area are placed in the room with the same floor diffuse reflectivity. The complexity is clearly seen in Room B where physical partitions and low reflectivity objects result in the worst reception environment where shadowing is created. Previous research work has shown that plaster walls reflect light rays in a form close to a Lambertian function [1]. Therefore, reflective elements were modeled as Lambertian reflectors. In order to simulate the proposed system under mobility, the transmitter was placed at three different locations on the CF (2m, 4m, 1m), (1m, 1m, 1m), and (2m, 7m, 1m). For each transmitter location, computations were carried out for 14 different receiver positions on the CF. Moreover, in order to assess the system’s mobility performance as well as examine the advantages of having an adaptive multibeam transmitter with an angle diversity receiver, eight halogen spotlights, which result in one of the most stringent optical spectral corruption to the received data stream, have been chosen. ‘Philips PAR 38 Economic’ (PAR38) was investigated. PAR38 emits a power of about 65 W in a narrow beamwidth which is modeled as a generalized Lambertian...
radiant intensity with order n = 33.1 (based on experimental measurement), which corresponds to a semi-angle of 11.70°. The eight spotlights were equidistantly placed in the ceiling at coordinates (X, Y, Z) = (1, 1, 3), (1, 3, 3), (1, 5, 3), (1, 7, 3), (3, 1, 3), (3, 3, 3), (3, 5, 3), and (3, 7, 3). Furthermore, in order to combat background noise as well as multipath dispersion, a diversity receiver is an appropriate choice, where significant performance improvements can be achieved by receiving signal from different spatial orientation and using appropriate combining techniques. The receiver diversity system considered consists of seven photodetector branches. Each face bears a certain direction that can be defined by two angles: azimuth (Az) and elevation (El) angles. While the El of six photodetectors remains at 20°, the seventh one faces up with El of 90°, and the Az for the seven branches of the receiver are fixed at 0°, 55°, 90°, 125°, 235°, 270°, and 305°, and the corresponding field-of-views (FOVs) were restricted to 12°, 30°, 30°, 25°, 25°, and 30° respectively. The Az, El, and FOVs were chosen through an optimization [4] to achieve the best SNR considering the transmitter locations as well as the system motion. The angle diversity receiver is designed so that at least five diffusing spots are always positioned within the receiver FOV, providing a robust link against diffusing spot blockage and achieving the best SNR considering the transmitter positions as well as the system motion. The performance under mobile adaptive multibeam transmitter configurations was evaluated and compared at different receiver location on the CF.

III. MOBILE ADAPTIVE SYSTEM CONFIGURATION

The most important issue that an OW system designer must take into account is the amount of received power which varies with the distance between the transmitter and the receiver. Due to this fact, a possible technique that can increase the received power, decrease multipath dispersion, and reduce the performance degradation due to user motion as well as improving the system performance at the least successful receiver positions is an adaptive technique. In contrast to previous work in [5], [14], where the multibeam transmitter distributes the total power, 1W, on diffusing spots in equal intensities, in this system the adaptive multibeam transmitter distributes the total power so as to optimize the receiver SNR. In effect the spots nearest to the receiver are allocated the highest power level, while the farthest spot is assigned the lowest power level, so as to maximize the receiver SNR. The new adaptive algorithm adjusts the transmit powers of the individual beams as follows:

1. Distribute the total power, 1W, on the spots in equal intensities.
2. Switch on each spot individually, compute the power received at the diversity receiver as well as calculate SNR. In a practical implementation, circuits can be designed with an appropriate MAC protocol to compute the SNR.
3. Send a control feedback signal at low rate to inform the transmitter of the SNR associated with the beam (spot).
4. Repeat steps 2 and 3 for all the spots.
5. Distribute the total power on the spots according to the SNR they produce at the receiver, where a spot that produces maximum SNR gets the highest power level.

In this work we extend the treatment presented in [14] by introducing transmit power adaptation implemented on the beam (spot) powers and considering user mobility. The results demonstrate that significant performance (SNR) improvement can be obtained. To help visualise the mobile ALSMS configuration for Room A, Figs. 2(a), and (b) show the mobile ALSMS configurations at three different transmitter positions on the CF (2m, 4m, 1m), (1m, 1m, 1m), and (2m, 7m, 1m). The multibeam transmitter is assumed to produce 80×1 beams aimed at the ceiling with different intensities, and to form a line of diffusing spots in the middle of the ceiling at x = 2m and along the y-axis. The difference in distance between adjacent spots is 10cm when the transmitter is at the centre of the room. These spots become secondary distributed emitters which emit Lambertian radiation. ALSMS at the room centre is used to compute the beam angles associated with the diffusing spots. The computation calculations were carried out, following the procedure in [5] and the new spot locations are determined based on the beam angles and transmitter location. The transmit powers associated with the beams are adjusted according to the algorithm given earlier in this section. Several parameters are of interest such as channel impulse response, signal-to-noise ratio (SNR), and root-mean-square (rms) delay spread (D) given by

\[ D = \sqrt{\frac{\sum (t - \mu)^2 h^2(t)}{\sum h^2(t)}}, \quad \text{where} \quad \mu = \frac{\sum h^2(t)}{h^2(t)} \]  \hspace{1cm} (2)

where \( t \) is the time delay associated with the received optical power \( h(t) \) and \( \mu \) is the mean delay. The discretization is the result of dividing the reflecting surfaces into small elements. Since the positions of the transmitter, receiver, and the reflecting elements are fixed, the received optical power and the delay spread would be considered as deterministic for given transmitter and receiver locations.

Fig. 3 compares the delay spread distribution of three mobile OW systems with an angle diversity receiver for the two room scenarios (Room A and B); LSMS for Room A, ALSMS and ALSMS for Room B, when the transmitter is placed at three different positions (2m, 4m, 1m), (1m, 1m, 1m), and (2m, 7m, 1m), and the receiver moves at constant x = 1m, and along the y-axis over the CF. It can be seen that the LSMS for Room B has a lower delay spread compared to the LSMS for Room A when the transmitter is placed at (1m, 1m, 1m) due to the limit range of rays captured by the receiver. This is a result of the fact that some rays are blocked by opaque objects, and some spots, which fall on the glass windows (according to the transmitter location) are lost. Note that the reduction in delay spread here is accompanied by a reduction in collected power and therefore SNR is a better measure of performance. Moreover, the delay spread of the mobile LSMS increases, as the receiver moves away from the transmitter, for Room A and B, and reaches almost 6 ns and 5.3 ns respectively at one of the least successful locations when the transmitter is placed at (2m, 7m, 1m) and the receiver is at (1m, 1m, 1m). Our
results indicate that a significant reduction in the delay spread distribution is achieved by utilizing an adaptive mobile multibeam transmitter for Room B which represents a shadowed environment. This is due to assigning the majority of the transmitted power to the spots nearest to the receiver. Degradation in the delay spread performance of the mobile OW system, due to user mobility, is improved by employing the adaptive multibeam transmitter configuration in conjunction with diversity detection at all transmitter and receiver locations in the worst reception environment where shadowing is created.

Fig. 4 illustrates the detected SNR of the previous mobile OW systems when the transmitter is placed at three different positions, and the receiver moves at constant x = 1m, and along the y-axis over the CF. The results show that the SNR is maximum at the positions when the transmitter and receiver are nearest each other, and degrades as the receiver moves away from the transmitter. Performance degradation in the mobile LSMS OW system is observed due to the reduction in the total received power as a result of shadowing in Room B, which represents a poor communication environment for all transmitter and receiver locations. Furthermore, a significant performance improvement in the mobile LSMS OW system is achieved by using the adaptive multibeam transmitter configuration with an angle diversity receiver in the poor communication environment (Room B). About 13 dB performance improvement is obtained at the least successful positions of the shadowed room when the transmitter is placed at (1m, 1m, 1m) and the receiver is at (2m, 7m, 1m) when the ALSMS replaces LSMS. Note that LSMS outperforms the conventional diffuse systems (CDS) and the conventional hybrid system (CHS) [14]. The adaptive technique demonstrates a significant reduction in the performance degradation due to user mobility, optical signals blockage based on the presence of windows, office cubicles, and bookshelves in the environment considered. This is due to the fact that ALSMS is more robust against shadowing owing to allocating higher power levels to the spots nearest to the receiver and thus enhancing the LOS components wherever present.

![Figure 1: ALSMS mobile configuration; (a) transmitter is placed at the room centre (2m, 4m, 1m) and (b) transmitter is placed at two locations (1m, 1m, 1m) and (2m, 7m, 1m).](image1)

![Figure 3: Delay spread distribution of two mobile OW system; LSMS and ALSMS, dot-dashed lines represent the LSMS for Room A, and solid lines represent the LSMS for Room B, and dotted lines represent the ALSMS for Room B, when the transmitter is placed at three different positions and the receiver is at constant x = 1m and along the y-axis.](image3)

![Figure 4: SNR of two mobile OW system; LSMS and ALSMS, dot-dashed lines represent the LSMS for Room A, and solid lines represent the LSMS for Room B, and dotted lines represent the ALSMS for Room B, when the transmitter is placed at three different positions and the receiver is at constant x = 1m and along the y-axis.](image4)

IV. OW MC-CDMA SYSTEM MODEL

The OW MC-CDMA system employs N subcarriers and each user transmits M bits during a signaling interval, leading to the spreading factor (the processing gain), \( N_s = N \).

Fig. 5 shows the transmitter of the OW MC-CDMA system for user \( k \) with binary phase shift keying (BPSK) modulation. In the transmitter, the \( m^k \) th input information bit \( b_{mk} \) of user \( k \) is copied and fed to \( N \) branches (corresponding to the number

![Figure 5: Real environment office (Room B) that has three large glass windows, a door, a number of rectangular-shaped cubicles with surfaces parallel to the room walls, and other furniture such as bookshelves and filing cabinets.](image5)
of sub-carriers). Each branch is multiplied by one chip of the spreading code \( c_i^k \) \( (i = 0, 1, \ldots, N - 1) \) of user \( k \) with length \( N \) and chip duration, \( T_c \), where \( t \) denotes the \( t^{th} \) branch, then it is modulated on a subcarrier separated from its neighboring subcarrier by \( 1/T_b \). These signals can be efficiently modulated and demodulated using Fast Fourier Transform (FFT) devices without substantially increasing the receiver’s complexity. FFT implementation was highlighted, but this can lead to complex implementation as the imaginary part has to be handled. In a practical implementation, two oscillators can be used to operate the modulation and demodulation processes, one to generate the real part and the other with a 90° phase shift to generate the imaginary part. The MC-CDMA symbol can drive directly the light source after adding an appropriate DC offset to avoid negative values. The transmitted signal corresponding to the \( m^{th} \) data bit of user \( k \) is written as

\[
s^k(t) = \sum_{n=0}^{N-1} \sqrt{P} b_n^k c_n^k (1 + \cos(2\pi f_d t)) \cdot p(t - mT_b)
\]  

(3)

where \( P \) represents the electrical transmitted power of the data bit, \( N \) is the number of subcarriers as well as the spreading gain, \( b_n^k \) is the \( m^{th} \) data bit of user \( k \), and is assumed to be a random variable taking values of -1 or 1 with equal probability, \( c_n^k \) is the \( n^{th} \) chip of the spreading code, \( c^k = [c_0^k, c_1^k, \ldots, c_{N-1}^k]^T \) assigned to user \( k \), which is also assumed to be a random variable taking values of -1 or 1 with equal probability, \( f_d = n/T_b \) with \( n = 0, 1, \ldots, N - 1 \) are the subcarrier frequencies, and \( p(t) \) is a rectangular pulse defined over \([0, T_p]\). The signal \( s^k(t) \) is proportional to the electrical current which in turn is proportional to the transmitted optical power. If the laser transfer characteristics are assumed to be ideal, then \( s^k(t) \) can be used to represent the transmitted optical power. An exact analysis will have to consider the laser transfer characteristics which are not included here. In this MC-CDMA system the subcarrier frequencies are chosen to be orthogonal to each other. When the number of subcarriers increases, the MC-CDMA symbol duration \( T_s = NT_c \) becomes large compared to the duration of the impulse response \( \tau_{\text{max}} \) of the channel, and the amount of ISI reduces. This transmitted signal \( s^k(t) \) is distorted by channel response and corrupted by noise (channel noise and preamplifier thermal noise). The overall noise process is modeled as zero-mean additive white Gaussian noise (AWGN) with two-sided power spectral density \( N_0/2 \).

The receiver model of the OW MC-CDMA system for user \( k \) is shown in Fig. 6. In the receiver, the received signal is copied and fed to \( N \) branches. Each branch is demodulated and multiplied by one chip of the spreading code, and then the branches are summed up and integrated. Finally, the original data may be recovered. The received signal can be written as

\[
y(t) = \sum_{k=0}^{N-1} \sum_{m=0}^{K-1} P \sum_{n=0}^{N-1} R \beta_n^k 0^k_n \left[ d_n^k t_{m}^l + d_n^k R_{m,n}^l \right] + n(t)
\]  

(4)

where \( \beta_n^k \) is the \( n^{th} \) sub-channel gain of the \( k^{th} \) user, \( t_m^k, 0 \leq t_m^k \leq T_b \) is the \( n^{th} \) sub-channel transmission delay of the \( k^{th} \) user, and \( n(t) \) is the additive white Gaussian noise (AWGN) with two-sided power spectral density \( N_0/2 \).

V. MC-CDMA SYSTEM PERFORMANCE ANALYSIS

Without the loss of generality, we consider the signal from the first user \( (k = 0) \) as the desired signal and the signals from all other users as interfering signals. We have used equal gain combining (EGC) as it results in simple implementation in a practical system. Some of our previous work [4] has compared maximum ratio combining (MRC) and EGC for the single user case OW channel. EGC performs slightly worse than MRC, but is simpler. Further work will address OW MC-CDMA MRC receivers. With coherent demodulation and the first user as the reference user, the decision variable \( v_0 \) of the \( m^{th} \) data bit of the first user is given by

\[
v_0 = \frac{1}{T_b} \int_{mT_b}^{(m+1)T_b} y(t) \sum_{n=0}^{N-1} c_n^0 \cos(2\pi f_d t) \, dt
\]  

(5)

where \( T_b \) is the bit duration and it has been assumed that one data bit occupies all subcarriers and the receiver is synchronized with the desired user \( (k = 0) \). Due to the orthogonality of the subcarrier signals with the same user, no self-interference is inflicted by the reference signal on the \( n^{th} \) subcarrier. Upon substituting Equation (4) into Equation (5), and if the time synchronization for user \( (k = 0) \) is perfect \( (t_m^0 = 0, t_m^e = 0) \), then the decision variable \( v_0 \) for \( m = 0^0 \) can be simplified to

\[
v_0 = S + I + \eta.
\]  

(6)

The first term \( S \) is a desired signal component from the desired user, and can be written as

\[
S = \sqrt{T_p R N} \sum_{n=0}^{N-1} \beta_n^0
\]  

(7)

The last term \( \eta \) is a noise component, which is a zero-mean Gaussian random variable. The variance \( \sigma_\eta^2 \) is written as

\[
\sigma_\eta^2 = \frac{N_{\text{a}} N_{\text{b}}}{2 T_b}
\]  

(8)

The second term \( I \) is an interference component from the other user, which is composed of two terms; \( I_{\text{ref}} \), the same subcarrier interference, and \( I_{\text{ref}x} \), the other subcarrier interference. They are expressed as

\[
I_{\text{ref}} = \sqrt{T_p R} \sum_{k=1}^{K-1} \sum_{n=0}^{N-1} \beta_n^k 0^k_n \left[ d_n^k t_{m}^l + d_n^k R_{m,n}^l \right]
\]  

(9)
Then, the signal to interference plus noise ratio (SINR) can be obtained as
\[ \text{SNIR} = \frac{S^2}{\sigma_{\text{est}}^2 + \sigma_{\text{est}}^2 + \sigma_n^2}. \]  
Thus, the BER of the OW MC-CDMA system is obtained as
\[ \text{BER} = \frac{1}{2} \text{erfc} \left( \sqrt{\frac{\text{SNIR}}{2}} \right). \]
The MC-CDMA system offers attractive features compared to OOK, OFDM, and CDMA systems. Unlike OOK and OFDM, it offers multi-user capabilities. These capabilities are offered at symbol rates much lower than those associated with CDMA. The improvement in performance over OOK and CDMA can be quoted as a reduction in the SNR required at a given BER. For example, at BER of $10^{-4}$ a 4 user OW MC-CDMA system calls for a 7 dB and 10 dB lower SNR compared to a single user OW OOK system and 4 user OW CDMA system respectively. This is due to the large duration of the MC-CDMA symbol compared to the duration of the impulse response of the channel and high frequency diversity gain based on converting a serial high-rate data stream onto multiple parallel low-rate sub-streams. The performance degrades gradually as the number of users increases due to the increase in multiple access interference (MAI). Simulation results of both OW MC-CDMA system and OW CDMA system are demonstrated over LSMS configuration with an angle diversity receiver, which is placed at the room centre, throughout Room A.

Fig. 8 illustrates the BER performance of two mobile MC-CDMA OW systems, MC-CDMA LSMS and MC-CDMA ALSMS with an angle diversity receiver in a shadowed room (Room B) at two transmitter locations (2m, 4m, 1m), (1m, 1m, 1m) and two receiver locations, (1m, 1m, 1m), and (2m, 7m, 1m) with 20 users. The mobile MC-CDMA ALSMS system with an angle diversity receiver demonstrates an enhanced BER performance compared to the mobile MC-CDMA LSMS system at all transmitter and receiver positions. Employing a beam power adaptation in the mobile MC-CDMA OW system improves BER performance by almost an order of magnitude at the least successful positions when the transmitter is placed at (1m, 1m, 1m) and the receiver is at (2m, 7m, 1m) for 20 users under highly impaired environment where shadowing exists. Our results indicate that the BER performance depends on the symbol rate, delay spread, receiver structure, and positions of transmitter and receiver. The results clearly show that the OW MC-CDMA system performance is a function of the channel characteristics (delay spread and SNR which are position dependent on transmitter and receiver structures which affect both).

Fig. 9 displays the BER performance of the mobile OW MC-CDMA system with an angle diversity receiver for the case of LSMS and ALSMS over the worst communication environment (Room B) when the transmitter is placed at (1m, 1m, 1m) and the receiver moves at constant $x = 1m$, and along the y-axis with multiple users. A significant BER performance improvement is achieved in the mobile MC-CDMA ALSMS system over a real indoor environment due to the strong received power based on assigning higher powers to spots nearest to the receiver. The results show that the mobile MC-CDMA ALSMS system reduces BER performance degradation due optical signals blockage and shadowing by taking advantage of beam power adaptation. The BER performance improvement obtained through the use of adaptive LSMS with a seven-direction diversity receiver is about $10^{-4}$ when the number of active users is 2, at the least successful locations within the worst communication link when the transmitter is placed at (1m, 1m, 1m) and the receiver is at (1m, 7m, 1m). Fig. 9 also shows that the presence of cubicles and the shadowing introduced has a larger impact on the MC-CDMA LSMS systems as manifested in BER degradation sudden changes. These effects are significantly reduced through transmit power adaptation in MC-CDMA ALSMS systems.

**IV. CONCLUSIONS**

A novel mobile adaptive OW MC-CDMA system is proposed as a method that can provide multiple access facilities suited to the limited bandwidth in OW systems under a shadowed configuration. BER performance degradation is observed in the mobile MC-CDMA LSMS system due to user mobility and a weak received power as a result of the presence of windows, office cubicles, and bookshelves in the environment considered. An adaptive LSMS has been proposed, studied and shown to be a desirable means for improving the performance of mobile OW MC-CDMA systems in a highly impaired environment where shadowing exists. Our results show that a significant performance improvement is obtained, including an extensive drop in the noise power level, a strong received power, reduction in delay spread, and improvement in SNR in the mobile MC-CDMA ALSMS system based on an angle diversity receivers over the mobile MC-CDMA LSMS system in presence of very directive noise in addition to impaired propagation where shadowing exists. A real communication environment, which takes into account partition design, cubical design, window availability, and cabinets, has been considered. Based on the results, a multibeam transmitter with beam power adaptation in conjunction with diversity detection can be a suitable candidate to combat shadowing which is formed by physical partitions. Degradation in the BER performance is observed when the number of active users increases due to the increase in the MAI. Finally, a consistent BER performance is achieved within the worst communication room at all receiver positions when mobile MC-CDMA ALSMS system in conjunction with an angle diversity receiver is used, whereas degradation in BER performance, due to the presence of opaque objects yielding shadowing, is observed in the mobile MC-CDMA LSMS.
channel noise

represent the mobile MC-CDMA LSMS system and dotted lines represent the CDMA LSMS and MC-CDMS ALSMS with an angle diversity receiver in Figure 8: BER performance of two mobile OW MC-CDMA systems, MC-CDMA (k = 20) and ALSMS for Room B of multi-user when the transmitter is placed at (1m, 1m) and the receiver moves at constant x = 1m and along the y-axis.

Figure 6: Receiver model of the MC-CDMA system for user k

Figure 7: BER performance of the MC-CDMA system and the CDMA system with multi-user over an indoor OW channel in different SNR levels, since, solid line represents the theoretical results, dot-dashed line represents the simulation results, and dot-dashed lines represent the simulation results of the CDMA OW system, and compared to the conventional OOK.

Figure 8: BER performance of two mobile OW MC-CDMA systems, MC-CDMA LSMS and MC-CDMS ALSMS with an angle diversity receiver in Room B at two transmitter and receiver positions of 20 users, solid lines represent the mobile MC-CDMA LSMS system and dotted lines represent the mobile MC-CDMA ALSMS system.

Figure 9: BER performance of two mobile OW MC-CDMA systems; LSMS and ALSMS for Room B of multi-user when the transmitter is placed at (1m, 1m, 1m) and the receiver moves at constant x = 1m and along the y-axis.

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