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Collaborative Adaptive Optical Wireless System in Realistic Indoor Environment

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***Abstract*—In this paper, we propose and evaluate a collaborative mobile optical wireless (OW) system that employs a collaborative adaptive beam clustering method (CABCM) in conjunction with an imaging receiver. Three cases involving two, three and five receivers are considered. A collaborative maximum ratio combining scheme is used to collaboratively distribute the transmit power among the diffusing spots. Our ultimate goal is to increase the received optical power and improve the signal-to-noise ratio (SNR) at each coexisting receiver when the system operates in a multiuser scenario under the constraints of background noise, multipath dispersion, mobility and shadowing typical in a real indoor environment. Our proposed system (collaborative adaptive beam clustering method) is evaluated at 30 Mbit/s to enable comparison with previous work, and is also assessed at higher bit rates: 2.5 Gbit/s and 5 Gbit/s. Simulation results show that the mobile CABCM system 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 multiuser line strip multibeam system (LSMS). However, the performance degrades gradually with increase in the number of users.**

Keywords—adaptive multibeam system; optical wireless; beam power adaptation; beam clustering; imaging receive

I. INTRODUCTION

In the last decade, the rapid growth of portable wireless devices has created a need for faster communication links [1], [2]. The optical spectrum has the potential to provide a high-speed transmission medium for short-range indoor wireless communication systems. The OW link provides a secure and promising complement to radio frequency (RF) links as well as an abundant unregulated bandwidth that enables rapid deployment at low cost [1]. However, the design challenges of OW systems lie in two major impairments when employing intensity modulation with direct detection (IM/DD). These impairments include multipath dispersion and additive noise due to sunlight and artificial background light. The former degrades the signal-to-noise ratio (SNR) while the latter limits the link capacity. In addition, OW links are subjected to eye and skin safety regulations which restrict the maximum allowed optical power transmitted [2], [3].

OW links are often categorized into two basic classification schemes: direct LOS and diffuse systems. Direct LOS links improve power efficiency and minimize multipath dispersion, but inherently require transmitter–receiver alignment and can suffer from shadowing due to moving objects. Diffuse systems offer links that are robust in the presence of shadowing, but severely suffer from multipath dispersion in addition to higher path losses compared to direct LOS links. A possible efficient technique that can exploit the advantaged of direct LOS systems and overcome the drawbacks of diffuse links is a multibeam transmitter [4] – [9]. The multibeam transmitter was proposed to tackle the impact of multipath dispersion, mitigate the shadowing effects and improve SNR. The multibeam transmitter is used to generate multiple diffusing spots pointed in different directions in a room, which act as secondary transmitters [5], [9]. Another efficient and simple technique that can reduce the destructive effects of multipath dispersion and ambient light noise is diversity detection [10] – [13]. Combining a multibeam transmitter with a diversity receiver can significantly enhance the overall system performance. Previous work has shown that significant performance improvement can be achieved by employing different multibeam geometries such as the line strip multibeam system (LSMS) introduced in [5] - [7] or the beam clustering method (BCM) in [14] –[16]. An adaptive multibeam transmitter in conjunction with a range of receivers has been evaluated in [17] - [22] and shown to offer good performance.

The authors in [18] have considered several multi-user scenarios where receivers are positioned in different layouts and a comparison between collaborative combining techniques, such as maximum ratio combining (MRC) and equal gain combining (EGC), was reported. It was found that the MRC scheme offers comparable SNR over multiple receivers (users) [18], and therefore it is adopted in this work.

This paper introduces for the first time multi-user collaborative OW systems based on an adaptive multibeam transmitter and imaging receivers in a realistic office environment that consists of windows, a door, minicubicles, bookshelves, and other objects. The proposed transmitter and receiver configuration helps mitigate the shadowing effect, reduces multipath dispersion, and improves the system performance under transmitter-receiver mobility at high data rates. In [23], we introduced a collaborative multibeam transmitter to the design of OW systems where high data rates were shown to be feasible. In this paper, we model our collaborative adaptive beam clustering method (CABCM) in conjunction with an imaging receiver considering 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 results are compared with: a multiuser conventional diffuse system (CDS) and multiuser LSMS coupled with non-imaging diversity receiver as well as imaging receiver. The rest of the paper is organized as follows: Section II gives a description of the mobile OW system model. The transmitter configurations are summarized in Section III. Simulation results are given in Section IV. Finally, conclusions are drawn in Section V.

II. OW System Model

Intensity modulation (IM) is the most viable modulation technique for indoor OW communication links, in which the desired waveform is modulated onto the instantaneous transmitted power. The most practical down conversation technique is direct detection (DD), where a photodetector generates a current, which is proportional to the instantaneous received optical power. The indoor OW channel using IM/DD can be modelled as a baseband linear system and characterized by [5] – [10],

$$I(t) = R\,x(t) + R\,n(t) \qquad (1)$$

where $I(t)$ is the received instantaneous current at the output of the photo-detector at a certain position, t is the absolute time, $x(t)$ is the transmitted instantaneous optical power, $\otimes$ denotes convolution and R is the photo-detector responsivity (R = 0.54 A/W). The ambient background noise (BN) is denoted by $n(t)$ which is independent of the received signal and is modelled as white and Gaussian.

The characteristics of the mobile channel formed by the combination of a collaborative adaptive multibeam transmitter and imaging receivers (users) are investigated. The simulation was developed in a room with dimensions of $4\text{m} \times 8\text{m} \times 3\text{m}$ (width×length× height) for two different configuration denoted as Room 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 (including ceiling) and floor of the room are modelled as ideal Lambertian reflectors with a reflectivity of 0.8 for the ceiling and walls, and 0.3 for the floor. Reflections from doors and windows are considered to be the same as reflections from walls. In order to investigate the collaborative OW system under mobility, the multibeam transmitter is placed in different locations, pointed upward and emitted 1 W optical power. Computer-generated holographic beam-splitters are assumed to be mounted on the emitter to generate multiple narrow beams, forming multiple clusters of line spots (100 diffusing spots are considered in our case and each spot is assigned 10 mW). A liquid crystal device can be used to adapt the power among the beams at low complexity, having microseconds to milliseconds response times [24]. The room illumination is assumed to be provided by eight spotlights ('Philips PAR 38 Economic' (PAR38)). The eight spotlights were placed on the ceiling at coordinates of (1 m, 1 m, 3 m), (1 m, 3 m, 3 m), (1 m, 5 m, 3 m), (1 m, 7 m, 3 m), (3 m, 1 m, 3 m), (3 m, 3 m, 3 m), (3 m, 5 m, 3 m) and (3 m, 7 m, 3 m). Each spotlight emits an optical power of 65 W and was modelled as a Lambertian radiant intensity with mode order n = 33.1, which corresponds to a semi angle of 11.7°. Fig. 2 shows the simulation setup of the proposed method (CABCM) when the transmitter is placed at the room centre (2m, 4m, 1m) and two receivers located at (1m, 1m, 1m) and ((2m, 7m, 1m).

Furthermore, an imaging receiver is implemented in order to minimize the BN effect, reduce multipath dispersion and improve the system performance. The imaging receiver utilizes an imaging concentrator that forms an image onto photodetector pixels, each equipped with a separate preamplifier. The photocurrents received in the pixels can be amplified separately, and the resulting electrical signals are processed in an approach that maximizes the power efficiency of the system. Several possible diversity schemes such as select-best (SB), and MRC can be considered. The imaging receiver employs a detector array segmented into J equal-sized rectangular-shaped pixels. We assume that there are no gaps between the pixels. Therefore, the area of an individual pixel is the photodetector's area, which is exactly equal to the exit area of the concentrator employed, divided

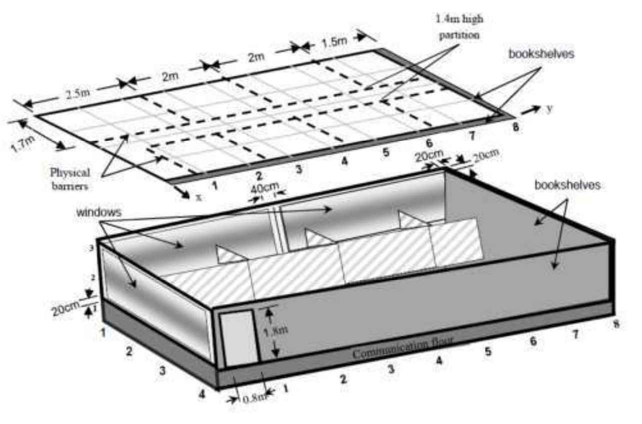

Figure 1. Schematic representation of a realistic indoor office environment (Room B).

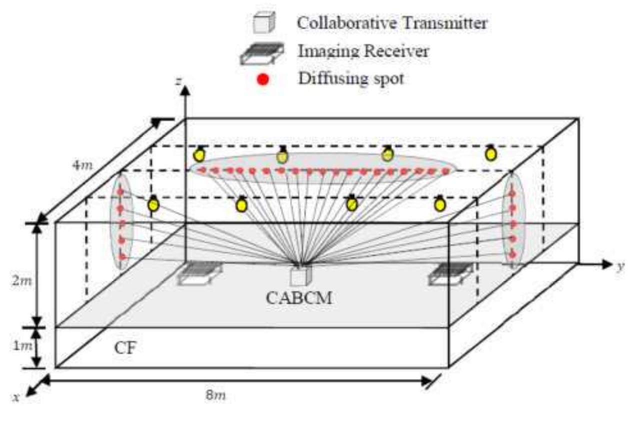

Figure 2. CABCM mobile configuration when the transmitter is placed at the room centre (2m, 4m, 1m) and two receivers are located at (1m, 1m, 1m) and (2m, 7m, 1m).

by the number of pixels. In this case and under most circumstances, the signal (image of each spot) falls on no more than four pixels. The photodetector array is segmented into 200 pixels. In our imaging receiver's analysis, we employ the imaging concentrator that was used in [25]. The transmission factor of this imaging concentrator is given by

$$T_{c,IMG}(\delta) = -0.1982\delta^2 + 0.0425\delta + 0.8778 \qquad (2)$$

where δ is measured in radians. Our imaging receiver has a refractive index N = 1.7 and the entrance area considered is $A = 9\pi/4\ cm^2$ with concentrator's acceptance semi angle restricted to $\psi_a = 65^o$. The receiver's exit area is $\acute{A} = A\ sin^2(\psi_a)/N^2$.

In order to evaluate the proposed method in a collaborative environment, multi-user scenarios are considered, as depicted in Fig 3. Three cases were investigated involving two, three and five receivers. In these cases, we consider two scenarios. The first has stationary receivers as seen in Fig. 3(a). In the second, a user is at constant x-axis and moves along the y-axis and the other users are stationary as shown in Fig. 3(b). The Receivers' positions were chosen based on several criteria. These criteria include transmitter-receiver separation distance, mobility and weakest points in the communication links.

III. Transmitter Configuration

The spot distribution pattern based on a beam clustering method proposed and examined in [14] – [16] is extended in this system, where the total power distribution is collaboratively adapted among the beams. The power allocated for each spot is calculated using a collaborative combing technique (in this work collaborative MRC is considered), based on the number of coexisting receivers. In contrast to previous work [18], where the collaborative transmitter is coupled with a non-imaging angle diversity receiver, in this system an imaging receiver is employed. Our system employs 100 diffusing spots with total power 1 W and each spot is allocated a different power level. The adaptive multibeam clustering transmitter produces 100 × 1 beams that form three groups of spots aimed at the three main surfaces ceiling and two end walls. The CABCM geometry employs three clusters of beams, distributed when the transmitter is at the room centre as follow: 10 spots on each wall and 80 spots on the ceiling. For a collaborative transmitter and multiple receivers at given set of coordinates, the collaborative adaptive algorithm adjusts the transmit powers of the individual beams as follows:

1. Distribute the total power, 1 W, on the spots in equal intensities.
2. Individually turn on each spot j, compute the power received $(P_{i,j})$ at receiver i as well as calculate the SNR(γ_i).
3. Inform the transmitter of the SNR associated with the spot by sending a feedback signal at a low rate.
4. Repeat steps 1 and 2 for all the spots.
5. Re-distribute the transmit power among the spots using collaborative MRC.

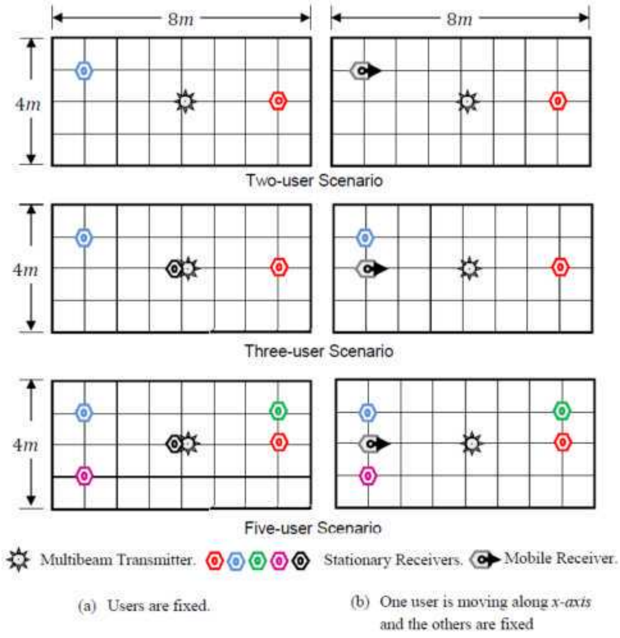

Figure 3. Transmitter and receivers positions on the communication floor.

In the presence of a single user, the transmitted power can be adapted based on a single receiver location. However, in a multiuser scenario a collaborative combining technique is required. Previous work has shown that the power can be distributed collaboratively among the multiple receivers (users) in LSMS configuration [18]. The findings of [18] have shown that MRC offers uniform SNR improvement over EGC, therefore it is considered in this work. Based on MRC, the adapted power for spot j can be defined as in [18]:

$$P_{j,MRC_{Coll}} = \sum_i \left(\frac{P_{i,j}}{\gamma_i}\right) \times k\,, \qquad (3)$$

where

$$k = \frac{1}{\sum_i \left(\frac{1}{\gamma_i}\right)}\,, \qquad (4)$$

and γ_i is the computed SNR for receiver i when the transmitted power is distributed equally and $P_{i,j}$ is the power requested by receiver i for spot j.

IV. Collaborative OW System Performance

The performance of the proposed collaborative adaptive multibeam system (CABCM in conjunction with an imaging receiver) is evaluated in the presence of ambient light noise, multipath propagation and mobility. In a realistic OW environment in the presence of transmitter and receiver mobility, a simulation tool similar to the one implemented by Berry et al. [26] was developed. Comparisons with the multiuser CDS and multiuser LSMS are also presented.

A. *Delay spread evaluation and channel bandwidth*

Due to diffuse transmission, indoor OW links are subjected to multipath dispersion, which results in ISI. The root mean square delay spread is a good measure of signal spread due to temporal dispersion. The delay spread of an impulse response is given by

$$D=\sqrt{\frac{\int (t-\mu)^2 h^2(t)dt}{\int h^2(t)dt}}, \quad where \quad \mu=\frac{\int th^2(t)dt}{\int h^2(t)dt} \tag{5}$$

For delay spread assessment, we considered two user scenario where a user moves along the x=1m line and the other is fixed at (2m, 7m, 1m). Fig. 4 compares the delay spread distribution of the proposed mobile OW for the mobile receiver when the transmitter is placed at the edge of the room (2m, 7m, 1m) in Room A scenario. It can be seen that the multibeam transmitter coupled with angle diversity receiver reduces the delay spared from 2.4 ns to 0.5 ns due to the limited range of rays captured by the receiver. Furthermore, the imaging multiuser LSMS offers further reduction from 0.5 ns to 0.11 ns over the non-imaging multiuser LSMS. A significant reduction to almost 0.04 ns in the delay spread compared with multiuser systems is achieved when our proposed collaborative multibeam system is adopted. This is attributed to the allocation of higher power levels to the spots nearest to the receivers and the limited range of rays accepted in a small pixel with narrow FOV. The results can be visualized as a bandwidth efficiency improvement as seen in Table I. The results indicate that the proposed method produces a significant improvement in the overall system bandwidth (ie channel included). At transmitter-receiver separation of 6m, our imaging CABCM offers an increase in bandwidth from almost 300 MHz to 5.27 GHz when the CABCM replaces the multiuser LSMS. It can be seen clearly that the collaborative adaptive multibeam clustering method is an appropriate choice to combat the multipath dispersion, and hence improve the system performance to achieve higher data rates.

B. *SNR performance analysis*

Indoor OW communication links are strongly impaired by the shot noise in the receiver's electronics induced by ambient light. On-off keying is the simplest modulation

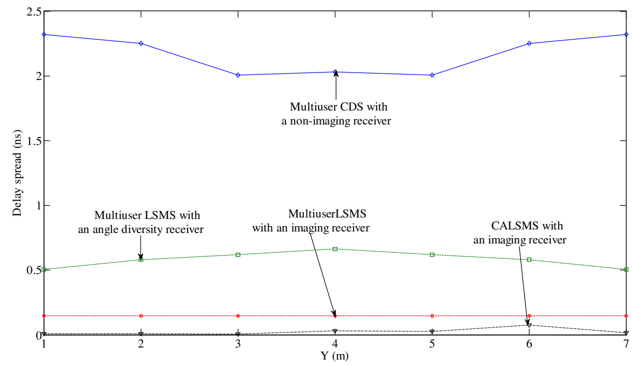

Figure 4. Delay spread distribution for the proposed configurations.

format for use in OW systems. Considering the impact of pulse spread caused by ISI where P_{s1} - P_{s0} accounts for the eye opening at the sampling instant, the SNR is given by:

$$SNR=\left(\frac{R\times(P_{s1}-P_{so})}{\sigma_0+\sigma_1}\right)^2 \tag{6}$$

The noise σ_0 and σ_1 associated with the signal and can be obtained from

$$\sigma_0=\sqrt{\sigma_{pr}^2+\sigma_{bn}^2+\sigma_{s0}^2} \quad and \quad \sigma_1=\sqrt{\sigma_{pr}^2+\sigma_{bn}^2+\sigma_{s1}^2} \tag{7}$$

where σ_{bn} is the background shot noise and σ_{pr} is the preamplifier noise. The preamplifier used in this study for the OOK system is the p-i-n photodetector in conjunction with FET-based transimpedance preamplifier which was used in [25]. Higher data rates of 5 Gbit/s and 2.5 Gbit/s are also considered and here we used the receiver in [27].

In the imaging receiver, we consider two combining approaches to process the resulting electrical signals, namely, select-best (SB) and maximal-ratio combining (MRC). SB represents a simple form of diversity and the SNR here is given by

$$SNR_{IMG,\,SB}=\max_J\left(\frac{R\times(P_{s1}-P_{so})}{\sqrt{\sigma_{pr}^2+\sigma_{bn}^2+\sigma_{s0}^2}+\sqrt{\sigma_{pr}^2+\sigma_{bn}^2+\sigma_{s1}^2}}\right)^2 \tag{8}$$

where J=200 which represents the number of pixels. In contrast to the SB approach, MRC combines all branches using weights that are proportional to their SNR. The SNR obtained using MRC is given by

$$SNR_{IMG,\,SB}=\sum_{i=1}^{J} SNR_i \tag{9}$$

The performance of the proposed collaborative multibeam system (CABCM) coupled with an imaging receiver is compared with multiuser CDS (wide FOV receiver of 65°) and multiuser LSMS, operating at 30Mbit/s, when the transmitter is place at (1m, 1m, 1m). The results are depicted in Fig. 5(a) and (b) for two room scenarios (Room A and Room B), respectively when the transmitter is placed at the room corner (1m, 1m, 1m) and a mobile receiver moves along the x = 2m line in the presence of stationary receiver at (2m, 7m, 1m). The results of unshadowed configurations indicate that the CABCM system offers

TABLE I. 3dB CHANNEL BANDWIDTH OF THE PROPOSED SYSTEM AND COMPARISON WITH MULTIUSER SYSTEMS.

Configuration	3 dB CHANNEL BANDWIDTH (GHz) Y (m)						
	1	2	3	4	5	6	7
Multiuser CDS (wFOV)[a]	0.045	0.056	0.071	0.073	0.074	0.083	0.08
Multiuser LSMS (ADR)[b]	0.021	0.024	0.087	0.23	0.14	0.29	0.27
Multiuser LSMS (IMG)[c]	0.29	0.64	1.22	1.19	1.03	1.01	0.93
CABCM (IMG)	5.27	5.35	5.28	5.67	5.47	5.7	5.71

[a]wFOV: wide FOV receiver - [b]ADR: Angle diversity receiver - [c]IMG: imaging receiver

significant SNR improvement, almost 21 dB and 39 dB over the imaging and non-imaging multiuser LSMS systems, respectively at a transmitter-receiver separation of 6 m. This improvement is attributed to two effects. First the use of collaborative adaptive power distribution. Here the spots nearest to the receivers are assigned high power levels. Second, the small size of the pixel associated with narrow FOV which eliminates the effect of BN. Furthermore, an even SNR distribution can be achieved when the multiuser LSMS replaces the multiuser CDS and a diversity receiver replaces the wide FOV receiver. The results show that the imaging multiuser LSMS is slightly impaired by the impact of shadowing compared to the other multiuser configurations. This is due to the ability of spot diffusing structure to maintain direct light of sight components at every receiver locations.

The high and uniform SNR improvement shown in the results can prove extremely useful in increasing the data rate of the system. High bit rates (2.5 Gbit/s and 5 Gbit/s) indoor optical wireless systems are shown to be feasible through the combination of collaborative multibeam transmitter and an imaging receiver. In realistic office environment, the SNRs associated with 2.5 Gbit/s and 5 Gbit/s CABCM in conjunction with an imaging receiver for a moving user within three-user and five-user scenarios, are depicted in Fig. 6(a) and (b) at a transmitter location (2m, 1m, 1m). It can be seen that the achieved SNR levels are influenced by the number of coexisting users. The results show that a stationary user at the worst case scenario (6m horizontal separation between the transmitter and receiver) still can achieve SNR of almost 14 dB when the system operates at 2.5 Gbit/s in three-user scenario, where SNR is still greater than 9.5 dB ($BER < 10^{-3}$). Therefore, forward error correction (FEC) can be used to further reduce the BER from 10^{-3} to 10^{-9} in our proposed system. The influence of the increase of the number of coexisting users on the SNR level can be seen when the CABCM is employed in a realistic room (Room B) in the presence of five users as depicted in Fig. 6(b). At a transmitter-receiver separation of 6m, the two receivers at the far end (receivers at [2m, 7m, 1m] and [1m, 7m, 1m]) received less power than those users located close to the transmitter. This is due to lowering the transmitted power of the spots close to the far end receivers and reallocating the power to the spots close to receivers that are near the transmitter. Therefore, fairly distributing the transmit power among diffusing spots warrants further study. The performance degrades gradually with increase in the number of users. The higher date rates of the CABCM are shown to be feasible through a combination of the proposed methods (a collaborative multibeam transmitter and an imaging receiver).

V. CONCLUSIONS

In this paper, a collaborative multibeam transmitter (CABCM) was introduced in collaborative OW systems to improve the system performance even in the presence of shadowing. The system's performance was evaluated in the presence of up to five receivers considering two different scenarios based on several criteria including transmitter-receiver separation distance, mobility and weak points in the communication link. Simulation results of our proposed method in conjunction with an imaging receiver have shown that high data rates are feasible in collaborative OW systems. In an unshadowed link at 30 Mbit/s, the proposed system offers significant SNR improvement, almost 21 dB and 39 dB over the imaging and non-imaging multiuser LSMS systems, respectively. This improvement was achieved by introducing a beam clustering geometry, beam power adaptation using collaborative combining techniques and small size pixels with narrow FOVs. Degradation in the SNR is observed when the number of existing users increases. The improvement in SNR can be used to achieve higher data rates and 2.5 Gbit/s and 5 Gbit/s were shown to be feasible in the multiuser environment considered.

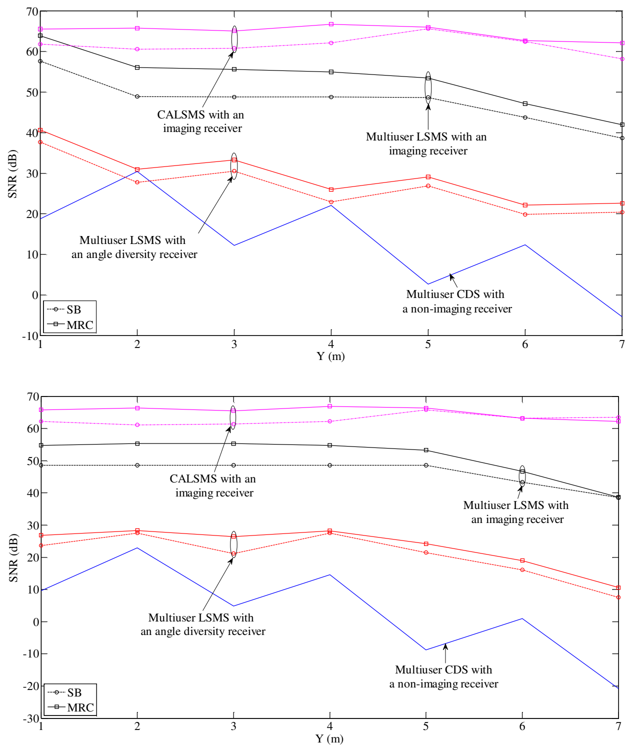

Figure 5. SNR of four mobile OW systems; CDS with a single non-imaging receiver, LSMS with a non-imaging diversity receiver, LSMS and CALSMS in conjunction with a single imaging receiver based on (SB and MRC) for two room scenarios (Rooms A and B) when the transmitter is placed at (1m, 1m, 1m) and the receiver is at constant x = 2m and along the y-axis at a bit rate of 30 Mbit/s. (a) Room A. (b) Room B.

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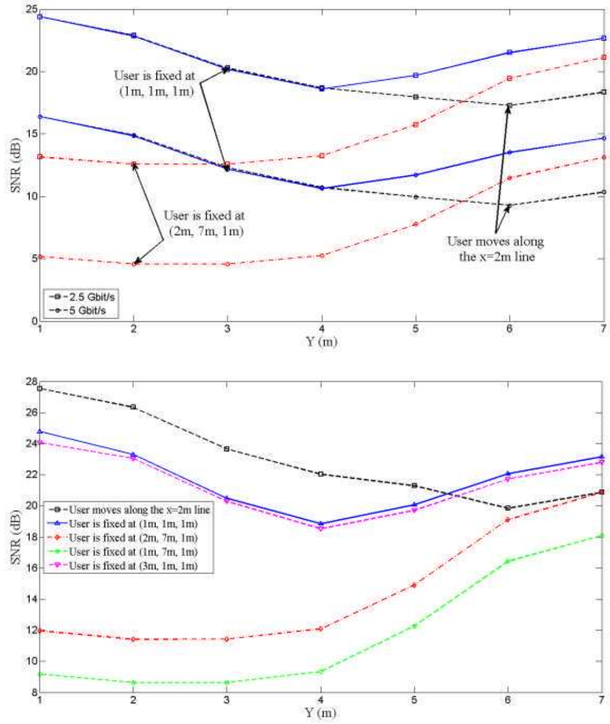

Figure 6. SNR of the proposed system (CABCM) in in conjunction with an imaging receiver based on MRC when the transmitter is placed at (2m, 1m, 1m) and (a) three receivers are present; two users are fixed and one moves along the x=2m line at bit rates of 2.5G and 5G (b) five receivers are present; four are fixed and one moves along the x=2 line within Room B.

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