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# Collaborative Multibeam Transmitter and Imaging Receiver

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**ABSTRACT**
In this paper, we propose a collaborative mobile optical wireless (OW) system that employs a collaborative adaptive beam clustering method (CABCM) in conjunction with an imaging receiver. Collaborative maximum ratio combining ($MRC_{Coll}$) scheme is used to collaboratively distribute the transmit power among diffusing spots. The main 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 and mobility. 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 at a bit rate of 30 Mbit/s, a significant SNR improvement of 39 dB is achieved when a CABCM system replaces a multiuser line strip multibeam system (LSMS) at a 6 m transmitter-receiver horizontal separation. The results also show that the proposed system can achieve a 22 dB SNR when the system operates at 2.5 Gbit/s in a two-user scenario.
**Keywords**: Optical wireless, collaborative multibeam transmitter, beam clustering, beam power adaptation.

## 1. INTRODUCTION

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 a 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 performance. 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 a line strip multibeam system (LSMS) introduced in [5] – [7] or a beam clustering method (BCM) [14] – [16]. An adaptive multibeam transmitter in conjunction with a range of receivers has been evaluated and shown to offer good performance [17] – [22].

The work in [18] has 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 uniform 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, where this transmitter and receiver configuration helps mitigate the shadowing effect, reduce multipath dispersion, and improve the system performance under transmitter-receiver mobility at high data rates. In this paper, we model our collaborative adaptive beam clustering method (CABCM) in conjunction with an imaging receiver and compare the results with: multiuser conventional diffuse system (CDS) and multiuser LSMS coupled with non-imaging diversity receiver as well as imaging receiver.

The remainder of this paper is organized as follows: the channel characteristics and simulation model are given in Section 2. The transmitter configurations are summarised in Section 3. Section 4 outlines the results and conclusions are drawn in Section 5.

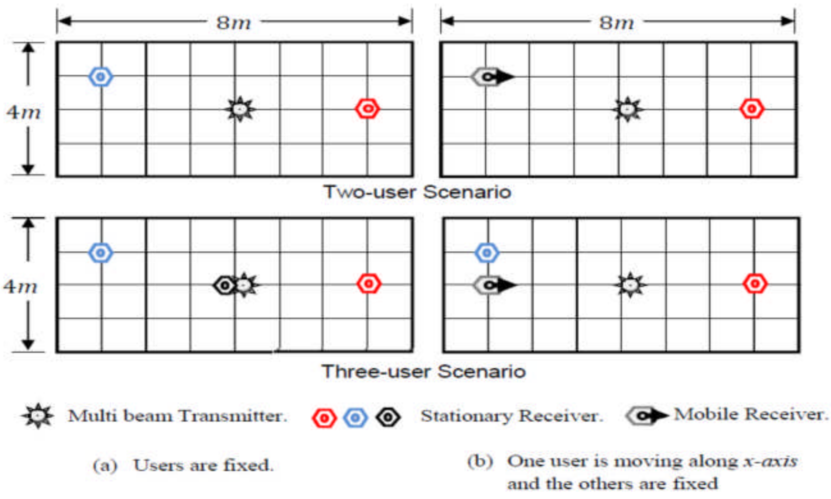


*Figure 1: The Transmitter and receivers positions on the communication floor.*

## 2. CHANNEL CHARACTERISTICS AND SIMULATION MODEL

Intensity modulation with direct detection (IM/DD) is the preferred method for OW communication links. Multipath propagation in an indoor OW channel using IM/DD can be characterized by the impulse response *h(t)* of the channel [5] – [10],

$$I(t) = R\,x(t) + R\,n(t) \tag{1}$$

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 conducted in an empty rectangular room, which has a width of 4 m, a length of 8 m, and a height of 3 m. 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 [23]. 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 model order $n$ = 33.1, which corresponds to a semi angle of 11.7°.

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 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 [24]. The transmission factor of this imaging concentrator is given by

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

where $\delta$ 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 1. Two scenarios were investigated. The first was with stationary receivers as seen in Fig. 1(a). In the second, a user moves along the y-axis and the other users are stationary as shown in Fig. 1(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.

## 3. 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 collaborative combing technique (in this work collaborative MRC is considered), based on the number of coexisting receiver. 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($\gamma_i$).
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 using collaborative MRC technique.

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]:

$$P_{j,MRC_{Coll}} = \sum_i \left( \frac{P_{i,j}}{\gamma_i} \right) \times k, \quad where \quad k = \frac{1}{\sum_i \left( \frac{1}{\gamma_i} \right)} \tag{3}$$

where $\gamma_i$ 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*.

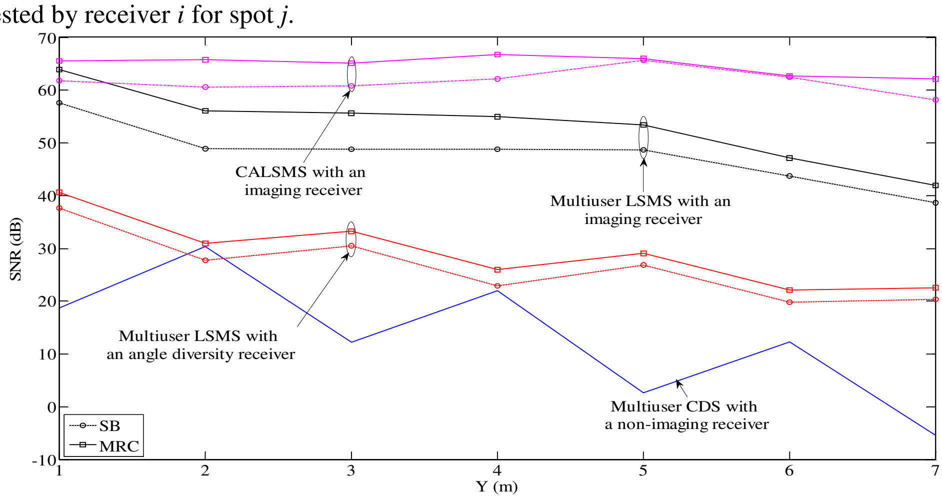


*Figure 2: SNR of four mobile OW systems; CDS with a single non-imaging receiver, LSMS with a non-imaging diversity receiver, LSMS and CALSMS in conjunction with a single imaging receiver based on (SB and MRC) when the transmitter is placed at (1m, 1m, 1m) and the receiver is at constant x = 2m and along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

## 4. PERFORMANCE ANALYSIS AND SIMULATION RESULTS.

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. Comparisons with the multiuser CDS and multiuser LSMS are also presented. On-off keying is considered to be simplest modulation 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:

$$SNR = \left( \frac{R \times (P_{s1} - P_{so})}{\sigma_0 + \sigma_1} \right)^2 = \left( \frac{R \times (P_{s1} - P_{so})}{\sqrt{\sigma_{pr}^2 + \sigma_{bn}^2 + \sigma_{s0}^2} + \sqrt{\sigma_{pr}^2 + \sigma_{bn}^2 + \sigma_{s1}^2}} \right)^2, \tag{4}$$

where $\sigma_0$ and $\sigma_1$ are the noises associated with logic 0 and 1 respectively. 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 [24]. Higher data rates of 5 Gbit/s and 2.5 Gbit/s are also considered and here we used the receiver in [25].

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

$$SNR_{IMG,\,SB} = \max_i \left( \frac{R \times (P_{s1} - P_{so})}{\sqrt{\sigma_{pr}^2 + \sigma_{bn}^2 + \sigma_{s0}^2} + \sqrt{\sigma_{pr}^2 + \sigma_{bn}^2 + \sigma_{s1}^2}} \right)^2, \quad 1 \le i \le J \tag{5}$$

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

$$SNR_{IMG,\,SB} = \sum_{i=1}^{J} SNR_i \tag{5}$$

Figure 2 shows the SNR of the proposed collaborative multibeam system (CABCM) coupled with an imaging receiver, 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 show the SNR achieved by a mobile user moving along the x = 2 m line in the presence of stationary receiver at (2m, 7m, 1m), see Fig. 1(b). The results indicate that the CABCM system offers 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, collaborative adaptive power distribution where 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 SNR results of proposed collaborative system and multiuser systems operating at 30 Mbit/s are summarized in Table 1. The results show that the CABCM offers 12.2 dB SNR improvement over the multiuser LSMS when the receiver is closer to the transmitter.

*Table 1. SNR of the proposed collaborative system and multiuser systems when the transmitter is at (2m, 7m, 1m) and three stationry usersoperating at 30Mbit/s.*

| **Configurations** | **SNR (dB)** | | |
|---|---|---|---|
| | Receivers locations (m) | | |
| | (1, 1, 1) | (2, 7, 1) | (2, 4, 1) |
| **CDS with a wide FOV receiver** | -9.44 | 29 | 30.3 |
| **LSMS with an angle diversity receiver** | 21.6 | 30.2 | 40.5 |
| **LSMS with an imaging receiver** | 40.6 | 53.9 | 54.7 |
| **CABCM with an imaging receiver** | 42.46 | 66.13 | 62.5 |

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. The SNRs associated with 2.5 Gbit/s and 5Gbit/s CABCM in conjunction with an imaging receiver for a moving user within two-user and three-user scenarios, are depicted in Fig. 3 at two transmitter locations (2m, 4m, 1m) and (2m, 1m, 1m). In a two-user scenario, the SNRs achieved in the proposed system were about 22 dB and 14 dB at 2.5 Gbit/s and 5 Gbit/s. 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 13.9 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 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).

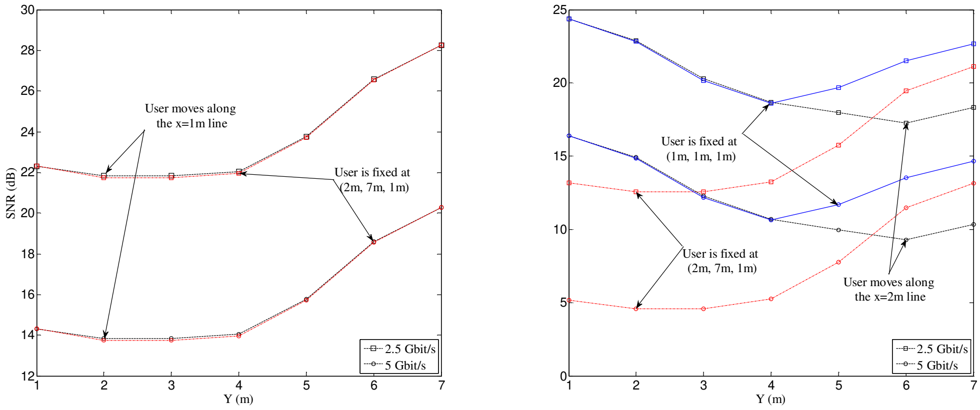


*Figure 3: SNR of the proposed system (CABCM) in conjunction with an imaging receiver based on MRC when the transmitter is placed at (a) (2m, 4m, 1m) and two receivers are present (b) (2m, 1m, 1m) and three receivers are present; two users are fixed and one moves along the x=1m line; with operation at bit rates of 2.5Gbit/s and 5Gbit/s.*

## 5. CONCLUSIONS

In this paper, a collaborative multibeam transmitter (CABCM) was introduced in collaborative OW systems. The system's performance was evaluated in the presence of up to three 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 high data rates are feasible in collaborative OW systems. 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. The improvement in SNR can be used to achieve higher data rates and 2.5 Gbit/s and 5 Gbit/s which were shown to be feasible in the multiuser environment considered.

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