Assessment of Angle Diversity and Spot Diffusing Techniques in Combating the Multipath Dispersion on Non-directed Diffuse Wireless Channels

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Abstract— Non-directed diffuse optical wireless (OW) channels are mainly impaired by multipath propagation, which results in pulse spread and intersymbol interference (ISI). Ambient light noise, however, is also a notable impairment in indoor systems, and can degrade the system performance. In this paper, we present and investigate a new geometry that uses a line strip spot-diffusing transmitter in conjunction with an angle diversity receiver. The receiver employs only three photodetectors and the influence of multipath dispersion and very directive noise sources is considered. Original results are presented evaluating and assessing the system performance when based on the proposed geometry, and comparison is carried out with four other geometries under the same conditions. Simulation results show that a significant performance improvement (about 15 dB signal-to-noise ratio improvement over the other conventional geometries) is achieved when a line strip multibeam transmitter (LSMT) with a three-direction diversity receiver is employed in order to combat multipath dispersion and background noise effects. Moreover, the system performance improvement over the conventional diffuse system with respect to the delay spread and signal-to-noise ratio is demonstrated.

1. Introduction

Non-directed OW systems can mainly be classified into two configurations: line-of-sight (LOS) and diffuse systems. LOS can only be established by having a direct path between transmitter and receiver. Diffuse systems are a very attractive alternative [1], they offer robust links as well as alleviating the problem of shadowing, since diffuse systems do not rely on the transmitter and receiver alignment and only count on reflections from walls, ceiling, and other reflectors. Both configurations are affected by multipath propagation, where the impact of this effect is less for LOS systems. Furthermore, in indoor OW systems, background optical noise sources such as sunlight or artificial light (for example incandescent lamps) induce significant shot noise in the photodetectors and can burn out the received data, especially when the receiver lies underneath the noise source.

In this paper, several spot diffusing configurations using multibeam transmitter are proposed in order to reduce the effect of the above obstacles and to improve the system performance. The transmitter is placed on the communication floor (CF) and pointed up. A holographic optical diffuser is assumed to be mounted on the emitter resulting in multiple narrow beams, which illuminate multiple small areas forming a lattice of diffusing spots on the ceiling [2, 3]. Careful hologram design can even offer intensity distribution within the spots. Multiple spots organized in uniform, diamond, and LSMT configurations are studied and compared with the conventional diffuse system (CDS), that employs a wide transmitter beam and a wide field-of-view (FOV) receiver. Multibeam transmitters can be practically implemented using computer-generated holograms (CGH) for a particular spot intensity and/or intensity distribution [4]. Compared to the other geometries, the LSMT system provides a significant performance improvement when it is accompanied by an angle diversity receiver that employs three narrow FOV photodetectors tilted in different directions, thereby separating signals that arrive from different directions. Using more than one receiver can assure uninterrupted reception of the optical signal when there is transmission blockage. In addition, the use of LSMT combined with angle diversity detection (three receivers) has demonstrated a SNR improvement of about 15 dB over the spot diffusing systems that employ wide FOV receiver and 20 dB SNR improvements over the CDS system.

2. System model

In this section, the characteristics of the channel formed by a multibeam transmitter (uniform, diamond, and LSMT illumination) are studied and compared with the CDS. The transmitted signal propagates to the receiver through multiple reflections from room surfaces. Propagation simulations were conducted in an empty room with floor dimensions of 8m × 4m (length × width), and ceiling height of 3m. It is assumed that the room has neither doors nor windows. Up to second order reflections were taken into account and full walls reflectivity are assumed. High reflectivity is chosen as it results in the highest multipath dispersion, thus significant pulse spread. The transmitter is placed in the middle of the CF, one meter above the floor and is modeled as a generalized Lambertian emitter, with a radiant intensity (W/sr) given by

$$R(\phi) = \frac{n+1}{2\pi} \times P_s \times \cos^n(\phi) \qquad (1)$$

where P_s is the total average transmitted optical power radiated by the Laser/LED source, ϕ is the angle of incidence with respect to the transmitter's surface normal, and n is the mode number describing the shape of the transmitted beam, the higher the mode n the narrower the light beam.

A simulation tool similar to the one developed by Barry *et al*. [5] has been used to produce the impulse responses, power distribution, and to calculate the delay spread. To model the reflections, the room reflecting surfaces were divided into a number of equal size square shaped reflection elements. The accuracy of the received pulse shape, and the received optical signal power are controlled by the size of the surface elements. For all geometries, the surface elements of 5 cm × 5 cm for the first order reflections, and 20 cm × 20 cm for the second order reflection were used. The reflecting elements have been treated as small transmitters that diffuse the received signals from their centers in the form of Lambertian pattern with a radiation lobe mode number n =1. In all the cases studied a single photodiode has been located at different locations on the CF, 1 m above the floor, with a photosensitive area (A_r) of 1 cm^2. In addition to the high reflectivity surfaces and in order to assess the system's performance, in a realistic situation, eight halogen spotlights, which result in one of the most stringent optical spectral corruption to the received data stream, have been chosen to illuminate the environment. To evaluate the impact of ambient light, the background noise (BN) distribution pattern of an incandescent light was investigated. 'Philips PAR 38 Economic' (PAR38) was investigated. PAR38 emits a power of about 65 W in a narrow beamwidth in which it is modeled as having a generalized Lambertian radiant intensity with order n= 33.1. The eight spotlights were placed 2 m above the CF and positioned equidistantly on the ceiling. These lamps produced a well-illuminated environment. Furthermore, simulation of the optical noise power along both axes of CF was carried out in steps of 10 cm.

3. Transmitter Structures

3.1 Conventional diffuse system (CDS)

This is the basic configuration and has been widely investigated [4- 8]. The conventional diffuse link uses a single beam transmitter and a wide single element receiver (FOV=180^{o}). For comparison purposes, a conventional diffuse link has been simulated to generate channel impulse responses, power distribution, and delay spread. For impulse response assessment, the receiver location was chosen at the room corner (x= 1m, y= 1m, z= 1m) in order to examine the worst receiver position case. The impulse response of the CDS configuration is shown in Fig 1. In the case of the CDS, as the distance between the transmitter and the receiver becomes large, the power of the collected optical signal decreases rapidly and thereby the total coverage is reduced [7, 8].

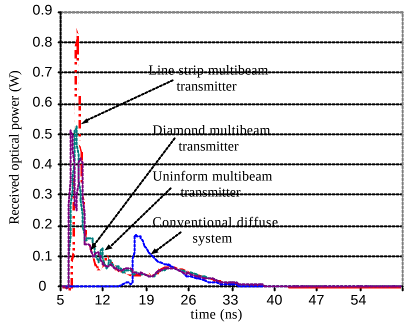

Fig. 1. Impulse responses of diffuse OW link. Simulations were performed near room corner at (1m,1m,1m) for the four configurations.

3.2 Uniform multibeam transmitter

The multi-spot diffusing link was firstly proposed by Yun *et al*.[2]. It utilizes narrow beams pointed in different directions aimed at the ceiling. This structure is evaluated in order to assess the potential gain to be made using our proposed structures (line strip and diamond multibeam transmitters). A holographic optical element mounted on the transmitter is assumed to create multiple narrow beams and to form 16 × 8 diffusing spots. These diffusing spots are evenly distributed on the ceiling with equal intensities, in which the distance between two adjacent spots is 50 cm. Such configuration for a case of wide FOV receiver is illustrated in Fig. 2. Observing Fig. 1, it is clear that the impulse response spread has significantly increased compared to the CDS. This is due to two major factors: the use of single wide FOV detector and the contribution of the diffusing spots. Furthermore, due to the large distance between the diffusing spots and the detector (at room corner) and since the received signals, at any point on the CF, can come directly from diffusing spots as well as other directions (walls and ceiling), sever pulse spreading results as shown in Fig. 1. An improvement in the received optical power is clearly visible when the uniform multibeam transmitter is employed instead of the CDS as can be seen in Fig. 1. This significant improvement is due to the full ceiling coverage with uniform distribution of diffusing spots, which leads to a reasonably uniform power distribution as shown in Fig. 2.

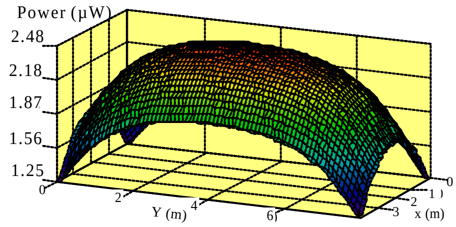

Fig. 2. Power distribution of the uniform multibeam transmitter.

4.3 Diamond multibeam transmitter

In this section, another geometry of multibeam transmission link is simulated. The link produces four line strips forming a diamond shape of diffusing spots on the ceiling. Fig. 3 shows the power distribution for a diamond multibeam transmitter, when a wide FOV receiver is used. Every line in the diamond consists of 20 spots, where the separation between two adjacent spots is about 10 cm. The impulse response, at the room corner, for the diamond configuration is shown in Fig. 1. The power distribution over the CF for the diamond multibeam transmitter is illustrated in Fig. 3. The results show a less uniform power distribution since most of the collected power lies on the area close to the line strips, where the distance between transmitter and receiver is the minimum. From Fig. 3, it can be clearly seen that at x = 2m and along the y-axis the signal power level increases slightly in particular at room sides and corners due to the extra number of diffusing spot contributions at these locations. In contrast, near the room center, the signal power is small due to the large distance between the diffusing spots and the receiver, which makes the direct path link between spots and receiver weak. The collected power level near the side walls, however, increases due to the diamond spots construction wherein the maximum collected power is found in the regions where two adjacent line strips can concurrently illuminate the receiver directly.

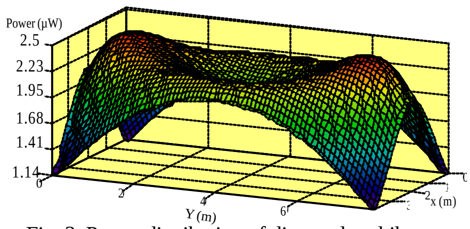

Fig. 3. Power distribution of diamond multibeam transmitter.

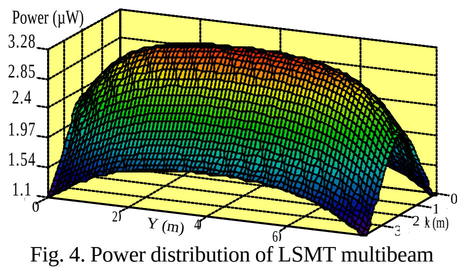

Fig. 4. Power distribution of LSMT multibeam transmitter.

3.4 Line strip multibeam transmitter

A novel structure of diffusing spots that employs multibeam transmitter is proposed and examined. Fig. 4 shows the power distribution for the diffuse optical wireless communication system that employs the proposed line strip multibeam transmitter in conjunction with a wide FOV receiver. The same multibeam transmitter is assumed to produce 1 × 80 beams aimed at the ceiling with equal intensities, and to form a line of diffusing spots in the middle of the ceiling at x= 2 m and along the y-axis The difference in distance between each two adjacent spots is 10 cm. It is clearly seen that the power received by the multibeam transmitter structures is significantly better than the CDS. This is due to the fact that the impulse response of these configurations contains many peaks corresponding to the different direct path components between the diffusing spots and the receiver. In addition, our impulse response results have further confirmed the findings in [2] that most of the collected signal is in the first order reflection, concentrated within a very short time period due to the contribution of the many direct paths components. On the other hand, impulse responses for these configurations (that use single wide FOV receiver) suffer from pulse spread due to multipath propagation. In order to reduce the effect of multipath dispersion, different techniques can be implemented.

4. Performance Evaluation

4.1 Delay spread performance

Figure 5 shows the delay spread performance of the four non-directed multibeam transmitter configurations as well as the CDS considering a receiver positioned on CF; x= 1m and x= 2 and along the y-axis. For the multibeam transmitter case, where a single wide FOV receiver is used, the delay spread is clearly larger than that of the CDS (single beam transmitter and wide receiver FOV) over the entire communication floor. This is due to the fact that the multibeam transmitter features many signal propagation paths between transmitter and receiver. Fig. 5 also shows, for the CDS case, that there is a direct relation between the delay spread and the distance from the transmitter.

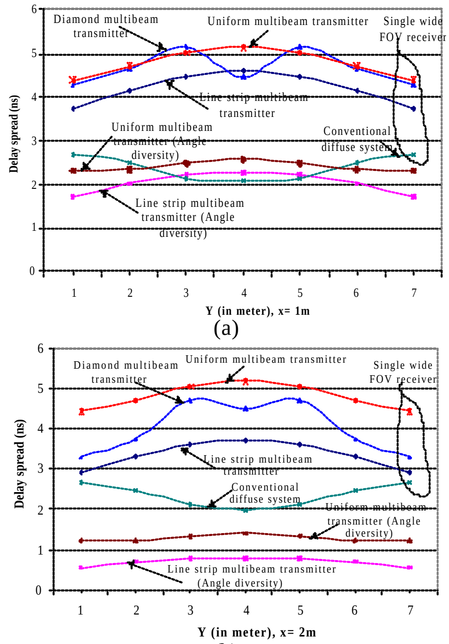

Fig. 5. Delay spread performance.

In contrast to the CDS configuration, the delay spread variation, for the case of the spot diffusing technique, is small (towards the room corners), which is due to the presence of spot diffusing transmission points near the room corners and the lower contribution of the far spot points. Furthermore, for the case of wide single receiver, Fig. 5 shows that the delay spread for the diamond configuration is lower than that associated with the uniform multibeam configuration, in particular, at x= 2m and along the y-axis. On the other hand, the delay spread values increased slightly in the area where the diffusing spots illumination is low. Comparing the cases of spot diffusing techniques when a single wide receiver is used (Fig. 5), it is to be noted that the lowest delay spread values are obtained by the proposed LSMT with angle diversity receiver. The smallest delay spread associated with the LSMT and three narrow branches receiver is 0.5 ns which is 9.5 dB, 8.2 dB, 7.6 dB, and 6 dB lower than the smallest delay spread associated with uniform spot diffusing system, the diamond spot configuration, the LSMT when single wide FOV receiver is used, and the CDS geometry system respectively. Also, the delay spread that associated with LSMT and diversity detection is smaller than the one associated with uniform spot diffusing and angle diversity detection by about 4 dB. The maximum delay spread associated with the LSMT and angle diversity receiver is also low and has a value of 2.2 ns. This is 4 dB, 4 dB, 3.6 dB, and 2 dB lower than the maximum delay spread associated with the three systems (in the same respective order). While for uniform multibeam transmitter, LSMT demonstrates lower delay spread.

4.2 Performance assessment of the Line strip multibeam transmitter with angle diversity receiver

In contrast to single wide-FOV receiver, in this section, the receiver is a collection of narrow-FOV detectors oriented in different directions, forming an angle diversity configuration. The optical signal power received in the various receivers can be treated separately, and can be processed using several techniques such as combining or selection. Furthermore, in order to combat background noise as well as multipath dispersion, diversity detection is an appropriate choice, where a significant performance improvements can be achieved [7]. The detectors are placed on square pyramidal faces, which form a new geometry that is investigated in this work. By using such configuration, and by optimizing the FOV, directional interference can be minimized. The square pyramidal detector diversity system considered consists of three photodetectors, mounted only on three-square pyramid faces. Each face bears a certain direction that can be defined by two angles: azimuth (*Az*) and elevation (*El*) While the *El* of two photodetector remains at 35^o, the third one is facing up with *El* of 90^o, and the *Az* for the three faces of the detectors are fixed at 0^o, 180^o and 0^o. In addition, their FOVs have been chosen to achieve the best SNR, hence, two of them were restricted to 35^o, whereas the detector that faced up was set to 20^o. The design of the receiver structure was based on line strip spot diffusing configuration. This structure is able to look at the spot diffusing points from the entire CF. SNR was evaluated for each configuration. For the diversity detection case, we consider one way of processing the resulting electrical signal from the different photodetectors, namely, selection of the photodetector with the best SNR. Furthermore, the received pulse shapes for the four configurations have been considered in calculating P_{s1} and P_{s0}, the power associated with logic 0 and logic 1 respectively. The probability of error (P_e) of the indoor OW communication system can be written as

$$P_e = Q\left(\sqrt{SNR}\right), \qquad (9)?$$

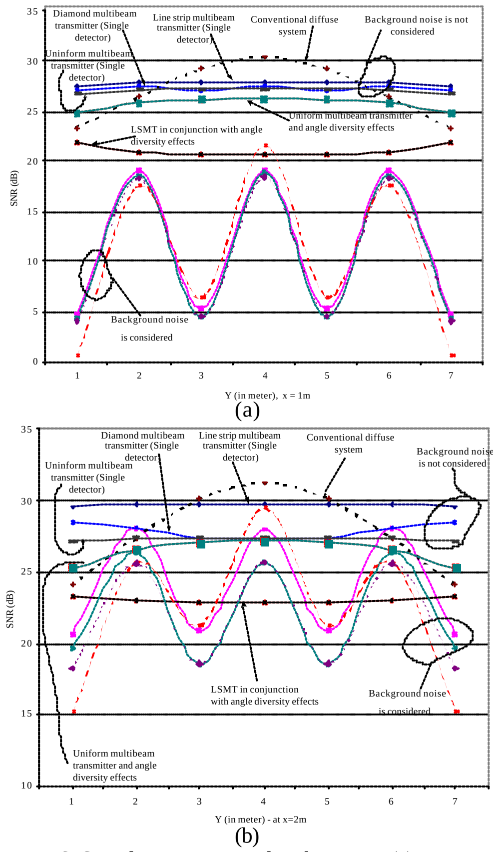

Fig. 6. Signal-to-noise ratio distribution at: (a) x= 1m and (b) x= 2m and along the y-axis.

where $Q(x)$ is the Gaussian function which assumes a value of 6 at probability of error $P_e = 10^{-9}$, and SNR taking P_{s1} and P_{s0} into account (hence ISI) is given by

$$SNR_s = MAX_i \left(\frac{R \times (P_{s1} - P_{s0})_i}{\sigma_{t,i}} \right)^2, 1 \le i \le I \qquad (10)$$

where I is number of photodetectors, R = 0.5 A/W is the photodetector responsivity, and σ_t is the total noise variance which can classified into three categories: background light-induced shot noise (s_{bn}), which can be evaluated by computing the corresponding shot noise current. It can be calculated from its respective associated power level (P_{bn}) using

$$\sigma_{bn} = \sqrt{2 \times q \times P_{bn} \times R \times BW}, \qquad (11)$$

where q, P_{bn}, and BW are the electron charge, received background optical power, and receiver bandwidth, respectively. Secondary, noise induced by the received signal power which consists of two components: shot noise current (s_{s1}) when a '1' is received and shot noise current (s_{so}) when a '0' is received. This signal dependent noise is very small in this case and can be neglected. Finally, receiver noise normally generated in the preamplifier components. The preamplifier used in this study is the PIN-BJT design proposed by Elmirghani *et al*. [9]. This preamplifier has a noise current density of 2.7 pA/$\sqrt{Hz}$ and a bandwidth of 70 MHz, therefore the preamplifier shot noise is given by

$$s_{pr} = 2.7 \times 10^{-12} \times \sqrt{70 \times 10^6} = 0.023\, mA \qquad (12)$$

hence, s_t is $s_0 + s_1$, which represent the noises associated

$$\sigma_o = \sqrt{\sigma_{pr}^2 + \sigma_{bn}^2 + \sigma_{s0}^2} \text{ and } s_1 = \sqrt{s_{pr}^2 + s_{bn}^2 + s_{s1}^2} \qquad (13)$$

The assumption of Gaussian noise statistics holds in our case, since thermal and shot noise can be accurately modeled as Gaussian processes. In order to investigate and examine the effect of the background noise (BN), two cases are presented. The first case is implemented when the communication environment is free of BN. The directive BN is the second case. Figure 6 shows the detected SNR, for the previous two cases, when the system operates under the constraints of background noise (eight directed spotlights n= 33.1) and fully multipath dispersion, at the x co-ordinate that contains the weakest and the strongest received optical signal power along the y-axis as well as when there is no BN. Note also, neither optical concentrator nor optical filter was used. Under these conditions, all the four configurations (single wide FOV=180^o) are compared with the angle diversity receiver when LSMT and uniform multibeam transmitter are used. Observing Fig. 6, high level of SNR can be easily achieved in particular when there is no BN. While under the constraint of BN, it results in a very deteriorated system performance. In addition, Fig. 6 shows that SNR is maximum at points close to the diffusing spots and far away from the BN sources.

Furthermore, the impact is more evident when the wide FOV receiver is placed directly under a light source (or towards the room corners where the distance between the transmitter and the receiver is large, hence the signal is weak). This is due to the fact that the increase in the FOV yields an increase in the amount of BN detected by the receiver. This can be easily seen at y= 1m, 3m, 5m, and 7m, where the SNR has its minimum values. Comparing the results shown in Fig. 6, it can be seen that, in spite of employing different types of transmitters, the signal degradation is clearly visible at locations near room sides and corners as the difference in distance between the transmitter and the receiver increases and the diffusing spot illuminations decrease. In contrast, a remarkable improvement in the SNR is seen, in particular when a LSMT with angle diversity receiver is used. Fig. 6 shows SNR improvement in particular at room corners and along the y-axis where the directional interference peaks exist. This is attributed to the fact that the noise levels at these locations are significantly reduced due to diversity and due to reduction in the FOVs. Furthermore, due to the receiver structure, Fig. 6 shows that the adapted LSMT as well as uniform spot diffusing configuration have not been affected by the BN, where the SNR are almost the same in all points on the CF. The improvement obtained by using the proposed structure can be seen; a significant SNR improvement over both CDS and the conventional multibeam structures is obtained as shown in Fig. 6. Compared to CDS, uniform spot diffusing and LSMT configurations, when they are combined with angle diversity detection, yield SNR improvement of more than 20 dB and about 15 dB, respectively.

5. Conclusions

This paper has presented a new spot diffusing configuration based on line strip multibeam transmitter. LSMT in conjunction with angle diversity receiver (having narrow directive FOVs) has improved the performance of non-directed (diffuse) OW systems. The proposed system has demonstrated significant optical power as well as decrease in the delay spread towards the walls and corners. Such a system combines the advantages of both direct path link and diffuse transmission in an economic attractive fashion. Additionally, it employs a smaller number of detectors (only three) in contrast to the existing diversity detection methods, which results in lower complexity and cost.

6. References

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