Line Strip Multibeam Transmitter for Optical Wireless systems

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Abstract: We propose a novel optical wireless (OW) configuration that employs a line strip multibeam transmitter (LSMT) in conjunction with a narrow field-of-view (FOV) direction diversity receiver. Such a configuration overcomes the drawbacks and combines the advantages of both types of optical wireless links namely line-of-sight and diffuse links. The main target is to combat the effect of multipath dispersion and to improve the system performance when the system operates under the constraints of background noise and multipath dispersion. Compared to conventional diffuse system that employs a wide FOV receiver, SNR results are presented demonstrating that our LSMT with only three branches diversity gives about 23 dB improvement. The results also show that the pulse spread, which induces intersymbol interference, is significantly reduced when the LSMT with diversity detection is used.

1 Introduction.

The two major OW transmission link configurations are direct light-of-sight (DLOS) and diffuse (non-direted) links [1-3]. The most important issues that an OW system designer must take into account are the amount of received power, the received pulse shapes, background interference, and the permissible transmitter power (eye safety). A possible technique that can increase the received optical power, mitigate shadowing effects, and reduce multipath dispersion is the multibeam transmitter [4,5]. Systems that adopt this approach possess the advantages of the DLOS and overcome the drawbacks of the diffuse links (that appear in a form of multipath distortion). Proposals that utilise this method of transmission have included uniform distribution of multiple diffusing spots produced by a multibeam transmitter, which cover the whole room ceiling [5]. Although an improvement in performance was achieved, the proposed structures accomplished it at a considerable increase in complexity.

This paper proposes a LSMT structure in conjunction with diversity detection technique, where only three receivers are used. This proposed configuration produces an increase in the received optical power level as well as a reduction in multipath dispersion. This is achieved by employing a less complex multibeam transmitter structure. Svetla *et al*. [5], have used one transmitter, to produce 100 uniform multibeam diffusing spots, in conjunction with angle diversity detection in which a seven-branch composite receiver was used. While the uniform multibeam transmitter provides a considerable improvement in signal-to-noise ratio (*SNR*), it has more complexity in terms of spot distribution. The proposed strategy reduces the system complexity, because it employs a limited number of receivers, hence reducing the cost and implementation difficulty. In addition, the use of LSMT combined with angle diversity detection (three receivers) has demonstrated an improvement of about 23 dB. Furthermore, the LSMT employed with diversity detection offers 17 dB *SNR* over the LSMT system that employs a wide FOV receiver.

2. Propagation model.

In order to investigate the effects of diffuse transmission on indoor OW propagation characteristics, propagation simulations were conducted in an empty room (without furnishings) with dimensions of 8m $\times$ 4m $\times$ 3m. Walls (including ceiling) and floor are modelled as Lambertian reflectors of the first order with reflectivity coefficients of 0.8 and 0.3, respectively. Previous research work has shown that plaster walls reflect a light ray in a form close to a Lambertian function [6]. Reflections from doors and windows are considered completely the same as reflections from walls. The multibeam transmitter is assumed to produce $N \times 1$ beams to form N spots on the ceiling with equal densities, see Fig. 1.

To quantify the performance of the multibeam transmitter, three configurations were considered; CDT where one transmitter and a wide FOV receiver are employed and LSMT with both wide FOV receiver and angle diversity receiver. The transmitter is always located in the middle of the communication floor (CF), 1m above the floor, at the room centre (4 m $\times$ 2m), pointed upwards, and emits 1 W total optical power with an ideal Lambertian radiation pattern. The power incident on a reflecting element either on the ceiling or walls can be modelled by the Lambertian law

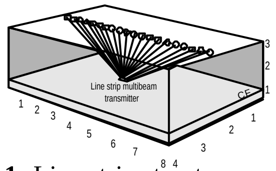

Figure 1: Line strip structure.

$$dp_n = \frac{n+1}{2p} \times cos^n \vartheta_i \times P_S \times \frac{dA}{R_1^2} \times cos ß \, , \qquad (1)$$

where P_s is the total average transmitted optical power radiated by the Laser/LED source J_i is the angle of incidence with respect to the transmitter's surface normal, R_1 is the distance between the transmitter and the element dA, b is the angle between the surface normal of the element dA and the incident ray, 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*. [7] was used to produce the impulse responses, power distribution, and to calculate the channel characteristics. To model the reflections, the room reflecting surfaces were divided into a number of equal size square shaped reflection elements. Surface elements of 5cm × 5cm for the first order reflections, and 20cm × 20cm for the second order reflection were used for both the conventional diffuse link and LSMT configuration. In all the cases studied a photodiode has been placed at different locations on the CF, with a photosensitive area of 1 cm^2, and with a wide angle of reception (FOV of 180^o) for the case of one receiver. The simulations were carried out at several receiving positions within the room.

3. Channel characteristics and ambient light modelling.

Because of the diffuse transmission, indoor OW is subjected to multipath dispersion, which can cause ISI. D is a good measure of signal pulse spread due to temporal dispersion of the incoming signal. The delay spread of an impulse response is given by

$$D=\sqrt{\frac{\sum (t_i-m)^2 P_{ri}{}^2}{\sum P_{ri}{}^2}}\ ; \quad m=\frac{\sum t_i P_{ri}{}^2}{\sum P_{ri}{}^2}, \qquad (2)$$

where t_i is the delay time associated with the received optical power P_{ri} (P_{ri} reflects the impulse response $h(t)$ behaviour) and m is the mean delay.

In order to assess the system's performance as well as examine the advantages of having a diversity detection receiver, eight halogen spotlights, which result in one of the most stringent optical spectral corruption to the received data stream, have been chosen. To evaluate the impact of ambient light, the 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 modelled as having a generalised Lambertian radiant intensity with order n= 33.1. The eight spotlights were placed 2 m above the CF at locations as shown in Fig. 2. These lamps produced a well-illuminated environment. Further, simulation of the optical noise power along both axes of CF was carried out in steps of 10 cm.

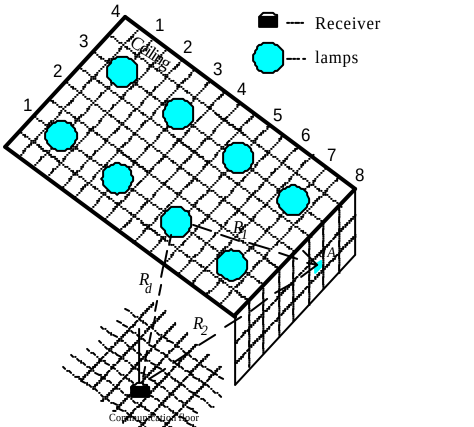

Figure 2: Eight spotlights distribution in an OW configuration.

6. LSMT in conjunction with diversity detection

Angle diversity detection can be presented in two main ways: using an imaging receiver that employs a detector segmented into multiple pixels [1] or using an array of photodetectors oriented in different direction. In this section, we evaluate the system performance when a LSMT employs an array of detectors pointed in different directions to achieve diversity detection.

6.1 Angle diversity receiver analysis

In contrast to the conventional systems where a single wide-FOV receiver is employed, in this section the receiver is a collection of narrow-FOV receivers 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 improvement can be achieved [8]. The detectors are placed on square pyramidal faces as shown in Fig. 3. This forms a new geometry that is investigated in this work.

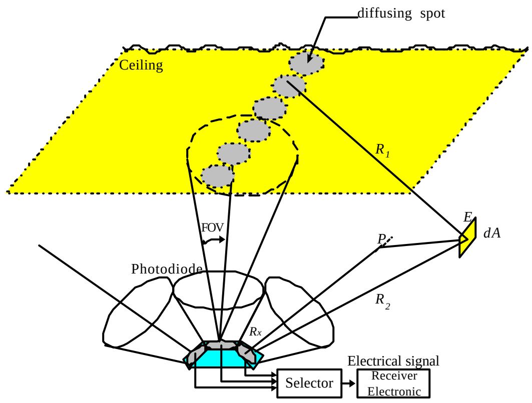

Figure 3: Line strip diffusing spot configuration in conjunction with diversity detection receivers.

By using such configuration, and by optimising the FOV, directional interference can be minimised. 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) angles. 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°, whereas the detector that faced up was set to 20°. Moreover, 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. The faces of the square pyramid are inclined and hence the single detector with a wide FOV analysis, which assumes an upwards-facing detector, has to be modified. Compared to the optical signal analysis that was used in the conventional configuration, where the vector normal to the receiver is also perpendicular to the CF, changes in the calculations for the received power analysis need to be made in the case of the square pyramidal diversity receiver. The reception angle can be calculated by employing the trigonometry of rectangular triangles, in which *Az* and *El* angles for each detector are considered.

For comparison purposes, the impulse response of the three configurations (CDT, LSMT with wide FOV receiver, and LSMT with angle diversity receiver) at the room corner (1m,1m,1m) is depicted in Fig. 4. It is clearly seen that the multibeam transmitter structures are significantly better than the CDT. This is due to the fact that the impulse response of these configurations contains many peaks corresponding to the different DLOS between the diffusing spots and the receiver. The results have also shown that most of the collected signal is in the first order reflection, concentrated within a very short time period due to DLOS. The CDT has shown much more signal delay spread (over a large time period) due to the diffuse transmission and wide received angle (FOV=180°). This figure has also shown a remarkable improvement in the received optical power and a significant reduction in the signal spread for the LSMT, in particular when it is accompanied by the angle diversity receiver, over the other configurations.

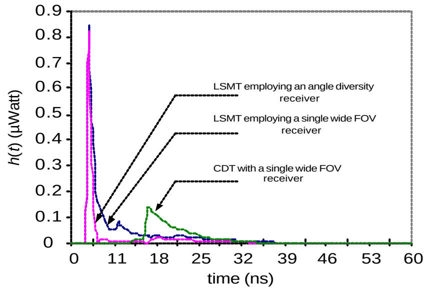

Figure 4: Impulse response for three configurations at the room corner (x= 1m, y= 1m) on the communication floor.

6.2 SNR analysis

For simplicity, we consider one way of processing the resulting electrical signal from the different photodetectors, namely, selection of the photodetector with the best *SNR*, which can be written as

$$SNR_S = MAX_i \left(\frac{R \times \left(P_{s1} - P_{s0}\right)_i}{\sqrt{s_{pr}^2 + s_{bn}^2 + s_{s0}^2} + \sqrt{s_{pr}^2 + s_{bn}^2 + s_{s1}^2}} \right)^2 , \quad (3)$$

where ($1 \le i \le I$) is number of photodetectors, (s_{bn}) is the background light-induced shot noise, 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, and the receiver noise normally generated in the preamplifier components (s_{pr}).

LSMT in conjunction with the three square pyramidal receivers can significantly reduce the effects of ambient light noise and multipath distortion, since normally the desired optical signal reaches the receiver from all directions unlike the undesired interface signals. The background noise detected by a receiver from eight spotlights is calculated using (1) taking into account the *Az* and *El* angles. Consequently, the maximum BN level (P_{bn}) collected by the single wide FOV detector was found to be 8820 µW, when the room was illuminated by very directive eight spotlights, and 11.2 µW in either of the three detectors on the square pyramidal, which is a significant drop in the received BN.

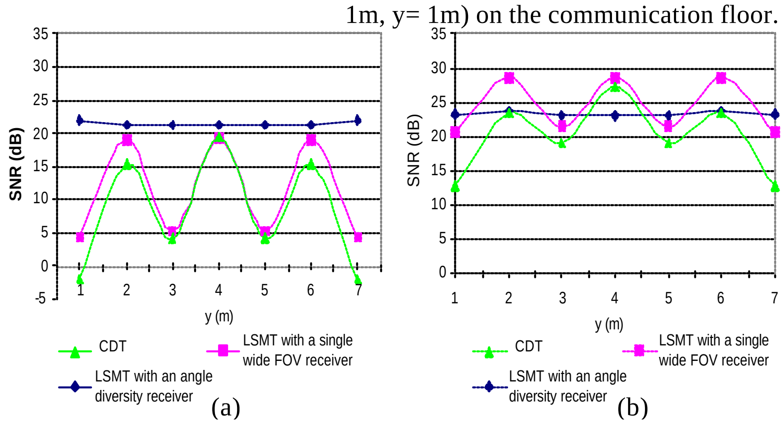

Figure 5: Signal-to-noise ratio level for CDT, LSMT with a single wide FOV receiver, and LSMT in conjunction with an angle diversity receiver, at (a) x= 1m, (b) x= 2m along the y-axis.

Observing (18), it is clear that the *SNR* improves by utilising an LSMT in conjunction with a receiver having angle diversity detector. Note that neither optical filter nor concentrator was used. Fig. 5 displays the *SNR* under the constraints of multipath dispersion and the impact of the background noise coming from highly directive spotlights (*n*= 33.1). The values for x and y in both figures refer to the corresponding Cartesian coordinates on the CF. Due to the symmetry property of the room, the results for *x* =3m equal the results for *x*= 1m.

System performance improvement is clearly observed when angle diversity detection is used. Fig. 5 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 reduced due to diversity and due to reduction in the FOVs. The improvement obtained by using the proposed structure can be seen; a significant *SNR* improvement over both CDT and the conventional multibeam structures is obtained as shown in Fig. 5.

LSMT with a wide FOV yields about 6 dB *SNR* improvement over CDT system with a comparable wide FOV, see Table 1. Furthermore, with only three branches diversity, the proposed LSMT is about 17 dB better than an LSMT that employs a wide FOV receiver as shown in Table 1. It also outperforms the CDT system (wide FOV) by 23 dB see Table 1.

Table 1. Maximum background noise level evaluated under eight spotlights (n= 33.1), maximum delay spread, and minimum *SNR* evaluated over the entire CF.

Configuration	Maximum P_{bn} (μW)	Maximum shot noise current (μA)	Maximum Delay spread (ns)	*SNR* (dB)
CDT with single wide FOV receiver	8820	0.314	2.45	-1.973
LSMT with single wide FOV receiver	8820	0.314	1.99	4.259
LSMT with angle diversity receiver	11.2	0.0112	0.979	20.822

Fig. 6 compares the delay spread performance for the three configurations at x= 1m, x= 2m and along the y-axis over the CF. It can be clearly seen that the LSMT combined with angle diversity technique has the lowest delay spread compared to the other configurations. This is due to the limited FOV associated with the diversity receivers. This limited FOV limits the number of diffusing spot contributions as well as the range of rays accepted. It can be clearly seen that the delay spread decreases towards the room wall sides and room corners, which is completely different to the CDT case.

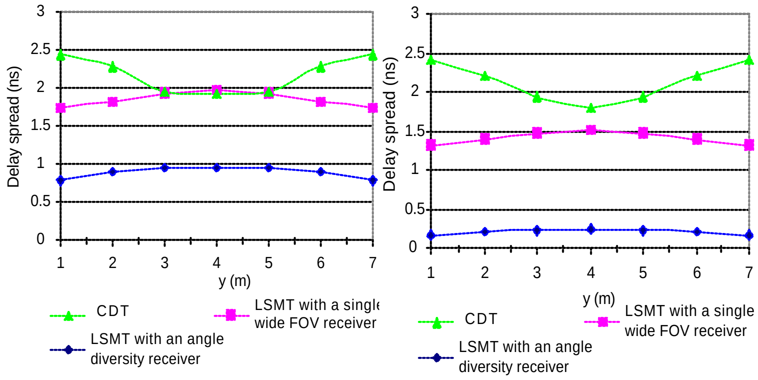

Figure 6: Delay spread for the three proposed configurations, at (a) x= 1m and (b) x= 2m along the y-axis.

7. Conclusions

The proposed line strip multibeam transmitter combined with angle diversity receiver (having narrow directive FOVs) can improve the performance of diffuse OW systems. Such a system combines the advantages of both DLOS links and diffuse systems. The improvement in performance achieved is due to the significant reduction in background noise as well as reduction in ISI effects. Using the multiple diffusing spot characteristics produced by the LSMT configuration it was demonstrated that a remarkable improvement can be achieved including: an extensive drop in the noise power level and a strong received signal due to the decrease in transmitter receiver separation as the transmitters (diffusing spots) are now large in number. Furthermore, our results indicated that in an LSMT link, a diversity receiver with three branches can improve the SNR by up to 23 dB compared to single-element receiver with a wide FOV, while providing a smaller rms delay spread and more robustness.

7. References

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