Analysis of Antenna Diversity Combining Schemes for LSMS in an Optical Wireless System

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Abstract— In this paper, we analyze and evaluate the transmission link performance of various receiver antenna diversity schemes for use in combination with a novel line strip spot diffusing optical wireless configuration in non line-of-sight (LOS) environments. The proposed line strip multibeam systems (LSMS) employ a multibeam spot diffusing transmitter and a composite receiver consisting of narrow field-of-view (FOV) branches. Equal gain combining (EGC), maximum ratio combining (MRC), as well as selection combining (SC) are analyzed in this work for the proposed strategy. The impairments performance imposed by multipath dispersion and ambient light noise are assessed with particular attention to their impact on the combining schemes. Furthermore, LSMS employing angle diversity receiver with three and seven narrow FOV branches is evaluated. We have also compared the LSMS results with a conventional system that employs a wide FOV receiver. Simulation results show that the MRC method, when seven branches are employed and under the constraint of multipath propagation and directive noise sources, demonstrates a promising performance improvement of up to 4 dB in signal-to-noise ratio (SNR) over the case of three branches and 28 dB over the conventional diffuse link.

1. INTRODUCTION

In an optical wireless (OW) system, channel impairments including ambient light noise and multipath propagation are the most important factors that need to be investigated. A useful observation is that the diffuse signal arrives at the receiver from a multitude of directions, whereas the noise in an indoor environment tends to be directive. Therefore diversity techniques can be beneficially employed. Changes in the ambient light noise and multipath propagation can cause large variations in the received SNR, depending on many issues: (a) the transmitter position as well as its radiation pattern, (b) receiver's location orientation and its FOV, and (c) noise sources; their position and their directivity. One of the most efficient and simple techniques that can be used to overcome the destructive effects of multipath dispersion and background noise as well as minimise the effects of SNR fluctuation is diversity. Diversity is conventionally considered as a method of mitigating fading effects in radio frequency by obtaining independent replicas of the transmitted signal [1]. In OW systems where fading is not an issue [2], diversity serves other purposes, such as rejecting ambient light noise sources, increasing signal collection, and combating shadowing. OW diversity techniques depend on employing several receivers, where each receiver is oriented at a specific angle. By having more than one direction to select from, both the received optical signal and SNR can be significantly improved in the receiver. The use of diversity techniques in OW environments was studied by several researches [2 - 4]. One of the diversity techniques that has been widely studied is the angle diversity receiver (ADR) configuration. Several receiver branches with a relatively small FOV usually compose an ADR.

Previous studies [2, 3] have shown that a limited receiver FOV may improve the SNR as well as reduce the impact of multipath propagation. Further improvements may be obtained by using a number of narrow FOV receivers oriented in different directions. In order to achieve a high SNR, the diversity receiver has to process the received signals in a fashion that maximizes the power efficiency of the system. There are several possible diversity schemes that can be considered. The most common techniques include MRC, SC, and EGC, which differ according to how the signals are weighed and combined. These methods are discussed in the following sections.

2. CHANNEL PROPAGATION MODEL UNDER DIVERSITY DETECTION

In OW communications IM/DD is the preferred choice [1]. Multipath propagation in an indoor OW channel using IM/DD can be fully characterised by the impulse response $h(t)$ of the channel

$$I(t, Az, El) = \sum_{k=1}^{L} R\, x(t) \otimes h_k(t, Az, El) + \sum_{k=1}^{L} n_k(t, Az, El) \;, \qquad (1)$$

where $I(t, Az, El)$ is the received instantaneous current in the photodetector at certain position due to m reflecting 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, $x(t)$ is the transmitted instantaneous optical power of the transmitter, $\otimes$ denotes convolution, the receiver responsivity is R, and $n(t)$ is the ambient light noise. By evaluating the OW impulse response (through numeric simulation [2]), several parameters can be obtained such as power spatial distribution, channel pulse response, SNR, and root-mean-square delay spread. The reflecting elements were formed by dividing the room surfaces into a number of equal size square shaped reflection elements. These were subsequently represented as secondary emitters and modeled as Lambertian reflectors with a specific reflection coefficient. In this paper, the reflection coefficient is taken to be 0.8 for walls and ceiling, and 0.3 for the floor. The angular distribution of the emitter radiation intensity is given by

$$R(J) = \frac{n+1}{2p} P_s \cos^n(J) \qquad (2)$$

where P_s is the total average transmitted optical power, J is the angle with the normal to the emitter surface element, and n is the mode number describing the shape of the transmitted beam.

The simulation was performed using an empty rectangular room, which has a width of 4m, a length of 8m and a height of 3m. The transmitter was always located at the center of the room at (4 m, 2 m, 1m), pointed upwards and emitted 1W total optical power. Safety standards have been established for laser safety and optical transmitters are classified in accordance with the total transmitted power [5]. Optical radiation at such amount of power can present a hazard to the eye and to the skin. In spite of that, different techniques can be used to reduce the impact of such a high power source. For example, the size of the optical source can be extended and a hologram mounted on the transmitter as in spot diffusing techniques can be used [6]-[8]. The simulation was carried out with the receiver placed at different locations on the communication floor (CF). The ADR and the single detector (for the conventional diffuse link) were always placed on the CF, a plane 1m above ground. Throughout this paper, a photodetector with a photosensitive area of 1 cm^2 and a responsivity of 0.5 A/W are used. The room illumination was provided by eight spotlights of 65 W power positioned equidistantly in the ceiling. For our purpose these represent ambient background interference. Spotlights were deliberately assumed as they can be (at one extreme) very directional and result in signal burn-out effects underneath such a source. Spotlights, however, have been modeled as generalized Lambertian sources of order n= 33.1. Interference from daylight (windows and doors) was not considered in this work.

3. DIVERSITY RECEIVER PERFORMANCE ANALYSIS

The main role of the optical receivers in an OW environment is to convert the incident optical power P_r into electrical current through a photodetector. Since the diversity receiver consists of multiple branches each having its own photodetector, the average signal (photocurrent) I_{rk} of diversity branch k is directly proportional to the incident P_r, which can be written as

$$I_{r_k} = RP_{r_k} \qquad (3)$$

Because the received optical signal is affected by the ambient light noise as well as the electrical noise induced by current fluctuations, the photocurrent generated in response to the received optical signal as well as the noise for the diversity branch k as in (1) can be rewritten as

$$I_k = I_{r_k} + I_{n_k}, \qquad (4)$$

where I_{nk} is the noise current at diversity branch k and is (assumed to have a Gaussian distribution) and include all the different noises such as background shot noise, signal shot noise, and preamplifier noise. The variance, s_n^2, of the associated shot noise current can be calculated from the autocorrelation function of I_n, [9] which is related to the spectral density $S_n(f)$. The total shot noise is well described by Gaussian statistics with zero mean and variance

$s_{n_k}^2 = \left\langle I_{n_k}^2 \right\rangle = \int_{-\infty}^{\infty} S_{n_k}(f)\, df = 2\, q\, R\, P_{n_k} BW$, where q is the electron charge, P_n is the noise power associated with the current noise I_n, BW is the receiver bandwidth. The noise associated with the received signals can be subdivided into two parts s_{s0}^2 and s_{s1}^2 which represent the variances of the shot noise currents on the '0' and '1' of the optical data stream, respectively, therefore

$$s_{s0}^2 = 2\, q\, R\, P_{s0}\, BW, \quad s_{s1}^2 = 2\, q\, R\, P_{s1}\, BW, \text{ and } s_{bn}^2 = 2\, q\, R\, P_{bn}\, BW \qquad (5)$$

where P_{s0} and P_{s1} are the signal powers associated with logic '0' and logic '1'. Both signals (P_{s0} and P_{s1}) are corrupted by the background noise power P_{bn} (eight flood spotlights), whose shot noise contribution is

Since the adopted preamplifier offers a noise current spectral density S_{pr} of 2.7 $\mathrm{pA}/\sqrt{\mathrm{Hz}}$ [10] over a bandwidth of 70 MHz, s_{pr} is given by

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

Notice that the sum of Gaussian random variables is also a Gausssian random variable with a standard deviation

$$s_0 = \sqrt{s_{pr}^2 + s_{bn}^2 + s_{s0}^2} \text{ and } s_1 = \sqrt{s_{pr}^2 + s_{bn}^2 + s_{s1}^2} \qquad (7)$$

where s_0^2 and s_1^2 are the noises associated with logic '0' and logic '1'. The probability of error in such a system can be evaluated as [9]

$$P_e \approx \frac{e^{-Q^2/2}}{Q\sqrt{2p}} \text{ with } Q = \frac{RP_{s1} - RP_{s0}}{s_0 + s_1} = \frac{I_r}{s_n} \text{ and } SNR = Q^2 \qquad (8)$$

As previously mentioned, the performance of an OW system depends on the SNR. SNR_k is defined as the instantaneous signal-to-noise ratio of the k^{th} diversity branch in an L diversity branches scheme. Therefore the instantaneous SNR can be expressed as $\mathrm{SNR}_k = (I_r/s_n)^2_k$.

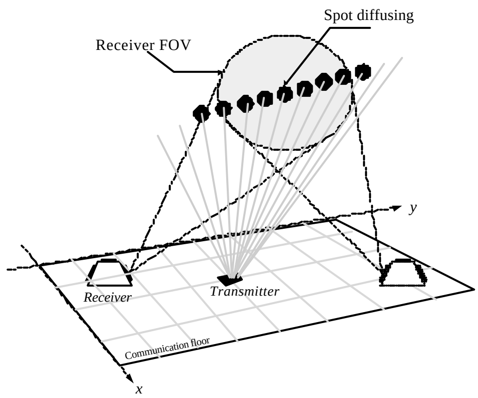


Fig. 1 Line of diffusing spots formed on the ceiling by multibeam transmitter and directional diversity receivers located on the communication floor.

4. SELECTION AND COMBINING TECHNIQUES

In this section, the application of selection and combining techniques for ADR as well as computing the SNR are carried out. In order to process the resulting electrical signals, three techniques are proposed, namely, selection combining, maximum ratio combining, and equal gain combining.

4.1 Selection combining (SC)

The mechanism of SC is usually based on the examination of the received signal components from each branch where the best SNR is selected. Within this work, three and seven diversity branches are examined. In general, let L represents the total number of diversity branches and let the k^{th} branch SNR be SNR_k. Therefore the SNR after considering the selection technique is given by:

$$\mathrm{SNR}_{SC} = \max_k \left(\frac{R\left(P_{s1} - P_{s0}\right)_k}{s_{n_k}} \right)^2, 1 \le k \le L \qquad (9)$$

4.2 Maximum ratio combining (MRC)

In contrast to the SC approach where the multiple signals on the diversity branches are not fully utilized, the output signals of all the receiver branches are combined through an adder circuit, in which each output is directly proportional to its SNR, this approach is referred to as maximum ratio combining. Each receiver branch comprises one SNR estimator circuit and a variable weighting circuit, hence the weighted output signals are summed. In this technique, the received signals are adjusted in magnitude by weighting factors in order to maximize the SNR at the output of the combiner. Also the weighting applied to each diversity branch is adjusted independently according to the SNR. The signals from all L branches are combined using weights equal to w_k. One of the main advantages of the MRC scheme is that it reduces the dominant effect of background shot noise by assigning a low w_k value to the branch that is most severely affected by BN, hence improving the system performance. It can be demonstrated that the SNR of the maximal ratio combiner is maximum when the weight factor w_k at receiver branch k is chosen to be proportional to each branch signal-to-noise-variance ratio, i.e, $w_k = I_{rk}/s^{2}_{nk}$. Therefore, the SNR obtained using MRC method is obtained by

$$\mathrm{SNR}_{MRC} = \frac{\left(\sum_{k=1}^{L} w_k I_{r_k}\right)^2}{\sum_{k=1}^{L} w_k^2 s^2_{n_k}} = \frac{\left(\sum_{k=1}^{L}\left[\frac{I_{r_k}}{s^2_{n_k}}\right] I_{r_k}\right)^2}{\sum_{k=1}^{L}\left[\frac{I_{r_k}}{s^2_{n_k}}\right]^2 s^2_{n_k}} = \sum_{k=1}^{L}\frac{I^2_{r_k}}{s^2_{n_k}} = \sum_{k=1}^{L}\mathrm{SNR}_k \quad (10)$$

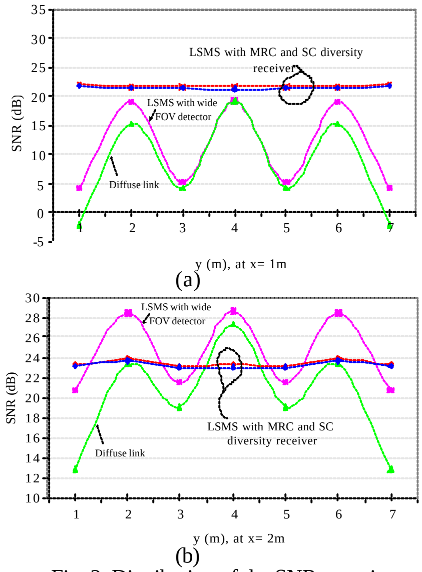


Fig. 2. Distribution of the SNR at various locations on the CF.

4.3 Equal gain combining (EGC)

The equal gain combiner is generally maximum ratio combiner, but without attempts of weighting the signals; all the weights at all the diversity branches are equal to a constant. The same previous description for the signal processing can be used for the EGC method. The SNR of the equal gain combiner for a multiple branches receiver is given by $\mathrm{SNR}_{EGC} = w_1 \times \mathrm{SNR}_1 + w_2 \times \mathrm{SNR}_2 + w_3 \times \mathrm{SNR}_3$, and the overall form of the SNR for the EGC can be written as

$$\mathrm{SNR}_{EGC} = \sum_{k=1}^{L}\left(\frac{R\,(P_{s1}-P_{s0})}{\sqrt{s^2_{pr}+s^2_{bn}+s^2_{s0}}+\sqrt{s^2_{pr}+s^2_{bn}+s^2_{s1}}}\right)_k^2 \quad (11)$$

5. SIMULATION RESULTS

5.1 LSMS in conjunction with three receivers

A new structure composed of diffusing spots that employ multibeam transmitters is proposed and examined. For this case where 80 diffusing spots are employed, the total allowable optical power produced by the transmitter remains at 1 W and therefore each spot will contribute 12.5 mW. Figure 1 shows the diffuse optical wireless communication system model with the proposed line strip multibeam transmitter. The multibeam transmitter is assumed to produce 80 × 1 beams aimed at the ceiling, 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 the adjacent spots is 10 cm. These spots become secondary distributed emitters, which emit Lambertian radiation. 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 of the 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°, the third one is facing up with *El* of 90°, and the *Az* for the three faces of the detectors are fixed at 0°, 180° and 0°. 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°. These angles were chosen such that the ADR is designed with at least five diffusing spots 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 of the conventional diffuse link, where a wide single receiver is used and 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 performance of an OW system using LSMS in conjunction with diversity detection is investigated for the three diversity processing methods of detection SC, EGC, and MRC. Furthermore, comparison with a conventional diffuse link is made in order to assess the merits of the LSMS configuration. The performance of the three signal processing schemes is compared in Fig. 2. It is also given in a tabular form (Table 1) for a receiver position near one of the room corners where the distance between transmitter and receiver is maximum and the noise source is dominant. Figure 2 illustrates the SNR of three configurations conventional diffuse link, LSMS with a wide FOV receiver, and LSMS with three diversity receivers. The values of x and y in this figure refer to the corresponding Cartesian coordinates on the CF. Due to the symmetry property of the room, the results for x =3 equal the results for x= 1. SNR calculations were performed for both systems in seven different locations along the y-axis at constants x= 2m and x= 3m which scans the peaks and troughs of BN.

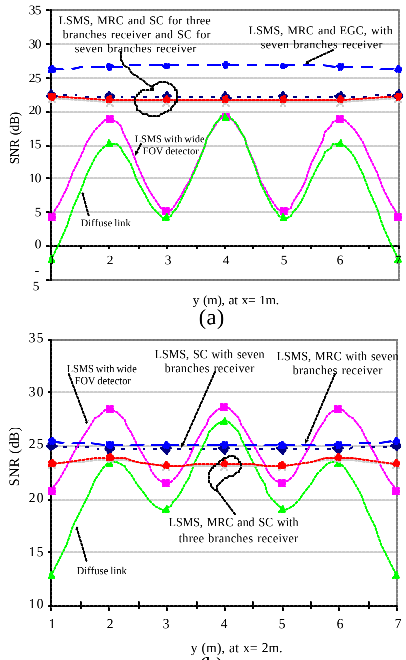
Conventional system	Line strip multibeam transmitter			
Diffuse link with single wide FOV receiver	LSMS with Single wide FOV receiver	Diversity detection with SC	Diversity detection with MRC	Diversity detection with EGC
-1.973 dB	4.259 dB	21.88 dB	22.148 dB	22.148 dB

Table 1. Comparison of SNR for a LSMS system and a conventional diffuse system at the room corner.

Figure 2 shows that when LSMS is accompanied by the three square pyramidal receivers, the impact of ambient light noise and multipath distortion are significantly reduced. This is due to the fact that normally the desired optical signal reaches the receiver from all directions unlike the undesired interface signals. The BN detected by a receiver from eight spotlights is calculated taking into account the *Az* and *El* angles. At locations near the room walls, corner, and even at the room center, the maximum BN level P_{bn} collected by the single wide FOV detector was found to be 9.45 dBm, when the room was illuminated by very directive eight spotlights. The maximum BN power dropped to -43.46 dBm in any of the three detectors of the square pyramidal, which represents a significant drop in the received BN. System performance improvement is clearly observed when angle diversity detection is used. Figure 2 shows SNR improvement in particular at room corners and along the y-axis where the directional interference peaks exist. Compared to diffuse link, LSMS configuration yields an SNR improvement of more than 6 dB when a single wide FOV receiver is used and about 24 dB when it is combined with angle diversity detection (SC, EGC, and MRC), see Table 1. Simulations and theoretical calculations have shown that utilizing such diversity receiver structure has led to comparable SNR results for the SC, MRC, and EGC techniques. This is due to the limited number of detectors (three) as well as being due to the physical design of the receiver where the power received by one of the detectors is dominant compared to the others. Because of the difficulty associated with the SC and MRC in terms of SNR estimation, EGC (where the combining weight may all be set to unity as in our case) can be used due to its simplicity compared to the other combining techniques. Therefore, employing EGC with a unity-weighing factor can lead to an SNR comparable to that of the MRC diversity method with low cost and lower complexity.

5.2 LSMS in conjunction with seven receivers

In contrast to the previous section where three diversity detectors were used, in this section a seven branches receiver is used instead. The *El* of six photodetector remains at 35°, the first branch faces up with *El* of 90°, and the *Az* for the six faces of the detectors are fixed at 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. In addition, their FOVs have been chosen to achieve the best SNR, hence, six FOV branches are restricted to 35°, whereas the detector that faced up was set to 25°. These FOVs were selected so that five spots can be seen by the respective detectors as in the previous section. System performance improvement is clearly observed when LSMS utilizes seven branches detector. Figure 3 shows SNR improvement in particular when the MRC scheme is used. It also demonstrates an SNR improvement of about 4 dB over the case of SC scheme at positions near the room corners and a comparable SNR level underneath the line of diffusing spots. It also shows a significant SNR improvement, of about 28 dB over the conventional diffuse link. This improvement is due to the fact that a seven branches detector is used instead of three, as well as to the MRC features as clearly seen from (10). It is found that about 22 dB SNR improvements for the SC and 26 dB SNR improvements for the EGC and MRC combining methods over the conventional diffuse link.



(a) (b)

Fig. 3 SNR distribution.

Figure 3 has combined all the configurations studied in this paper, with respect to the SNR. It has demonstrated that the MRC scheme provides the best system performance over the others. A conclusion that can be drawn is that at the price of increased circuit complexity, MRC can achieve better performance. Furthermore, observing (9) and (10) confirm the fact that the MRC approach does outperforms the SC approach. However, this improvement is realized at the cost of increased complexity in addition to considerable signal processing in order to achieve the correct weighting gain factor compared to the simple SC method. Further, MRC can produce a reasonable SNR even when the output signals of each diversity branches are not acceptable. On the other hand, comparing the SNR curves shown in Fig. 3, LSMS accompanied by seven branches receiver can achieve a better SNR compared to the three branches receiver. Furthermore, as in (11) and previous discussion, EGC offers a comparable SNR level compared to the MRC, which yields to a good OW system performance in an economic fashion.

6. CONCLUSIONS

We have analyzed, simulated, and compared two different structures of reception; three and seven detectors in conjunction with a line spot diffusing configuration. We have examined the system performance under the constraints of background noise interference and multipath dispersion. It was found that LSMS with only three branches receiver and using simple diversity techniques such as SC or EGC offers a significant SNR improvement (of about 24 dB) over the single detector configuration. The three receiver configuration also offers the advantage of a low cost and lower complexity. The seven branches detector structure offered only 4 dB additional improvement using EGC or MRC detection techniques, and thus offered about 28 dB improvement over the conventional diffuse link at the cost of a substantial increase in complexity. A conclusion that can be drawn is that the LSMS with diversity detection and EGC offers a significant SNR improvement over the conventional diffuse system. Increasing the number of the receiving elements, however, can improve the signal detection and system performance but at the price of high cost and complexity.

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