Multi-line Multi-Spot Diffusing Indoor OW Channel with A 7-Detectors Diversity Receiver

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Abstract: We evaluate the optical gain achieved in an indoor optical wireless (OW) channel when increasing the number of branches of the angle diversity receiver from three to seven. Simulation is carried out for five different spot diffusing geometries as to compare the systems' performance when the square-base three branch angle diversity receiver is replaced by a hexagonal-base and seven-branch design. The channel performance is evaluated in terms of signal-to-noise ratio (SNR) where the results are computed and plotted for various receiver positions. Further channel gain of up to 5 dB at worst links is also shown when the diversity receiver's signals are all combined using Maximum Ratio Combining (MRC) instead of only selecting the one branch with best SNR.

1. INTRODUCTION

Within the indoor environment, the factors that affect optical signal reception are mainly the background noise [2] and the multipath reflection. The background noise has more degradation influence on the optical pulse collected by the optical receiver than the noise induced by the electronic components within the receiver. The interference from the ambient noise caused by artificial lighting in the room such as florescent and/or incandescent light sources introduces corruption on the received pulses. Signal multipath propagation results in temporal spreading of the pulse that in turn causes the binary transmitted symbols to overlap which introduces severe Inter Symbol Interference (ISI) that, if not completely corrected, will result in erroneous message detection and interpretation.

IR links can be established under two main classifications: 1) directional or non directional and 2) line-of-sight (LOS) or non LOS. Directed links improve power efficiency and minimise multipath dispersion, but require inherent alignment between the transmitter and receiver to establish communication. LOS links impose the necessity to maintain an uninterrupted line of sight between the transceivers. To avoid the restrictions imposed on directed LOS links, non directed links, also known as “diffuse links”, allow the system to operate even when barriers are placed between the transmitter and receiver; and are therefore becoming increasingly popular. A diffuse transmitter points vertically upwards towards the ceiling, emitting a wide beam of infrared energy and the receiver has a wide field-of-view (FOV), to enable it collect the signal from all reflective surfaces after it has undergone multiple reflections from the ceiling, walls and room objects. Due to these multiple paths, the transmitted pulse duration associated with the binary bit will become expanded when the optical receiver detects most of the signal. Moreover, the signal level will become impaired as the background noise rays travel the same paths as the transmitted signal before reaching the receiver.

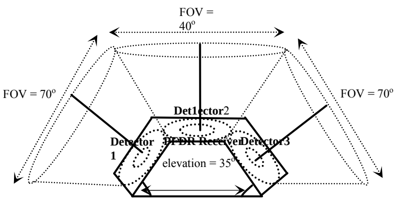
To mitigate these effects, the fully diffuse transmitter would be replaced by one that produces multiple narrow-beams casting small diffusing spot on the ceiling. This technique, known as spot diffusing [3-7], has been proposed and proved to improve the signal quality in the room where the spots will become secondary Lambertian transmitters of the total optical transmitter power being evenly distributed among their beams. The narrow beams can be practically produced with holographic optical diffuser mounted on the face of the transmitter or by computer generated methods known as CGH [8,9]. The latter has the advantage of varying the intensity of a particular spot and/or the intensity distribution of the spots. The propagation of the transmitted signals follows multiple paths before reaching the receiver’s collection area in the indoor environment thus causing temporal dispersion on the received pulses.

The severe effect of the background noise on the transmitted signal can be reduced by replacing the wide field-of-view receiver with an angle diversity design incorporating multiple photodetectors. Such designs have detectors pointed to different directions and therefore offer two advantages: a) the achievement of high optical gain over their wide field-of-view counterparts and b) the significant reduction of the effects of ambient light noise. With circuitry in the optical receiver to implement signal combining techniques, the diversity receiver is able to combine signals from its branch detectors or select the one with best SNR; since noise is directional in this environment. An efficient angle diversity receiver design has to produce a high and uniform SNR distribution within the room. Increasing the number of side branches of the diversity receiver with an optical photo detector on each has been shown to improve the gain achieved with spot diffusing configurations [12]. Our previous research work showed that considerable gain for an indoor OW channel was attained over the conventional diffuse system (CDS) by using spot diffusing transmitter instead of a fully diffuse one and a three branch angle diversity receiver in place of a single wide field-of-view (FOV) receiver. In this paper, we extend the treatment given in [1] by investigating the advantages of employing a seven detectors receiver.

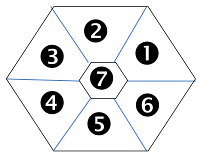
2. SYSTEM SETUP

The communication plane (CP) of this optical wireless link is 1 meter above the floor. A totally empty mid-sized room (size: 4m×8m×3m Length, Width, Height) was used for the simulation. The room has no doors or windows and the walls and ceiling plastering results in 80% reflectivity of incident light whereas the floor tiles produce reflectivity of 30%. A 1W upright optical transmitter (90^{o} elevation) is placed on the centre of the communication plane (at x = 2m and y = 4m). Multiple narrow beams are produced with a holographic device mounted on the face of the optical transmitter that diverge the emitted optical power hence resulting in a cluster of equally-separated narrow beams casting a line (s) of spots on the ceiling.

The fully diffuse conventional transmitter (CDS) had a single transmitter and a single receiver with wide FOV; i.e., full range, reception angle=180^o. The five spot diffusing configurations were: i) a single line of 80 spots on the ceiling at x = 2m and along the room width; ii) three lines of 30 spots each on the ceiling at x = 1, 2 and 3m and along the room width; iii) two intersecting diagonals of 40 spots each on the ceiling and iv) a vertical line of 20 spots and a horizontal line of 60 spots intersecting in the centre of the ceiling. The two angle diversity receiver's angles corresponding to side elevation, azimuth and detectors FOVs are shown in Figure 1 c).



a) side view: 3 detector



b) top view: 7-detectors

	7-detector	3-detector
Elevation angles	20^o/20^o/20^o/20^o/ 20^o/20^o/90^o	35^o/35^o/35^o
Azimuth angles	55^o/90^o/125^o/235^o/ 270^o/325^o/0^o	0^o/180^o/0^o
Fields-of-view (FOV)	60^o/50^o/60^o/60^o/ 50^o/60^o/24^o	70^o/40^o/70^o

c) 3 and 7-detectors angle diversity receivers angles

Figure 1: Angle diversity receivers

In order to evaluate the effect of background noise in the channel, eight incandescent light sources (Philips PAR 38) were placed equidistantly on the ceiling, two metres apart (along the lines x = 1m and x = 3m) starting at x = 1m and y = 1m; thus producing a well-illuminated environment. The optical power emitted by each lamp is 65W.

Multipath simulation was carried using ray-tracing method for both received optical signal and peak background noise following the algorithm explained by Barry et al. [10] up to second order reflection with modification to cater for the reception angle of a detector placed on an elevated branch of an angle diversity receiver, as will be explained in Section 3. Simulation was carried out along the line near a wall (x = 1m) where signal receptions is expected to be weaker than along the room centre line due to reflections. Due to symmetry in the room shape and the studied spot diffusing configurations, receiver locations along the room centre line will mark higher performance than at the two room sides.

3. SYSTEM ANALYSIS

A. Impulse response

The impulse response was calculated in time bins based on the time rays take to arrive at the detector. The time bin value was set to the time light takes to travel between neighbouring elements and is given by $\Delta t = \sqrt{\Delta A}/c$ where ΔA is the area of the differential element and c is the speed of light. This time bin smoothes the artificial discretisation process introduced (discrete reflecting elements).

The pulse response of the link is produced by convolving a pulse corresponding to the maximum optical power of the transmitter (1 Watt) and with duration equal to the inverse of the bit rate (50 Mbits/s in our case), with the time impulse of the system.

The optical power received at a receiver's detector has a direct power component when there is an unobstructed line-of-sight (LOS) path between the transmitter and the receiver in addition to the powers received from the first and second order reflections.

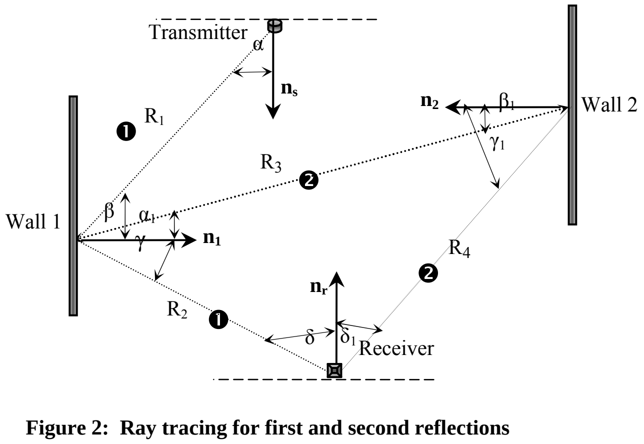


Figure 2: Ray tracing for first and second reflections

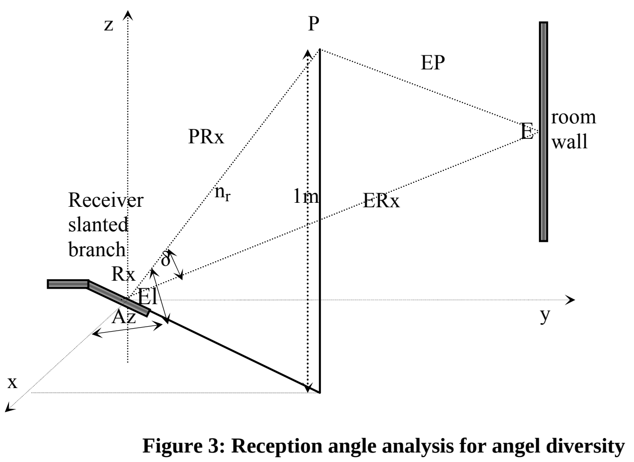


Figure 3: Reception angle analysis for angel diversity

Hence, $P_r = P_d^{(0)} + \sum_{i=1}^{M} (dp_r^{(1)})_i + \sum_{i=1}^{N} (dp_r^{(2)})_i$ where P_d is the direct optical power reaching the receiver, dp_r is the differential optical power of a reflective element off room surfaces, M and N are the number of reflecting elements of the first and second order reflections in the room, respectively.

Following the geometrical analysis shown in Figure 3 when an angle diversity receiver is used, the reception angle δ is given by

$$\cos(\delta) = \frac{\left(1+\frac{1}{(\tan(\mathrm{El}))^2}\right)+\left((x_r - x_E)^2 + (y_r - y_E)^2 + (z_r - z_E)^2\right) - \left(\left(\frac{\cos(Az)}{\tan(El)} + x_r - x_E\right)^2 + \left(\frac{\sin(Az)}{\tan(El)} + y_r - y_E\right)^2 + ((z_r+1) - z_E)^2\right)}{2\sqrt{(x_r - x_E)^2 + (y_r - y_E)^2 + (z_r - z_E)^2}\sqrt{\left(\frac{\cos(Az)}{\tan(El)} + x_r - x_E\right)^2 + \left(\frac{\sin(Az)}{\tan(El)} + y_r - y_E\right)^2 + ((z_r+1) - z_E)^2}}$$

B. Signal-to- noise ratio calculation

Using the simple On-Off keying (OOK) modulation technique for our OW system, the SNR associated with the received pulse is figured using the difference between the two power levels of the transmitted binary symbols. Hence, SNR is given by $SNR = \left(R \times \left(P_{s1} - P_{s0}\right)/\sigma_t\right)^2$ where R is the detector responsivity (R = 0.5 A/W in this study), P_{s1} and P_{s0} are the power associated with a received signal of logic "1" and logic "0" respectively and σ_t^2 is the total noise variance which can be classified into three categories as $\sigma_t^2 = \sigma_{bn}^2 + \sigma_{pr}^2 + \sigma_s^2$.

The background induced shot noise, σ_{bn}, can be computed from its respective associated background noise power level P_{bn} using $\sigma_{\mathrm{bn}} = \sqrt{2 \times q \times P_{bn} \times R \times BW}$ where q is the electron charge and BW is the receiver bandwidth.

The preamplifier produced shot noise σ_{pr} was calculated as equal to 0.023 μA when a bandwidth of 70 MHz is used in conjunction with the amplifier proposed by Elmirghani et al with positive-intrinsic-negative base-junction-transistor (PIN-BJT) design [11], where its noise current density is 2.7 pA/√Hz.

Finally, the noise induced by the received signal power σ_s is very small in this work and therefore can be neglected.

C. Selection/Combining Techniques

In an optical receiver with multiple branches, the collected signal from each branch detector is processed separately to produce the resulting output electrical signal. Circuitry integrated within the optical receiver has the function of either the selection of one branch detector or the combination (with some predefined criteria) detected optical signal from some or all branches. The select best scheme also known as selection combining (SC) chooses the branch with best SNR value. Therefore, $\mathrm{SNR}_{\mathrm{SC}} = \max\left(I/\sigma\right)_i^2,\ 1 \le \mathrm{i} \le \mathrm{j}$ where j is the number of detectors. Two other widely known combining techniques in diversity reception are the equal gain combining (EGC) and the maximum ratio combining (MRC).

While the EGC method adds the detected signals from all branches together, the MRC combines these signals according to weights proportional to their collected noises. It turns out that the EGC technique is a special case of the MRC with the combining weights set to unity (i.e., 1). For such receiver, a signal multiplier circuit is added before the combiner circuit which takes the weight factor from the SNR estimator of a branch detector to produce the proportional gain of that branch. The maximal-ratio combiner circuit requires a variable gain amplifier per sector and a summing circuit. Clearly, the advantages of the combining methods are best achieved as the unbalancing in the distribution of the SNR among the sectors increases. Under the assumption of independent noise, the optimum output SNR is achieved by the maximal-ratio combining receiver [12]. The result is maximum SNR produced as the severely noise degraded signals have much less contribution when computing the total SNR of the receiver than signals attained by branches that significantly avoid the directive noise. The SNR using the MRC method is given by $\mathrm{SNR}_{\mathrm{MRC}} = \left(\sum_{i=1}^{j}(w_i \cdot I_i)\right)^2 / \sum_{i=1}^{j}(w_i \cdot \sigma_t)^2, \quad 1 \le \mathrm{i} \le \mathrm{j}$, where σ_t is the total noise standard deviation. And with the weight $\mathrm{w_i} = I_i/\sigma_t^2$,

$$\mathrm{SNR}_{\mathrm{MRC}} = \sum_{i=1}^{j}\left(I_i/\sigma_t\right)^2, \quad 1 \le \mathrm{i} \le \mathrm{j}.$$

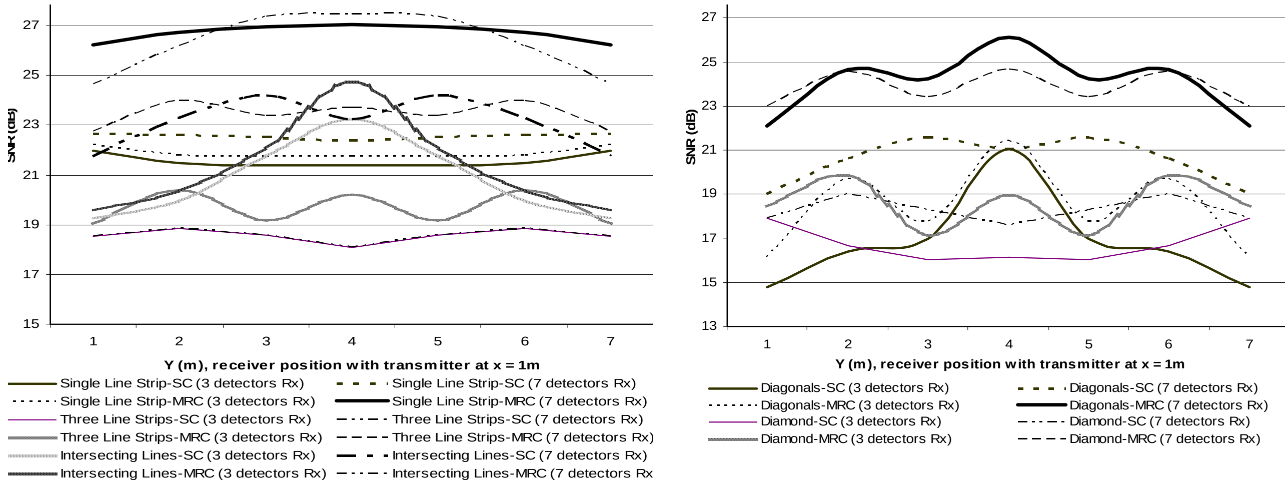
4. SIMULATION RESULTS

The SNR distribution along the x = 1m line for the single line, three lines and the intersecting lines is plotted in Figure 4 a) while Figure 4 b) shows SNR results for the diagonals and diamond configurations. The increase in SNR due to the seven detectors receiver compared with the three detectors can be clearly observed for all five configurations. It is worth noting that using MRC technique, the intersecting lines achieves a uniform and higher SNR than the single line when the receiver is closer to the transmitter and away from the room walls. This is due to the increased number of diffusing spots in the vertical line intersecting at the room centre on the ceiling, which strengthened signal reception around the room centre. However, near the room walls, a higher gain in terms of SNR is achieved by the intersecting lines employing the seven detectors receiver compared to that obtained by the single line.

The SNR distribution for the three line strips configuration shows an oscillating pattern with minimums at receiver positions directly under noise sources, i.e., the spot lamps (at y = 1m, 3m, 5m and 7m). This is attributed to the fact that a large number of diffusing spots on the ceiling reverts to the conventional diffuse transmitter. Employing the seven detectors receiver with this spot diffusing configuration improves the overall performance particularly noted at locations severely influenced by the directive noise sources.

The results for both the diagonals and the diamond spot diffusing configurations show about a 4 dB SNR increase with the seven detectors receiver than with the three detectors when MRC is adopted, which is 2 dB higher than when using SC. It is also interesting to see that the use of the seven detectors receiver considerably increased signal reception for the diagonals configuration- compared with the three detectors receiver- at room edges but not at the room centre; however resulted in the opposite for the diamond configuration, as their SNR plots show in Figure 4 b).

Among all five configurations and using MRC with the seven detectors receiver, the three line strips produces the worst performance. The optical signal from the diffusing spots on the first and last line (along x=1m and 3m) is significantly corrupted by the noise sources that share the same lines. Hence with same transmitted optical power as other configurations, the total SNR levels for the three lines become lower.



a) single line, three lines and intersecting lines configurations

b) diagonals and diamond configurations

Figure 4: Signal-to-noise ratio (SNR) distribution for five different spot diffusing patterns under three and seven detectors angle diversity receivers with SC and MRC (along room width)

5. CONCLUSIONS

The advantage of using a seven-branch angle diversity receiver in conjunction with spot diffusing transmission for an indoor optical wireless channel has been demonstrated. Higher SNR levels have been shown for all five spot diffusing geometries over the case when a three detector receiver was used with an SNR increase of up to 2 dB. Further optical gain in terms of SNR was also attained with the employment of MRC combining technique. The intersecting lines configuration achieved the highest SNR levels when the receiver is placed away from the room walls. Moreover, the results show that the desirable evenly distributed high SNR is obtained with the simple line strip configuration marking more than 5 dB increase when adapting the seven detector receiver. Future work will investigate the effect of the optical transmitter's mobility on the performance of these spot diffusing configurations.

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