Evaluation of An Indoor OW Channel Employing A Mobile Multi-line Multi-Spot Diffusing Transmitter and A Seven Detectors Angle Diversity Receiver

Jamal M. Alattar and Jaafar M. H. Elmirghani

Institute of Advanced Telecommunications
University of Wales Swansea

Abstract: Multiple narrow beams' transmitters have been shown to improve the performance of the indoor optical wireless channels by a remarkable higher signal-to-noise ratio (SNR) and a lower signal delay spread over the conventional diffuse transmitters, especially at weak locations (when the transceivers have the highest separation distance). Further performance improvement is attained through the use of angle diversity receivers incorporating multiple detecting elements as well as circuitry for signal combining techniques as to enhance signal reception and to combat the background noise associated with the indoor channel. This work is an expansion of previous research with five different spot diffusing geometries and a hexagonal-base seven-branch receiver where the assumption of a stationary transmitter is extended to fully mobile transmitter and receiver along same communication plane. We present novel results for the influence of transmitter mobility on SNR at various receiver positions and provide detailed comparison among the five spot diffusing pattern. The results show high optical gain compared to conventional diffuse system when spot diffusing and angle diversity detection were used particularly at worst communication links with improvement of more than 30 dB.

1. INTRODUCTION

For efficient high speed optical wireless communication, the system designer has to take into account several factors that affect the channel performance. For the indoor environment, two main factors affect optical signal reception namely: 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.

The amount of received power and the received pulse shapes are influenced by the transmitter power and the sort of communication kind between the transceivers. To avoid the restrictions imposed on directed line-of-sight (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 can 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 distribution 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 FOV receiver by an angle diversity design with multiple photodetectors [5-7]. 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 branch 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.

In contrast to the general case where the transmitter is always placed at a fixed position, transmitter motion increases complexity of simulation. The influence of mobile transmitter on both conventional diffuse system and systems employing the spot diffusing transmission in conjunction with angle diversity detection is studied. The presented results for different patterns show higher SNR distribution compared with that of the conventional case even under the mobility effect.

2. SYSTEM SETUP

The optical wireless link is established on a communication plane (CP) 1 meter above the floor in a totally empty mid-sized room (size: 4m×8m×3m Length, Width, Height). 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 so as to diverge the emitted optical power therefore resulting in a cluster of equally-separated narrow beams which cast a line of spots on the ceiling.

In addition to the fully diffuse conventional transmitter (pointing upward with 1W optical power) with receiver having a wide FOV, the five simulated spot diffusing configurations shown in Figure 1 are: 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 angle diversity receiver's top view and azimuth angles, elevation angles and FOVs of its seven detectors are shown in Figure 2.

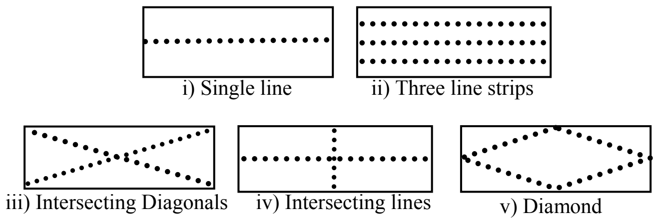
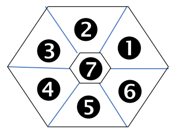


Figure 1: Simulated spot diffusing configurations on the ceiling



Elevation angles	$20^o/20^o/20^o/20^o/20^o/20^o/90^o$
Azimuth angles	$55^o/90^o/125^o/235^o/270^o/325^o/0^o$
Fields-of-view (FOV)	$60^o/50^o/60^o/60^o/50^o/60^o/24^o$

Figure 2: 7-detectors angle diversity receiver

Background noise was evaluated using eight incandescent light sources (Philips PAR 38) 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.

Ray-tracing simulation for received optical signal and for peak background noise following the algorithm explained by Barry et al. [10] up to second order reflection was developed in C++ with modification to cater for the reception angle of a detector placed on an elevated branch of an angle diversity receiver, as was analysed in [1]. Simulation was carried out along two lines on the communication plane: one closer to a wall, x = 1m (where the signal reception is expected to be weak due to reflections) and the other along the middle line of the CP, x = 2m. With 1m receiver position intervals, results were produced for 14 different receiver locations (starting 1m away from the wall). Due to symmetry in the room and spot patterns, results for the line x =3 will be the same as for x = 1m.

3. SYSTEM ANALYSIS

A. Mobile transmitter Analysis

The evenly spaced beams are produced with equal emitted angles. Based on the fact that as the transmitter moves around on the communication plane the beams angles are kept unchanged, the new coordinates of the spots can be computed with respect to the original transmitter location (at the centre of the communication plane). As the transmitter approaches close to a wall, some spots will start appearing on the wall as their beams get intercepted by that wall, Fig. 3a. A transmitter's motion in either the x or y direction causes spots to fall on the wall which the transmitter is approaching.

When the transmitter moves in the y direction (along room width), for example, the diffusing spots will move away from one wall and become closer to the other facing wall and vice versa. Further transmitter movement will result in some spots to fall from the ceiling and appear on the wall which blocks the beam making the spot to be cast on the wall instead of the ceiling. Therefore, as shown in Figure 3b, the new vertical distance Z_s (from the CP) of the spot that appears on a wall is found from $Z_s = Y_{t1} / \tan(\alpha_i)$ where $\tan(\alpha_i) = h_s/d_{yi}$ and $d_{yi} = width/2 - width/2N_y.\ i$ for $1 \le i \le N_y$ ($N_y \equiv$ number of spots on a line in the Y direction) and h_s = height – CP = 2m. Likewise, the new spot vertical distance corresponding to transmitter motion in the x direction can be computed by replacing the value of the room width by its length.

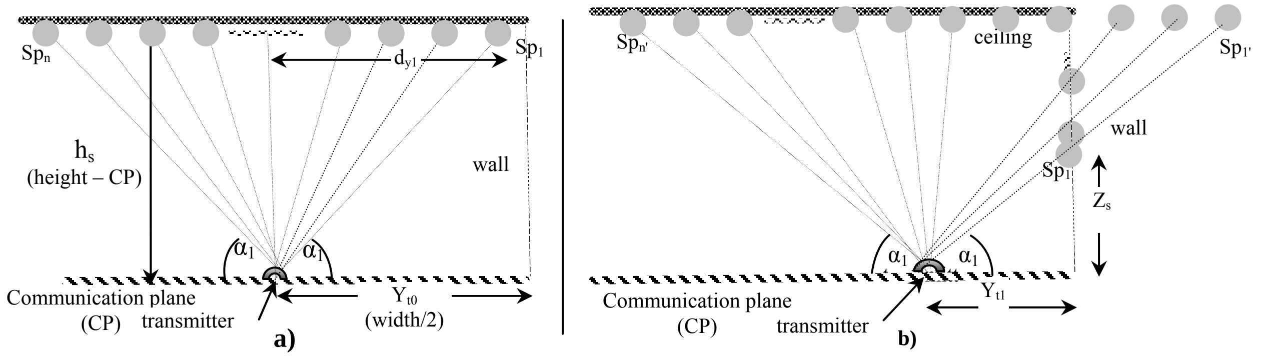


Figure 3: Mobile transmitter scenarios

B. Signal-to-noise ratio calculation

For simplicity, we use the On-Off keying (OOK) modulation technique for our OW system which employs a rectangular pulse with duration equal to the inverse of the bit rate (50 Mbits/s in our case), for each binary bit to be transmitted. The SNR associated with the received signal is given by $SNR = (R \times (P_{s1} - P_{s0})/\sigma_t)^2$ 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 first, σ_{bn}, is the shot noise induced by the background light which can be computed from its respective associated background noise power level P_{bn} using $\sigma_{\text{bn}} = \sqrt{2 \times q \times P_{bn} \times R \times BW}$ where q is the electron charge and BW is the receiver bandwidth.

The second noise component is the receiver noise generated in the preamplifier components. The preamplifier used in this work is the positive-intrinsic-negative base-junction-transistor (PIN-BJT) design proposed by Elmirghani et al [11]. This preamplifier structure has a noise current density of σ_{pr} = 2.7 pA/√Hz and a bandwidth of 70 MHz. Therefore, the preamplifier shot noise σ_{pr} is computed as $\sigma_{\text{pr}} = 2.7 \times 10^{-12} \sqrt{70 \times 10^6} = 0.023\ \mu\text{A}$.

Finally, the noise induced by the received signal power σ_s, which consists of two parts depending on the logical level of the received signal. The shot noise current is σ_{s1} when a signal of logic "1" is received and a different shot noise current σ_{s0} when a signal of logic "0" is received. This signal dependant noise is very small in this work and therefore can be neglected.

C. Maximum ratio combining

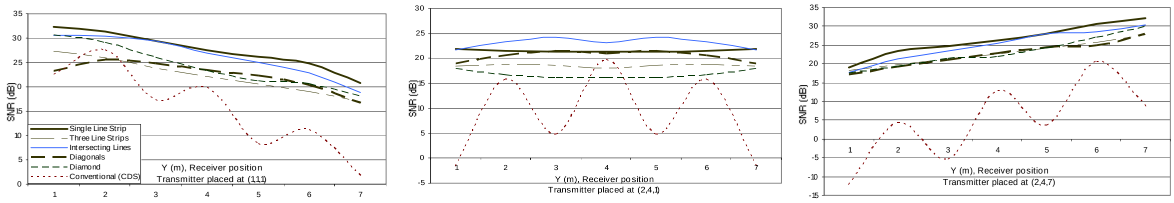
In an optical receiver with multiple branches, the collected signal from each branch detector is processed separately to produce the resulting output electrical signal. Circuitry integrated within the optical receiver has the purpose of either the selection of one branch detector or the combination (with 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. Two 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 MRC 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 $\text{SNR}_{\text{MRC}} = \left(\sum_{i=1}^{J} (w_i \cdot I_i)\right)^2 / \sum_{i=1}^{J} (w_i \cdot \sigma_t)^2, \quad 1 \le i \le j$, where σ_t is the total noise standard deviation. Maximum SNR results when the weight $w_i = I_i / \sigma_t^2$, so $\text{SNR}_{\text{MRC}} = \sum_{i=1}^{J} (I_i / \sigma_t)^2, \quad 1 \le i \le j$.

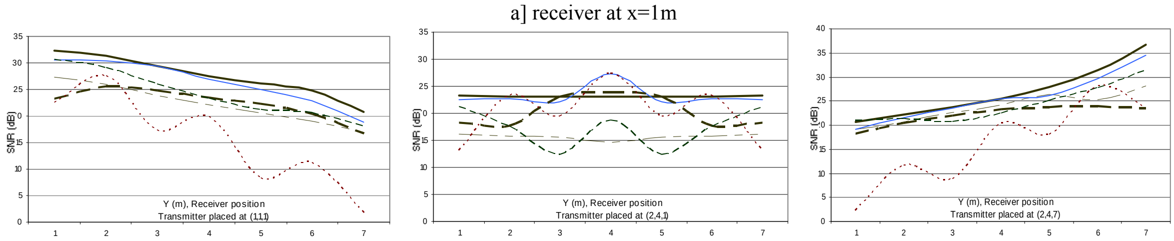
4. SIMULATION RESULTS

Figure 4 shows the SNR distribution at three transmitter locations (close to corner (1m,1m,1m), at room centre (2m,4m,1m) and close to a wall (2m,4m,7m)) using the maximum ratio combining of the detected signal from the seven branch diversity receiver. It is seen that the spot diffusing configurations achieve performance improvement over the diffuse system at weak positions (near walls; i.e., receiver away from the transmitter). The diffuse link produced an oscillating SNR with peaks at receiver positions away from the directive noise sources. Higher SNR is attained by the intersecting lines over all configurations at room centre and along the line close to a wall (x = 1m). Replacement of the single wide field-of-view receiver with a composite angle diversity receiver specially designed to collect most of the transmitted optical signal and reject the background noise where the reception was further optimised employing the MRC technique resulted in much better SNR performance at all receiver locations than with the diffuse case. It can be clearly observed how spot diffusing transmission improved the channel's performance at its weak links with an SNR gain of 22 dB with both the single line and the intersecting lines over that achieved by the conventional systems at same location (x = 1m and y = 1m and 7m) and 14 dB with the intersecting lines at the room centre (x = 2m and y = 4m). An angle diversity detection technique is an appropriate choice for reducing the background noise effect as it selectively confines the range of reception angles.

When a fully mobile transmitter is adopted for these indoor OW communication configurations, the results in Fig. 4 show that signal reception improves at receiver locations closer to the transmitter where the spots illumination increases and that a poor reception is marked with minimum SNR when the distance that separates the transmitter and receiver is maximum as is noticed from the first and last plots of Figure 4 a) and b).



a] receiver at x=1m



b] receiver at x=2m

Figure 4: Signal-to-noise ratio (SNR) comparison of mobile spot diffusing transmitter for five different spot diffusing patterns under seven detectors angle diversity receiver and a conventional diffuse system with MRC (along room width)

5. CONCLUSIONS

In this paper, we investigated the influence of transmitter mobility on five spot diffusing geometries with a composite receiver consisting of seven branches and performing diversity detection for infrared wireless communication within an indoor environment. Adoption of spot diffusing techniques in conjunction with diversity reception yielded performance improvement of up to 22 dB over the conventional diffuse system noticed at the weakest receiver positions (room corners). Furthermore, when a mobile spot diffusing transmitter is used the channels performance still marks a significant SNR improvement even at when the receiver is placed far away from the transmitter. The effect of the background noise on the OW channel's performance has been considerably reduced through the design of the angle diversity receiver, as could be seen from the results obtained with all the spot diffusing patterns, even at locations directly underneath a noise source. With maximum ratio signal combining technique, the simple line strip spot diffusing and diversity detection are therefore promising even in the case of mobile transmitters. The effects of windows, door and partitions within the indoor environment warrants further study.

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