A System Using Combined Emitter and Receiver Diversity to Combat the Multipath Dispersion of the Diffuse Optical Channel

Cipriano R. Lomba[†], *Rui T. Valadas, A. M. de Oliveira Duarte*
University of Aveiro, 3800 Aveiro, Portugal
Fax: +351 34 381941 Email: cipl@ua.pt

Abstract

Over the last few years, there has been a growing interest in using infrared (IR) radiation on high speed indoor wireless communications. However, the inter-symbol interference (ISI) introduced by multipath propagation of the optical signal imposes a penalty for baud rates above about 10 Mbps. The use of angular diversity in both emitter and receiver is also proposed to combat effectively the multipath dispersion of the indoor optical channel. The system considers an array of several narrow beam LEDs, pointed to different directions, combined with a multi-detector sectored receiver. The results show that using this system configuration it is possible to transmit baud rates above one hundred Mbps on diffuse IR systems, with low ISI penalty. Results are compared with those from systems without emitter diversity, showing a substantial reduction on the delay spread of the received signal. Moreover, it is shown that this system configuration results in a negligible power penalty relatively to non diversity systems.

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1 Introduction

In recent years, there has been a growing interest on using wireless local area networks (WLANs) [2, 4, 8]. To assure the competitiveness of future WLANs with cabled networks it is necessary to increase their transmission baud rate. The radio frequency spectrum is scarce and, in general, requires licensing. Infrared (IR) technology has a very large spectrum, free of use in most countries, and can be considered one of the supporting technologies for future broadband WLANs. To develop high speed (and high performance) optical WLANs it is necessary to overcome the main limitations imposed by the indoor channel: (i) intense noise, introduced by ambient illumination, (ii) large and variable propagation losses and (iii) time dispersion in the received signal, due to multipath propagation of the optical signal. The first two factors limit the system range and performance, while the third one originates inter-symbol interference (ISI), that imposes a growing penalty for baud rates above about 10 Mbps [4, 5]. An appropriated selection of emitter and receiver patterns may reduce significantly the penalty introduced by these factors [5, 9, 11, 13].

The propagation characteristics of the indoor optical channel are fully described by the channel impulse response, which depends upon multiple factors, namely, the room geometry, the reflection characteristics of the surfaces, the emitter and receiver patterns and the relative positioning of emitter, receiver and reflection surfaces. The delay spread of the received signal can be evaluated from the channel impulse response, which can be estimated through analytical modelling, experimental data or computer simulation. In most cases, the simulation approach seems to be the most convenient. The results presented in this work were obtained using a simulator of the indoor optical channel (SCOPE) [5]. The SCOPE simulator implements several models [5, 6]: a lambertian radiation model for the source, two receiver models (the conic model and the sectored receiver model), three IR

[†]Currently at the R&D department of **ENT** *Empresa Nacional de Telecomunicações, SA*, Maia, Portugal. The author would like to thanks JNICT for its financial support through a PhD grant – BD/1682/91-IA.

reflection models (the model of Lambert, the model of Phong and the model of Torrance-Sparrow) and three signal propagation models (the line-of-sight model, the single reflection model and the multiple reflections model). Previous studies [5, 6] showed that, to simulate accurately the propagation of optical signals in most indoor channels it is necessary to consider up to 5 reflections of the emitted signal. Consequently, in this study, all the simulations consider 5 reflections. This paper investigates the use of combined emitter and receiver angular diversity to combat the multipath dispersion in indoor IR diffuse systems. While these techniques have been extensively used in radio systems [3, 10], their utilisation in indoor IR systems was only recently investigated [14, 7, 9, 11]. In Section 2, we describe the parameters considered to evaluate the diversity gain using angular diversity. Section 3 presents the main characteristics of the indoor space considered in this study. Section 4 discusses the diversity gains resulting from the use of sectored receivers with multiple segments of sectors. Section 5 presents the diversity gains achieved by using combined emitter and receiver diversity. Section 6 sumarizes the conclusions of this work.

2 Diversity Gain Parameters

To evaluate the multipath dispersion of the indoor optical channel two parameters will be considered: the rms delay of the collected signal (σ_τ) and the -3 dB channel bandwidth (BW). If the total delay spread of the collected signal is smaller than the symbol duration and the receiver system does not use advanced processing techniques to mitigate the signal dispersion (e.g. equalisation), then the bit error rate is directly related with the rms delay of the collected signal [1]. In most indoor IR channels those conditions are verified for baud rates up to several tens of Mbps. The rms delay of the collected signal may be estimated from the channel impulse response by

$$\sigma_\tau = \sqrt{\frac{\sum_{i=0}^{N-1} (\tau_i - \overline{\tau})^2 p_i}{\sum_{i=0}^{N-1} p_i}} \tag{1}$$

where p_i is the power received with delay τ_i and the factor $\overline{\tau}$ is the average delay of the collected signal and is given by

$$\overline{\tau} = \frac{\sum_{i=0}^{N-1} \tau_i p_i}{\sum_{i=0}^{N-1} p_i} \tag{2}$$

The values of σ_τ and BW are evaluated from the channel impulse Response, which is obtained by using the SCOPE simulator. Those parameters are evaluated at a representative set of different receiver positions in the communication cell.

We will also consider the -3 dB channel BW, which corresponds to the minimum frequency where the magnitude of the channel transfer function is 3 dB bellow its maximum value.

The characteristics of the indoor optical channel make the "selection technique" one of the combining methods best suited for IR diffuse systems [7, 5]. This method will also be considered in this work. Therefore, at any given instant, only the signal from one of the sectors will be at the receiver output. Two distinct selection criteria are considered:

1. **Best-Sector** (BS) – The sector with the lowest rms delay or the maximum BW will be selected. The receiver has to estimate the impulse response in all sectors and a complex receiver structure may result.
2. **Any-Sector** (AS) – The sector is selected using a criterion independent of the channel impulse response (e.g. using the signal-to-noise ratio (SNR) as in [14, 12]). In this case, any sector (from the point of view of the multipath dispersion) could be selected. In order to assess the performance of this method, we define the BW and rms delay of the receiver as the average of all sectors BWs and rms delays, respectively.

The delay spread of the collected signal depends significantly on the emitter and receiver positioning and on the selected sector. The statistics of the simulation results are evaluated over a representative set of receiver positions in the room space. Those statistics consider, at each receiver position, the sector with the "best value", in the BS criterion, and all the receiver sectors, in the AS criterion.

3 The Case Study

To investigate the use of diversity we considered an empty room with $8\ m \times 8\ m \times 4\ m$. All the room surfaces have an IR reflection coefficient of 0.7. The emitter is fixed at the centre of the room, $1\ m$ above the floor, and emits a total optical power of $1\ W$. The receiver moves on a plane also $1\ m$ above the floor. This study will consider two types of sources: one with a lambertian radiation pattern (*reference emitter*) and other with multiple emitting elements (*diversity emitter*). At the receiver side, we will considered one receiver with a single element detector (*reference receiver*) and a receiver with multiple detectors (*sectored receiver*). The reference emitter and receiver are always aimed vertically.

4 Sectored Receivers with Multiple Segments of Sectors

The use of angular diversity on the receiver to combat the multipath dispersion of the diffuse optical channel was first studied by considering a few receiver configurations with a single segment of sectors operating in a specific room space [7]. This study was also extended to receivers with multiple segments of sectors. The results showed that to obtain significant diversity gains it is necessary: (i) to consider at least 4 segments of sectors, (ii) the sectors should not present values of fov higher than $20°$ and (iii) a BS selection has to be used. We also verified that sectors with inclination angles higher than about $50°$ do not originate substantial diversity gains.

From the set of receiver configurations studied, the one that resulted in higher diversity gains consists of 4 segments of sectors with 1, 8, 12 and 12 sectors each, as illustrated in Figure 1. The channel characteristics were obtained for a representative set of about 80 positions of the receiver (equally distributed over the room space) and the statistics of the results were evaluated considering a BS selection. The delay spread (σ_τ) of the receiver output signal varies between 0.9 and 2.0 ns, and has an average value of 1.5 ns. The resulting channel BW values vary between 80.0 and 338.7 MHz, and present an average value of 191.2 MHz. These results show that this sectored receiver configuration reduces considerably the delay spread of the collected signal all over the room space. Moreover, there is a considerable improvement relatively to sectored receiver configurations with a single segment of sectors, where for the same room space the maximum value of σ_τ was about 10 ns and the minimum value of BW was below 10 MHz. It should also be noted that the receiver configuration that results in higher diversity gains depends on the room dimensions, reflection characteristics of the existing surfaces and also on the source emitting pattern.

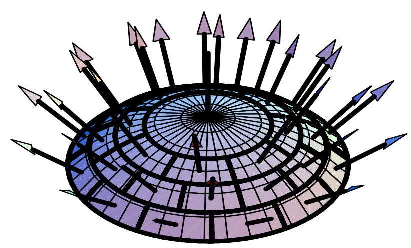

Figure 1: Sectored receiver configuration with multiple segments of sectors.

5 Combined Emitter and Receiver Diversity

In the previous section, it was shown that the use of a sectored receiver with several segments of sectors, associated with a BS selection, allows to reduce substantially the collected signal dispersion. In this section, we propose the use of combined emitter and receiver angular diversity to effectively reduce the delay spread at the receiver output. When the source radiation pattern is narrowed, the delay spread of the signal collected after one reflection is also reduced. Moreover, the source may have a set of narrow emitting beams conveniently oriented to distribute the signal over the room space. This set of narrow beams originates a group of reflecting spots over the existing surfaces. The use of a sectored receiver configuration, where at least one sector sees exactly one of those reflecting spots for must of the receiver positions, should result in a substantial reduction in the delay spread of the collected signal. In most of the receiver sectors, the collected signal would be dominated by the signal going into the detector after the first reflection, which presents very reduced delay spread.

The use of diversity at the emitter should produce a matrix of reflection spots, uniformly distributed over the reflection surfaces allowing the use of sectored receivers with very narrow fov. The emitter diversity is created using a set of n_L narrow beam sources, conveniently oriented, and originate n_L reflecting spots, named *point sources*, over the surrounding surfaces. The use of narrow beam emitters will also originate directions where the radiation collected by the receiver results in a high SNR. To increase the diversity gain in terms of SNR, the number of point sources should be higher than the number of sources of optical ambient noise. To minimise the delay spread, each sector should not see more than one point source. Therefore, the number of sectors should be higher than the number of reflection spots n_L. To overcome safety aspects and reduce costs, the diversity at the emitter is implemented using a set of narrow beam LEDs conveniently oriented to minimise variations in the optical power density over all the communication space. The use of multi-beam transmitters in indoor optical systems was first proposed to reduce the channel propagation losses keeping the functionality and robustness of diffuse systems [15] and to increase the SNR of the collected signal [11].

5.1 Discussion of Results

The capabilities of combined emitter and receiver diversity to reduce the signal delay spread was evaluated considering the same room space of the previous section and 4 system configurations: (i) ideal lambertian emitter and reference receiver, (ii) ideal lambertian emitter and sectored receiver, (iii) multi-beam transmitter and reference receiver and (iv) multi-beam transmitter and sectored receiver. The emitter is still fixed at position $(0.0, 0.0, -3.0)$, emits a total power of 1 W and is vertically oriented. The global multi-beam transmitter pattern was optimised to minimise the worst-case propagation losses after one reflection of the emitted signal. The optimisation was done using the SCOPE simulator and considered only LEDs with half-power angle (hpa) of $1°$. After the optimisation process, the multi-beam transmitter was implemented by the following configuration of LEDs:

- 1 LED ($P_t = 80\,mW$ e $hpa = 1.0°$), vertically oriented.
- One matrix of 8 LEDs ($P_t = 115\ mW$ e $hpa = 1°$), inclined at $50°$ with the vertical and uniformly distributed over the azimuth.

Figure 2 illustrates the signal distribution over the room ceiling surface produced by the optimised radiation pattern when the transmitter is at the room centre. As expected, the signal distribution is equivalent to a set of point sources distributed over the ceiling surface. To implement diversity at the receiver side we considered one sectored receiver with one segment of 12 sectors ($fov_a = 30°$). This selection took into account previous results [5] and the fact that the source has 9 emitting beams. The narrow beam emitters are pointed at the ceiling surface, therefore the receiver sectors should also be preferably directed to the ceiling.

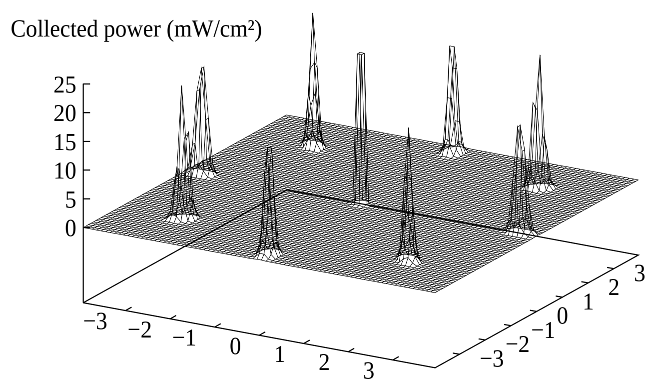

Figure 2: Signal distribution on the ceiling surface due to the multi-beam transmitter.

The channel characteristics were evaluated for a representative set of different receiver positions, maintaining the emitter fixed at the room centre. Figure 3 presents the statistics of the results obtained for the channel BW of the 4 system configurations in study. The figure shows the average values of BW and, for the system using diversity in both emitter and receiver with a BS selection (curve `Diver_Sect (BS)`), the minimum and maximum values are also presented. The legends indicate: (i) the emitter configuration (lambertian – `Lamb`, with diversity – `Diver`), (ii) the receiver configuration (reference – `Refer`, sectored – `Sect`) and (iii) the receiver combining mode used at the sectored receiver (AS or BS). In the sectored receiver case, the values of fov_v are given by

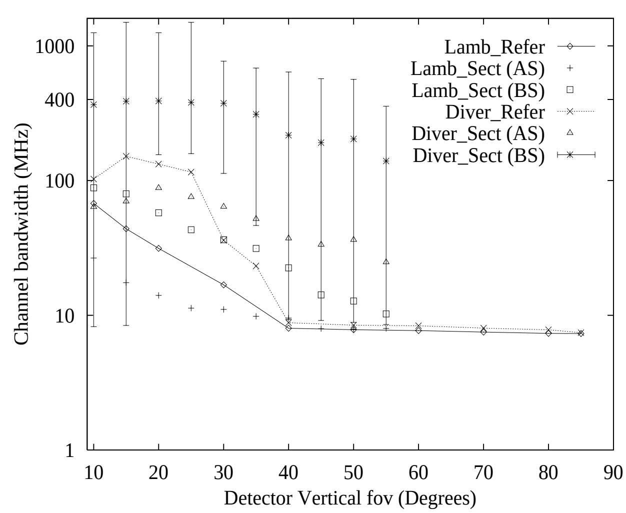

Figure 3: Diversity gain in terms of channel bandwidth.

$fov_v = \theta_h - \theta_l$. Table 1 shows the vertical limits of each sector. The results of the Figure 3 indicate

fov_v	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°
θ_l	45°	35°	35°	30°	23°	20°	20°	15°	15°	10°
θ_h	55°	50°	55°	55°	53°	55°	60°	60°	65°	65°

Table 1: Vertical limits of the sectors aperture.

that through the use of combined emitter and receiver diversity it is possible to increase significantly the channel BW over all room space, only when the sectors have a fov_v smaller than about 40°. In the reference system (lambertian emitter and reference receiver), the average values of BW is about 10 MHz. In systems using angular diversity only at the emitter or at the receiver, the average values of BW are, in general, smaller than 100 MHz. However, the minimum values of BW remain about 10 MHz. The use of combined emitter and receiver diversity with a BS selection originates a significant increase on the average values of BW to approximately 400 MHz. For configurations with $15° < fov_v < 35°$, the minimum values of BW are above one hundred MHz. Therefore, the use of combined emitter and receiver angular diversity is able to increase considerably the channel BW allowing to transmit at baud rates above one hundred $Mbps$ with small IES. When $fov_v \leq 15°$, the minimum value of BW is smaller as there are receiver positions where none of the sectors see any of the reflecting spots in the ceiling surface. Similarly, for $fov_v \geq 35°$ the minimum value of BW is reduced as there are receiver positions where some sectors see more than one reflecting spot, while the others do not see any reflecting spot.

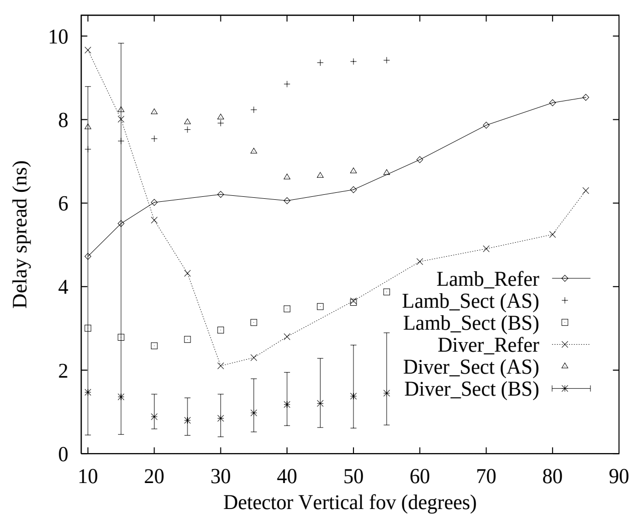

Figure 4: Diversity gains in terms of delay spread.

Figure 4 presents the statistics of the rms delay of the 4 system configurations in study. The results show that this system configuration allows to reduce considerably the delay spread of the received signal, but a BS selection is required. In fact, the AS selection originates an increase on σ_τ, which results from those sectors with very large delay spread. It is also essential to guaranty that, for each receiver position, at least one sector sees exactly one reflecting spot in the room ceiling surface. For $fov_v \leq 15°$, the results confirm the conclusions extracted from Figure 3 and indicate the existence of a few receiver positions where the received signal presents a large rms delay.

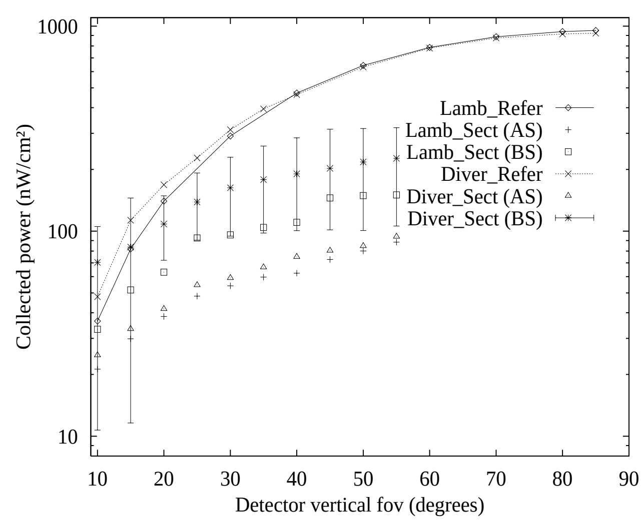

Figure 5: Diversity effects on the collected power.

Figure 5 shows the statistics of the collected power of the 4 system configurations in study. The values are normalised for an active area of 1 cm^2. The results show that the use of combined emitter and receiver diversity originates only a small reduction on the collected power, relatively to the reference system. The minimum values of the collected power for the other three system configurations are not shown, but they are, in general, much smaller than the minimum values corresponding to the configuration with diversity in both emitter an receiver. We notice that, in the configuration with combined emitter and receiver diversity and when $fov_v \leq 15°$, there are receiver positions where no sector sees any reflection spot in the ceiling surface. This fact is confirmed by the existence of receiver positions where the collected power is extremely reduced.

6 Conclusions

This paper studied the use of angular diversity in indoor infrared systems and proposed the use of combined emitter and receiver angular diversity to combat effectively the delay spread of the received signal in diffuse optical communication systems. A specific indoor optical channel was considered and the results showed that using angular diversity in both emitter and receiver it is possible to transmit data at a few hundred $Mbps$ in diffuse mode with small inter-symbol interference. Moreover, this system configuration originates only a negligible power penalty. In spaces with larger dimensions, the multipath dispersion of the optical signal Increases and the gains of using combined emitter and receiver diversity should also be more significant. The use of sectored receivers with multiple segments of sectors would result in higher diversity gains.

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