Sectored Receivers to Combat the Multipath Dispersion of the Indoor Optical Channel

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Abstract

This paper presents the first results of a study developed to evaluate the performance of sectored receivers in combating the multipath dispersion of the indoor optical channel. With this work, we intend to: 1) Evaluate the performance of sectored receivers in minimizing multipath dispersion and, 2) Conclude if sectored receivers may be used successfully to reduce both ambient noise and multipath dispersion, by estimating only the ambient noise at each sector of the receiver. The results show that sectored receivers can reduce significantly the multipath dispersion, but selection of the sector with best impulse response is required. Also, to achieve significant gains the field-of-view of the sectors have to be smaller than 50°.[‡]

1 Introduction

The success of indoor wireless communications is placing a demand on higher bit rate systems. Infrared (IR) technology offers the potential to become the support of such systems. However, it is fundamental to overcome the main limitations of the high-bandwidth indoor wireless optical channel: interference from ambient light (sun light and artificial illumination), multipath dispersion (for bit rates higher than about 10 Mbit/s) and technological limitations of the available optoelectronic devices. In most indoor IR systems, ambient noise is the dominant source of noise [1, 2]. The spatial distribution of the ambient noise is far from isotropic. It is higher near windows directly exposed to sun light and bellow spot lamps. There is also a certain directivity associated with the collected signal which, usually, is higher when the receiver is pointing towards the emitter. Therefore, the use of diversity techniques to exploit the directional nature in both signal and noise seems attractive. This issue has been first considered by Valadas [3]. The results have shown that, there is significant gain in using sectored receivers to reduce the effects of ambient noise.

In a diffuse IR system, the optical signal propagates by scattering and multiple reflections in the furniture and room surfaces. At bit rates higher than about 10 Mbit/s the multipath dispersion produces intersymbol interference (ISI) [1, 4, 5] which may become one of the main limiting factors.

This paper presents the first results of a study to evaluate the performance gains of sectored receivers in combating multipath dispersion of the diffuse indoor optical channel. The study is based on a simulation package described in [5]. In the next section, we present the model of the indoor optical channel. In section 3, we define the parameters used to evaluate the diversity gains of the sectored receiver. In section 4, we describe the parameters of a case study. In section 5, we present and discuss the results. Finally, in section 6 we present our conclusions.

2 System model

The indoor optical channel includes the emitter source pattern, the room propagation characteristics and the receiver collecting pattern.

2.1 Emitter Model

The emitter source is modeled using the generalized *Lambertian* law. The angular distribution of the emitter radiant intensity is given by

$$E(\phi) = \frac{n+1}{2\pi} P_t \cos^n(\phi) \tag{1}$$

where ϕ is the angle with the normal to the emitter surface and P_t is the total emitted power. The parameter n depends on the beam width and is given by $n = -0.693/\ln[\cos(hpbw)]$, where $hpbw$ is the half power beam width of the emitter pattern.

2.2 Room Propagation Model

There are mainly two factors defining the room propagation characteristics: the free-space propagation losses and the signal reflections on surrounding surfaces. The first is described directly by the $1/r^2$ law, where r represents the path distance. To model the signal reflections, the room surfaces are divided into incremental areas. Each incremental area is modeled as a *Lambertian* reflector with a given reflection coefficient.

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2.3 Receiver Models

In this section we describe two receiver models: one for the *reference* receiver and other for the *sectored* receiver.

Reference Receiver – The reference receiver corresponds to the optical receiver commonly used in diffuse optical systems. It is modeled as having a given active area and a cone-shaped aperture or FOV. Here, only the signal incident at angles not greater than the detector FOV is collected. The reference receiver will be used to assess the gains of the sectored receiver.

Sectored Receiver – The sectored receiver is assumed to be a hemisphere where a set of parallels and equally spaced meridians define the boundaries of the sectors. The region of the sectored receiver enclosed between two parallels is called a segment. The sectored receiver can be defined through a set of parameters specifying the number of segments and, for each segment, the limiting elevation angles, the number of sectors and the azimuth offset of the first sector. All sectors of each segment have an equal azimuth aperture and the same limiting elevation angles. Figure 1 [3], illustrates the model applied to a specific sectored receiver configuration.

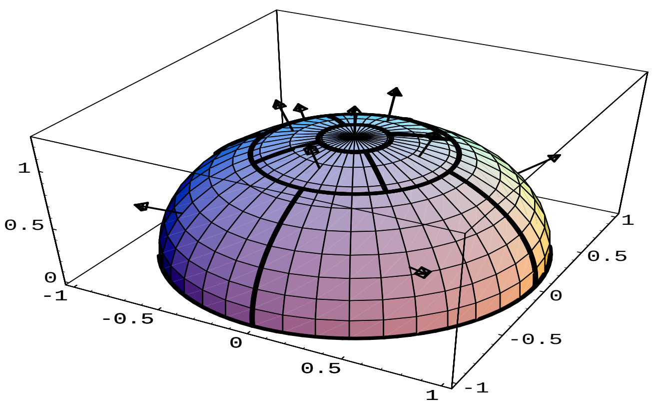

Figure 1: Sectored receiver with 3 segments and 9 sectors.

Each sector is completely defined through its active area and FOV. This is specified by the two limiting elevation angles, θ_l and θ_h, and the two limiting azimuth angles, φ_l and φ_h, where $\theta_l \leq \theta_h$ and $\varphi_l \leq \varphi_h$. The azimuth aperture is given by $(\varphi_h - \varphi_l)$ while the vertical aperture is evaluated by $(\theta_h - \theta_l)$. The orientation of each sector is defined as being a unitary vector with the following angles: $\varphi_x = (\varphi_l + \varphi_h)/2$ and $\theta_z = (\theta_l + \theta_h)/2$ relatively to xx and zz, respectively, except in the case of a polar sector where $\theta_z = 0$, (sector pointed vertically in Fig. 1). This sectored receiver model was proposed in [3] to assure no overlap between the reflecting surfaces seen by each sector.

2.4 Channel Propagation Model

The channel impulse response may be expressed by a discrete low pass impulse response given by

$$h(t) = \sum_{k=0}^{m} a_k \delta(t - \tau_k) \tag{2}$$

where k defines the path index from emitter to receiver and m is the total number of paths considered. The factor a_k is the signal gain for each path (including emitter and receiver gains), τ_k represents the propagation delay of each path and $\delta(t)$ is the Dirac delta function.

3 Diversity Gain

We will consider two parameters to evaluate the multipath dispersion: the *rms* delay and the -3 dB bandwidth. The *rms* delay is usually adopted in indoor radio systems [6]. If the total delay spread of the collected signal is smaller than the symbol duration and the system does not use techniques to mitigate the dispersion then the bit error rate is directly related with the *rms* delay of the collected signal [7]. Usually, in IR indoor systems these conditions are verified for baud rates up to several tens of Mbit/s.

The *rms* delay, σ_τ, of the collected signal may be estimated from the channel impulse response by

$$\sigma_\tau = \sqrt{\frac{\sum_{i=0}^{N-1} (\tau_i - \overline{\tau})^2 p_i}{\sum_{i=0}^{N-1} p_i}} \tag{3}$$

where p_i is the power received with delay τ_i and is the result of dividing the reflecting surfaces in incremental areas. The factor $\overline{\tau}$ is the average delay of the collected signal and is given by

$$\overline{\tau} = \frac{\sum_{i=0}^{N-1} \tau_i p_i}{\sum_{i=0}^{N-1} p_i} \tag{4}$$

The -3 dB or channel bandwidth corresponds to the minimum frequency where the magnitude of the transfer function is 3 dB bellow its maximum value.

The -3 dB bandwidth and the *rms* delay of the collected signal are evaluated from the simulated channel impulse response. This is done for all sectors at a representative set of different receiver positions in the room.

Diversity combining techniques have been extensively studied [8]. We will consider a selection diversity receiver, thus only the signal from one of the sectors will be fed to the receiver at any given instant. We will consider two distinct selection criteria:

1. **Best-Sector** – The sector with the best *rms* delay or -3 dB bandwidth will be selected. The receiver has to estimate the impulse response in all sectors and a complex receiver structure may result. Note that the *best-sector* in terms of -3 dB bandwidth may not be the *best-sector* in terms of *rms* delay.
2. **Any-Sector** – The sector is selected using a criterion independent of the channel impulse response (e.g. using the signal-to-noise ratio (SNR) as in [3]). This receiver would be less complex than the *best-sector* one. It could be used in high-bandwidth systems provided that significant diversity gains in terms of *rms* delay or -3 dB bandwidth could be obtained irrespective of the selected sector.

At any given instant, the rms delay or -3 dB bandwidth values seen by a given receiver depend on the receiver position and on the selected sector. We will calculate the statistics of the simulation results over a representative set of receiver positions in the room space. In the *best-sector* criterion, the statistics consider at each position only the sector with the best value. In the *any-sector* criterion, the statistics consider all receiver sectors at each position.

4 The Case Study

We consider an empty room with $8m \times 8m \times 4m$. The reflection coefficient is 0.7 for all the room surfaces. All simulations considered 5 order reflections. The emitter is always located at the center of the room, 1 m above the floor, aimed vertically, and emits 1 W total optical power with an ideal *Lambertian* radiation pattern, $n = 1$ in equation 1. The receiver is also located on a plane 1 m above the floor. The reference receiver is always aimed vertically. The sectored receiver has 1 segment with 8 sectors, (the azimuth aperture is 45°). The vertical aperture and orientation of the sectors will be varied.

5 Discussion and Results

This section presents the simulation results for our case study. To evaluate the diversity gain, the results of the sectored receiver are compared with those obtained for the reference receiver. Figures 2 and 3 present the impulse responses and magnitude of the frequency responses, respectively, for two very different situations in our case study. The continuous line is for a reference receiver with FOV$= 90°$, at the position that results in the maximum value of -3 dB bandwidth. The dashed line is for the *best-sector* of a sectored receiver with vertical aperture of 30°, ($\theta_l = 0°$ and $\theta_h = 30°$). The sectored receiver is also at the position that results in the maximum value of the -3 dB bandwidth. The impulse response of the sectored receiver, figure 2, was normalized to have the same area as the impulse response of the reference receiver. The magnitude transfer function of the sectored receiver, figure 3, was also normalized to have the same DC gain of the reference receiver. The impulse responses show that the sectored receiver collects most of the signal in a very short time period, first order reflection, while the signal collected by the reference receiver is much more spread due to the large FOV. The reference receiver also collects a higher percentage of signal from higher order reflections which reduces dramatically the -3 dB bandwidth. These facts result in very different -3 dB bandwidth and channel transfer functions as shown in figure 3.

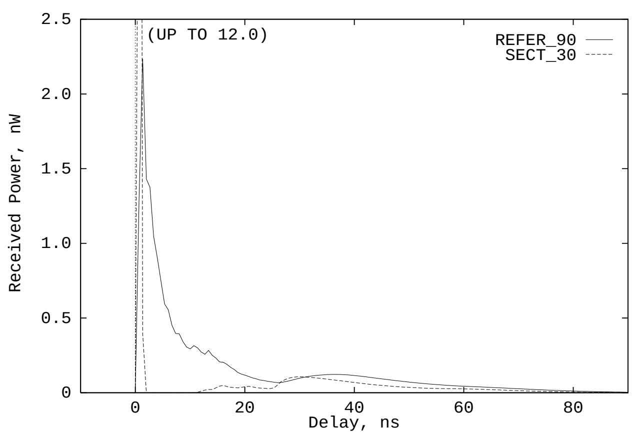

Figure 2: Channel impulse responses.

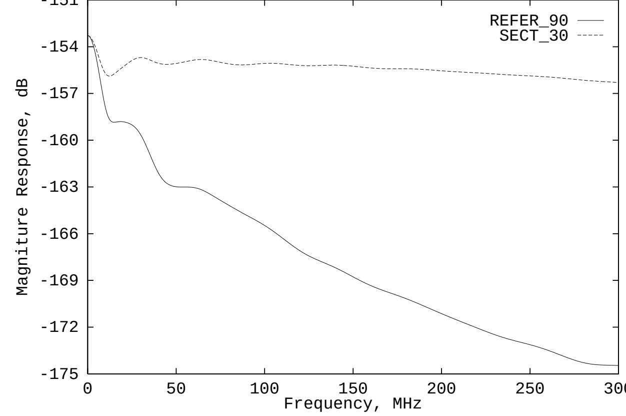

Figure 3: Magnitude of the channel frequency responses.

Figure 4 shows the channel bandwidth values for the reference receiver versus emitter to receiver distance. The results are presented for values of receiver FOV between 10° and 90°, in steps of 10°. A detailed analysis of figure 4 shows that: 1) for emitter to receiver distances larger than about 2 m the -3 dB bandwidth is almost independent of the receiver FOV, 2) for FOV values larger than 30°, the -3 dB bandwidth does not change significatively with the emitter to receiver distance and, 3) receivers with narrow aperture result in high values of -3 dB bandwidth for short distances between emitter and receiver.

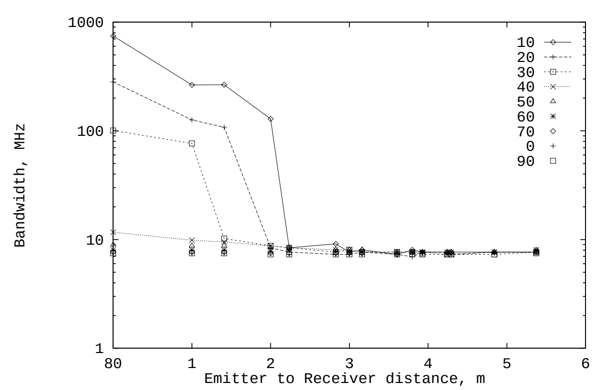

Figure 4: Channel bandwidth *versus* emitter to receiver distance.

Table 1 shows the statistics of the channel bandwidth and *rms* delay for FOV values of 30° and 90° for the reference receiver. When the FOV= 90°, the results show that multipath dispersion due to signal reflections is very limitative in terms of channel bandwidth. We should mention that, if only one reflection of the signal was considered, the channel bandwidth would be approximately 50 MHz. The results show also that the channel bandwidth is almost independent of the receiver position. When the receiver has a FOV= 30°, the results show a good improvement in terms of average and maximum values of bandwidth, however, the minimum values are equal. Thus, by reducing the reference receiver aperture, we can increase the channel bandwidth but only over some areas of the room. Similar conclusions can be drawn from the *rms* delay figures of table 1.

Receiver	Bandwidth, MHz			rms delay, ns		
FOV	min.	av.	max.	min.	av.	max.
30°	7.30	17.1	101.0	2.0	6.0	10.5
90°	7.30	7.35	7.48	6.0	8.4	9.8

Table 1: Statistical values for the reference receiver.

Table 2 shows the statistics of the channel bandwidth and *rms* delay for two different values of vertical aperture of the sectored receiver, 30° and 90° ($\theta_l = 0°$). Comparing the results of table 2 with those of the reference receiver, table 1, we verify that the sectored receiver with a vertical aperture of 90° has no diversity gain in terms of bandwidth or *rms* delay. However, if the vertical aperture is reduced to 30°, ($\theta_l = 0°$ and $\theta_h = 30°$) and a *best-sector* selection is used, there is a considerable diversity gain, except in terms of the minimum bandwidth.

	Rec.	Bandwidth, MHz			rms delay, ns		
	FOV	min.	av.	max.	min.	av.	max.
Any	30°	5.84	22.7	254.4	1.4	6.1	14.1
Sect	90°	6.57	7.04	8.39	5.2	11.1	16.5
Best	30°	7.30	60.9	254.4	1.4	2.9	6.3
Sect	90°	6.75	7.46	8.39	5.2	7.1	10.4

Table 2: Statistical values for the sectored receiver.

Figure 5 shows the channel bandwidth statistics versus vertical aperture of the sectored receiver considering a *any-sector* methodology (in all cases $\theta_l = 0°$). Similarly to the reference receiver case, the results of figure 5 show that: 1) the minimum value of the -3 dB bandwidth is almost independent of the receiver aperture, 2) the average and maximum values of the -3 dB bandwidth increase if the aperture is reduced and, 3) for aperture values larger than 50° the -3 dB bandwidth is nearly independent of the receiver position.

We will consider other configuration for the sectored receiver. It is similar to the previous one, but it has the vertical aperture of the sectors centered at 45°. Figures 6 and 7 show the statistics of the -3 dB bandwidth and *rms* delay, respectively, considering the *best-sector* methodology. In both pictures, the curves are for the reference receiver, label REFER., and for the two sectored receiver configurations, labels SECTvert and SECT45.

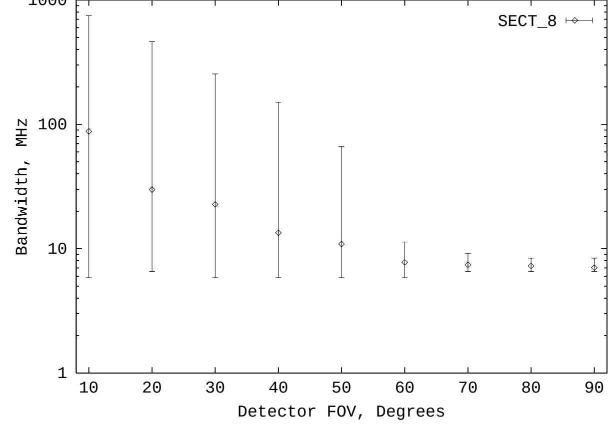

Figure 5: Statistics of the channel bandwidth *versus* vertical aperture of the sectored receiver.

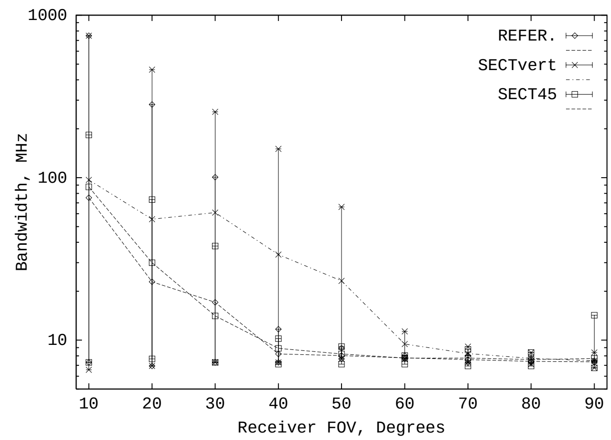

Figure 6: Statistics of the -3 dB bandwidth *versus* receiver aperture, following a *best-sector* methodology.

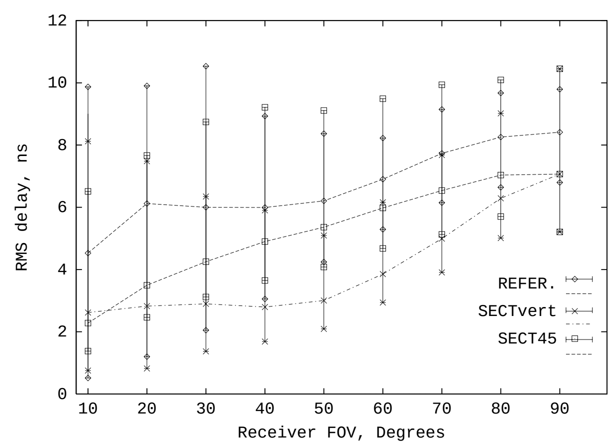

Figure 7: Statistics of the *rms* delay *versus* receiver aperture, following a *best-sector* methodology.

The results show that sectored receivers with *best-sector* selection reduce significantly the *rms* delay and may increase the -3 dB bandwidth. The sectored receiver configuration with $\theta_l = 0°$, label SECTvert, presents better results than the one with all sectors tilted at 45°. In addiction, it reduces significantly the average and maximum values of the *rms* delay. There is also a good increase in the average and maximum values of the channel bandwidth for aperture values smaller than 50°. However, the minimum values remain low and are almost independent of the receiver configuration. This happens because the sectored receiver is considering only one segment. When the receiver FOV is large, the bandwidth is small due to the large multipath dispersion. When the receiver FOV is narrow, there is always a few positions in the room where the receiver collects very little power from the first order reflections. Consequently, higher order reflections dominate the channel response reducing the bandwidth. This problem can eventually be minimized by using a sectored receiver with several segments of sectors.

We will now present some results comparing the performance of the *any-sector* and the *best-sector* methodologies. Figure 8 presents the average values of the *rms* delay for the 3 receiver configurations and, in the case of sectored receivers, for both selection criteria.

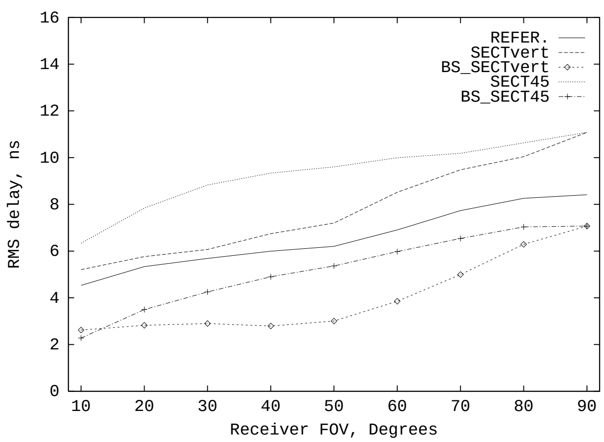

Figure 8: Average values of the *rms* delay *versus* receiver aperture.

According to figure 8, sectored receivers reduce significantly the average value of the *rms* delay if a *best-sector* selection is done. Following the *any-sector* criterion, sectored receivers present an average *rms* delay higher than the reference receiver. This happens because most of the sectors are not directed towards the center of the room, above the emitter position. Therefore, higher order reflections dominate the channel impulse response and, consequently, the collected signal is more spread in time.

The results of figure 8 show also that to reduce the *rms* delay using sectored receivers, we have to estimate the *rms* delay at each sector and then use a *best-sector* selection.

6 Conclusions

The use of sectored receivers can reduce the multipath dispersion of the indoor optical channel. We considered a particular sectored receiver, with only one segment and 8 sectors, and showed that significant diversity gains in terms of -3 dB bandwidth and *rms* delay are achievable. To obtain high diversity gains a *best-sector* selection is required and the aperture of each sector has to be smaller than 50°. Sectored receivers may be used successfully in combating both, ambient noise and multipath dispersion, but estimation of both is required.

The diversity gain of the sectored receiver may be increased by using a more complex receiver structure. This requires a more detailed study and design of sectored receivers with several segments of sectors with narrow aperture.

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