EXPERIMENTAL CHARACTERIZATION OF RATE-ADAPTIVE TRANSMISSION AND ANGLE DIVERSITY RECEPTION TECHNIQUES

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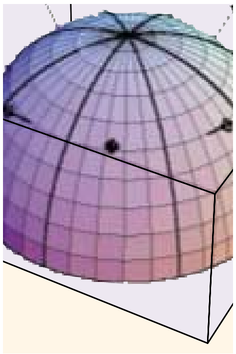

The authors discuss experimental results obtained from a testbed developed for comparing different techniques for SNR improvement. The two techniques analyzed are rate-adaptive transmission and angle-diversity reception.

ABSTRACT

Ambient light is the main impairment in indoor wireless optical communication systems for data rates up to several megabits per second. Its wide dynamic range, associated with the strong directivity of wireless optical signals, produce large variations on the received signal-to-noise ratio. This article discusses experimental results obtained from a testbed developed to compare different techniques for SNR improvement. The two techniques analyzed are rate-adaptive transmission, which introduces adaptive levels of redundancy in the transmitted signal to improve connectivity, and angle diversity reception, which exploits the inherent directionality of both signal and noise to improve the SNR at the receiver. Furthermore, systems employing both techniques simultaneously were also considered. The testbed replicated a typical indoor environment with both natural and artificial light, containing incandescent and fluorescent light sources. Both the SNR and the associated coverage areas were determined for all considered techniques. Our results show that the combined use of angle diversity based on maximal-ratio combining and rate adaptation through the use of repetition coding achieves very good performance with only moderate complexity, allowing connectivity at all locations with data rates close to the maximum possible. In particular, with incandescent illumination and without angle diversity, the data rate had to be decreased down to 2 and 1 Mb/s in 25.9 and 7.7 percent of the room area, respectively, whereas with maximal ratio combining a decrease to 2 Mb/s was only needed in 0.7 percent of the room area.

INTRODUCTION

Nondirected infrared wireless indoor communication systems were initially proposed in [1], but many developments have followed [2–14], covering both point-to-point systems and multipoint networks. Its key advantages rely on the virtually unlimited unregulated bandwidth, available worldwide, and its inherent security characteristics, achieved by the natural confinement of infrared signals inside closed rooms.

Wireless infrared communications are traditionally based on intensity modulation and direct detection of the optical carrier. Intensity modulation is performed by varying the current of a laser diode or an infrared LED, while direct detection is usually performed by PIN photodiodes that produce an electrical current proportional to the incident optical power. Unfortunately, infrared is spectrally near ambient light. As ambient light sources (sunlight and artificial light) radiate in the same spectral wavelengths used by infrared transducers, these induce shot noise at the photodiode that varies in both space and time. This noise is the main problem of infrared communication systems for data rates up to several megabits per second. For indoor systems, shot noise is larger when the receiver is placed under directional lamps and near windows exposed to sunlight, and varies drastically with the position of the sun and indoor lighting conditions [6]. A different, but equally strong, variation may also appear on the received signal, depending on the relative position between emitter and receiver. Therefore, the signal-to-noise ratio (SNR) at the receiver presents a large dynamic range, typically hard to accommodate with infrared devices. Thus, designers must overcome this problem at the system level, through either system design or protocol implementation.

In this article we consider two techniques to minimize the large SNR variations that impair the indoor infrared wireless channel: rate-adaptive transmission and angle diversity reception. The rate-adaptive strategy [6] maintains connectivity under noisy channel conditions through reduction of the data rate. Data rate reduction is accompanied by the introduction of increased levels of redundancy while keeping the effective bit rate constant. Two coding techniques are explored in this article: repetition coding and convolutional coding. On the other hand, the angle diversity strategy [7–9] explores the direc-

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tional nature of the SNR at the receiver. An angle diversity receiver is composed of multiple sectors (optical receivers) with relatively small fields of view (FOVs). The output signals of different sectors can have very dissimilar SNRs. These signals can be combined in order to decrease the overall SNR dynamic range. We analyzed several combination methods: select best (SB), equal gain (EG), and maximal ratio (MR). Finally, this article also evaluates the simultaneous usage of angle diversity reception and rate-adaptive transmission techniques. This work expands on our previous work in [10]; we experimentally evaluate the two strategies in detail and analyze their combined effect.

Both angle diversity reception and rate-adaptive transmission techniques can be applied to the infrared systems developed (or being developed) by the two main standardization bodies supporting worldwide standards for indoor wireless optical communication systems: IEEE 802.11 and the Infrared Data Association (IrDA). The focus of the IEEE 802.11 group, created in July 1990, was on nondirected indoor optical wireless LANs; angle diversity reception has already been proposed for application in 802.11 receivers [7]. The IrDA, created in June 1993, was initially oriented to short-range low bit-rate line-of-sight systems, and was not originally affected by the large SNR variation problems described above. However, in recent years the IrDA initiated two new projects, Advanced Infrared (AIr) and Very Fast IrDA (VFIr), whose main objectives are to establish standard extensions allowing nonoriented optical transmissions and achieving high bit rates, respectively. The AIr proposal is explicitly aimed at maximizing connectivity through data rate adaptation to variable channel conditions.

Ambient Light Noise Characterization

Indoor wireless infrared communication systems are exposed to sunlight and artificial light produced by incandescent and fluorescent lamps. The shot noise induced by these ambient light sources may vary over several decades during a day in a typical indoor environment [6] and determines, to a significant degree, the optical power budget required for reliable transmission. Sunlight and incandescent light have strong spectral components in the wavelength region corresponding to the highest sensitivity values of silicon PIN photodiodes [3]. In typical office environments, background light usually has a strong level, resulting in high shot noise values in these photodiodes. In addition, artificial light sources emit a variable light component with harmonics at multiples of twice the frequency of the power mains. Furthermore, fluorescent light also emits high-frequency components at multiples of the ballast operating frequency. The optical power collected by the PIN photodiode due to the combined contributions of the background ambient light can be tens of times higher than the received signal [6]. For example, IEEE 802.11 specifies that infrared systems operating under this standard should be able to work under background intensity of 100 $\mu W/cm^2$ while the minimum value of the received signal intensity is 20 nW/cm^2, which is about 5000 times lower [11]. For the basic IrDA specification (at much lower bit rates) these values are 490 $\mu W/cm^2$ and 4 $\mu W/cm^2$, respectively, corresponding to a relation of about 100 [12]. Because of this large difference between background and signal intensities, it is mandatory to use optical filtering in the receiver. However, with the optical filters typically used in these applications, the shot noise generated in the photodiode is still dominated by this background light. Also, its spatial distribution can vary drastically with the relative position of the sun, and with the position and orientation of the artificial light sources. The shot noise generated in a PIN photodiode due to the background light (at a particular position) can be modeled as additive white Gaussian noise with a one-sided power spectral density given by

$$N_0 = q\, I_{bg} \qquad (A^2/Hz), \tag{1}$$

where q is the charge of an electron, and I_{bg} is the dc photocurrent that is proportional to the background ambient illumination.

To evaluate the effects of this optical noise, we installed a testbed in a classroom of the University of Aveiro. This classroom is rectangular with large curtained windows on the west side, and with dimensions 7.0 m × 5.8 m × 2.9 m (length × width × height). To neglect the contribution of natural light, windows were covered by aluminum foil on the outside and large paper covers on the inside, with reflection characteristics similar to the surfaces of the walls. The measurement setup was placed 1.0 m above the floor at typical equipment height. We installed incandescent and fluorescent illumination in this room. Figure 1 shows the room plan, with the position of the lamps. In the first case, the illumination was produced by nine incandescent spot lamps with narrow half-power beam widths (Philips, R95, 20°, 100 W). In the second case, six fluorescent units with prismatic plastic lenses produced the illumination. Each fluorescent unit contains two 36 W tubular fluorescent lamps.

Rate-Adaptive Transmission

Usually, infrared communication systems make use of a single bit rate. However, the characteristics of the infrared propagation channel, as well as the large range of shot noise values encountered in indoor environments, provoke large SNR fluctuations, ultimately leading to loss of connectivity. This contrasts with the usual main request of mobile users, who demand that the infrared communication should be kept reliable, independent of the ambient light conditions or obstructions in the transmission channel. Full network connectivity can always be maintained at the expense of graceful throughput degradation for those terminals that are exposed to higher levels of ambient light [6], using rate-adaptive transmission. The transmission operation is quite simple:

- The receiver estimates the channel conditions and notifies the transmitter of the maximum bit rate that can be used to ensure a minimum bit error rate (BER) depending on transmitter-receiver distances, propagation properties, and ambient light levels.

Sunlight and incandescent light have strong spectral components in the wavelength region corresponding to the highest sensitivity values of silicon PIN photodiodes. In typical office environments, the background light usually has a strong level resulting in high shot noise values in these photodiodes.

- The transmitter adjusts the bit rate according to the feedback information received from the receiver.

This ensures smooth throughput degradation without sudden communication breakdown. Closer emitter-receiver distances may permit higher data rates, while, for instance, increases in background light levels may lead to data rate reductions. This is similar to AIr, where the Request-To-Send and Clear-To-Send mini-frames are used to negotiate the data rate [13].

To implement an adaptive data rate system for indoor optical wireless communications, several techniques can be adopted. We focus our analysis on the application of adaptive data rate techniques considering two methods:

- Repetition coding
- Convolutional coding

These methods are based on the introduction of coding redundancy through the use of repetition or convolutional codes, while maintaining constant the effective bit rate on the transmission channel. A possible alternative to these methods relies on the effective reduction of the bit rate, reducing the receiver bandwidth through the use of adaptive filtering. In theory, this strategy achieves results similar to repetition coding, but is harder to implement. As a consequence, we have not used adaptive filtering in our testbed.

The block diagrams of both rate-adaptive transmission systems are presented in Fig. 2, including the L-pulse position modulation (PPM) coder/decoder (L-PPM is the most common modulation scheme in wireless optical systems, used in both the IrDA and IEEE 802.11 specifications). The repetition coding technique is based on the introduction of coding redundancy through the repetition of each symbol a number of times. The block diagram on top of Fig. 2 illustrates an implementation of the adaptive data rate system based on the repetition coding technique assuming L-PPM soft decision decoding. This has an effective bit rate of $R_b = R_o/RR$, where RR is the rate reduction factor and R_o is the effective bit rate without any adaptive mechanism. The chip rate on the transmission channel is equal to $1/T_{chip} = R_o \cdot L/\log_2 L$, irrespective of the repetition rate. At the receiver side, the RR repeated L-PPM symbols are summed together. In this way the total chip energy is increased without increasing either the chip duration, collecting area, or emitted optical power. For a specific BER, each doubling of RR decreases the required SNR by 3 electrical dB [10].

The block diagram at the bottom of Fig. 2b illustrates a rate-adaptive transmission system based on convolutional coding. This technique allows error correction at the receiver. In order to enable direct comparison with the previous repetition coding system, only convolutional codes with code rates confined to $R_c = 1/RR$ were considered, where the reduction factor RR corresponds to the number of output bits for each input bit. This rate-adaptive transmission system works as follows. At the transmitter side, the convolutional encoder converts a bitstream, arriving at an effective data rate of $R_b = R_o/RR$ b/s, into a codeword with RR bits. Then the coded bit sequence is modulated and transmitted over the communication channel at a chip rate, $1/T_{chip} = R_o \cdot L/\log_2 L$, equal to that of the repetition coding system. At the receiver side, the receiver implements soft-decision L-PPM demodulation, followed by hard-decision Viterbi decoding.

The choice of the best convolutional codes with code rates $1/RR$ with RR = 2, 4, 8, 16, and 32 was performed considering constraint lengths K (number of stages in the encoder) limited to small values. Higher constraint lengths do produce better performance but increase the complexity of the decoding process, as the number of computations required at each stage increases exponentially with K [15]. Furthermore, this processing will be performed in real time, and thus channel bit rate imposes some limitations on system operating frequency. In our experimental prototype we used $K = 5$. For a specific BER, reducing the code rate of the convolutional coding system by a factor of 2 produces optical power gains close to 1.5 dB, which is similar to repetition coding. In [10] it was verified that for the RR factors considered in that work, the main improvements of the convolutional code with a constraint length of 5 over repetition coding varies from about 0.56 to about 1.11 dB. Thus, for the whole range of rate reduction factors, given the implementation complexity and optical power gains, the use of convolutional codes may not be a practical choice.

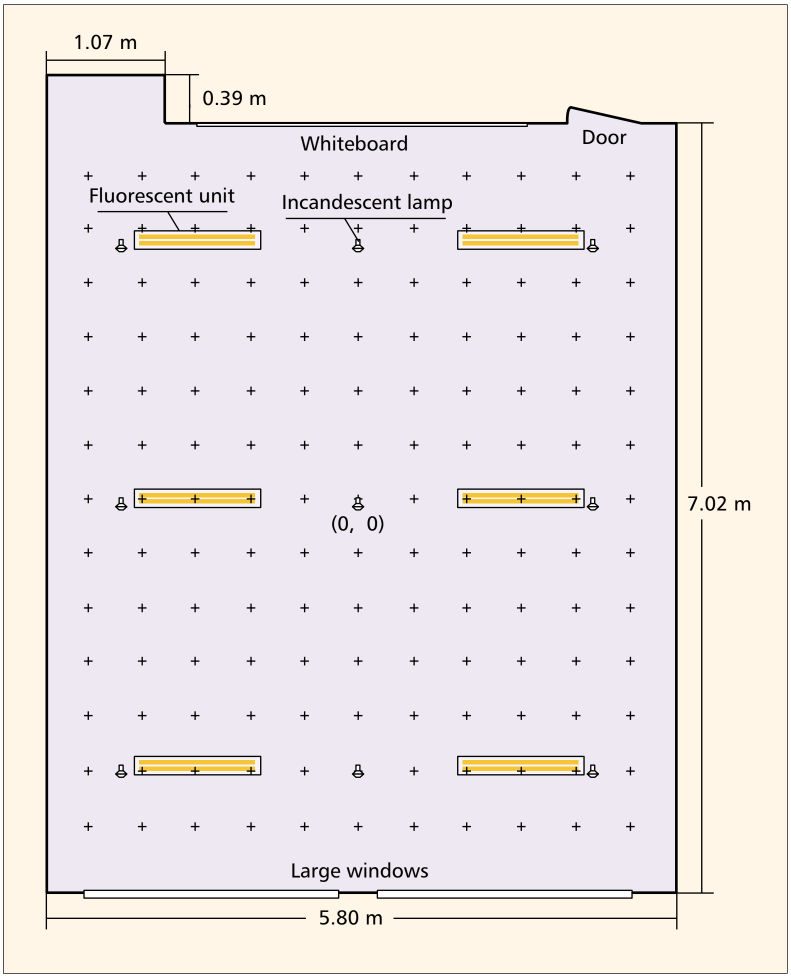


Figure 1. *The plan of the classroom, and relative positions of incandescent and fluorescent lamps.*

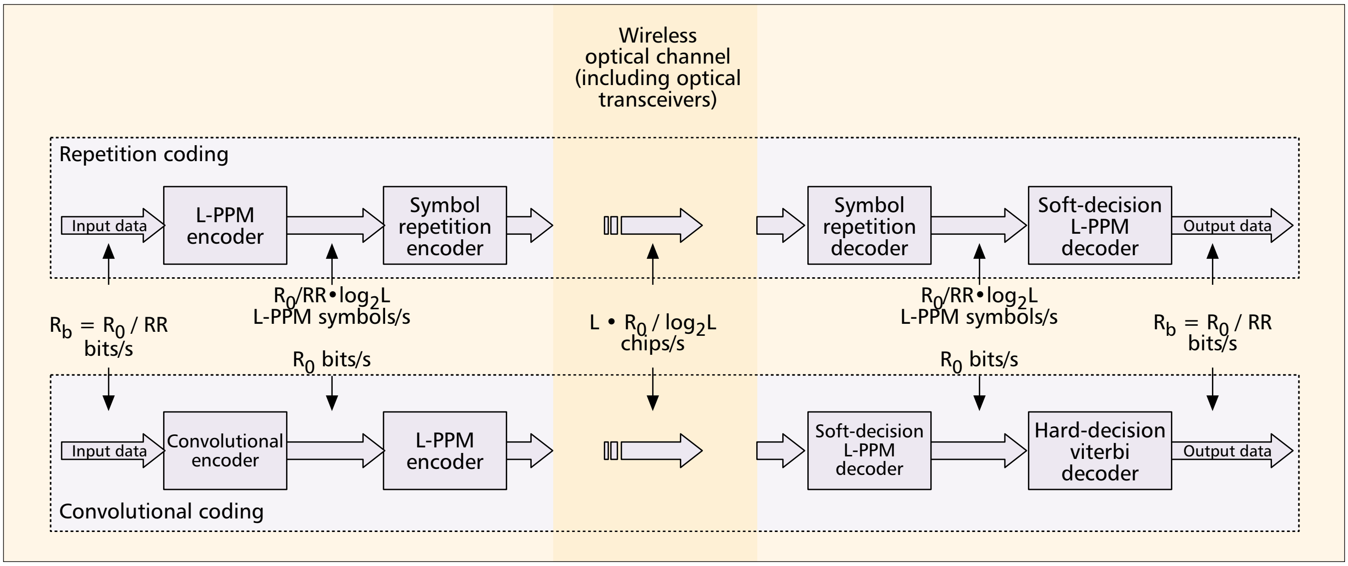


Figure 2. *Block diagrams of L-PPM adaptive data rate systems with soft-decision L-PPM decoding employing repetition coding and convolutional coding with a hard decision Viterbi decoder.*

Angle Diversity Reception

Generally, receivers for infrared communications are based on a single optical detector with a large FOV. This is a good configuration in environments where both signal and noise are isotropic, but this is not the usual situation. Indeed, a detector with a wide FOV collects a large percentage of undesired ambient light with the desired optical signal. For this reason, as we have seen, SNR can vary significantly, depending on the position, orientation, and radiation pattern of both signal and noise sources as well as the position, orientation, and FOV of the receiver. Theoretical significant performance improvements have been presented by using angle diversity receivers in these environments [7, 8]. An angle diversity receiver can be defined as a set of optical receivers (sectors) with relatively small FOVs that point in different directions. The receiver operates by estimating the SNR seen by each sector and combining the signals in order to improve the output SNR. These signals can be combined by three different ways depending on the combination technique employed: SB, EG, or MR. The structure of an angle diversity receiver is represented in Fig. 3.

In the SB technique, the combining circuit works as an analog multiplexer that selects the sector with the highest SNR. The SB combining technique improves the SNR by choosing the optical sector with the highest SNR only. Considering N sectors, the output SNR using an SB angle diversity receiver equals the maximum value of the input referred SNR of all sectors:

$$SNR_{SB} = \max_{i=1}^{N}\left[SNR_{S_i}\right], \tag{2}$$

where SNR_{S_i} is the input referred SNR of sector S_i.

For the MR receiver, the combining circuit implements a weighted summing circuit, according to the input referred SNR of the sector. When there is no correlation between the noise of the sectors, the optimum output SNR is achieved by the MR combining strategy. In this combining strategy, signals from N sectors are combined using weights, $w_{S_i} = r \cdot P_{S_i}/\sigma^2_{S_i}$, such that the resulting output SNR is given by

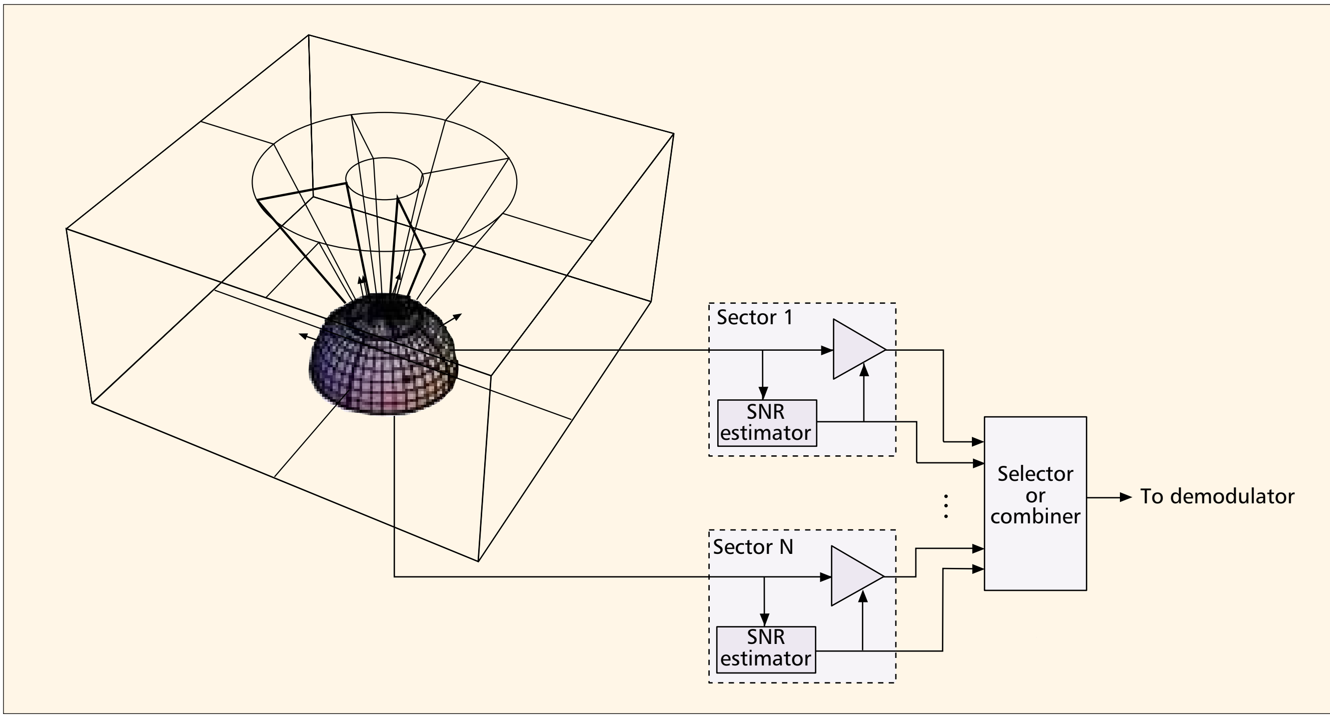
$$SNR_{MR} = \frac{\left(\sum_{i=1}^{N} r \cdot P_{S_i} \cdot w_{S_i}\right)^2}{\sum_{i=1}^{N}\left(w_{S_i} \cdot \sigma_{S_i}\right)^2} = \sum_{i=1}^{N} SNR_{S_i}, \tag{3}$$

where P_{S_i} and σ_{S_i} are the average received optical power and the root mean square value of the input referred noise of sector S_i, respectively.

Finally, in the EG combining alternative, the outputs of the diversity branches are weighted equally before being summed to obtain the resulting output. In an EG receiver, considering N sectors, the output SNR can be simply described by

$$SNR_{EG} = \frac{\left(\sum_{i=1}^{N} r \cdot P_{S_i}\right)^2}{\sum_{i=1}^{N} \sigma^2_{S_i}}. \tag{4}$$

Although the EG combining technique does not directly deal with the SNR directionality of the optical communication channel, there are two main reasons for considering its utilization: improving SNR and improving system bandwidth. For the former, if the received optical power is constant and the shot noise is induced by a steady background light, the SNR is increased by about 3 dB when duplicating the number of sectors. For the latter, this technique allows an increase in the effective collecting area without the associated loss of bandwidth caused by the increased junction capacitance of the photodetector. Here, independent photodiodes are used in independent front-ends with their total output signals combined.



■ **Figure 3.** *The general structure of an angle diversity receiver.*

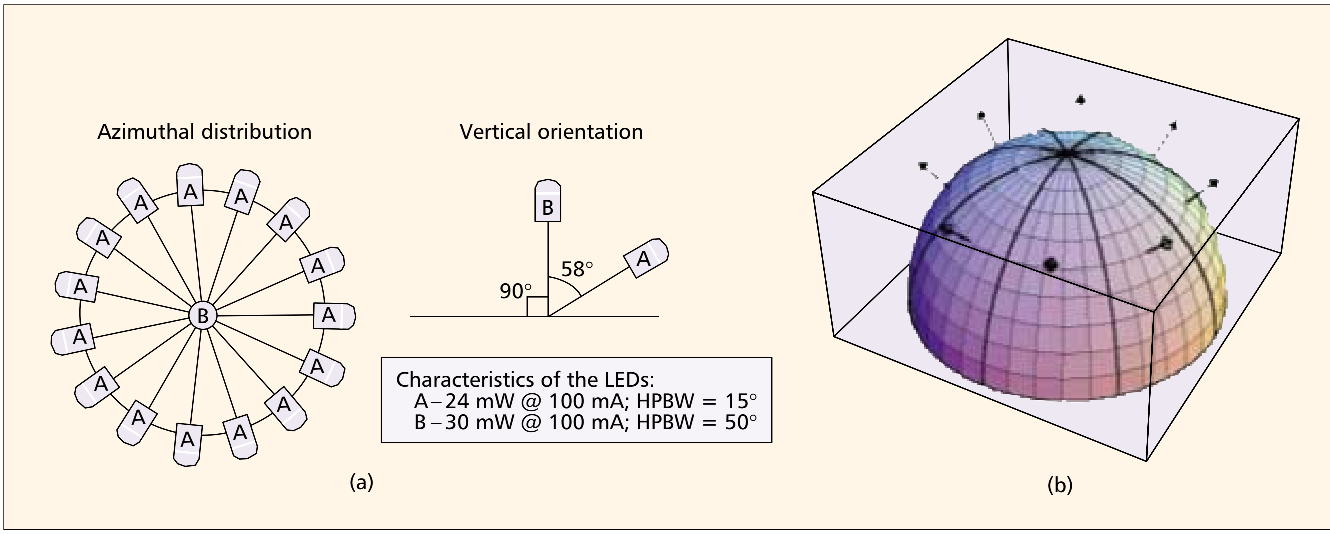
Experimental Results

The relative advantages of the strategies discussed in this work were evaluated based on measurements carried out with experimental transmission systems using rate-adaptive transmission and/or angle diversity reception strategies. Following the AIr proposals, the transmission systems were designed to operate at 4 Mb/s with a 4-PPM modulation scheme, using intensity modulation at the transmitter and direct detection at the receiver. The transmission system comprises a transmitter (with a matrix of LEDs carefully oriented) and two classes of receivers: a nonsectored receiver for the reference system and a sectored receiver with eight receivers arranged according to the angle diversity strategy. Rate-adaptive systems were implemented for both repetition and convolutional coding techniques. These systems implement five rate reduction factors of 2, 4, 8, 16, and 32, leading to effective data rates of 4 Mb/s, 2 Mb/s, 1 Mb/s, 500 kb/s, 250 kb/s, and 125 kb/s.

Experimental Prototypes

The main objective of this work was to evaluate the performance of both angle diversity and rate-adaptive transmission techniques. Thus, we opted for a single optical configuration in the transmitter, placed in the room center at the receiver plane. This optical transmitter was used to characterize both angle diversity and rate-adaptive techniques. The optical transmitter was composed of an LED matrix with the radiation pattern and orientation of the LEDs optimized in order to equalize the optical power distribution at the receiver plane within a room with dimensions similar to this one. The optimization was performed using a ray tracing simulation package [14]. Based on available low-cost LEDs and practical constraints, the optimization procedure resulted in a matrix of 16 LEDs using two types of LEDs. The LED arrangement is shown in Fig. 4a. One LED was vertically oriented emitting 30 mW at 100 mA, with a half power beamwidth of 50°, and the remaining 15 LEDs were uniformly distributed in the azimuthal plane making 58° with the normal to emitter plane, emitting 24 mW at 100 mA with a half power beamwidth of 15°. With this LED arrangement, the minimum and maximum irradiance values measured at the receiver plane were about 135 nW/cm^2 and 335 nW/cm^2, respectively.

The optical front-end design used for both rate-adaptive transmission and angle diversity systems was the same, since the effective bit rate in the communication channel was kept constant in both techniques. The photocurrent was amplified using a differential transimpedance preamplifier based on discrete components with a –3 dB cutoff frequency of about 8 MHz and a transimpedance gain of about 150 kΩ. A PIN photodiode with an active area of 0.85 cm^2, junction capacitance of 120 pF, and responsivity of 0.6 A/W was used to collect the optical power. To evaluate the performance of the angle diversity strategies, the preamplifier was replicated and integrated in the three angle diversity receiver prototypes, each implementing a different combining technique (SB, EG, and MR) with the optical configuration shown in Fig. 4b. This arrangement represents a trade-off between diversity gains and implementation complexity of the optical parts. The measured values of the input referred thermal noise of the receivers ranged from 4.9 pA/√Hz to 6.5 pA/√Hz with a mean value of about 5.5 pA/√Hz. Each optical receiver had an SNR estimation circuit providing an output signal proportional to the input



■ Figure 4. *a) Distribution and orientation of the infrared LEDs of the optical transmitter; b) optical structure of the angle diversity receiver with eight sectors uniformly distributed.*

referred SNR for posterior processing. The digital parts of the receiver electronics were integrated in a field programmable gate array (FPGA), and the Viterbi decoding process was performed through a dedicated digital signal processor (DSP) integrated with the FPGA controller.

Both combining and rate-adaptive techniques use identical SNR estimation circuits in the experimental implementations, using an original structure based on pure arithmetic analog circuits. The main objective of the SNR estimation circuit is to obtain an output signal proportional to the electrical input referred SNR. For the SB combining method, the SNR estimation circuit acts as an SNR estimator for each sector, which allows evaluation of the best sector in terms of the input referred SNR. For the MR combining method, the SNR estimation circuit is included in the forward path of the received signal, implementing a variable gain amplifier. For the EG combining method no SNR estimation is used. For both repetition and convolutional coding techniques, the SNR estimation circuit can be used to compute the SNR that determines the rate reduction factor. However, here this was done manually based on exhaustive measurements for optimum characterization of the connectivity areas.

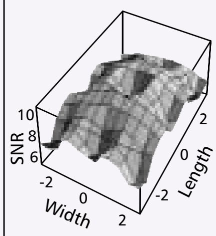
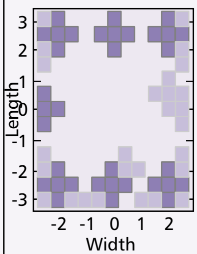
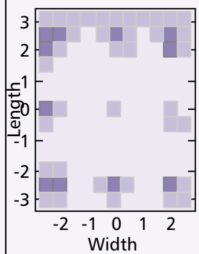
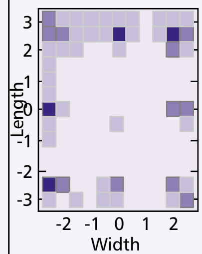
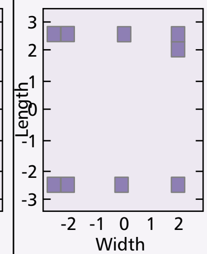
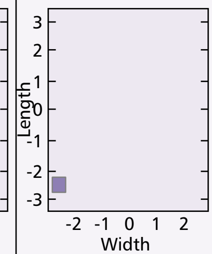
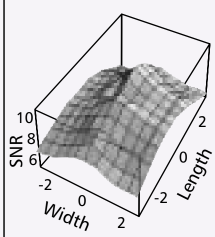
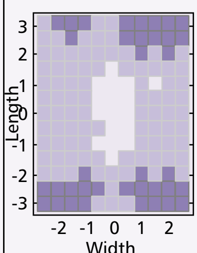
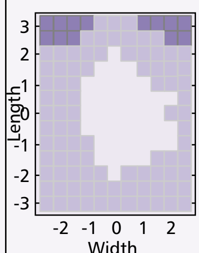
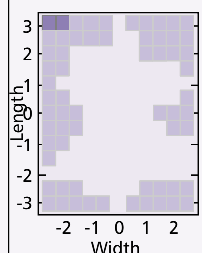
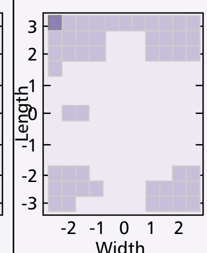
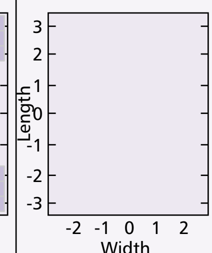
Measurements

The performance evaluation of both rate-adaptive transmission systems and angle-diversity receivers considers the ambient light configurations referred to earlier. Two rate-adaptive transmission systems and three combining methods for the angle-diversity receiver were characterized in terms of SNR enhancements and connectivity maps. All the measurements were carried out in the referred classroom, with the emitter placed 1 m above the floor, positioned in the room center and vertically oriented. For all transmission systems, the receiver was vertically oriented, placed 1 m above the floor, and moved across the room. The BER measures in most cases were made for 11×13 positions inside the room, creating a grid with a 0.5 m resolution. In systems that combined convolutional coding with angle diversity, the measurements were confined to the diagonal line delimited by the Cartesian points (–2.5, 2) and (2.5, 3), since these measurements consumed long periods of time. This is due to the need to smooth out error propagation effects in the decoding process.

The SNR measurements were carried out using a wideband 86100A Agilent infiniium digital communication analyzer. The BER measurements were carried out with an error rate measurement system, Anritsu ME522A. The definition of the connectivity areas was based on a criterion that limits the connectivity area to receiver zones where the measured BER is lower than 10^{-9}.

The Reference System — In order to assess the effective gains obtained by the rate-adaptive and angle diversity techniques, a set of measurements was made with a reference transmission system. The reference system is based on a single optical sector with an FOV of 90°, 4-PPM modulation, and a data rate R_o = 4 Mb/s. The measurements of the reference SNR and BER were carried out with this receiver being moved across the grid positions. For both incandescent and fluorescent lamps, the spatial distributions of the SNR are depicted in the first column of Table 1. The incandescent illumination scenario produced the lowest value of minimum SNR measured within the room and the highest SNR dynamic range. The connectivity areas are depicted in the other columns of Table 1 where the lightest zone indicates connectivity (at 4 Mb/s), and the darker and darkest zones indicate loss of connectivity. With the reference system the connectivity was established in 66.4 and 28.0 percent of the room area for incandescent and fluorescent illumination, respectively.

Rate-Adaptive Transmission — We carried out a large set of measurements with the rate-adaptive transmission systems for both repetition coding

	Signal-to-noise ratio referred to the reference system	Connectivity areas				
		Reference system with convolutional coding	Reference system with repetition coding	Select-best with repetition coding	Equal-gain combining with repetition coding	Maximal-ratio combining with repetition coding
Incandescent illumination	 Minimum SNR: 3.01 SNR range (dB): 9.73	 4 Mb/s: 57.3% 2Mb/s: 18.9% 1Mb/s: 23.8% 500 kb/s:	 4 Mb/s: 66.4% 2Mb/s: 25.9% 1Mb/s: 7.7% 500 kb/s:	 4 Mb/s: 65.7% 2Mb/s: 23.8% 1Mb/s: 7.7% 500 kb/s: 2.8%	 4 Mb/s: 93.7% 2Mb/s: 6.3% 1Mb/s: 500 kb/s:	 4 Mb/s: 99.3% 2Mb/s: 0.7% 1Mb/s: 500 kb/s:
Flourescent illumination	 Minimum SNR: 3.11 SNR range (dB): 6.59	 4 Mb/s: 11.9% 2Mb/s: 62.2% 1Mb/s: 25.9% 500 kb/s:	 4 Mb/s: 28.0% 2Mb/s: 62.9% 1Mb/s: 9.1% 500 kb/s:	 4 Mb/s: 55.9% 2Mb/s: 42.7% 1Mb/s: 1.4% 500 kb/s:	 4 Mb/s: 65.7% 2Mb/s: 33.6% 1Mb/s: 0.7% 500 kb/s:	 4 Mb/s: 100% 2Mb/s: 1Mb/s: 500 kb/s:

■ Table 1. *Signal-to-noise ratio and connectivity areas for rate-adaptive and angle diversity techniques under incandescent and fluorescent illumination.*

and convolutional coding techniques. These systems implemented a maximum data rate of R_o = 4 Mb/s and rate reduction factors RR = 1, 2, 4, 8, 16, and 32, resulting in effective data rates of 4 Mb/s down to 125 kb/s. The measured connectivity areas are presented in the second and third columns of Table 1.

For both incandescent and fluorescent illumination, the two rate-adaptive transmission systems allowed full connectivity in the room through the reduction of the effective bit rate from 4 to 1 Mb/s (darker areas mean lower bit rates). These techniques showed comparable results and produced effective gains over the reference system, particularly when the classroom was illuminated by directional incandescent lamps. There is a slight degradation with convolutional coding that can be attributed to the noise introduced by the DSP in the receiver.

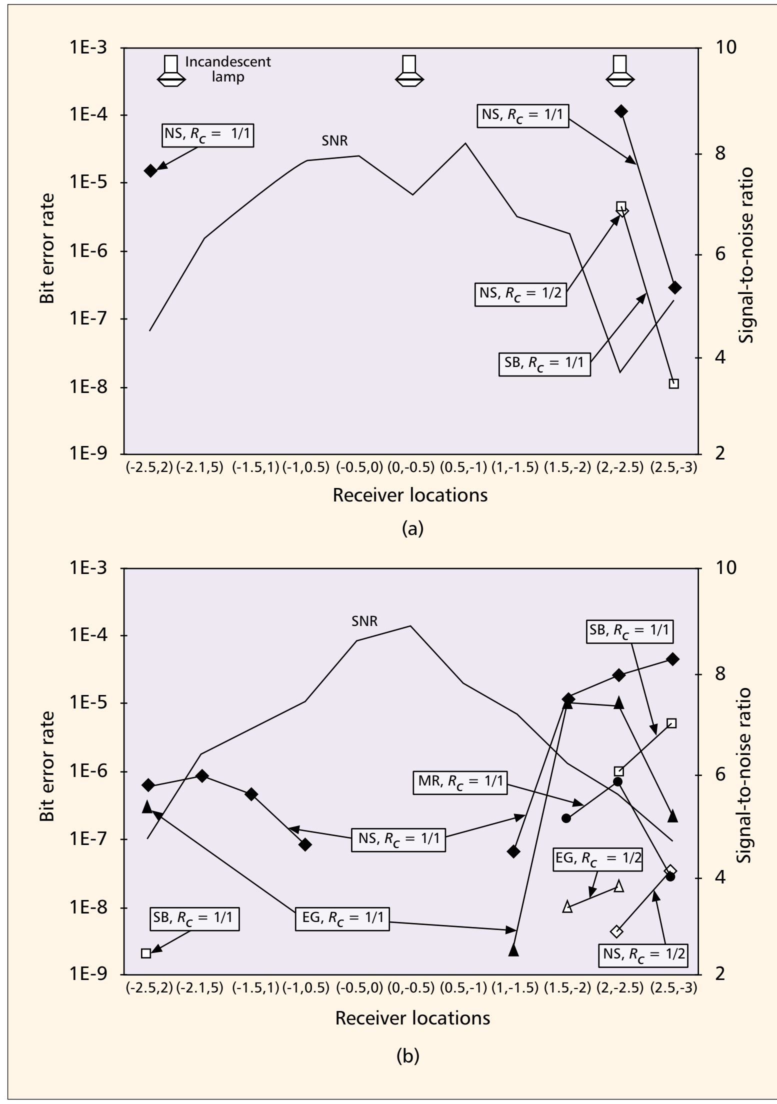
Angle Diversity Reception — To allow direct comparison between rate-adaptive transmission and angle diversity reception, we consider the same 4-PPM modulation with reference data rate R_o = 4 Mb/s. The benefits of angle diversity reception were evaluated through laboratory prototypes implementing the three combining methods covered in this work. The experimental measurements were carried out considering both incandescent and fluorescent illumination scenarios. A summary of the results reporting the connectivity areas is listed in the fourth, fifth, and sixth columns of Table 1 for SB, EG, and MR combining strategies, respectively. The measured connectivity areas correspond to the lightest zones; the remaining darker and darkest zones mean loss of connectivity. These colored areas will be explained in detail during analysis of the system using angle diversity reception and rate-adaptive transmission techniques. The MR combining method achieved the highest connectivity: 99.3 percent with incandescent illumination and 100 percent with fluorescent illumination. The EG method also achieved very good connectivity (93.7 percent) when the room was illuminated by incandescent lamps. However, under fluorescent illumination, the EG method achieved a connectivity area of about 65.7 percent, which was slightly better than the results obtained with the SB method for the same conditions (55.9 percent). These results can be justified by the low variations of the SNR spatial distribution, a situation where EG combining is especially suitable, and the existence of a number of fluorescent units lower than the number of sectors, especially adequate for the SB method. For these reasons, both EG and SB methods presented considerable connectivity range extensions over the reference system (28 percent). Finally, the SB combining method produced the lowest connectivity area for incandescent illumination (65.7 percent) even when compared to the connectivity area achieved by the reference system (66.4 percent). This is explained by the relatively low number of sectors, which is smaller than the number of incandescent lamps, precisely the opposite of the situation more adequate for the SB method.

In summary, almost all angle diversity strategies achieved connectivity areas higher than the reference receiver for both illumination scenarios. The only exception was the SB angle diversity receiver operating under incandescent illumination due to the large number of existing lamps.

Combined Use of Angle Diversity Reception and Rate-Adaptive Transmission — We further analyzed the simultaneous use of angle diversity reception and rate-adaptive transmission techniques. The three combining methods and two coding techniques were integrated, leading to a total of six experimental prototypes.

The prototypes employing repetition coding were evaluated at all grid points in the room. The experimental results are described in the fourth, fifth, and sixth columns of Table 1, respectively for SB, EG, and MR combining strategies. In the incandescent illumination scenario, the system with SB combining produced slightly lower performance than that with the nonsectored receiver: the former achieved connectivity at all locations with a minimum data rate of 500 kb/s, while for the latter the minimum data rate was 1 Mb/s. In the fluorescent illumination case, the system with SB combining achieved slightly better performance than the one with the nonsectored receiver, although in both cases the minimum data rate was 1 Mb/s. The system with EG combining achieved connectivity at all locations with a minimum data rate of 2 Mb/s and 1 Mb/s, respectively, for incandescent and fluorescent illumination. As expected, the best performance was obtained by the system with MR combining, which achieved connectivity in almost all room locations at the maximum data rate of 4 Mb/s.

The prototypes with convolutional coding were analyzed through measurements over a diagonal line in the room. The BER and SNR measurements of the nonsectored (NS) reference system, in both incandescent and fluorescent scenarios, are shown in Fig. 5. The graphs represent only the BER values corresponding to locations where connectivity was not achieved at a given code rate. Note that for the combination of repetition rate coding and angle diversity, a similar analysis over the diagonal line can be obtained from the connectivity graphs of Table 1. With incandescent illumination (Figure 5a), both the systems with EG and MR combining achieved connectivity with no rate reduction at any location. Accordingly, in Fig. 5 there are no BER values relative to these two cases. The system with SB combining needed to reduce the data rate to 2 Mb/s at locations near an incandescent lamp. With incandescent illumination, the reference receiver achieved the worst performance, as data rate reduction was required in three locations (the three points represented in Fig. 5a). With fluorescent illumination (Fig. 5b), the data rate had to be reduced to 1 Mb/s at some points to ensure connectivity with both the nonsectored and EG angle diversity receivers. With the SB and MR angle diversity receivers, the minimum data rate was only 2 Mb/s.



■ Figure 5. *Bit error rate measured over the diagonal line considering a) incandescent and b) fluorescent illumination.*

Conclusions

We present experimental results obtained from a testbed developed to compare the combined use of angle diversity and rate-adaptive techniques for SNR improvement in shot-noise-limited transmission channels. The testbed replicated a typical indoor environment with artificial light containing incandescent and fluorescent light sources.

Both angle diversity reception and rate-adaptive transmission produced very good results in mitigating SNR fluctuation effects. The results obtained with the rate-adaptive transmission systems lead to the conclusion that even simple repetition coding techniques can be very effective in extending coverage area, while maintaining reasonable transmission rates. For the code rates used, the convolutional coding receiver does not seem to provide performance improvements to justify its added complexity. On the other hand, the utilization of angle diversity reception allows larger connectivity areas operating at maximum throughput, in particular with MR angle diversity receivers; its sole usage

The main objective of the SNR estimation circuit is to obtain an output signal proportional to the electrical input referred SNR. For the SB combining method, the SNR estimation circuit acts as an SNR estimator for each sector, which allows an evaluation of the best sector in terms of the input referred SNR.

allowed connectivity at maximum data rate at almost all room locations for both incandescent and fluorescent illumination scenarios. Although conceptually more complex, MR does not essentially require much more electronics than SB combining, but provides substantial gains.

We believe that the combined use of angle diversity and rate-adaptive techniques is inevitable in high-performance wireless infrared systems. Angle diversity reception maximizes area coverage, while adaptive rate transmission ensures connectivity under (localized) severe channel conditions. A solution with MR combining and repetition coding is preferred since it achieves very good performance with moderate complexity: in our experimental scenario, this system was able to obtain connectivity at the maximum data rate in almost all room positions, in both incandescent and fluorescent illumination. These techniques can easily be implemented in packet systems using bit rate negotiation protocols based on retransmission schemes (e.g., automatic repeat request) with either SNR or frame error rate estimation techniques.

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