Indoor infrared wireless communications using spot diffusing and fly-eye receivers

Communications intérieures sans fil par infra-rouge avec diffusion spéculaire et récepteurs à orientation diverse

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In this paper, a new configuration is proposed for indoor optical wireless communication systems. The main features are the use of spot diffusing, multiple lines of sight and fly-eye receivers. Design issues such as the power budget, ambient-light interference and farsighted-eye designs for the receivers are discussed using simple models. An experimental set-up demonstrating the feasibility of the spot-diffusing concept is also described.

Dans cet article, on propose une nouvelle configuration de systèmes de communication intérieure optique, donc sans fil. Les principales caractéristiques sont l'utilisation d'une technique de diffusion spéculaire, de multiples lignes de vue et de récepteurs alignés mais orientés dans différentes directions, comme les yeux d'une mouche (fly-eye). Les paramètres de conception tels la puissance disponible, l'interférence par la lumière ambiante et la conception de récepteurs hypermétropes sont discutés en utilisant des modèles simples. Un montage expérimental est aussi décrit, lequel démontre la faisabilité du concept de diffusion spéculaire.

I. Introduction

The purpose of using optical wireless communication systems in an indoor environment is to eliminate wiring. As the variety of user terminals increases, a rewiring job may involve increasingly substantial cost and loss of time. In addition, exposed wiring can be dangerous and unsightly. For many reasons, infrared (IR) indoor wireless communication systems are desirable under certain circumstances. The major advantage of an IR system over a radio frequency (RF) system is the absence of electromagnetic (EM) interference. Consequently, IR systems are not subject to spectral regulations as RF systems are. Compared with an RF system, another advantage of an IR system is its inherent channel diversity, which makes multipath propagation fading much less of a problem. First, IR systems have inherent frequency diversity due to the remarkable line width (roughly 5 to 50 nm) of the light sources employed in indoor applications. This line width measures at least hundreds of gigahertz, and hence the lightwave carrier is composed of a tremendously large number of independent frequency components. This provides a high degree of frequency diversity, reducing the negative effects of multipath propagation fading. It is known that the illumination from a wide-band light source, containing more independent frequency components, is smoother (thus resulting in less frequency-selective fading in the terminology of communications) than that of a narrow-line-width source. Also notice that, in optical-fibre applications, it is desirable to make the line width of the lightwave carrier as narrow as possible to reduce dispersion in fibres; while in IR indoor wireless applications, the line width can be, to some extent, beneficial.

Second, it is known that the dimension of the coherent area of a fully scattered light field is roughly of the order of its wavelength [1]. Consider that the wavelength of IR radiation is of the order of one micron, while the dimension of a typical photodiode is of the order of one millimetre. An optical receiver actually receives a large number (hundreds of thousands) of independent signal elements at different locations on the receiving aperture. This in fact provides spatial diversity, which is very similar to those RF techniques employing multiple, geographically separated antennae. In summary, because of the inherent diversity channels, the frequency-selective fading effect at the optical-carrier frequency level is not a problem in an IR system. However, at the baseband, when the modulation bandwidth is more than about 10 MHz, multipath fading will still be observed.

There are typically two configurations for IR indoor communications. One is the Directive Beam Concept (DBC) [2], in which each user terminal is connected to the local area network by two collimated infrared light beams, one for the downlink (network to terminal), the other for the uplink (terminal to network). The second configuration is termed Diffuse Infrared radiation Configuration (DIC) [3]. It employs a wide-angle diverging beam to illuminate the entire or part of the ceiling and walls. DIC has the merit of being operationally simple due to the elimination of alignment requirements. However, the negative aspects are the required high transmission power (typically one watt), multiple signal paths, wide-angle acceptance of ambient light and high capacitance of the large-area photodiode. In contrast to DIC, a DBC system can have a bit rate a few orders of magnitude higher due to the use of narrow transmission beams, small field-of-view (FOV) receivers and a single transmission path. Nevertheless, the line of sight can easily be blocked and the alignment requires high mechanical stability for the optical antenna systems. This, to some extent, defeats the purpose of having a wireless system.

Some novel configurations have been proposed and implemented in order to obtain a more balanced performance [4]-[5]. In both [4] and [5], a central repeater or reflector is designed to produce a wide-angle beam for broadcasting of the downward signals. For the uplinks, a narrow beam is used to reduce the required uplink transmission power. To avoid being blocked, the lines of sight are arranged 8 ft above the floor in [4], and the active reflectors in [5] are mounted on the ceiling. These configurations can still be categorized as DBC. The innovation lies in the use of a wide-angle beam and a wide FOV receiver to alleviate the alignment requirement at the repeater or the reflectors. The price paid here is the wide-angle ambient light acceptance by the repeater or the reflector. Clearly the installation of an active reflector or repeater may also turn out to be inconvenient, because wiring is still required.

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In this paper, we propose a new approach which we call Spot-diffusing Multi-line-of-sight Configuration (SMC). The idea is based on the following observation: according to the measurements conducted in [3], the use of diffused reflection is not the source of the required high transmission-power requirement, since the plaster coating usually has a high reflectance in the near IR range and is usually a good Lambertian reflector unless the incident angle is very close to 90° [3]. In fact, the high power budget of DIC is caused by the use of large FOV (typically, over 120°) receivers. They receive an excess amount of ambient light and rule out the possibility of applying passive concentrators (e.g., lenses) to increase the receiving aperture. It is known that according to the second law of thermodynamics, there is no way to use a passive optical system to increase the receiving area while at the same time keeping the same FOV. In the case of DIC, if a passive power collector is used, the increased receiving area will not increase the received power, because the receiver will collect optical power from a smaller solid angle. Consequently no gain will be obtained in the received power, though the multipath propagation problem can be eliminated at the cost of extra optical components.

In the next section, the features of SMC will be discussed in detail. The design issues will be discussed in section III. A spot-diffused broadcasting experiment will be described in section IV, followed by the conclusions.

II. The concepts

The proposed SMC employs two new features, as shown in Fig. 1. One feature is called spot diffusing. The light power from a transmitter is projected over a small area of the diffusing surface called the diffusing spot. Using spot diffusing provides the following advantages: First, passive power concentrators can be used to increase the aperture size of the receivers because of a narrow field-of-view (FOV). This will decrease the required transmission power by the ratio of the concentrator receiving area to the photodiode area. Second, since a narrow beam is used between the transmitter and the diffusing spot, the channel power loss will be basically independent of the length of this section of the channel. Furthermore, the rearrangement of the network is relatively easier because no active reflectors need to be installed in the ceiling. The diffusing-spot position can be easily rearranged by steering the projected IR beams.

The other feature of SMC is the use of multiple lines of sight, allowing each user terminal to send more than one IR beam to geographically separated diffusing spots and to have multiple receivers aimed at different diffusing spots. With one diffusing spot and one transceiver for each user, there is a single line of sight for each user terminal, which can easily be blocked. However, with multiple lines of sight there is little chance that all of them will be blocked at the same time. Obviously this multi-line-of-sight arrangement adds redundancy to the system, but it makes the connections more robust because of the added angular diversity channels. Besides, in an SMC system the multipath propagation is not as severe a problem as in DIC. In a DIC system, there are countless different paths between any pair of transceivers, while in the SMC there are only a finite number of distinct paths. It is theoretically easier to deal with these angularly resolved paths by, for example, switching to the strongest path, etc.

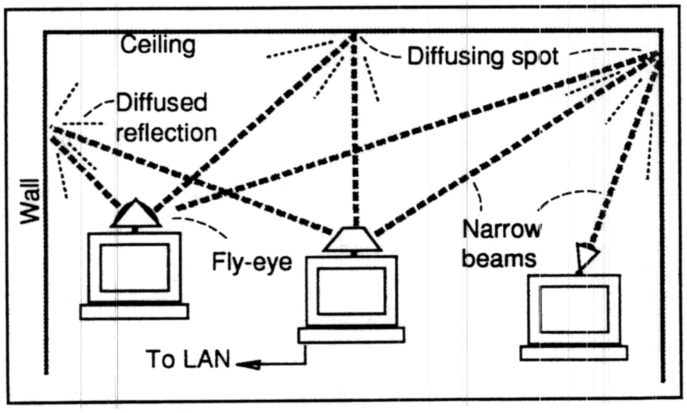

Figure 1: *Spot-diffusing multi-line-of-sight concept (SMC).*

Since each user may use more than one receiver in an SMC system and each receiver is aligned in a different direction, we can properly call the collection of receivers for a user terminal a "fly-eye" receiver and each element of the collection an "eye." Clearly, compared to a transceiver with a single "eye," a transceiver structured as a fly-eye is more complicated. However, it will be shown in section III.E that some novel designs may reduce the added complexity to an acceptable level. Furthermore, in order to avoid excess complexity, the number of eyes will be limited, typically to no more than three. Besides this, the system can always be customized according to the budget and particular arrangement requirements. In one extreme case, if a terminal can be arranged in a location such that its line of sight can rarely be blocked, a transceiver with a single "eye" may be used to minimize the cost, if a properly designed network protocol is used to coordinate communication among user terminals.

III. Design issues in SMC systems

In designing an SMC system, three factors should be considered:

1) Required transmission power: This value is determined by the specified bit error rate (BER), the range, the bit rate, the optical front-end design and the safety standard considerations.
2) Simplicity: The network will be used by laymen. The alignment and the adjustment operations should be easy to perform. Also, simplicity in the design results in a more cost-effective system.
3) Robustness: The antenna system should tolerate mechanical disturbances and misalignments.

A. Model for power analysis

Two kinds of light sources may be used for an SMC system; namely, light-emitting diodes (LEDs) and laser diodes (LDs). In considering the power budget of an SMC system, we note that major difference between the two is that LEDs are Lambertian sources while LDs can be considered as perfect point sources. Notice that this is not the only difference between the two in practice. They also differ in cost, available power, modulation bandwidth and safety requirements, etc.

The model for a design using LDs is shown in Fig. 2, where no lower bound is placed on the size of the diffusing spot. The model for LED systems is depicted in Fig. 3. The difference between Figs. 2 and 3 lies in the fact that the emitting area of an LED cannot be neglected. Generally, a laser can be viewed as a "Lambertian" source with the emitting area equal to zero. The symbols used in Figs. 2 and 3 are defined as follows:

L_T: distance between the transmitter lens and the diffusing spot.
l_T: distance from the transmitter lens to the light source.
f_T: focal length of the transmitter lens.

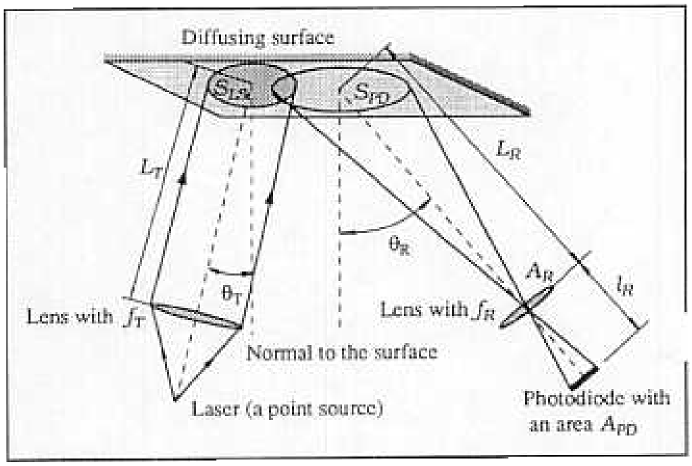

Figure 2: *Power analysis model for a laser system.*

L_R: distance between the receiver lens and the diffusing spot.
l_R: Distance from the receiver lens to the photodiode.
f_R: focal length of the receiver lens.
S_{LS}: projection of the light source on the diffusing surface or its area.
S_{PD}: projection of the photodiode on the diffusing surface or its area.
A_{LS}: emitting surface of the light source or its area.
A_{PD}: receiving surface of the photodiode or its area.
A_R: aperture area of the receiver lens.
θ_T: angle of the line of sight of the transmitter with the normal of the diffusing surface.
θ_R: angle of the line of sight of the receiver with the normal of the diffusing surface.

In the case of a laser, the size of the diffusing spot can range from infinity to the diffraction limit, which can be considered as a geometric point in this application. However, in the case of an LED there is a lower bound. The minimum spot size is achieved when the condition

$$\frac{1}{L_T}+\frac{1}{l_T}=\frac{1}{f_T} \tag{1}$$

is satisfied. Usually, $L_T >> f_T$, and consequently $l_T \approx f_T$. Under this condition, the minimum spot area is, according to Fig. 3, approximately expressed as

$$S_{LS\,min} \quad \frac{L_T\,A_{LS}}{f_T\,\cos\theta_T} \tag{2}$$

Equation (1) may not be satisfied in practice, since the required focusing operation may not be performed for the sake of simplicity. Hence, the actual size may be larger than S_{LSmin}.

In the following sections, it will be assumed that the reflection surfaces are perfectly Lambertian, meaning that the intensity of the reflected light satisfies the cosine law. In practice, this may not be true because a diffusing surface may have a considerable specular-reflection component, especially when the incident beam is close to the glancing angle. However, the authors believe that, from the point of view of broadcasting, the specular component is by no means desirable and can simply be considered as loss, implying that only the worst-case scenario is considered in this paper. In addition, in a real system, when the reflecting surface has a low reflectance or a strong specular component, a special "pad" coated with a material of the desired quality may be applied on the diffusing spots to improve the system performance. This is obviously not an expensive solution. It is also important that the glancing incidence always be avoided by properly arranging the positions of the diffusing spots.

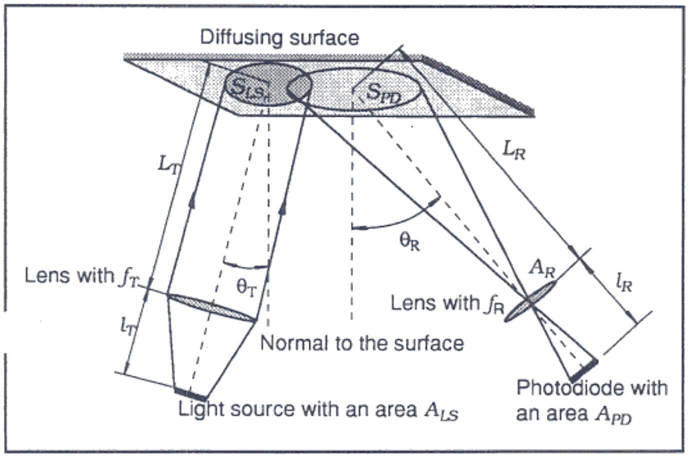

Figure 3: *Power analysis model for an LED system.*

An expression similar to (2) can be derived for evaluating the projection of the photodiode on the diffusing surface:

$$S_{PD}=\frac{L_R\,A_{PD}}{f_R\,\cos\theta_R}. \tag{3}$$

It is evident that the received power is determined by the overlapped area of S_{LS} and S_{PD}, and that the maximum received power can be achieved when

$$S_{PD} \geq S_{LS}$$

and when the diffusing spot is completely within the field of view of the receivers. If we assume the diffusing surface to be a Lambertian reflector, the received power can be expressed as

$$P_R=\frac{P_T}{S_{LS}}A_R\int_{S_{LS}\cap S_{PD}} R\frac{\cos\theta_R}{\pi L_R^2}\,d\sigma \tag{5}$$

where P_T stands for the total optical power projected on S_{LS} and R is the reflectance of the diffusing component of the surface. In (5), it is also assumed for the sake of simplicity that the illumination over S_{LS} is uniform. Generally, all the parameters in the integral may be considered as functions of the position of the element area, $d\sigma$, on the diffusing surface. Notice that the diffusing spot may not be flat and its dimension may not be neglected when compared with L_R. For $L^2{}_R >> A_R$ and $S_{PD} \geq S_{LS}$, the above equation becomes

$$P_R=\frac{A_R\,P_T\,R\cos\theta_R}{\pi L_R^2} \tag{6}$$

1. Example

Given $P_T = 5$ mW, $L_R = 5$ m, $A_R = 10$ cm^2, $\cos\theta_R = 0.5$ and $R = 0.5$, we have, from (6):

$$P_R = 0.159\ \mu\text{W} = -38\ \text{dBm}.$$

In a DIC configuration, since a large FOV is required to maximize the received power and to accommodate hand-held terminals, the received power may be approximately estimated as:

$$P_R=\frac{A_{PD}\,P_T\,R\cos\theta_R}{\pi L_R^2}, \tag{7}$$

where to make (6) valid, we have assumed that all the diffusing-element area in the integral (5) can be equivalently placed at a single spot at a distance L_R from the receiver.

Therefore, the gain of SMC over DIC is

$$G=\frac{A_R}{A_{PD}}, \tag{8}$$

which is the ratio of the area of the concentrator lens to that of the photodiode.

2. Example

$$A_R = 0.1\ \text{m}^2,\ A_{PD} = 1\ \text{cm}^2,\ G = 100 = 20\ \text{dB}$$

Remember that a photodiode with $A_{PD} = 1$ cm^2 is very large. Its capacitance may make the receiver design difficult. For a smaller photodiode with, say, $A_{PD} = 2$ mm^2 and $G = 2500 = 34$ dB, the gain is even more significant.

B. Angular tolerance

The angular tolerance of the antenna is a vital issue for an SMC system. Since lines of sight still exist in the system, a larger angular tolerance means less difficulty in alignment. It also means a more robust set-up with sufficient immunity to mechanical disturbances. The angular tolerance of a receiver is determined by the light-source projection, S_{LS}, and the projection of the photodiode, S_{PD}, which is an equivalent depiction of FOV. It is apparent that the receiver receives power only when the two projections overlap, as shown in Fig. 4. Hence, we may define a field of tolerance (FOT) in steradians as

$$FOT = \frac{S_T \cos\theta_R}{L_R^2}, \tag{9}$$

where S_T represents the projection of this solid angle on the diffusing surface, as shown in Fig. 5. The angular tolerance of an eye can thus be defined approximately but acceptably as $\delta\theta_{max} = \sqrt{FOT}$.

According to (9) and Fig. 2 or 3, there are two ways to increase the tolerance:

1. Increase the spot size, S_{LS}. If an LD is used, this can be done by placing the light source closer to the transmitter lens, so that the beam becomes divergent. This defocusing technique also works well with LEDs. However, according to Fig. 3, if an LED is used, S_{LS} can be increased by decreasing f_T or by using a diode with a larger emitting area, because from Fig. 3,

$$\frac{L_T^2}{f_T^2} A_{PD} \tag{10}$$

where it is assumed that $L_T >> f_T$. In fibre systems, LEDs are supposed to be made small to increase the source-to-fibre coupling efficiency. However, in an SMC system, the size of the LED is less important. According to Fig. 3, if $S_{LS} = S_{PD}$ can be considered a desirable match for efficient power transmission, and if it can be assumed that $L_T \approx L_R$ (as is desirable in a practical network arrangement), we have $A_{LS} \approx A_{PD}$; i.e., the size of the LED can be of the same order as that of the photodiode. Consider that a typical photodiode can have a diameter of a few millimetres, much larger than that of LEDs used in fibre communications. This is significant in the sense that a large-area LED can be made to achieve a higher output power more easily.

2. Increase the photodiode size or reduce the focal length. The former is limited by the photodiode capacitance; the latter is limited by the aperture size of the lens.

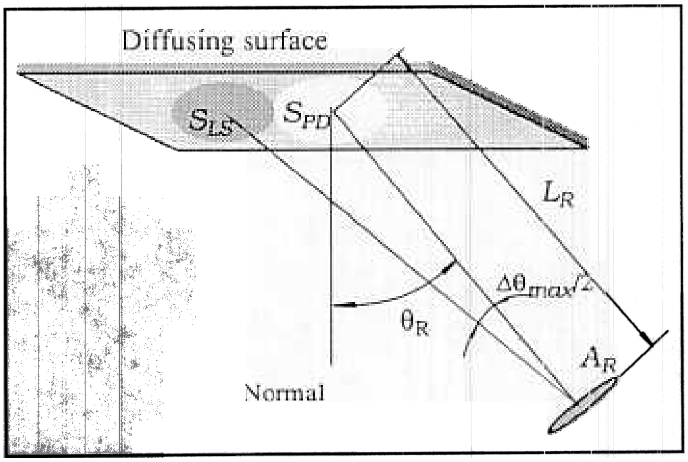

Figure 4: *Angular tolerance of a receiving eye.*

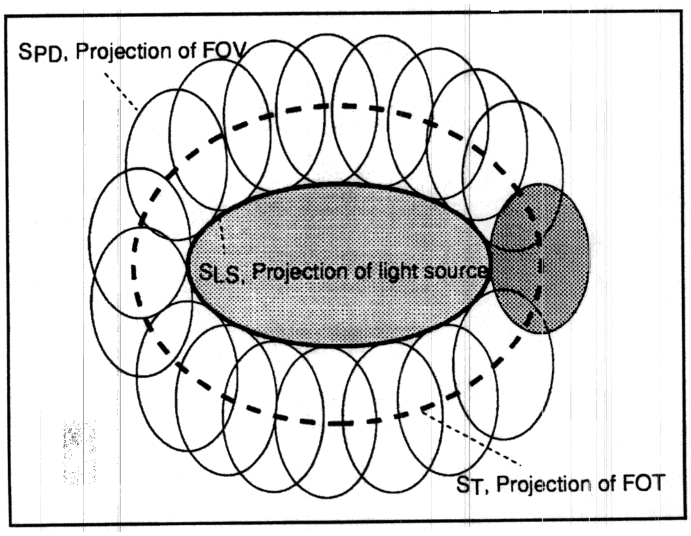

Figure 5: *A description of S_T, the projection of FOT on the diffusing surface.*

1. Example

$$f_R = 50 \text{ mm}, \sqrt{A_{PD}} = 3 \text{ mm}, \delta\theta_{max} = 6.84°$$

In this case the alignment can be easily achieved without using any precision mechanical devices.

C. Ambient light

In contrast to fibre-optic systems, an indoor optical wireless communication system is exposed to ambient light. The common sources of ambient light are daylight, incandescent and fluorescent lamps. Ambient light can introduce shot noise, saturate the photodetector when it is very strong (e.g., in the case of direct sunlight) and cause interference when it is modulated. Ambient light can be much stronger than the signal light in terms of power, but its influence can be reduced in a number of ways. First, the power of ambient light is distributed over a wide spectral range, in contrast to the light sources used in indoor applications, which have a typical line width of 10 nm in the case of multi-longitudinal-mode lasers and 50 nm in the case of LEDs. Hence, a narrow-band optical filter can remove most of the radiation from the ambient light sources.

The second method used to deal with ambient light makes use of the fact that ambient light is basically unmodulated. An ac coupled receiver can easily remove the dc component generated by the ambient light. Some artificial light sources have rapidly fluctuating components, but they are usually associated with the harmonics of the fundamental frequency of the power line, and can be removed with electrical filters. When an electrical filter is used, some kind of spectrum-shaping line code should be used to reduce the resulting intersymbol interference.

The third approach uses the difference between the spatial characteristics of ambient light and signal sources. Ambient light is usually very well diffused; by contrast, when the spot-diffusing concept is used, the light signal is concentrated on a small area. Hence, a small field-of-view receiver can have a much lower ambient-light level than a wide FOV receiver. This is illustrated in Fig. 6. The gain in signal-to-ambient-noise ratio achieved by using small FOV receivers over DIC is approximately equal to

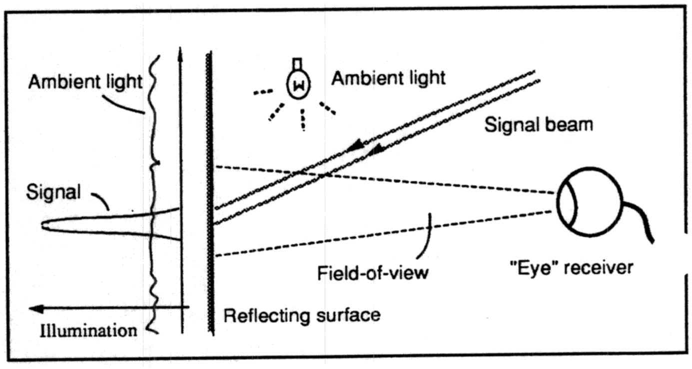

Figure 6: *Ambient light can be suppressed using a narrow FOV receiver, because the light signal is concentrated on a small area.*

$$G_{amb} \quad \frac{2\pi}{FOV} \tag{11}$$

where FOV is in steradians, and the numerator stands for the solid le of a hemisphere. The gain shows another advantage of SMC over DIC: with a small FOV receiver, it is easy to avoid the interfering light sources being put into the FOV of the receivers simply by arranging the diffusing spots at appropriate locations.

D. Farsighted eyes

As we mentioned at the beginning of this section, simplicity is a major concern in the design of an SMC network. In this section, the possibility of using farsighted eyes to simplify the receiver design will be discussed. Receivers with a focus fixed at infinity are termed farsighted. On the other hand, it is assumed that a "perfect eye" should have the ability to focus itself to get a sharp picture of the diffusing surface on the photodiode, so that the maximum amount of power can be received. This focusing operation can usually be achieved by changing the relative position between the receiver lens and the photodiode in the longitudinal direction. However, a farsighted eye has its photodetector fixed at one focal length away from the receiving lens, and is therefore simpler in structure and easier to use. Next, it will be shown that under a certain condition, a farsighted eye can be a good choice from the point of view of power reception.

For a perfect eye (an eye with focusing ability), it can be shown, using the model given in Fig. 2 or 3, that the power received versus the distance is expressed by

$$P_R = \begin{cases} \dfrac{P_T A_R}{\pi f_R^2} \dfrac{R}{\left(\dfrac{L_R}{f_R}\right)^2} & \dfrac{L_R}{f_R} \geq 1 + \dfrac{D_S}{d_{PD}} \\[2ex] \dfrac{P_T A_R}{\pi f_R^2} \dfrac{A_{PD}}{A_{LS}} \dfrac{R}{\left(\dfrac{L_R}{f_R}\right)^2} & \dfrac{L_R}{f_R} < 1 + \dfrac{D_S}{d_{PD}}, \end{cases} \tag{12}$$

where D_S stands for the lateral dimension of the projection of S_{LS} in the direction of the receiver line of sight, and d_{PD} for the diameter of the photodiode.

For a farsighted eye without focusing ability, the received power can have a lower bound expressed as

$$P_R = \begin{cases} \dfrac{P_T A_R}{\pi f_R^2} \dfrac{R}{\left(\dfrac{L_R}{f_R}\right)^2} & \dfrac{L_R}{f_R} \geq \dfrac{L_c}{f_R} = \dfrac{D + D_{LS}}{d_{PD}} \\[2ex] \dfrac{P_T A_R}{\pi f_R^2} \dfrac{A_{PD}}{(D+D_S)^2} \dfrac{R}{\left(\dfrac{L_R}{f_R}\right)^2} & \dfrac{L_R}{f_R} < \dfrac{D + D_S}{} \end{cases} \tag{13}$$

where D stands for the diameter of the receiver lens. The received power in (13) represents a lower bound because a simplified model shown in Fig. 7 is used for the derivation. A uniform power-distribution profile is assumed, which has in fact a more centrally concentrated distribution.

Both (12) and (13) are plotted in Fig. 8. It can be seen that when the working distance is larger than a certain value L_c, both receivers have the same power-versus-distance characteristics. For a photodetector having a sensitivity better than s_c, the performance of a farsighted receiver is just sufficient. Though the perfect eye can receive more signal power at a shorter range, the extra received power is wasted if the maximum working distance is designed to be larger than L_c for a specified BER.

Other concerns include the ambient noise and the angular tolerance. It turns out that, in the long-range region, both kinds of eyes will receive the same amount of ambient light; while over a shorter range, the farsighted eye receives slightly more, because the photodiode is closer to the lens aperture. The angular tolerance of a farsighted eye is larger than that of a perfect eye in all ranges, because of the spreading of the blurred image of the diffusing spot.

In conclusion, in order to simplify the structure of fly-eye receivers, a farsighted eye design can be used for an SMC network.

E. Novel designs for the fly-eyes

A disadvantage of a fly-eye receiver is that the lens system can be quite complicated, because it must look in different directions at the same time. The most straightforward way of realizing fly-eyes is to employ separate eyes, each having its own lens and photodiode system. However, using too many lenses will probably make the system bulky and undesirable. A novel design may solve the problem. One possibility is to employ a glass or plastic ball as the lens for the eyes. Since a ball has a very good symmetry, all the eyes can use the same ball. In Fig. 9, an example of two eyes sharing one ball lens is depicted. The problem with this design is that a ball lens can be very heavy when a large aperture is required. Hence, it is suitable only for systems covering a small room.

Another design is shown in Fig. 10, in which the off-axis imaging ability of a lens is explored. The design can have a large-size aperture, especially when a Fresnel lens is used. Compared with the ball lens, different lines of sight cannot be arranged very far apart from the optical axis of the lens, or the aberration becomes significant. Though a larger photodiode can tolerate greater aberration, the design flexibility is limited. As an example, consider a standard camera lens. Knowing that the focal length is 50 mm and that the diagonal dimension of a frame of standard 35-mm film is about 43.5 mm, we can safely

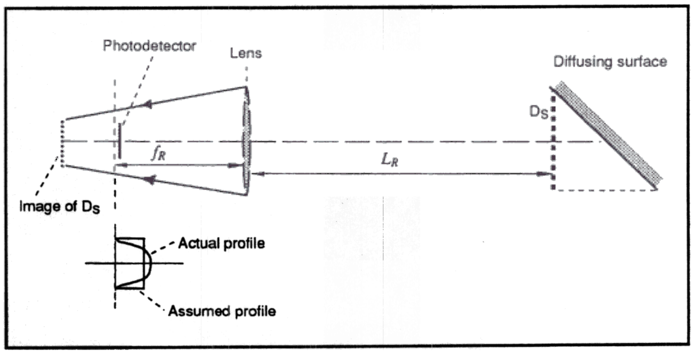

Figure 7: *Model for the derivation of (13).*

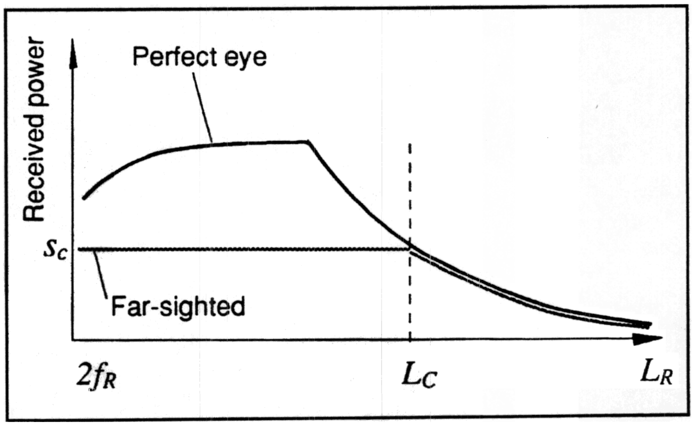

Figure 8: *The received power by a perfect eye and a farsighted eye.*

assume that the maximum angle between two lines of sight is $2\tan^{-1}\frac{43.5/2}{50} = 47°$, if this lens is used for light collecting. In practice, consider that since a photodiode is much larger than the resolution required for photography, this angle is by no means an upper bound.

IV. Experiment

A spot-diffusing IR link was built to demonstrate its feasibility. The set-up is depicted in Fig. 11. The distance between the diffusing spot and the receiver was about 3 m. The line of sight made an angle of 45° with the normal line of the diffusing surface. A 780-nm CD laser was used to emit an average power of 0.8 mW. The light from the laser was projected on a plaster wall by a telescope eyepiece with a focal length of 25 mm and an aperture size of 18 mm. The light projected on the wall measured 0.366 mW. The loss in power was caused by the wide divergence angle of the CD laser, in the direction perpendicular to the junction plane. This loss could be reduced by using more sophisticated projecting lenses. A plastic Fresnel lens (an Edmund Scientific product, not a true diffraction Fresnel lens) was used for light collecting. The lens has a focal length of 3″ and a diameter c (with an aperture stop). An EG&G C30808 PIN photodiode was used to build a transimpedance receiver. Both optical and electrical filters were used to reduce the interference from fluorescent light. The optical filter was a coloured glass filter which blocks the visible light. The cutoff wavelength was 720 nm. The filter also caused a loss of 10% in the signal power. The electrical filter used was a third-order Butterworth high-pass filter with a cutoff frequency at 2 kHz. A piece of cardboard coated with white latex flat paint was used as the diffuse reflector. The reflectance was measured as 0.718. The bit rate was 2 Mbps. PRBS-9 was used for BER measurement, so that the lowest signal frequency was about 4 kHz. The measured bit error rate was 1.1×10^{-9}. The measurement was conducted over a period of 1 h. Eight bit errors were recorded, with the number of error deciseconds equal to eight. Fig. 12 shows the eye diagram. No light sources were placed in the receiver FOV. The alignment was not difficult, although the FOT was about 2°. It was easily achieved with the help of an oscilloscope displaying the received signal level. We believe that the range of the link can easily be increased by using a more powerful light source and an optimized receiver. The received signal power at the focal plane was measured as 52 pW, which is about –43 dBm. From (6), the calculated value is 51 pW, matching the measured value to within 2%.

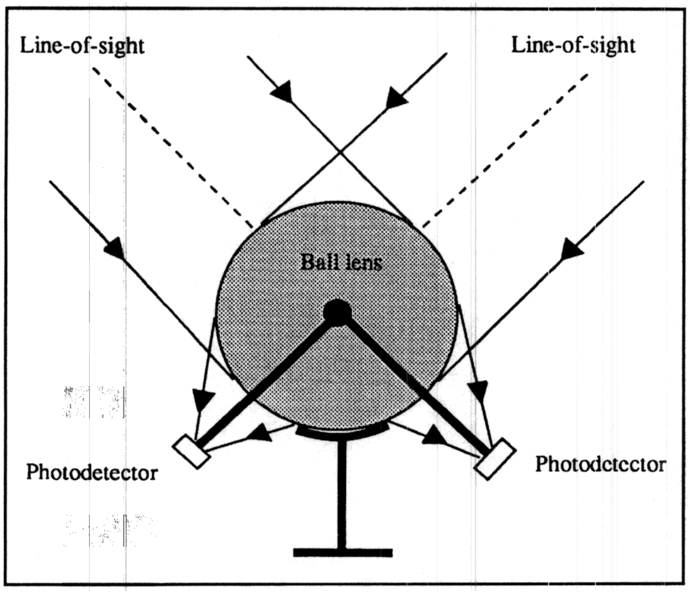

Figure 9: *A compact fly-eye design using a ball lens.*

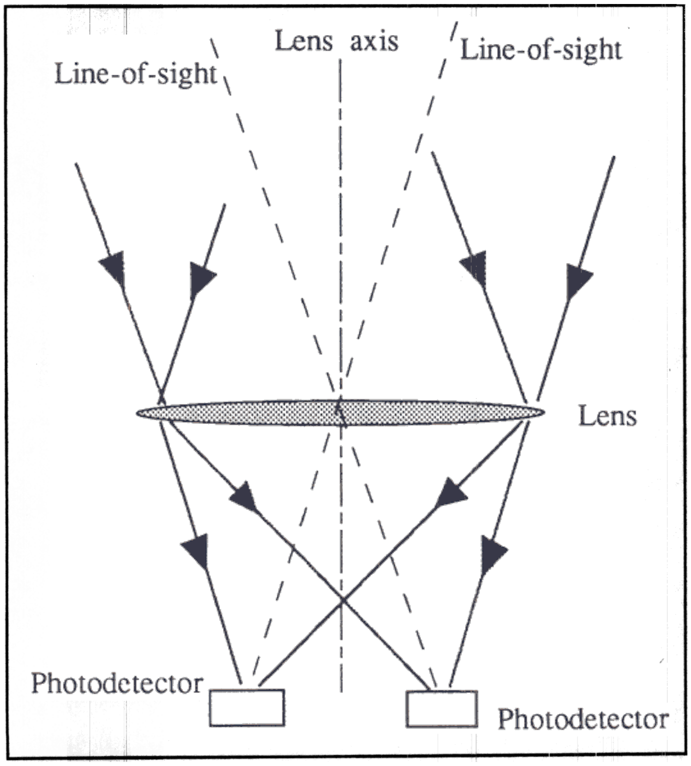

Figure 10: *A compact fly-eye design using lens.*

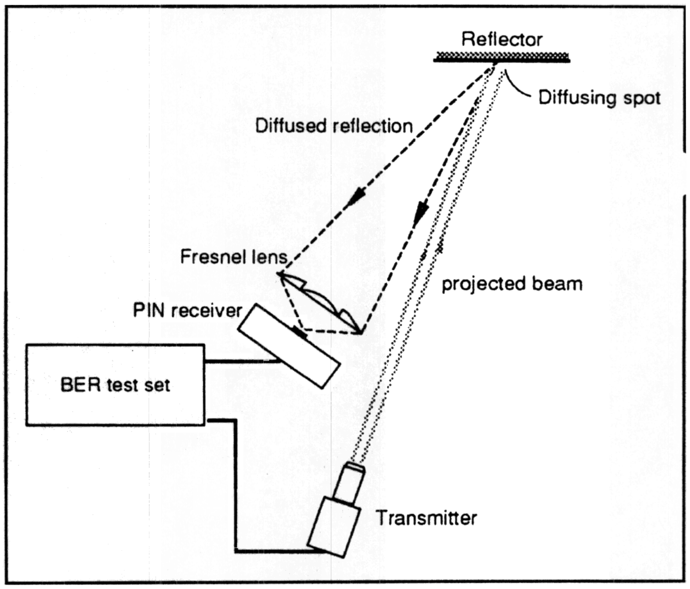

Figure 11: *An illustration of the experimental set-up.*

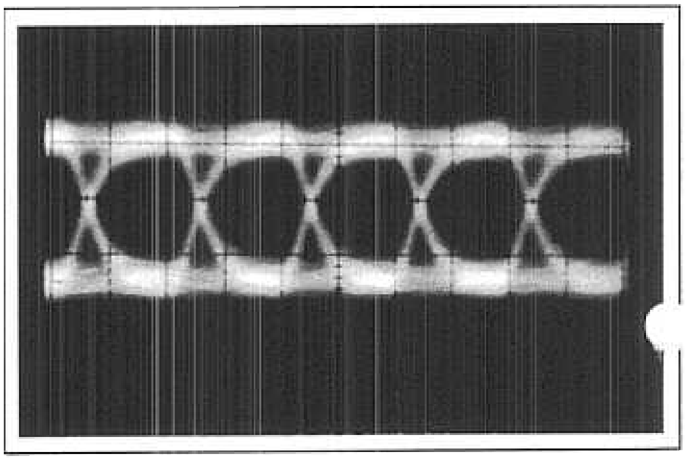

Figure 12: *Eye diagram of the received signal.*

V. Conclusions

In this report, a new configuration was proposed, which is termed Spot-diffusing Multi-line-of-sight Configuration (SMC). This configuration uses spot diffusing to achieve a power efficiency at least 20 dB higher than the diffused light configuration while maintaining an equivalent broadcasting capability. It achieves acceptable link robustness by employing angular diversity channels which are realized by using multiple transmission beams and fly-eye receivers. The expected performance was compared with existing configurations. Design issues conserning this configuration were elaborated, including models for optical power analysis, possible light sources for transmission, alignment issues, ambient-light interference and novel designs for a receiver lens system. An experimental spot-diffusing link set-up was also described. A BER of 1.1×10^{-9} was measured with 0.8 mW laser power, over a distance of 3 m.

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