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SPOT-DIFFUSING AND FLY-EYE RECEIVERS FOR INDOOR INFRARED WIRELESS COMMUNICATIONS

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abstract: A new configuration featured as using spot-diffusing, multiple line-of-sights and fly-eye receivers is proposed for indoor optical wireless communications. Design issues such as suitable light sources, power budget, ambient light interference and fly-eye design are discussed based on simple geometric models. An experiment is conducted to demonstrate the feasibility of the spot diffusing concept.

Introduction

For many reasons, infrared (IR) indoor wireless communication systems are preferred in certain circumstances. The major advantage of an IR system over an radio frequency (RF) system is the absence of interference. In addition, in an indoor environment, an IR system can benefit from a simpler channel characteristic. This is because, first, a light source has a remarkable linewidth which provides a good frequency diversity. Secondly, the light field has a very delicate structure due to the short wavelength, there can be a large number of peaks and troughs across the receiving area of a photodetector, so that the variation in field intensity can not be "felt" by the detector.

There are typically two kinds of IR indoor wireless communication systems. One uses the directive beam configuration (DBC) [1], in which each user terminal is connected to the local area network by two collimated IR light beams, one for the down-link, the other for the up-link. The other configuration is termed here as diffuse infrared configuration(DIC) [2], which employs a wide beam to illuminate the entire or part of the ceiling and the walls. The diffused reflection from the ceiling and the walls is received by receivers with a wide acceptance angle. DIC has the advantage of operational simplicity due to the elimination of alignment requirement. However, the inefficient power transmission, multi-path effect and wide angle acceptance of ambient light lead to a low data rate and a high transmission power. In contrast, 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 single transmission paths. 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, makes a DBC system less competent.

Some novel configurations have been proposed and implemented [3][4]. In [3] and [4], either a central repeater or a reflector is designed to produce a wide angle beam for broadcasting the downward signals. For the up-links, a narrow beam is used for an efficient transmission. To avoid blocking the line-of-sights, the transceivers are arranged 8 feet above the floor in [3], and the reflectors in [4] are mounted on the ceiling . We believe that these two configurations can still be categorized as DBC. The novelty is the use of a wide beam and a wide FOV receiver to eliminate the alignment operations at the repeaters or the reflectors. The price paid is the wide angle ambient light acceptance. Apparently, the installation of an active reflector or repeater may also turn out to be inconvenient.

In this paper, we propose a new approach which we call spot-diffusing multi-line-of-sight configuration (SMC). With the new configuration, we try to reduce the required power level of a diffused infrared system, while at the same time keep the broadcast feature and a similar robustness.

The concepts

The proposed configuration is shown in Fig. 1. It has two new features. The first is termed spot-diffusing. The IR light power is projected onto a small area of the reflecting surfaces such as the ceiling or the walls. This requires the transmitter to send collimated or slightly diverted beams. An IR illuminated area is called a diffusing spot, from which light is reflected and diffused to cover all the user terminals in the room. Using spot-diffusing leads to a few advantages: first, in comparison with a flooding DIC, large area power concentrators can be used for the receivers because the receivers can now have a narrow FOV. Secondly, since a collimated beam is used between the transmitter and the diffusing spot, the channel loss is basically independent of the length of this section of the channel. Furthermore, the rearrangement of the network is relatively easier compared with [3] and [4], because no active reflectors need be installed on the ceiling. The diffusing spot position can be easily rearranged by steering the collimated beams.

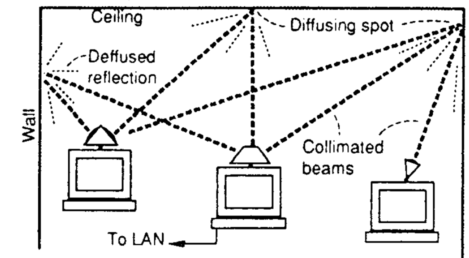

Figure 1: Spot-diffusing multi-line-of-sight concept (SMC).

A second feature is the use of multiple lines-of-sight which allows each user to send more than one beam to geographically separated diffusing spots and to employ more than one receiver viewing these spots. With multiple line-of-sights, there is little chance that all of them are blocked. Therefore, a good robustness can be achieved. Notice that the multi-path propagation is not a severe problem compared with DIC. In a DIC system, there are countless different paths between any pairs of transceivers; while in the SMC , there are only a countable number of angularly resolved paths. Furthermore, since each user may use more than one receiver in a SMC system and each receiver is aligned to a different direction, we can properly call the collection of the receivers as a "fly-eye" receiver and each element of the collection an "eye". Apparently, the use of a fly-eye will add some complexity to the system, in order to avoid excess complexity, the number of eyes will be small in principle. Typically, the number will be no more than three and the users can decide how many eye elements they use according to the specific room arrangement. Particularly, users are allowed to use only one eye for their terminals in the case when multi-line-of-sight is not necessary or too costly.

Design issues on SMC systems

Guidelines

In designing an SMC system, three factors should be considered. They are (1) the power budget, which determines the required power, the range, the bit rate, the safety standard and the cost; (2) the simplicity in both the device and the operation aspects, and (3) tolerance, which implies that the antenna system should not be too sensitive to

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mechanical disturbances and misalignments.

Two kinds of light sources can be used for an SMC network: light-emitting diodes (LEDs) and laser diodes (LDs). An LD is an ideal choice for a SMC network in the sense that it has a large bandwidth, high output power and a coherent wavefront. Particularly, the coherent wavefront makes it possible to have a well collimated beam which means no restriction on the size of the diffusing spot. The price of a CD laser can be as low as a few dollars, which makes it a practical choice for SMC networks.

However, there are some negatives about LDs. The most important one is the potential safety hazard. Since a laser has a coherent wavefront which can be focused perfectly by human eyes, the intensity of light beam should be kept low or a wide beam should be used, especially when collimated beam is used. In contrast, LEDs do not usually cause safety hazard, because LEDs are Lambertian sources. The relatively larger linewidth of LEDs is not a problem, because the dispersion does not matter in short distance transmission. A good LED can be operated at a bit rate of 100 Mbps which is adequate for most applications. Some LEDs can emit an output light at over 30 mW power which is ideal for an SMC system. Furthermore, we can show that the Lambertian nature of an LED may not be a problem

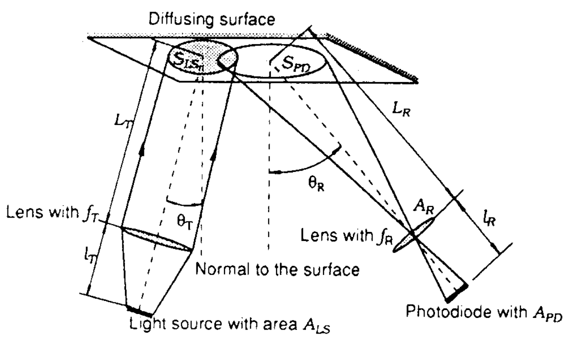

Figure 2: Power analysis model for an SMC system.

when a high angular tolerance is required by the system, because large diffusing spots may be used in this case.

Model for power analysis

Fig. 2 shows a model used for SMC performance analysis, where the symbols 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.
- 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 defusing 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 of the receiver lens or its area.
- 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.

The model can be used for both LED and LD systems, because an LD is only different from LED in the sense that it can be considered as an geometric point source due to the coherence of its wavefront. In the case of a LD, no limit is placed on the size of the diffusing spot; while an LED system has a minimum spot size due to the Lambertian nature which implies the emitting area of an LED must not be neglected. The minimum spot size is achieved when

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

is satisfied. Usually, $L_T \ll f_T$, and consequently $l_T \approx f_T$. Under this condition, the minimum spot area is approximately:

$$S_{LSmin} \approx \frac{L_T A_{LS}}{f_T \cos\theta_T} \tag{2}$$

An expression similar to Eq. 2 is used 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 $S_{PD} \geq S_{LS}$ which means the diffusing spot can be completely fitted into the field-of-view of the receivers.

Assume the diffusing surface is a Lambertian reflector, the received power can be expressed as:

$$P_R = P_T \int_{S_{LS} \cap S_{PD}} \frac{A_R \cos\theta_R}{\pi L_T^2 S_{LS}} d\sigma \tag{4}$$

where P_T stands for the total optical power projected on S_{LS}, and all the parameters in the integral can be considered as functions of the integration variable. For $L_T^2 \gg A_R$ and $S_{PD} \geq S_{LS}$, the above equation becomes:

$$P_R = \frac{A_R P_T \cos\theta_R}{\pi L_R^2} \tag{5}$$

As an example, for $P_T = 5\ mW$, $L_R = 5\ m$, $A_R = (10\ cm)^2$, $\cos\theta_R = 0.5$, we have: $P_R = 10^{-3}\ mW = -30\ dBm$. A DIC configuration corresponds to the case when $S_{LS} \rightarrow \infty$. Therefore, $S_{PD} \rightarrow \infty$ must be satisfied in order to have a maximum power reception. This implies a 180° FOV which implies the use of a bare photodiode. In this case, the received power is:

$$P_R = \frac{A_{PD} P_T \cos\theta_R}{\pi L_R^2} \tag{6}$$

Therefore, the gain of SMC over DIC is: $G = \frac{A_R}{A_{PD}}$ which is the ratio of the area of concentrator lens to that of photodiode.

Angular tolerance

The angular tolerance of the antenna system is a vital issue for an SMC network. Since lines-of-sights exist in the system, a larger angular tolerance means less difficulty in alignment. It also means a more robust set-up which has enough immunity to outside disturbances. As the alignment should not be difficult to achieve for some unskilled person without using any precision mechanics, we assume the angular tolerance should be at least 5°. The 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 only when the two projections have an overlap, can the receiver receive power. This is shown in Fig. 3. Hence, we may define a "Field-of-Tolerance (FOT)" in steradian as

$$FOT = \frac{S_T \cos\theta_R}{L_R{}^2} \tag{7}$$

where S_T represents the projection defined in Fig. 4 on the diffusing surface. The angular tolerance of an eye can thus be defined approximately, however reasonably as: $\delta\theta = \sqrt{FOT}$. As an example, for a infinitely small S_{LS}, $f_R = 75\ mm$, and $\sqrt{A_{PD}} = 3\ mm$, $\delta\theta_{max} = 4.56°$

According to Eq. 7 and Fig. 2, there are two ways of increasing the tolerance. The first is increasing the photodiode size or reducing the focal length. The former is limited by the response time of the photodiode; the later is limited by the aperture of the lens. The second is to increase the spot size S_{LS}. According to Fig. 2 , this can be done by either decreasing f_T or increasing the emitting area of the LED, or by placing the light source closer to the transmitter lens, so that beam becomes diverted. The limit in doing so is: $\frac{S_{LS}}{L_T^2} \le \frac{A_{PD}}{f_R^2}$, so that a good maximum power efficiency can be maintained

It is important to note the role that the size of the light emitting area A_{LS} plays in an SMC system, when an LED is used. In fiber optics, LEDs are supposed to be made small to increase the source-to-fiber coupling efficiency. However, in an SMC system, the size of the LED can be more tolerated. According to Fig. 2, if we consider $S_{LS} = S_{PD}$ as an acceptable match in terms of power transmission and if we assume $L_T \approx L_R$, which is actually desirable in a practical network arrangement, we have $A_{LS} \approx A_{PD}$, i.e., the size of the LED can be in the same order as that of the photodiode. Considering that

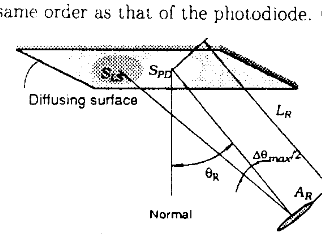

Figure 3: Angular tolerance of a receiving eye.

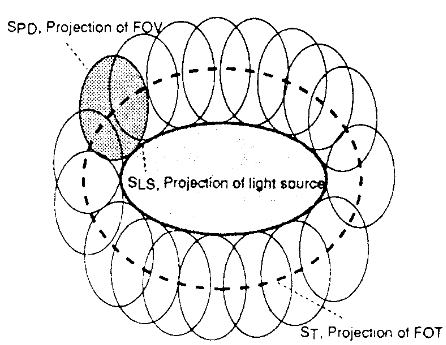

Figure 4: A description of the field-of-tolerance.

a typical photodiode can have a diameter in the order of millimeters, which is much larger than any LEDs used in fiber communications, this can be significant in the sense that a large area LED can be more easily made to have a higher output power.

Ambient light

In contrast to fiber optic systems, an indoor optical radio communication system is exposed to the 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., direct sun light) and cause interference when it is modulated. Though ambient light can be much stronger than the signal light in power, a few measures e.g., narrow band optical filtering and electrical filtering can be taken to reduce its influence. In an SMC system, there is an extra measure that is to use the difference between the spatial characteristics of ambient light and signal sources. The ambient light is usually very well diffused; while the light signal is concentrated in a small bounded area when spot diffusing concept is used. Hence, a small field-of-view receiver can have a much lower ambient light level than a wide FOV receiver. The gain in signal-to-ambient noise ratio by using small FOV receivers over DIC is approximately:

$$G_{amb} = \frac{2\pi^2}{FOV} \tag{8}$$

where FOV is in steradian, the numerator stands for the solid angle of a hemisphere. The gain shows another advantage that SMC has over DIC. Actually, with a small FOV receiver, it is easy to avoid the interference light sources being put into the FOV of the receivers by simply arranging the diffusing spots at the proper locations.

Fly-eye design

A fly-eye receiver consists of a number of independent element eyes. each element eye receives signals from a certain direction. Therefore, each eye should have its own alighnment mechanism. Besides, in an indoor environment, the distance between any diffusing spot and an eye varies from about 1 meter to 20 meters. It is not difficult imaging that a "perfect eye" should not only have the ability of aligning its field-of-view to the subject it wants to see, but also be able to focus itself to get a clear picture of the subject, in this case, a sharp picture of the diffusing surface on a photodiode, in order to achieve the maximum reception. The focusing activity is usually achieved by changing the relative position between the receiver lens and the photodiode in the longitudinal direction. We may alternatively give up this attempt by fixing the photodiode at one focal length behind the lens, which results in a far-sighted eye. Using the model given in Fig. 2, we compare the performance of a perfect eye with that of a far-sighted eye in terms of received power. We get the typical power versus distance curve shown in Fig. 5, from which it can be found that a far-sighted eye has basically the same performance as a perfect eye when the working distance is long and an essentially constant response over the close range. We may therefore conclude that a far-sighted eye can be more desirable than

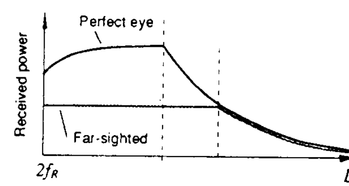

Figure 5: The received power of a perfect eye and a far- sighted eye.

a perfect eye if the optical receiver has a sufficiently good sensitivity. In this case, we may gain in simplicity due to the absence of focusing operation, in dynamic range due to the flat response and suffer no loss in performance due to the performance similarity of the two kinds of eyes at long range region.

Another problem about a fly-eye receiver is that the lens system can be quite complicated, because it has to view different directions at the same time. The most straightforward way of realizing fly-eyes is to employ separate eyes which have their own lens and photodiode systems. However, using too many lenses will probably make the system bulky and undesirable. Some novel design may solve the problem. One possibility is to employ a glass or plastic ball as the lens of the eyes. Since a ball has a very good symmetry, all the eyes can use the same ball. In Fig. 6, an example of two eyes sharing one ball lens is depicted. The problem of this design is that a ball lens can be very heavy when a large aperture is required. Hence, it is only suitable for networks covering a small room.

Another design is shown in Fig. 7, in which the off-axis imaging ability of a lens is explored. The design can have a large aperture, especially when a Fresnel lens is used. Compared with the ball lens, different lines-of-sights can not be arranged very far apart from the optical axis of the lens, otherwise the aberration will become significant. Though a larger photodiode can tolerate more aberration, the flexibility of the design is limited.

Experiment

A spot-diffusing IR link was built for demonstrating the feasibility. The set-up is depicted in Fig.9. The distance between the diffusing spot and the receiver is about 3 meters. The line of sight makes an angle of 45° with the normal line of the diffusing surface. A 780 nm CD laser is used to emit an average power of 2dBm. The light from the laser is projected on a plaster wall by a telescope eye piece which has a focal length of 25 mm and an aperture of 18 mm. The light projected on the wall measures as -2 dBm. The loss in power is caused by the wide divergence angle of the CD laser in the direction perpendicular to the junction plane. This loss can be reduced by using more sophisticated projecting lenses. A plastic Fresnel lens is used for light collection. The lens has a focal length of 3 inch and a diameter of 6 inch. The receiving aperture was reduced to 4 inch with an aperture stop to show the potential of a more compact size, since it was found that the center part of the lens provides a much higher per-unit-area light collecting power. A PIN high-impedence receiver is used to provide the required sensitivity. Both optical and electrical filters are used to reduce the interference from the fluorescent light. The optical filter is a coloured glass filter which blocks the visible light. The cut-off wavelength is 720 nm. The filter also causes a loss of 10 percent in the signal power. The electrical filter is a 3rd order Butterworth high pass filter with a cut-off frequency of 2 kHz. The bit rate is 704 kbps. A ternarry AMI line code is used to shape the spectrum. The bit error rate was measured as 2.4×10^{-9}. The measurement was conducted over a period of 3 hours. Figure 11 shows the eye-diagram. No light sources were placed in the receiver FOV. The alignment turned out to be easy. We also presume that the range of the link can easily be increased by using a more powerful light source.

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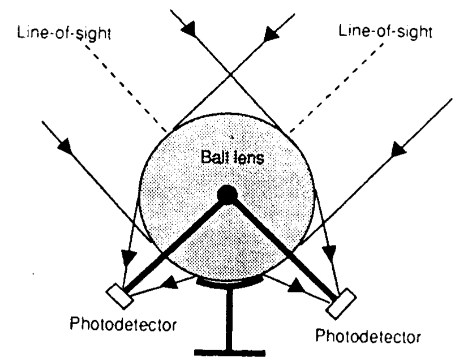

Figure 6: A compact fly-eye design using ball lens.

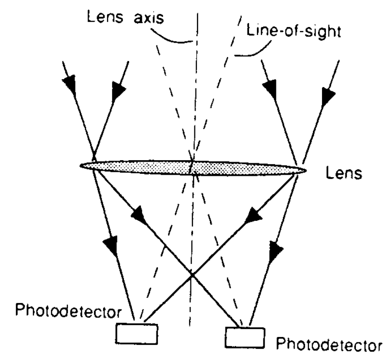

Figure 7: A compact fly-eye design using lens.

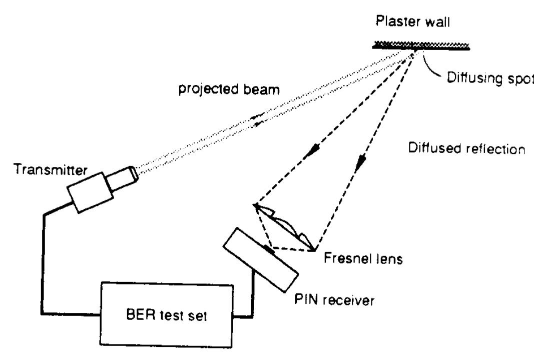

Figure 8: An illustration of the experimental set-up.

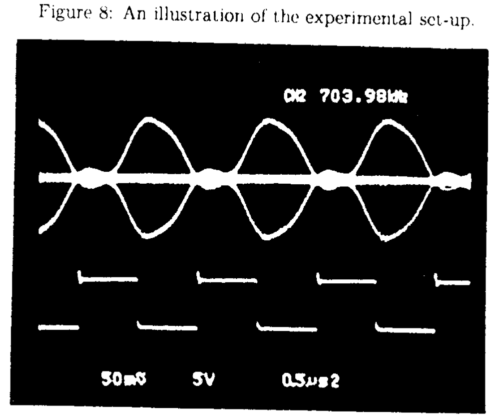

Figure 9: Eye-diagram of the received signal.