Shadowing and Blockage in Indoor Optical Wireless Communications

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Abstract – **In this paper, we investigate vulnerability of a so called "cellular" and that of a multi-spot diffusing (MSD) Multi-Input-Multi-Output (MIMO) architecture to shadowing and its effect on communications cell size and the required transmit power. Because signal path obstruction by furniture is easier to predict and avoid, we are mainly concerned with shadowing and blockage caused by people either sitting or standing. To avoid blockage of communication link by a user of portable units, maximum radiation angle at the transmitter in both configurations must not exceed 45°. This restricts communication cell size. We show the probability of blockage of a cellular link depends almost linearly on the distance of the portable unit from the communication cell center. Unlike cellular links, MSD-MIMO links can be designed to be robust against blockage, though still vulnerable to shadowing. In a typical office having a height of 3m, probability of shadowing is less than 2% and in majority of cases shadowing causes less than 50% reduction in the received signal power. Power penalty due to shadowing is insignificant (less than 0.1dB) with a 1% outage.**

I. INTRODUCTION

Infrared is diffusely scattered by most objects in an office. Thus, in optical wireless communications indoors, signals reach receiver after multiple reflections off the room walls and furniture. The immense number of signal paths leads to signal distortion and, as a consequence, may cause intersymbol interference. Multipath induced signal distortion is one of the major challenges that researchers encounter when working on optical wireless LANs for indoor use.

In the last few decades, various configurations for this type of wireless communications have been researched [1-5]. Line-of-sight (LOS) directed links, although very power efficient and free from multipath distortion, are applicable to point-to-point communications only and we are not going to consider these in the present paper. Diffuse systems are very well suited for point-to-multipoint connectivity, however, both power efficiency and multipath signal distortion are issues of concern.

In this paper, we investigate the two most promising architectures that have been suggested up to now. These are the so-called "cellular" [6-8] and multi-spot diffusing (MSD) Multi-Input-Multi-Output (MIMO) architectures [9-13]. Cellular system employs ceiling based base station that emits infrared light in a large angle, delivering optical signal to all the terminals that are within the cone of light. In cellular architecture, communications between portables is accomplished through a base station.

MSD-MIMO system uses a multi-beam transmitter and a direction diversity receiver. Base station unit and portable units have identical design and are placed at a desktop level, thus MSD-MIMO is naturally suited for ad hoc networking, as well.

Both cellular and MSD-MIMO links [12, 13] are virtually free from multipath signal distortion because a major portion of signal power is received via a single path. Cellular links rely on line-of-sight while MSD-MIMO links use diffuse reflections off the room ceiling. It is clear then that cellular links exhibit a higher power efficiency level. On the other hand, MSD-MIMO links are attractive, considering that no installation work is necessary, and ad hoc networking capability is an inherent property of such architectures.

Any optical wireless link can be a subject of shadowing, and sometimes, even blockage, caused by moving or stationary objects. In this paper, we investigate the vulnerability of cellular and MSD-MIMO links to shadowing and blockage and their effects on communications cell size and required transmit power.

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Shadowing effects depend on objects inside an office. It is extremely difficult to generalize an investigation of these effects. Therefore, we accept some reasonable constraints on the position and size of the shadowing objects. These objects cannot be closer to a portable unit (or base station in the case of MSD-MIMO) than 50cm. Because shadowing or blockage by furniture is easier to predict and avoid, we are mainly concerned with those caused by sitting and standing people. We model the cause of shadowing as having a lateral dimension of 50cm. We assume all portable units (and the base station in the MSD-MIMO case) are placed at a desktop level (about 90cm above the room floor). In other words, communications cell floor is 90cm above the room floor. A sitting person has a height of about 140cm, or about 50cm above desktop level, while for a standing person we assume a height of 180cm, or 90cm above the communications cell floor.

II. CELLULAR LINKS

II.1. Communication cell size

It is reasonable to assume that the users would be sitting by their portables while networking and there might be a large number of seated people in this office environment. It is unacceptable for a communication link to be blocked by a user sitting by a portable terminal. From Fig.-1, it is evident that the maximum angle, Φ, at which the base station can transmit, is 45°. At larger angles, a user sitting at 50cm from the portable unit may block the line-of-sight between the terminal and a base station. Thus, the communication cell radius, R, is equal to the distance, H, between the ceiling and the communication cell floor.

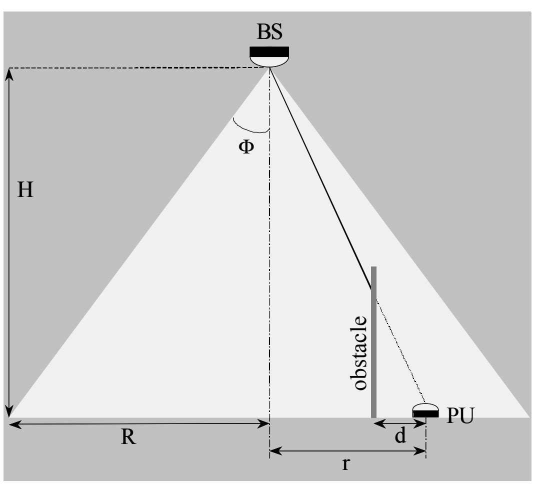

Fig.-1 Cellular architecture.

II.2. Shadowing and blockage probability

In line-of-sight links, there is no shadowing. Any object that obstructs the line-of-sight between a portable unit and base station actually causes complete blockage of the link. Because of the imposed restrictions on the communication cell size (as defined in the previous section), we need to consider only blockage by standing people. We assume that it is equally probable for a person to stand anywhere within the communication cell, except for the close proximity to a portable unit. Then, the probability of being at any point in the cell is:

$$P = \frac{1}{A_{cell} - A_{Rx}},$$

where $A_{cell} = \pi R^2$ is the area of the communication cell floor and $A_{Rx} = \pi r_0^2$ is the area around the portable unit where a person is not likely to be able to stand. As we assumed earlier, $r_0 = 50\text{cm}$.

The maximum distance from the portable unit, at which a person may cause blockage of the link, is:

$$d = \frac{rh}{H},$$

where *r* is the distance from the center of the communication cell and *h* is the height of the obstacle, i.e., the vertical size of the blocking object as measured from the communication cell floor.

The probability of blockage of the link by a standing person is determined by the area A_{block} in Fig.-2, that combines all possible positions, at which a standing person would block the line-of-sight:

$$P = \frac{A_{block}}{A_{cell} - A_{Rx}}.$$

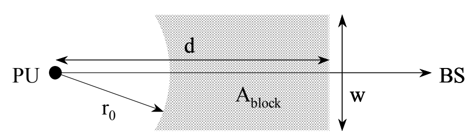

Fig. - 2 The area within which a standing person would block the line-of-sight between the portable unit and the base station. Here *w* is the lateral dimension of the obstacle and *d* is the maximum distance from the portable unit, at which a person may cause blockage of the link.

II.3. Effect of link blockage on required transmit power

Fig.-3 shows the blockage probability as a function of the distance from the center of the communication cell for the case of a 3m-high office, i.e., $H = R = 2.1$ meters. The computations have been done with the assumption that there is only one blocker within the communication cell. The probability of blockage would increase as a geometrical progression when the number of blockers is increased.

When a communication link is blocked, communication is ceased and no increase of the transmit power can compensate for it. If blockage is caused by a moving object, the interruption in communications is temporary and its effect can be eased by utilization of appropriate coding schemes and protocols.

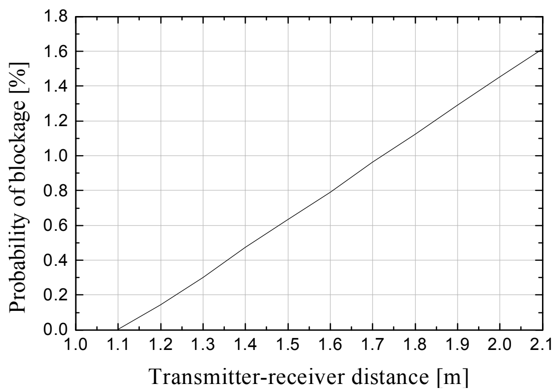

Fig. - 3 Blockage probability as a function of the horizontal transmitter-receiver distance.

III. MSD-MIMO LINKS

III.1. *Communication cell size*

In MSD-MIMO configuration, transmitter emits multiple narrow beams that shine small areas, called diffusing spots, on the room ceiling. Then the optical signal is received by a multi-element receiver through several diffusing spots that lie within a receiver field-of-view.

Analogously to the case of a cellular architecture, we may deduct that the maximum angle of radiation at the transmitter, Φ, should be 45°. Again, it is unacceptable that a sitting user may block some of the transmitter beams emitted by its unit. This implies again a communication cell radius, R, equal to the distance, H, between the communication cell floor, i.e., desktop level, and the room ceiling.

A circular communication cell can be conveniently illuminated by diffusing spots on a hexagonal mesh like the one in Fig.-4. For a typical 3m-height office, the communication cell radius is 2.1 meter and the circular area on the ceiling may be covered by 37 diffusing spots spaced by 70 cm.

III.2. Shadowing and blockage probability

In MSD-MIMO, total receiver field-of-view must be large enough to cover several diffusing spots. On the other hand, receiver FOV should be as narrow as possible to allow utilization of an optical filter with a narrower spectral bandwidth for better optical noise rejection [14]. We can derive a value for the total receiver field-of-view from some arguments about system vulnerability to blockage.

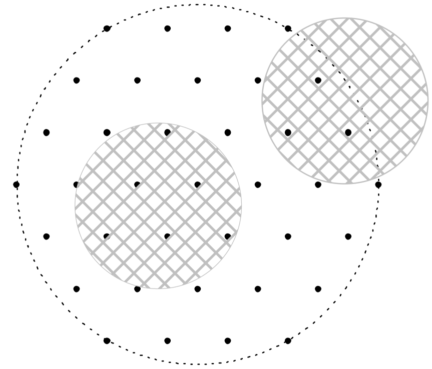

Fig. - 4 Circular communication cell formed by 37 diffusing spots. The two patterned circles represent the areas on the ceiling as seen by two receivers having a field-of-view of 25° at two randomly chosen positions within the communication cell.

In Fig.-5 (a), d_h is the minimum distance from transmitter at which an obstacle may be placed without blocking all of the transmitter beams that produce diffusing spots within the receiver field-of-view. d_h depends on the obstacle height, h. In certain cases, a person standing even closer to the transmitter may not block all transmitter beams. This happens when the blocker lateral dimension, w, and its position are such that some of the transmitter beams can go round and still produce diffusing spots within receiver FOV. d_w in Fig.-5 (b) is the minimum transmitter-obstacle distance at which not all transmitter beams are blocked due to the obstacle width.

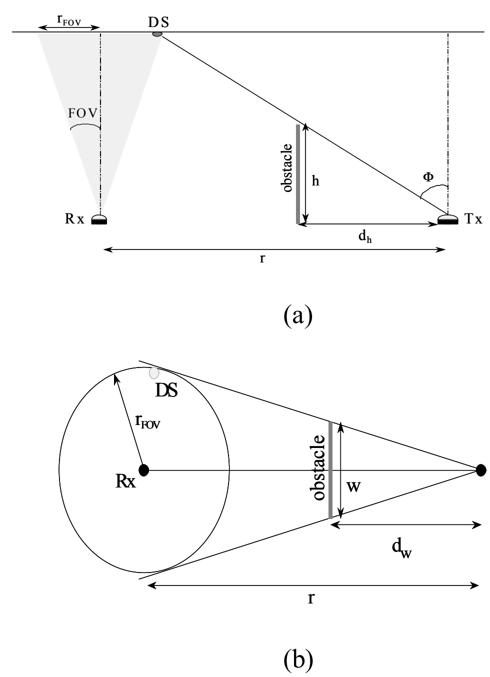

Fig.-5 Link blockage conditions in MSD-MIMO configuration.

Finally, we may conclude that the obstacle must be at a distance, d, from the transmitter that is larger than the shorter one of d_h and d_w, in order to prevent blockage of all the beams responsible for transmitting data to a particular user:

$$d \geq \min(d_h, d_w)$$

$$d_h = \frac{h}{H}(r - r_{FOV})$$

$$d_w = \frac{w}{2\tan\left[\arcsin\left(\frac{r_{FOV}}{r}\right)\right]},$$

where $r_{FOV} = H \tan FOV$ is the radius of the circular area on the room ceiling seen by the receiver.

Fig.-6 presents d_h and d_w as functions of the receiver field-of-view for a receiver positioned at the edge of the communication cell ($r = R$) for the case of a typical 3m-high room. For receiver FOV values above 24.5°, both d_h and d_w are below 50cm. As we assumed earlier, it is not very likely for an obstacle to be within 50cm from a portable unit or the base station. Therefore, a receiver field-of-view of 24.5° or more would make the communication system robust against blockage. Throughout the rest of this paper, we use a value of 25° for the receiver field-of-view in MSD-MIMO links. Such a field-of-view allows for 25nm spectral bandwidth of the optical filter at the receiver.

In a 3m-heights room, a receiver having a field-of-view of 25° would see a circular area of radius 98cm on the room ceiling, embracing several diffusing spots (Fig.-4). Although there is practically no chance for such a communication link to be blocked, it can be shadowed, i.e., not all but some of the diffusing spots within the receiver field-of-view can be blocked.

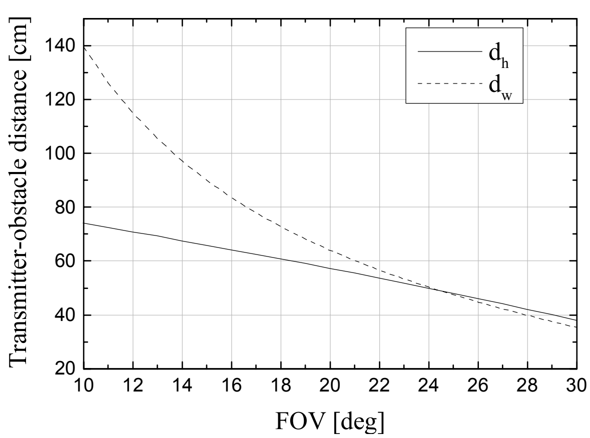

Fig.-6 Transmitter-obstacle distance beyond which the obstacle cannot block all the beams responsible for transmitting data to a particular user at the edge of the communication cell. d_h depends on the obstacle height; d_w depends on the obstacle lateral size.

The probability and the extent of shadowing depend on the spot-array parameters and the particular receiver position with respect to the spot array. There is no analytical function that can describe the effect of shadowing in MSD-MIMO links. Therefore, in this work, we apply a statistical approach. We have simulated the communication link for 10,000 sets of random receiver and shadowing-object positions. We assume that receiver is of an imaging type like the one described in [15]. The receiver lens system images the diffusing spots onto a hexagonal array of 37 photodiodes. The entrance aperture of receiver optics is 1cm^2.

In only about 1.7% of the cases there is some shadowing. The distribution of the probability for certain reduction in the received signal power caused by shadowing is shown in Fig.-7. In majority of cases, shadowing causes less than 50% reduction in received power.

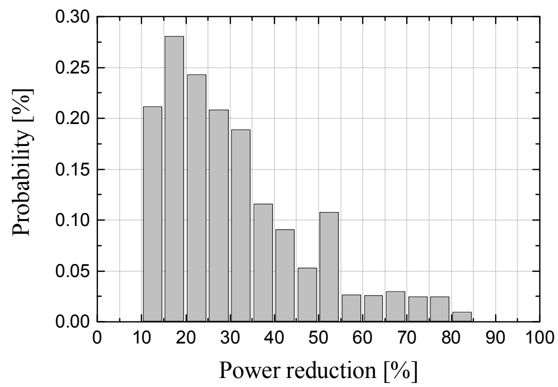

Fig.-7 Probability distribution of power reduction due to shadowing.

III.3. *Effect of link shadowing on required transmit power*

We have shown in the previous section that, unlike cellular links, MSD-MIMO links can be designed to be robust against blockage. Thus, no complete interruption of data transfer would ever occur. However, possible shadowing may reduce the received signal power and cause erroneous reception of symbols. Effect of shadowing on link quality can be alleviated either by use of appropriate coding schemes, or by an increase in the transmit power. Computations show that power penalty due to shadowing for on-off keying is less than 0.1dB in 99% of the cases (1% locations outage).

IV. Conclusions

A vital factor that affects the quality of service in indoor optical wireless communication systems is their vulnerability to shadowing and blockage. An opaque object can shadow partly or block completely an optical link because infrared light does not penetrated opaque objects.

Both cellular and MSD-MIMO configurations have great potential for high-speed communications. We have investigated robustness of LOS links in cellular architecture and non-LOS links in multi-spot diffusing architecture to obstructions of signal path. We have considered shadowing and blockage caused by sitting and standing people. Based on the results of our investigations, we have concluded that maximum radiation angle at the transmitter, in both configurations, shouldn't exceed 45^{o}, which restricts the communication cell size.

We have shown that the probability of blockage of a cellular link depends almost linearly on the distance of the portable unit from the communication cell center.

On the contrary, MSD-MIMO links can be designed to be robust against blockage, though still vulnerable to shadowing. In a typical office having a height of 3m, the probability of shadowing is less than 2% and in the majority of the cases the shadowing causes less than 50% reduction in the received signal power. Power penalty due to shadowing is insignificant (less than 0.1dB) in 99% of the cases.

ACKNOWLEDGEMENT

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