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Transceiver Design Concept for Cellular and Multispot Diffusing Regimes of Transmission

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A number of attempts have been made in an effort to combine the advantages of line-of-sight and diffuse configurations for indoor optical wireless communications via sophisticated combinations of elements that are characteristic for these architectures. A different approach has been followed in the present investigation, namely, developing a transceiver capable of operating in both configurations. It is proposed that the transceiver design be based on the utilization of two-dimensional arrays of infrared light-emitting devices and photodetectors. Basic design parameters of transceiver optics are derived from considerations about link blockage and system compliance with the unique features of line-of-sight and diffuse methods of transmission.

Keywords and phrases: optical communications, wireless communications, local area networks.

1. INTRODUCTION

It has been more than two decades now since Gfeller and Bapst [1] suggested that diffusely scattered infrared light could be utilized as a medium for wireless communications indoors. Various system configurations for optical wireless local area networks have been investigated since then. They differ in the degree of directionality of the transmitter and receiver and the orientation of the units. The latter factor underlies the development of two major classes of link topology: line-of-sight (LOS) links, in which an LOS path between receiver and transmitter exists, and non-LOS or diffuse links, which rely on diffuse signal reflections off the room surfaces. In this paper, the term "diffuse" is used for a link architecture that prohibits the existence of an LOS between receiver and transmitter regardless of the transmitter radiation pattern. This is in distinction from other investigations that apply this term to links that employ a transmitter with a Lambertian radiation pattern, even when an unobstructed LOS signal path exists (see, e.g., [2]).

Line-of-sight architectures

LOS links exhibit low power requirements when transmitted optical power is concentrated in a narrow beam thus creating a high power flux density at the receiver. Furthermore, such links do not suffer from multipath signal distortion. If additionally a narrow field-of-view (FOV) receiver is used, an efficient optical noise rejection and a high optical signal gain are achievable [3]. Generally speaking, narrow LOS links (NLOS, narrow transmit beam and small receiver FOV) are applicable to point-to-point communications only. NLOS links cannot support mobile users because alignment of receiver and transmitter becomes necessary. However, elements that are meant for point-to-point links are being incorporated into different link configurations in search for better power efficiency and higher data rates. For example, the so-called tracked system [4] utilizes a narrow beam transmitter and a small FOV receiver with the addition of steering and tracking capabilities.

In LOS optical wireless LANs, the base station is typically located on the room ceiling. In order to serve multiple mobile users within a relatively large coverage area, the narrow transmit beam is now replaced by a wide light cone, which defines a communication cell. This configuration has been called "cellular" [5]. A large area communication cell is achieved at the cost of reducing the power efficiency since

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more launch power is needed to ensure the required power flux density at the receiver. In cellular configuration, optical signal is delivered to all the terminals within the light cone. Communication between portables is accomplished through a base station, that is, in a star network topology.

An important development in LOS-LANs may be described as a merger of cellular and NLOS tracked systems. The essence is in the utilization of two-dimensional arrays of emitters and detectors. Base station is placed above the coverage area. The sources in the transmitter array emit normally to the plane of the array. Then, an optical system performs spatial-angular mapping, that is, a light beam is deflected into a particular angle depending on the spatial position of the source in the array. As a result, the communication cell is split into microcells, each illuminated by a single light source of the array. At the receiving end, the opposite transform, angular-spatial mapping is performed, so that the optical signal is collected and focused onto a particular detector in the detector array, depending on the angle of arrival. The benefits of introducing detector and emitter arrays are as follows. Tracking and pointing functions are electronically realized using a spatial-angular-spatial mapping performed by the transceiver optics [2, 6]. Power savings can be realized by switching off the sources that do not illuminate a user terminal. Transmitter can be designed so that sources in the emitter array transmit different data streams, thus significantly increasing the overall capacity of the communication system. The pixels in the detector array exhibit low capacitance and small FOV because of their small size. The small detector capacitance allows for an increase in the transmission bandwidth and the small FOV reduces the ambient light reception.

Diffuse architectures

In classical diffuse links [7], base station is located at a desktop level and transmitter emits upwards. Usually, transmitter radiation pattern is Lambertian, therefore the entire room ceiling and large portions of the walls are illuminated. Since infrared is diffusely scattered by most room surfaces, 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. Another issue of concern is power efficiency. As a rule, diffuse configurations are characterized by high signal path loss. Therefore, a receiver having a large effective collection area and a wide FOV must be used. Nevertheless, diffuse links cannot compete with LOS links in terms of power efficiency. The high optical signal path loss and the multipath distortion limit the achievable transmission speed to a few tens of Mbps. On the other hand, while LOS links can easily be blocked, diffuse links have the advantage of being very robust to shadowing and blockage. Diffuse system is very well suited for point-to-multipoint connectivity and with it star, as well as mesh networks can be established.

Yun and Kavehrad [8] proposed a diffuse-type configuration that utilizes a multiple narrow-beam transmitter and a multibranch angle-diversity receiver, thus a multi-input multi-output (MIMO) system. This architecture is referred to as multispot diffusing (MSD). Transmitter projects the light power in form of multiple narrow beams of equal intensity, over a regular grid of small areas (spots) on a diffusely reflecting surface such as a ceiling. This way, the signal power is uniformly distributed within the office and the link quality does not depend on the receiver-transmitter distance. Each diffusing spot, in this arrangement, may be considered a secondary light source having a Lambertian radiation pattern. Receiver consists of several narrow FOV receiving elements aimed at different directions. A good portion of optical signal power is received by each receiver branch via a finite number of distinct signal paths; a number equal to the number of spots seen by the branch. When properly designed, MSD links are virtually free from multipath signal distortion. It has been shown that the communication channel exhibits a vast bandwidth (greater than 2 GHz on a 3 dB basis [9]) and can be considered virtually ideal at data rates of hundreds of Mbps. The narrow FOV of the receiver elements provides means to decrease the level of ambient light reception utilizing narrow spectral bandwidth optical filters and by spatial separation of desired signal from strong ambient light sources. Receiver consists of more than one element in order to cover several diffusing spots, thus ensuring uninterrupted communication in case some of the transmitter beams are blocked. Additionally, a multiple-element receiver provides diversity, thus it allows combining the output signals from different receiver elements using effective combining techniques.

Like in LOS links, the latest development in quasidiffuse links is the use of emitter [10] and detector arrays [8, 10, 11]. Utilization of a compact two-dimensional array of semiconductor light sources allows for a reconfigurable transmitter output. Each light source in the array is responsible for creating a single diffusing spot on the room ceiling, that is, the number of sources equals the number of diffusing spots needed to cover the communication cell. If there is no need for optical signal within certain parts of the communication cell, the corresponding light sources are switched off. Thus, the system provides only the active users with signal and saves some power by not distributing optical signal where it is not needed. With such a transmitter design, independent communication channels (different information streams are launched through different diffusing spots) are feasible, thus providing a means for spatial diversity. Receiver design is also very similar to the one that has been proposed for LOS systems. Such a receiver possesses inherent angle diversity and the small FOV associated with a single detector pixel ensures an optimal ratio between signal and optical noise level at a receiving element. In contrast to LOS configuration, a user terminal communicates with base station through several communication channels whose number equals the number of diffusing spots within the overall receiver FOV.

The fundamental difference in signal propagation environments in LOS and diffuse links determines the advantages and the drawbacks of these link configurations. Despite all the efforts of a number of research groups over the years, LOS links still have benefits that none of the proposed non-LOS topologies offers, and vise versa. On the other hand, both LOS and diffuse configurations have evolved through the years and recent developments show that the researches have arrived at surprisingly similar transceiver optical designs. Therefore, a good direction for the future research efforts would be designing a transceiver that is capable of operating in both regimes, that is, in both LOS and non-LOS geometries. This is especially important for the portable units, which should be able to communicate with both types of base stations and with other portables. The aim of this paper is to make the first step towards the optical design of such a universal transceiver.

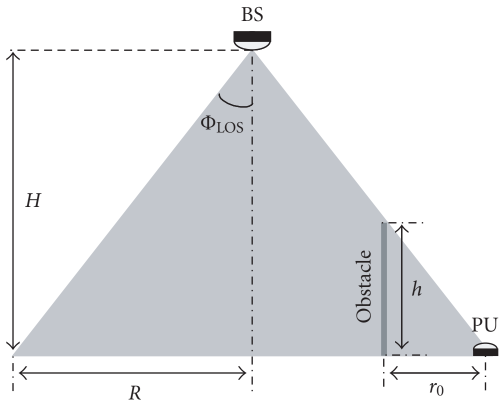


Figure 1: Cellular architecture: BS (base station), PU (portable unit), Φ_{LOS} (maximum transmit semiangle), H (communication cell height), R (communication cell radius), h (blocker height), r_0 (minimum possible blocker-portable unit distance).

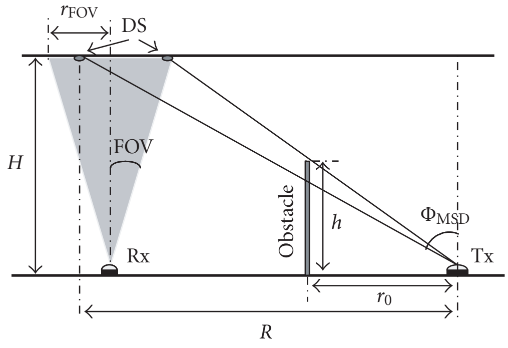


Figure 2: MSD architecture: Rx (receiver), Tx (transmitter), DS (diffusing spot), Φ_{MSD} (maximum transmit semiangle), FOV (receiver acceptance half angle), r_{FOV} (radius of the circular area in the ceiling that is seen by the receiver), H (communication cell height), R (communication cell radius), h (blocker height), r_0 (minimum possible blocker-portable unit distance).

2. TRANSCEIVER PARAMETERS AND LINK BLOCKAGE

In both cellular and MSD architectures, a large coverage area is desired. This imposes severe requirements on the transmitter and receiver optics. Wide receiver FOV and large emission angle are not routinely achieved. On the other hand, it is unnecessary to increase the coverage area beyond certain size because of the increased probability of link blockage. Even when care has been taken of the permanent blocking objects like furniture and partitions, the link still can be blocked by the people on the move. In the present investigation, the blockage of cellular and MSD links by people is carefully studied in order to ease the requirements on the transceiver optical system design.

Any optical wireless link is a subject to shadowing, and even blockage, caused by moving or stationary objects. Blockage and shadowing might be an important degrading factor for the system performance. When a link is blocked, the information transfer ceases. Therefore, special care must be taken to prevent link blockage and ensure uninterrupted communications.

Shadowing effects depend on the particular interior of an office. It is extremely difficult to generalize an investigation of these effects. Because the shadowing or blockage by furniture is easier to predict and avoid, we are mainly concerned with the blockage caused by people. The blocker is assumed to be a tall person who is modeled as having a lateral dimension of 50 cm and a height of 100 cm above communication cell floor. Cell floor is at a desktop level and the cell height is defined as the distance along a vertical line from the room ceiling to the desktop level. All portable units are assumed at the cell floor level. Base station in an LOS configuration is placed on the room ceiling while in MSD configuration it is on a desk. In the following analysis, it is assumed that a person cannot be closer than 50 cm to a portable unit (or a base station in the case of MSD). This restriction is justified by the fact that the portable terminals are usually placed on a desk, so that the area in close proximity to the portable unit is readily occupied by the desk.

Transmitter radiation angle

Consider first the LOS configuration depicted in Figure 1. Maximum semiangle, Φ, at which a base station can transmit with full connection availability, is determined by

$$\Phi_{\mathrm{LOS}} = \arctan\left(\frac{r_0}{h}\right), \tag{1}$$

where r_0 is the minimum possible blocker-portable unit distance, and h is the blocker height (above the communication cell floor). With $r_0 = 50$ cm and $h = 100$ cm, the maximum transmitter emission semiangle is 27°. At larger angles, a moving person may block the LOS between a terminal and a base station.

In diffuse architectures, there is a restriction about the angle by which the transmitted light beams strike the reflecting surface. Diffuse links rely on diffuse reflections from reflecting surfaces. Increasing the angle of incidence above 60°, the reflection pattern of typical office surfaces (ceiling and walls) deteriorates from Lambertian reflector and exhibits strong specular reflections [1]. According to the analysis provided in [10], the maximum semiangle of transmitter radiation, ϕ_{MSD}, is further restricted down to 45° by considering link shadowing and blockage (see Figure 2). It has been

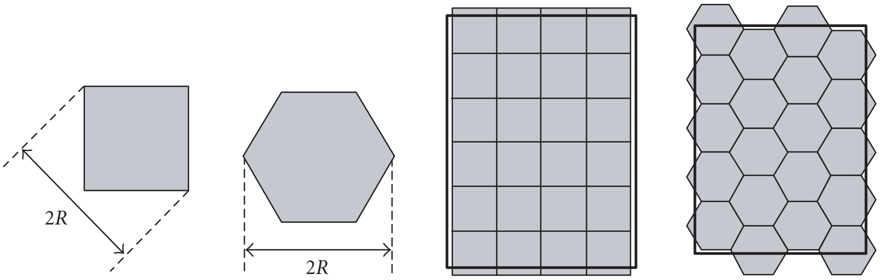


Figure 3: A large rectangular area covered by sets of square or hexagonal communication cells of equal largest horizontal size. In the case of square cells, 24 base stations are needed as contrasted to only 20 base stations in the case of hexagonal cells.

shown that with this restriction standing or moving people cannot block the link although some shadowing is possible. That is, a person near the base station might block some but not all transmitter beams that produce diffusing spots within receiver FOV. Furthermore, the power penalty due to shadowing has been computed and it does not exceed 0.1 dB in 99% of the cases.

Receiver acceptance angle

In order to operate at different angles of acceptance in cellular and MSD configurations, receiver optical system will necessarily be quite complex. Therefore, it is desirable that the receiver has a fixed value of its FOV instead of a variable one.

From Figure 1, it is evident that in LOS configuration the receiver acceptance angle must be wide enough to encompass the base station at any receiver position within the communication cell. Then, the receiver FOV (half acceptance angle) must comply with the inequality $\mathrm{FOV} \geq \Phi_{\mathrm{LOS}} = 27^\circ$. Setting a safety margin of 10% leads to a value of about 30°: $\mathrm{FOV} = 1.1\Phi_{\mathrm{LOS}} = 29.7^\circ$.

In [10], it has been shown that receiver FOV in MSD configuration must be at least 25°. In other words, any value that is larger than 25° is acceptable.

Thus, a receiver FOV value of 30° would satisfy the requirements of both communication architectures.

3. TRANSMITTER RADIATION PATTERN

The communication systems under consideration are bound to operate in offices and other closed areas that have, in general, a rectangular form. The easiest and the most natural way to provide the service to all users in a rectangular room is to split the room in a set of square communication cells. However, when the largest horizontal size of the communication cell is restricted (e.g., by considerations regarding link blockage) a square cell covers a smaller area than the corresponding circular communication cell. On the other side, circular cells must partially overlap in order to avoid gaps. A honeycomb-like structure of communication cells provides the most efficient coverage. In order to serve a given area, one would need a larger number of base stations forming square communication cells as compared to the ones that produce hexagonal cells. This is illustrated in Figure 3.

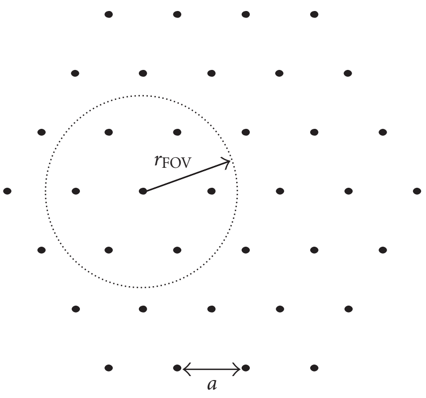
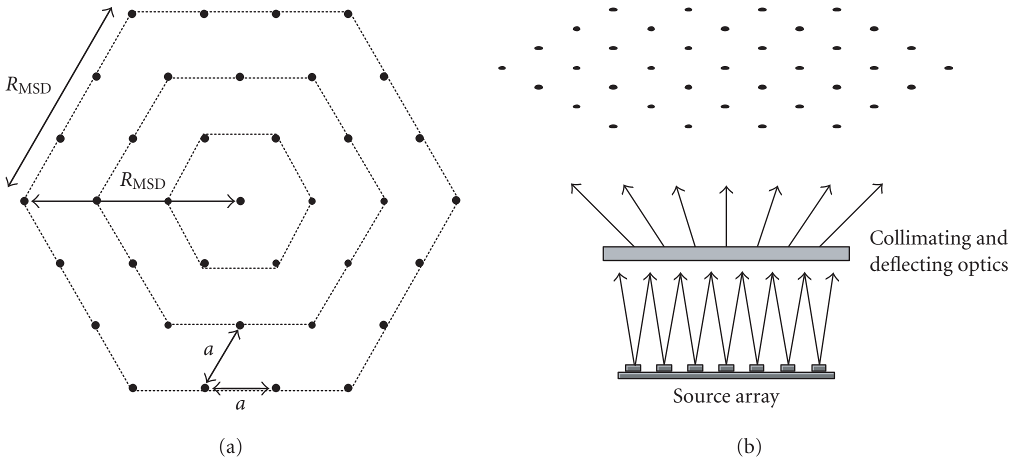


Figure 4: Triangular lattice of diffusing spots to define a hexagonal communication cell. The lattice spacing, a, must be smaller than the radius, r_{FOV}, of the circular area seen by the receiver.

Both square and hexagonal cells correspond to the same maximum transmission angle, that is, their maximal lateral dimensions, denoted by $2R$, are equal. The corresponding areas of a single communication cell are $A_{\text{square}} = (2R)^2/2$ and $A_{\text{hexagon}} = 3\sqrt{3}(2R)^2/8$, and their ratio is $A_{\text{hexagon}}/A_{\text{square}} = 1.3$. In Figure 3, a large rectangular area is covered by 24 square cells, that is, 24 base stations are needed to serve the whole area. In the case of hexagonal communication cells, the number of base stations is reduced to 20. In view of this, the following analysis is concerned with transmitter radiation pattern that produces a hexagonal communication cell.

Transmitter pattern in multispot diffusing configuration

In MSD configuration, transmitter must emit multiple narrow light beams towards the room ceiling. These light beams illuminate small areas on the ceiling, called diffusing spots. The most natural way of creating a hexagonal communication cell is to have diffusing spots on a triangular mesh, as it is shown in Figure 4. Transmitter optics collimates and deflects the beams from the source array to produce the desired triangular spot lattice. Receiver must always see more than one spot to ensure uninterrupted communications in case of shadowing. Therefore, the radius, r_{FOV}, of the circular area on the room ceiling that is seen by the receiver must be larger



(a)

(b)

Figure 5: (a) A hexagonal communication cell made of a triangular lattice of diffusing spots. The spots can be viewed as arranged in rings around the central diffusing spot. The side of the hexagonal communication cell, R_{MSD}, is an integer number times the lattice spacing, a. (b) Schematic of the proposed transmitter optics. The role of the optical system is to collimate and redirect the source beams in appropriate directions to create a light spots lattice.

than the spots lattice spacing, a:

$$r_{\mathrm{FOV}} = H \tan \mathrm{FOV} > a, \qquad (2)$$

where H is the communication cell height, that is, the distance from the room ceiling to the desktop level.

The lattice spacing can be expressed in terms of the horizontal communication cell size: $a = R_{\mathrm{MSD}}/n$. Here, R_{MSD} is the hexagonal cell side and n is the number of rings of spots around the central diffusing spot (see Figure 5a). Since $R_{\mathrm{MSD}} = H \tan \Phi_{\mathrm{MSD}}$,

$$a = \frac{H}{n} \tan \Phi_{\mathrm{MSD}}. \qquad (3)$$

Then, using the inequality (2), a condition about the integer n is obtained:

$$\begin{gathered} H \tan \mathrm{FOV} > \frac{H}{n} \tan \Phi_{\mathrm{MSD}}, \\ n > \frac{\tan \Phi_{\mathrm{MSD}}}{\tan \mathrm{FOV}} = \frac{\tan 45^\circ}{\tan 30^\circ} = 1.7 \quad (\text{i.e., } n \geq 2). \end{gathered} \qquad (4)$$

The total number of diffusing spots or, correspondingly, the total number of light sources in the emitter array is $N = 1 + \sum_{k=1}^{n} 6k$. The outputs of these light sources must be collimated and deflected to appropriate angles to create a triangular mesh of diffusing spots on the room ceiling, as shown in Figure 5.

Transmitter pattern in cellular configuration

In cellular configuration, the communication cell is split into a number of hexagonal microcells, as shown in Figure 6a. The resultant shape of the cell is close to a hexagon and multiple cells can adjoin without gaps.

The beam from each individual light source in the emitter array must be flattened, shaped, and deflected to illuminate uniformly the desired hexagonal area of a particular microcell. Apparently, transmitter optical system will necessarily differ somewhat from the one that is utilized in an MSD system. To facilitate the design of a transmitter optics that will serve both cellular and diffuse systems, the same beam deflection angles as in MSD configuration are retained. Then, as shown in Figure 6b, flattening and shaping of the light beams can be done using an additional diffractive optical element (see, for e.g., [12]) that will be exerted or activated when the system is to operate in LOS regime.

Further, in order to satisfy the requirement for the maximal radiation semiangle of 27°, not all N sources in the emitter array should be active in the LOS regime. We denote the number of sources that are used in LOS regime of operation by M, and the number of rings of hexagonal microcells around the central one by m. Again, these two quantities are interdependent through $M = 1 + \sum_{k=1}^{m} 6k$. From Figure 6a, it can be seen that the lateral size of the communication cell can be expressed in terms of the diffusing spots lattice spacing in MSD regime:

$$R_{\mathrm{LOS}} = \left(m + \frac{1}{2}\right) a, \qquad (5)$$

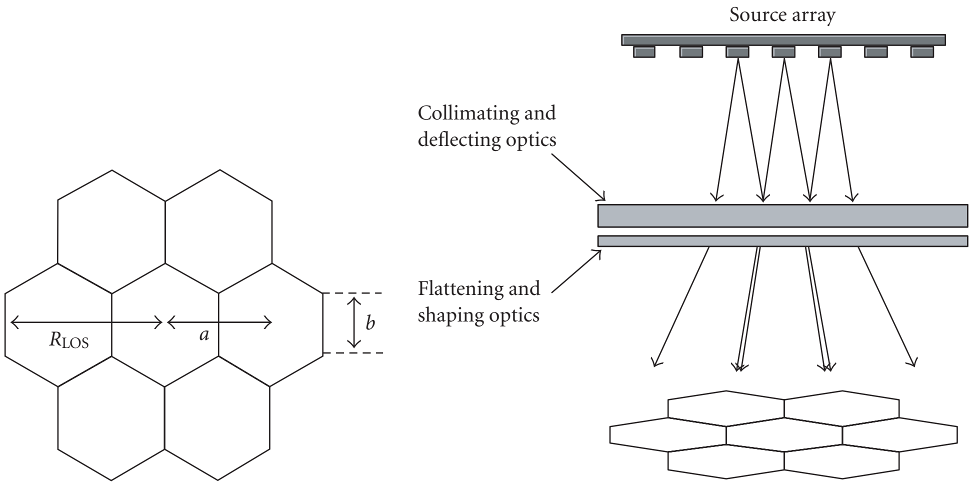
where a is given by (3). On the other side,

$$R_{\mathrm{LOS}} = H \tan \Phi_{\mathrm{LOS}}. \qquad (6)$$

Then, using (3) through (6), the possible values for m are obtained:

$$\begin{gathered} m = n \frac{\tan \Phi_{\mathrm{LOS}}}{\tan \Phi_{\mathrm{MSD}}} - 0.5 \approx 0.5n - 0.5 = 0.5(n-1), \\ n = 2, 3, 4, \ldots. \end{gathered} \qquad (7)$$

Note that m must be an integer. Equation (7) gives values for m that are close enough to an integer for the odd values of n.



(a) (b)

Figure 6: (a) A communication cell made of hexagonal microcells. The distance between the centers of two neighboring microcells, a, equals the distance between two neighboring diffusing spots in the case of MSD configuration. $2R_{\mathrm{LOS}}$ is the maximal lateral size of the communication cell; b is the side of the hexagonal microcell. (b) Schematic of the proposed transmitter optics. The role of the optical system is to flatten, shape, and redirect the source beams so that adjoining hexagonal areas are uniformly illuminated.

Thus, the smallest number of sources in the emitter array that will serve successfully both cellular and diffuse systems is obtained for $n = 3$:

$$N = 1 + \sum_{k=1}^{3} 6k = 37. \tag{8}$$

For $n = 3$, $m = 1$ and $M = 7$. The number of sources that are active in diffuse regime of operation is 37, while only 7 of them are needed in cellular regime. The optimum number of sources in the emitter array is not necessarily the smallest one. This should be a subject to further investigation although throughout the rest of this paper $N = 37$ is assumed.

4. LARGE OFFICE SPACE COVERAGE

When the office space that is to be covered is larger than the communication cell size, more than one base stations must be used to provide the service to all users, as shown in Figure 3. Since the communication cell size in MSD is larger as compared to cellular configuration, a larger number of base stations are needed for LOS communications. The difference in the base stations density may roughly be estimated by comparing the communication cells areas A_{LOS} and A_{MSD}:

$$A_{\mathrm{LOS}} = 7A_{\mu\,\mathrm{cell}}, \tag{9}$$

where $A_{\mu\,\mathrm{cell}}$ is the area of a single microcell in LOS regime;

$$A_{\mathrm{MSD}} \approx 37A_{\mu\,\mathrm{cell}} \approx 5A_{\mathrm{LOS}}. \tag{10}$$

Evidently, a much smaller number of base stations working in diffuse regime, as compared to their number in LOS regime, are required for the coverage of a given office space.

Expressed in terms of the communication cell height, the microcell area is

$$A_{\mu\,\mathrm{cell}} = \frac{3ab}{2} = \frac{\sqrt{3}}{2}\frac{H^2\tan^2\Phi_{\mathrm{MSD}}}{n^2}, \tag{11}$$

where $b = a/\sqrt{3}$ (see Figure 6a) and relation (3) has been taken into account. Thus, the density of base stations is inversely proportional to the second power of the office height:

$$\frac{1}{A_{\mathrm{LOS}}} \sim \frac{1}{A_{\mu\,\mathrm{cell}}} \sim \frac{1}{H^2}, \qquad \frac{1}{A_{\mathrm{MSD}}} \sim \frac{1}{A_{\mu\,\mathrm{cell}}} \sim \frac{1}{H^2}. \tag{12}$$

In other words, the higher the office, the smaller the number of base stations required.

In the case of hexagonal communication cells, the base stations are placed in the knots of a triangular mesh. The base stations grid spacing depends on the room height and, certainly, is different in LOS and diffuse architectures. In Figure 7, it is denoted by S_{LOS} and S_{MSD} for the cases of cellular and MSD configurations, respectively. S_{LOS} and S_{MSD} can easily be calculated if the office height is known:

$$\begin{aligned} S_{\mathrm{LOS}} &= \sqrt{(2a)^2 + (3b)^2} = \sqrt{(2a)^2 + \left(3\frac{a}{\sqrt{3}}\right)^2} \\ &= \sqrt{7}a = \sqrt{7}\frac{H\tan\Phi_{\mathrm{MSD}}}{n}, \\ S_{\mathrm{MSD}} &= \sqrt{(5a)^2 + \left(4\frac{\sqrt{3}a}{2}\right)^2} \\ &= \sqrt{37}a = \sqrt{37}\frac{H\tan\Phi_{\mathrm{MSD}}}{n}. \end{aligned} \tag{13}$$

For $n = 3$ and $\Phi_{\mathrm{MSD}} = 45^\circ$, the base stations grid spacing is $S_{\mathrm{LOS}} = 0.9H$ and $S_{\mathrm{MSD}} = 2H$ for the two architectures under consideration, respectively.

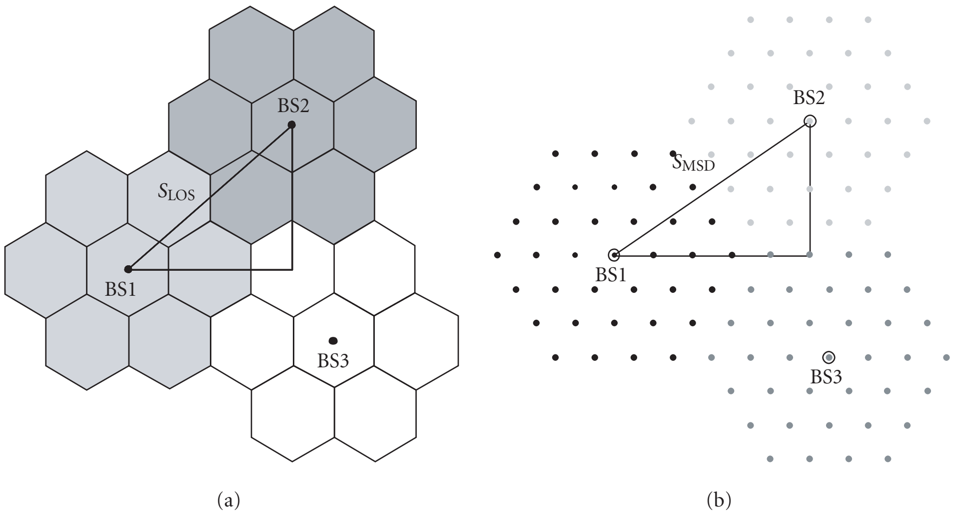


Figure 7: Illumination of three adjoining communication cells is shown for the case of (a) a cellular configuration and (b) an MSD configuration. The positions of the base stations, BSs, are projected on the illumination plane (desktop level in (a) and ceiling in (b)). The distances between the neighboring base stations are denoted by S_{LOS} and S_{MSD}, respectively.

5. SIGNAL PATH LOSS

Optical wireless communications are characterized by a high signal path loss. Therefore, receiver must necessarily exhibit a large receiving area. On the other hand, if a large area photodetector were used, the high capacitance associated with it would greatly reduce the receiver bandwidth.

Instead of a single large-area detector, a two-dimensional array of photodetectors is utilized, as has been proposed for the first time in [8]. A common optics serves all pixels in the detector array (see Figure 8). This way, the effective receiving area, which is the effective entrance aperture of the lens system, is large and collects a good portion of the optical signal. At the same time, the photodetector pixel, that actually receives the signal and converts it into an electrical one, has a small area, therefore a small capacitance. As a consequence, receiver can support high bit rates while receiving signals within a wide FOV. For example, in our recent three-lens optical design of an imaging receiver, presented in [10], we have achieved a full acceptance angle of 50°, an entrance aperture diameter of 30 mm, and an image spot size between 1.7 mm and 2.48 mm, depending on the angle of signal arrival. The segmented detector consists of 37 hexagonal pixels, each having a 2.8 mm side. Thus, a total image area of 750 mm^2 is covered while the active receiving element has a fairly small area of about 20 mm^2.

Another advantage of utilizing a detector array is the capability of such a receiver to distinguish between signals arriving from different directions, that is, different diffusing spots in the case of MSD or different base stations in the case of a cellular architecture. This is because receiver optical system actually performs angular-spatial mapping, as shown in Figure 8. A very small solid acceptance angle corresponds to each pixel in the detector array, so that optical signal power is focused onto a particular detector depending on the signal angle of incidence.

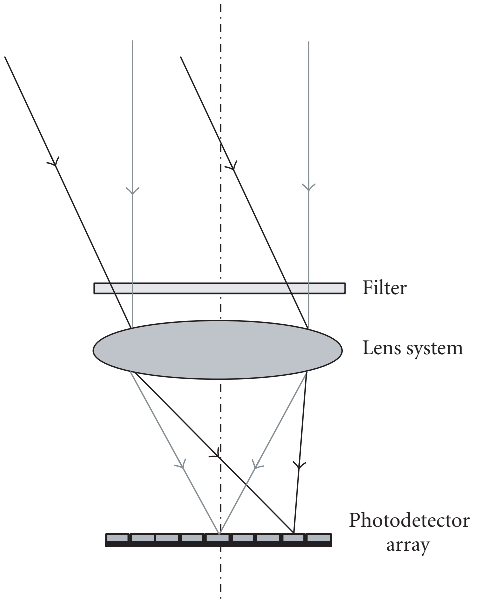


Figure 8: Receiver optical front end performs angular-spatial mapping. The lens system focuses light impinging at different angles onto different pixels in the detector array.

Optical signal path loss is quite different for LOS and diffuse architectures; it is higher in the case of diffuse configuration. In the following, it is shown that this difference is entirely within the capabilities of the commonly used photodiodes at the receiver to accommodate.

In MSD, received optical power that is launched through a single diffusing spot, that is, a single source in the emitter

Table 1: Representative link budget.

	Cellular topography	MSD topography
Wavelength	> 1400 nm	> 1400 nm
Eye-safe transmit power per emitting element	+10 dBm	+10 dBm
Optical path loss at cell edge	−48 dB	−66 dB
Receiver optics loss (filter and Fresnel losses)	−2 dB	−2 dB
Optical concentrator gain (3 cm entrance aperture diameter, 3 mm image spot diameter)	+20 dB	+20 dB
Received optical power	−20 dBm	−38 dBm
Receiver sensitivity at 155 Mbps (according to [2])	−28.5 dBm (PIN), −43.5 dBm (avalanche)	−28.5 dBm (PIN), −43.5 dBm (avalanche)
Irradiance at a 10 mm^2 receiving pixel	−10 dBm/cm^2	−28 dBm/cm^2
Required irradiance at 100 Mbps (according to [3])	−30 dBm	−30 dBm

array, is

$$P_{\text{MSD}} = \frac{P_0 \rho \cos\theta}{\pi r^2} A_{\text{rec}} \cos\theta = \frac{P_0 \rho \cos^4\theta}{\pi H^2} A_{\text{rec}}, \tag{14}$$

where P_0 is the launch optical power, ρ is the ceiling reflectance, θ is the angle between a vertical line and the line-of-sight between the receiver and the diffusing spot, $r = H/\cos\theta$ is the distance between the receiver and the diffusing spot, and A_{rec} is the receiver effective area. Received power is minimal when the diffusing spot appears at the edge of the receiver FOV, that is, when $\theta = \text{FOV}$:

$$P_{\text{MSD}}^{\min} = \frac{P_0 \rho \cos^4 \text{FOV}}{\pi H^2} A_{\text{rec}}. \tag{15}$$

Received optical power in cellular configuration depends on the size of the microcells:

$$P_{\text{LOS}} = \frac{P_0}{A_{\mu\,\text{cell}}} A_{\text{rec}} \cos\theta, \tag{16}$$

where P_0 is the launch optical power by the source in the emitter array that illuminates the particular microcell and θ is the angle of signal arrival. The received power is maximal at normal incidence, that is, for $\theta = 0$.

Then, the maximum received optical power in a cellular configuration is

$$P_{\text{LOS}}^{\max} = \frac{2}{\sqrt{3}} \frac{P_0 n^2}{H^2 \tan^2 \Phi_{\text{MSD}}} A_{\text{rec}}. \tag{17}$$

The ratio between the two extreme values, the maximum received optical power in cellular regime and the minimum received power in MSD regime, expressed in dB, is

$$\begin{aligned} D &= 10\log_{10}\left(\frac{P_{\text{LOS}}^{\max}}{P_{\text{MSD}}^{\min}}\right) \\ &= 10\log_{10}\left(\frac{2}{\sqrt{3}} \frac{\pi n^2}{\rho \tan^2 \Phi_{\text{MSD}} \cos^4 \text{FOV}}\right) \end{aligned} \tag{18}$$

and its value is 18.6 dB for $n = 3$, $\Phi_{\text{MSD}} = 45^\circ$, $\text{FOV} = 30^\circ$, and $\rho = 0.8$. The actual value of this ratio would be somewhat larger due to the dependence of the optical concentrator gain on the signal direction of arrival.

Note that in both configurations received optical power is inversely proportional to the squared communication cell height, so that D does not depend on the office size.

An exemplary link budget is given in Table 1. It assumes a wavelength longer than 1400 nm, at which 10 mW optical power can safely be launched [13]. At shorter wavelengths, holograms can be employed in order to make the transmitter eye-safe (see, e.g., [14, 15]).

6. CONCLUDING REMARKS

The basic idea that underlies the present investigation is to bring together the two most promising configurations for optical wireless networks indoors, namely, cellular line-of-sight and MSD configurations. This is attempted through developing a system that would be capable of operating in both configurations rather than a sophisticated combination of the architectures themselves. The latter has been tried before with limited success. Therefore, the idea is to redirect the research efforts and to develop a transceiver capable of operating in both cellular and MSD regimes. As a first step towards achieving this goal, it is proposed that transceiver design is based on utilization of two-dimensional arrays of infrared light emitting devices and photodetectors. Basic design parameters of transceiver optics are derived from considerations on link blockage and system compliance with the unique features of LOS and diffuse regimes of transmission. Currently, a detailed design of transceiver optical system is under way. For this purpose, conventional optics, diffractive, and holographic solutions are considered. Certainly, a compromise between transceiver complexity, cost, microcell size (in LOS regime), number of independent channels (established between two communicating devices in MSD regime), receiving pixel size, and so forth, has to be sought.

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