Assessing the Feasibility of New Diffused Configuration for Broadband Wireless Infrared Links

Y. Alqudah, M. Kavehrad (FIEEE)
Center for Information and Communications Technology Research (CICTR)
Department of Electrical Engineering
The Pennsylvania State University, University Park, PA 16802
Tel.: (814) 865-7179
Email: mkavehrad@psu.edu

***Abstract*-Traditionally, diffused infrared configuration has been studied with the assumption that the illuminated region is placed at room ceiling. This is done to ensure minimum path loss to a maximum number of receiver locations. In many practical situations, this arrangement might be difficult to implement, either due to the ceiling structure or the difficulty in illuminating the entire ceiling uniformly without introducing an intrusive transmitter. In this paper, we propose a new configuration, in which the upper regions of the walls are illuminated. Path loss and delay spread are used as performance measures to assess the feasibility of the proposed configuration.**

Keywords-component; indoor wireless; diffused; path loss; delay spread

I. INTRODUCTION

The large unregulated bandwidth of optical links makes it an attractive alternative to radio frequency for carrying broadband multimedia applications in wireless indoor access. The inability of optical signals to pass through opaque surfaces provides interference-free bandwidth-reuse in adjacent rooms. Susceptibility to shadowing, multipath dispersion, and limited range resulting from noise generated by ambient light are the main challenges in design of infrared link.

Several configurations are proposed and researched for link design. These are classified mainly according to their directivity and Line-of-Sight (LOS) nature. A link is referred to as directed if the receiver and transmitter have a narrow radiation pattern and Field-of-View (FOV), respectively. In a non-directed link, the transmitter has a broad radiation pattern and the receiver uses a large FOV. A LOS/non-LOS classification depends on whether or not an unobstructed path between a transmitter and a receiver exists.

Directed LOS links reduce path loss at the expense of disabling receiver mobility. The link can easily be lost if obstructed by an object. To solve this problem, non-directed non-LOS link (also know as diffused) is used. The optical power is projected onto a reflecting surface accessible to most receiver locations. The link does not require transmitter/receiver alignment and thus provides robustness against link loss due to blockage. This configuration suffers from a high-path loss due to the absence of a direct path and data rate limitation caused by reflections. This latter limitation results from multipath temporal dispersion caused by different paths (including reflections off of walls and ceiling) the signal takes to travel to a receiver.

The illuminated region is traditionally chosen to be the ceiling of a room as shown in Fig. 1 (a) [1]-[4]. This is because, this region is accessible to the largest number of receiver locations. In order to provide a uniform illumination, a transmitter placed at the room center is used. In some practical situations, this arrangement is difficult to implement. This is true when the room center is occupied or when moving objects constantly obstruct it. In this study, we propose an alternative that illuminates upper walls. A transmitter placed at the ceiling center is used to illuminate walls as illustrated in Fig.1 (b). This study assesses feasibility of the proposed configuration by comparing path loss and delay spread profiles to the traditional diffused configuration.

II. CHANNEL MODEL

Multipaths, the signals take in traveling between transmitter and receiver, complicate the calculations of channel impulse response in an indoor environment. These multipaths result from reflections off of room surfaces, furniture, etc. As the signal undergoes a reflection, its amplitude is reduced, and its arrival time is increased. To obtain an accurate model of the channel, several reflections must be considered. Due to attenuation that high order reflections suffer, most of the signal energy is confined in the first three reflections.

The impulse response of an indoor environment is obtained by dividing the room surface into N adjacent elements of equal size. Each element is identified by an index, (x, y, z) coordinates, an orientation, and a reflection coefficient ρ . The number of elements determines time resolution of an impulse response, increasing the elements improves resolution at the cost of increasing calculation time [2]. The elements illuminated directly by a transmitter act like sources, and thus are referred to as such.

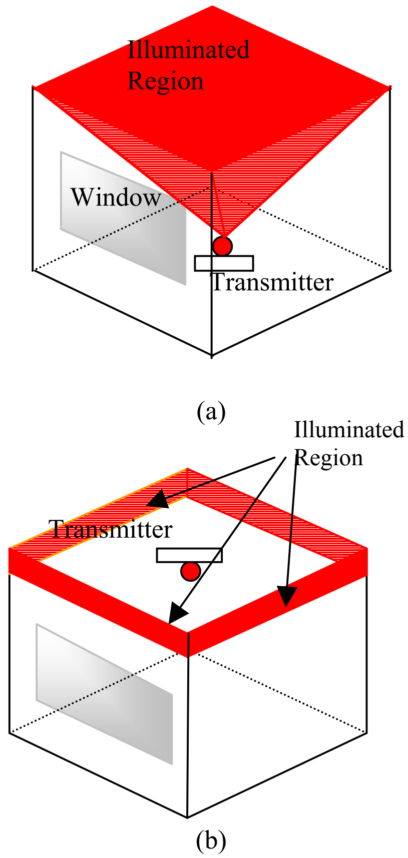


Figure 1. (a) Traditional diffused configuration. A transmitter placed at the room center is used to illuminate the ceiling. (b) Proposed configuration. A transmitter placed at the ceiling is used to illuminate the upper regions of the walls.

The impulse response can be expressed as:

$$H = \sum_{i=0}^{n} H^{(i)}$$
$$= F_s \cdot \Phi_n \cdot G_r + D \cdot G_r \,, \qquad (1)$$

where $H^{(i)}$ is the impulse response resulting from ith reflection, F_s is the source vector, Φ_n is the environment matrix, G_r is the receiver vector, and D is the direct response vector. In the following, we describe each of the components making up the impulse response.

A. Source Vector (F_s)

Source vector contains transfer function between a source and N surface elements. Since, the elements receive the signal directly, transfer function f_{sk} between a source s and an element k can be expressed as:

$$f_{sk} = \rho_k \delta(t - \frac{R_{Ts}}{c}) \frac{\cos(\theta_{sk})\cos(\varphi_{sk}) A_R}{\pi \cdot R_{sk}^2} \delta(t - \frac{R_{sk}}{c}) u(\frac{\pi}{2} - \theta_{sk}) \,, \qquad (2)$$

where the first two terms are added to account for the transfer function between transmitter and source, R_{ij} is the distance between element i and j, θ_{ij} is the angle between a vector perpendicular to j and a vector that lays on the straight line that connects i and j, φ_{ij} is equal to the dot product of two unit vectors, the first is perpendicular to i and the second originates from j and extends towards i, A_i is the element area, and c is the speed of light. For a single source s, the vector F_s is expressed as:

$$F_s = [f_{s1} \quad \cdots \quad f_{sN}] \,. \qquad (3)$$

To account for the multiple sources in a diffused configuration, an equivalent source vector F_{eq} is calculated according to:

$$F_{eq} = \sum_{i=1}^{S} F_i = [f_{eq1} \quad \cdots \quad f_{eqN}] \,, \qquad (4)$$

where S is the total number of sources and $f_{eqj} = \sum_{i=1}^{S} f_{ij}$. In a ceiling diffused case, these elements belong to the ceiling, while for a wall diffused; the elements belong to the upper region of walls.

B. Environment Matrix Φ_n

This component consolidates dependence on the indoor geometry, dimensions, and reflection coefficients. The component contains the transfer functions between any two elements. In matrix format and considering up to n reflections, it is expressed as:

$$\Phi_n = \begin{cases} I_{NxN} + \phi + \phi^2 + \phi^3 + \cdots \phi^{n-1} & , n \geq 2 \\ I_{NXN} & , n = 1 \end{cases} \,. \qquad (5)$$

Where I_{NxN} is the NxN identity matrix and ϕ is given by

$$\phi = \begin{bmatrix} \phi_{11} & \cdots & \phi_{1N} \\ \vdots & \ddots & \vdots \\ \phi_{N1} & \cdots & \phi_{NN} \end{bmatrix} . \qquad (6)$$

The entries ϕ_{ik} represents the transfer function between two elements i and k, and is given by:

$$\phi_{ik} = \begin{cases} 0 & , i = k \\ \frac{\rho_i \cos\theta_{ik} \cos\varphi_{ik} A_k}{\pi R_{ik}^2} \delta(t - \frac{R_{ik}}{c}) u(\pi/2 - \theta_{ik}) & , i \neq k \end{cases} \qquad (7)$$

The environment matrix is independent of transmitter and receiver configuration, once calculated; it can be used with any configuration.

C. Receiver Vector (G)

The receiver vector contains the impulse response dependence on receiver parameters such as location and FOV. In vector form, it is expressed as:

$$G_r = \begin{bmatrix} g_{1r} \\ \vdots \\ g_{Nr} \end{bmatrix}, \tag{8}$$

where the entry g_{ir} is given by:

$$g_{ir} = \frac{\rho_i \cos\theta_{ir} \cos\varphi_{ir} A_r}{\pi R_{ir}^2} \delta(t - \frac{R_{ir}}{c}) u(FOV_r - \theta_{ir}) . \tag{9}$$

The number of non-zero entries in G_r is directly proportional to the receiver FOV. Increasing FOV, increases the non-zero entries.

D. Direct Response Vector (D)

When a source is within a receiver FOV, a direct response results. This response is expressed as

$$H^{(0)} = D \cdot G_r , \tag{10}$$

where D is a 1xN vector given by:

$$D = [d_1 \quad \cdots \quad d_N]. \tag{11}$$

The entry d_i is equal to $\frac{1}{\rho_i}\delta(t - \frac{R_{Ti}}{c})$ if and only if an element i corresponds to a diffusing element and 0, otherwise. R_{Ti} is the distance between the element and transmitter.

E. Computer Simulation

In carrying out simulation on a personal computer, entries in F, Φ , G, and D are represented as complex numbers with phase equal to time delay. Since the delay takes on very small values, it is expressed as an integer multiple of sampling time T_s, where T_s is equal to the time it takes light to travel between neighboring elements, i.e.

$$T_s = \frac{d}{c} , \tag{12}$$

where d is the distance between neighboring elements. When performing addition, only terms that have equal delay are added together. Thus,

$$ax^{-n_i} + bx^{-n_j} = \begin{cases} (a+b)x^{-n_i} & ; i = j, \\ ax^{-n_i} + bx^{-n_j} & ; i \neq j. \end{cases} \tag{13}$$

The impulse response is defined as the received optical power when transmitted optical power is equal to a delta function with unit-area, i.e., 1W [2]. The resultant impulse response is in the form

$$H = h_0 x^{-n_0} + \cdots + h_{K-1} x^{-n_{K-1}} , \tag{14}$$

where h_i is the amplitude of the impulse response at time equals to $n_i T_s$. The room parameters used in this simulation are summarized in Table I.

TABLE I. ROOM PARAMETERS USED IN STUDY

Parameter	Ceiling Diffused	Wall Diffused
Width	6m	6m
Length	6m	6m
Height	3m	3m
$\rho_{walls} = \rho_{ceiling}$	0.7	0.7
ρ_{Window}	0.04	0.04
ρ_{floor}	0.2	0.2
Window height	1.2m	1.2m
Window width	4.6m	4.6m
Window elevation	1.0m	1.0m
Transmitter Location	(3,3,0.9)	(3,3,3)
Receiver FOV	90°	90°
d	0.2m	0.2m
N	3600	3600
Diffused region	Ceiling, 900 elements	Upper 0.4m of walls, 240 elements

The impulse responses for a receiver located at (1,2,0.9) are shown in Fig.1. The figure shows several peaks in the ceiling diffused impulse response since the diffusing elements are adjacent to each other, in the wall diffused, four peaks are shown corresponding to the four walls.

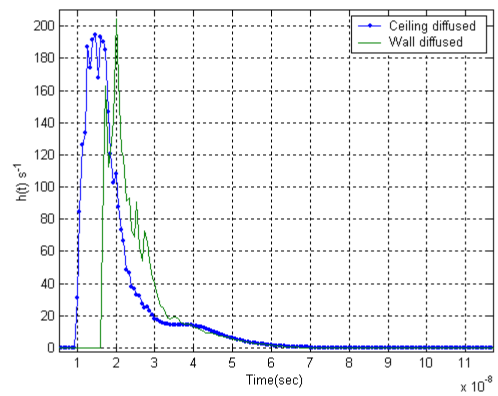


Figure 2. Comparing the impulse response of a receiver located at (1,2,0.9).

III. LINK PROFILE

Two parameters are used to examine the link performance. These are path loss and RMS delay spread.

A. Path Loss

The signal-to-noise ratio (SNR) at the receiver is one of the determining factors of the achievable bit rate. In any communication system, it is desirable to have as large a SNR as possible. In an infrared link, the amount of optical power transmitted is limited by eye safety considerations. Since the receiver in both configurations is exposed to the same ambient light, the noise value is the same for fixed receiver parameters in either configuration. Therefore, a comparison of SNR is possible through comparing received power. A measure of received power is provided by path loss defined as the dc value of channel frequency response [5]

$$PL = -10 * \log_{10}(\mathbf{H}(0))$$

$$= -10 * \log_{10}(\sum_{i=0}^{K-1} T_s H_i) \text{ (dBo)}. \quad (15)$$

Fig. 3 compares path loss histogram for the two configurations. The average path loss of the ceiling diffused configuration is equal to 58.33 (dBo) compared to 59.26 (dBo) of the wall diffused configuration. Another consideration is the uniformity of the received power loss throughout the room; this is illustrated in Fig. 4. The figure shows that the constant path loss region in the ceiling diffused belongs to rings surrounding the room center. The wall diffused case is depicted in Fig. 4 (b).

B. Delay Spread

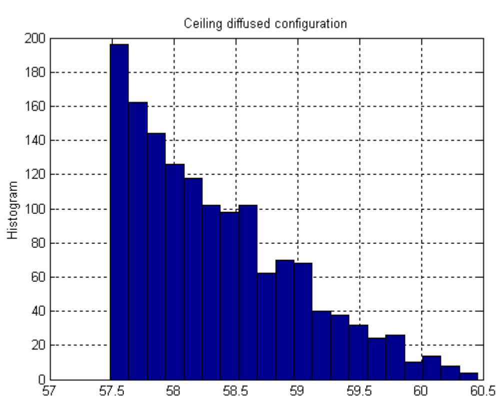
Intersymbol interference (ISI) resulting from propagation in a dispersive channel is a major problem in the design of a broadband wireless link. Dispersion sets the limit on the symbol length that can be used. As dispersion increases, symbols have to be placed at farther time intervals in order to reduce the adverse effect of ISI. This in turns reduces the achievable bit rate. A measure of dispersion is provided by room mean square delay spread ($T_{delayspread}$) defined as the second moment of the impulse response [6]

$$T_{delayspread} = \sqrt{E(\tau^2) - (E(\tau))^2} \, . \quad (16)$$

In terms of H

$$E(\tau^n) = \frac{\sum_i \tau_i^n h_i^2}{\sum_i h_i^2} = \frac{\sum_{i=0}^{K-1} (i \times T_s)^n \times h_i^2}{\sum_{i=0}^{K-1} h_i^2} \, . \quad (17)$$

Profiles of the ceiling diffused and wall diffused are shown in Fig. 5. The average delay spread is 4.46 (ns) in the ceiling diffused compared to 3.93 (ns) in the wall diffused configuration. The constant delay spread locations form a ring around the room center in the ceiling diffused configuration, with the highest spread being at the room center. In the wall diffused, the highest delay spread is located midway adjacent to walls, with room center experiencing lowest delay spread. This is illustrated in Fig. 6.



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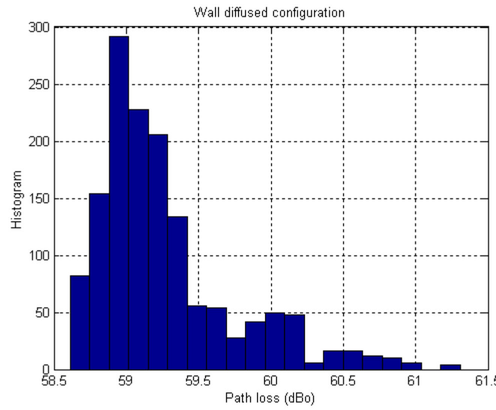
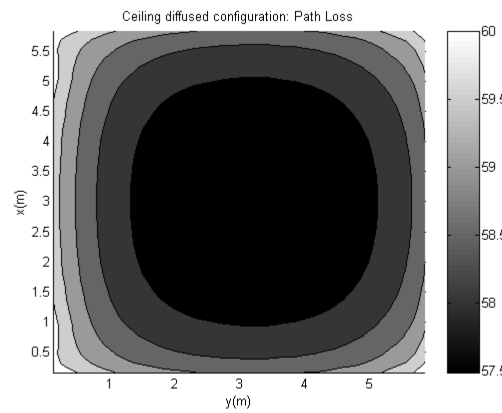


(b)

Figure 3. (a) Histogram plot of path loss for a ceiling diffused configuration. (b) Histogram of path loss for wall diffused configuration.



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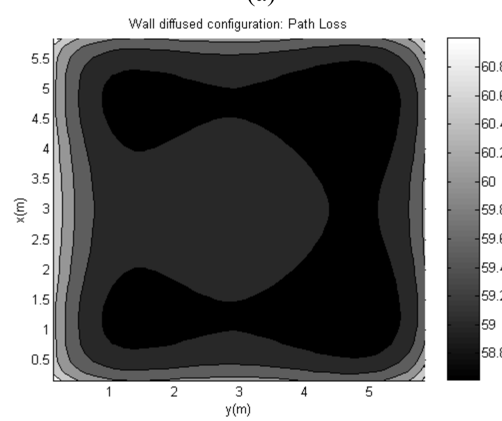
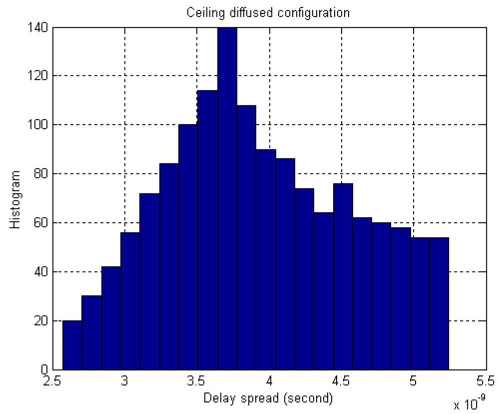


(b)

Figure 4. (a) Contour plot of path loss (dBo) for a ceiling diffused configuration. (b) Contour plot of path loss (dBo) for a wall diffused configuration.



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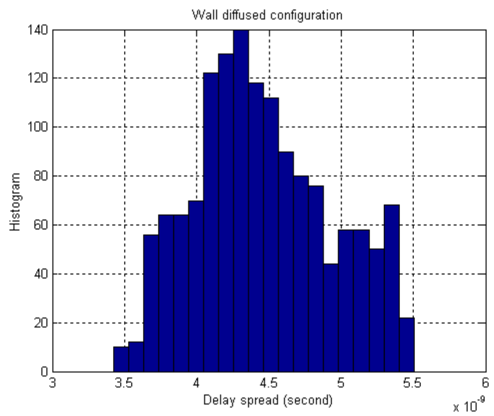
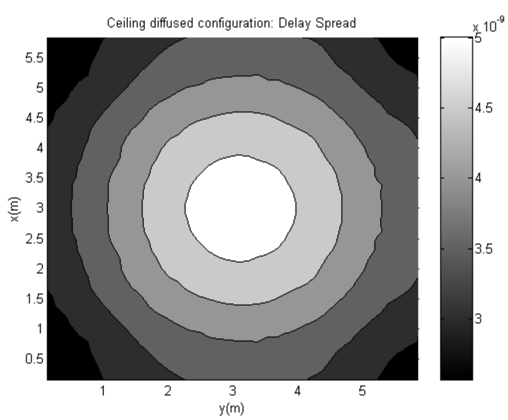


(b)

Figure 5. (a) Histogram plot of delay spread for a ceiling diffused configuration. (b) Histogram of delay spread for wall diffused configuration.



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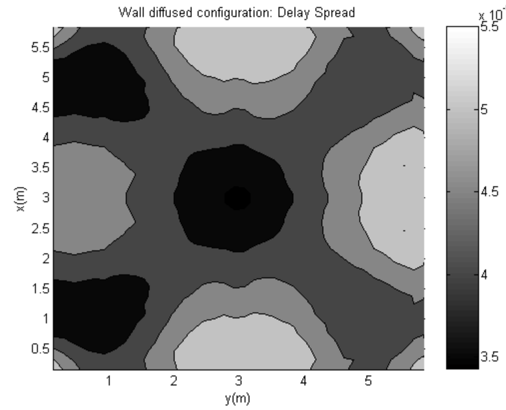

(b)

Figure 6. (a) Contour plot of delay spread (sec) for a ceiling diffused configuration. (b) Contour plot of delay spread (sec) for wall diffused configuration.

IV. CONCLUSIONS

In this study, we proposed a new diffused configuration. The upper regions on the walls are illuminated instead of the ceiling. The preliminary evaluation is encouraging. The average path loss is less than 1.0(dBo) higher than that of the ceiling diffused and the average delay spread is approximately 13% higher.

Although not considered in this study, it is obvious that when the ceiling is used to hold light fixtures, the wall diffused receiver can be designed to block the signals coming directly from the ceiling to reduce the noise caused by ambient light. This can be accomplished by utilizing a multi-branch receiver with branches tilted at an angle surrounding a ring.

Practical considerations such as the unavailability of room center, or when the room center is constantly blocked by moving objects makes the wall diffused configuration a promising alternative.

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