Indoor Wireless Infrared Channel Characterization by Measurements

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Abstract—Use of infrared light for indoor wireless communications has received considerable attention recently. In this paper, we present results obtained from a large set of measurements performed at the University of Ottawa. We investigate impacts of receiver rotation and shadowing on the properties of indoor infrared channels. This paper contains a description of a measurement system developed and used throughout the experiments. Measurement results are used to find and present methods to estimate variations of channel path loss for small changes in the receiver direction, using statistical techniques. This would be useful for generating samples of channel path loss for system performance simulations and modulation analysis. Using the measurement results, it is shown that variations of channel path loss are smooth and a simple curve-fitting algorithm can be used to accurately interpolate intermediate values. It is also shown that for a receiver changing its elevation angle from $0^\circ$ to $180^\circ$, five points along the entire path are sufficient to predict variation of channel path loss for the entire rotation range. The results also demonstrate a correlation between the channel delay spread and channel path loss for both diffuse and line-of-sight configurations. A simple formula can provide an estimate of channel delay spread for a known path loss of a given configuration. It is demonstrated that variations of channel path loss for small changes of receiver rotation can be described by a Gamma distribution. This enables generation of samples of channel path loss under general conditions for system-level simulation algorithms. Measurements have also been performed to investigate effects of shadowing on indoor infrared channel characteristics. Some important parameters that specify the impact of shadowing on the channel characteristics are included in the measurement plans. Variations of channel path loss due to shadowing and due to these parameters are investigated and detailed results are reported. It is shown that shadowing affects the channel delay spread. For the measured shadowing results, it is shown that channel path loss and delay spread are correlated and their relationship is provided.

I. INTRODUCTION

Use of infrared light has received considerable attention for indoor wireless communications. Infrared transceivers can provide inexpensive means of broadband communications in various applications. Further progress on design of reliable infrared transceivers depends on the designer’s knowledge of infrared channel and its variations under different conditions. An infrared source or receiver may change its position and/or orientation. This changes the channel characteristics. Furthermore, infrared light is subject to blockage and shadowing by nontransparent objects and this also has an impact on data transmission. In particular, infrared transmission is very sensitive to direction of the source and receiver. The sensitivity can be reduced by employing diffusing transceivers [1]. However, there are still considerable variations in the channel characteristics as the receiver or transmitter rotates.

In this paper, we investigate the impacts of transceiver rotation and shadowing on the properties of an indoor infrared channel. We present the results obtained from a large set of measurements performed at the University of Ottawa in Colonel By Hall (CBY). These measurements were conducted to examine the effects of receiver rotation and shadowing on the channel characteristics and represent the most extensive set of publicly reported measurements taken to investigate these effects.

This paper is divided into three major sections. The first section contains a description of measurement system that was developed and used for conducting the experiments. In the second section, measurement plans and results for rotation measurements are presented. It is shown that variation of channel path loss is smooth and predictable. A method of predicting the angle of minimum path loss along a rotation path is suggested and verified by comparison to computer simulations results. We have used measurement results to provide methods to estimate channel path loss variations as a result of small changes in the receiver angle, using statistical methods. This would be useful for generating samples of channel path loss for simulation of system performance and modulation analysis.

The third section of this paper presents measurement procedures and results obtained from a set of measurements performed to investigate the impact of shadowing on the infrared channel characteristics.

II. INFRARED CHANNEL MEASUREMENTS

The design of wireless communication systems using an infrared signal carrier requires extensive knowledge about the behavior of an indoor infrared channel. This requires channel measurements under different conditions and using different optical configurations. Such measurements could eventually lead us to an in-depth understanding of the channel behavior under different circumstances. Measurements are also essential in providing the required knowledge about distortions and noises that are encountered in actual application of these systems. For example, receiver rotation has an important effect on an indoor infrared link performance. The effect of receiver rotation for an infrared system would be an interesting subject to study in infrared channel measurements. Displacement of receiver as well
as receiver shadowing are other important events that affect the infrared channel and whose effects should be investigated.

Modeling and simulation of indoor infrared channel has been addressed in the literature with the pioneering work of Gfeller et al. [2], who introduced the idea of using infrared for indoor wireless communications. They analyzed the dispersion property of this channel using a simple model and demonstrated transmission of a baseband PCM signal at 125 kbps over this channel. Barry et al. [3] presented a general computer simulation method for infrared channel characterization. Experimental measurements of indoor infrared channel were performed at the University of Ottawa [4] over a 40-MHz band. Later, Krause et al. [5] measured an infrared channel over a 150-MHz 3-dB band, and the measurements at the University of Ottawa continued at a higher bandwidth of 400 MHz for many different configurations.

A wide-band measurement system was developed to investigate the effects of different parameters on the characteristics of an indoor infrared channel [6]–[8]. Techniques commonly used in radio channel measurements can be applied to characterization of this channel. One commonly used technique is the continuous-wave swept-frequency technique. This can be implemented easily and accurately using a network analyzer. The technique uses a constant-amplitude swept-frequency sinusoid to probe the channel. The received signal is multiplied by a transmitted signal and by a 90° phase-shifted version of the transmitted signal. The product signals are low-pass filtered and normalized to the transmitted signal amplitude, yielding estimates of real and imaginary parts of the channel frequency response. Therefore, the attenuation and phase shift (caused by the propagation medium) is obtained for each frequency component. A network analyzer was used for generating the swept frequency signal and calculating and recording the channel transfer function. This network analyzer is a high throughput instrument with a lab precision that covers 5 Hz to 500 MHz. It provides a resolution of 0.001 Hz, 0.001 dB, 0.0015°, and 10 ps for characterizing the linear behavior of either passive or active networks, devices, components, or systems in a laboratory or in production test areas. It has a built-in 1.44-GB disk drive for direct saving and recalling of instrument state, calibration data, and application programs, and it also supports an HPIB bus for data input and output. This bus has been used to transfer recorded channel transfer functions to a personal computer for further data processing.

Fig. 1 shows a block diagram of the measurement system. A sinusoidal signal from the network analyzer is amplified and converted to optical domain with an optical transmitter. A light-wave propagates in an indoor environment and is received by a portable optical receiver. The received signal is amplified and fed back to the network analyzer via a coaxial cable. The measurement system requires a high-power optical transmitter and a wide-band optical receiver with a large area photodiode. Because of the special requirements, off-the-shelf transmitters and receivers were not available.

Optical transmitter uses an 808-nm laser diode. The laser diode is impedance-matched with a 47-Ω resistor. A bias tee circuit combines the sinusoidal signal from network analyzer with a dc current from a power supply. The network analyzer signal is amplified by a wide-band power amplifier. The modulation bandwidth of the transmitter is from 1 KHz to 500 MHz, and the laser diode is biased such that its average output power is 180 mW. Lower levels of output power can be obtained by changing the bias point of the laser diode. The diode is fairly linear for this operation range. The optical transmitter is packaged in an aluminum box to minimize any RF leakage. A laser driver controls the transmitting laser diode operating bias and temperature. The laser bias point is chosen in the linear range of operation so as to avoid introduction of higher order harmonics into the measurement results.

There are various ways of arranging and designing an infrared wireless link. One possible configuration uses a line-of-sight (LOS) [1]. In this configuration, the receiver needs to have an unobstructed path to an infrared source. Th source is usually a base station that is ceiling mounted. If the receiver has a very small field-of-view (FOV) and needs alignment to receive a signal from the source, this configuration is called a directed LOS. If the receiver does not need to be aligned and only relies on an LOS path, configuration is called nondirected LOS or quasi-diffuse. Alternatively, infrared transceivers can be designed to operate in a diffuse mode. In this configuration, an infrared source shines the ceiling and the receiver relies on reflected light from ceiling, walls, and other objects for data detection. Diffuse and nondirected LOS are two useful configurations for relatively broad-band indoor wireless data communications. Therefore, we conducted our measurements based on these two possibilities. In the rest of this paper, the word LOS means a nondirected LOS configuration.

An external optical diffuser can be attached to a transmitter in order to build a diffuse link. An external diffuser can be a simple glass diffuser that shapes the radiation pattern of laser as a Lambertian pattern. The diffuser that we used would add 4.7 dB of loss to an optical path. To measure the channel using an LOS configuration, a Nikkor 50 mm f/1.4 lens was mounted on top of the transmitting laser source. The lens was then adjusted to create a focused laser beam on a diffusing surface on the ceiling. The lens introduces a loss of around 2.7 dB. Attenuation of the lens and diffuser is calibrated out of the reported results. A white sheet of paper with a reflectivity coefficient close to unity is placed on the ceiling so that the focused laser beam can be reflected without losing too much of its intensity. Therefore, a spot on the ceiling acts as a single-point Lambertian source of diffuse infrared energy, illuminating the measurement site. This method is called spot diffusing and allows us to measure channel characteristics in a LOS configuration without having to have a ceiling-mounted transmitter [9]. The developed optical receiver uses a large-area (25 mm²) silicon avalanche photodiode (APD). The packaged APD has no lens in front of the detector surface. Therefore, the optical receiver has a wide field-of-view of about 60°. For the front-end amplifier, a transimpedance receiver scheme is chosen to achieve a large dynamic range. A major challenge in receiver design is that an APD has a large capacitance of 30 pF and its bandwidth is limited by its transit time. The transit time is 5 ns and limits the 3-dB bandwidth of this APD to 200 MHz, as shown in Fig. 2(b). Frequency response drops by about 20 dB at 400 MHz. A resonant-type analog equalizer was designed to extend the receiver...
bandwidth to 400 MHz. Fig. 2(a) shows the frequency response of the optical receiver with an equalizer. The overall bandwidth extends approximately from 10 KHz to 400 MHz.

APD is biased at 410 V, resulting in a multiplication factor of 110 at room temperatures. To avoid the use of optical filters for rejecting ambient light, measurements were conducted in dark rooms. Otherwise, ambient light would saturate the receiver. Optical filters should be used to allow proper operation of the receiver in the presence of strong background light. The drawback of using optical filters is that off-the-shelf filters severely limit the receiver FOV, which is not desired for our measurement objectives. Therefore, most of our measurements were performed without an optical filter. A summary of measurement setup parameters is presented in Table I.

Noise level at the network analyzer can be reduced by choosing a small intermediate frequency (IF) bandwidth, which in turn increases the required time for recording a frequency response. The minimum IF bandwidth of the network analyzer is 2 Hz and was set to 20 Hz for these measurements. When choosing a small IF bandwidth, RF interference, due to RF leakage from the transmitter and pickup by the receiver, becomes a major factor limiting the receiver performance.

When operating at a distance of approximately 3 m from the transmitter, received interference level is about −160 dB at 300 MHz and −140 to −150 dB at 400 MHz. Therefore, the ratio of transmitter power to receiver interference equivalent power is about 80 dBo (optical dB) at 300 MHz and 70–75 dBo at 400 MHz. For each desired frequency response, a set of 128 samples was chosen. The signal frequency response on a network analyzer is swept from 30 kHz to 400 MHz in steps of 3.125 MHz to record 128 points. The start frequency is chosen to avoid effects of dc-blocking capacitance, used in the receiver circuit.

A. Calibration of the Measurement System

The measurement system is calibrated by putting the transmitter/receiver together in a back-to-back configuration. Let us assume that the transmitter side of the system has a frequency response of \( T(f) \) and the receiver side has a frequency response of \( R(f) \) (see Fig. 1). The recorded frequency response by a network analyzer can be expressed as \( H_{\text{rec}}(f) = T(f)R(f)H_{\text{cal}}(f) \), where \( H_{\text{cal}}(f) \) is the desired channel frequency response. A normalization curve is recorded by placing the transmitter and receiver in a back-to-back configuration. In this configuration, receiver and source are placed such that they face one another within a distance of a few centimeters. To avoid saturating the APD due to a high amount of received optical power, optical attenuators (like sheets of white paper) are placed between the transmitter and receiver. Recording the back-to-back frequency response yields \( H_{\text{back2back}}(f) = T(f)R(f)K_{\text{back2back}} \).

Here, \( K_{\text{back2back}} \) is an unknown attenuation caused by the paper sheets. This attenuation is frequency independent and therefore can be assumed to be a constant. To find the \( K_{\text{back2back}} \), current passing through a resistor, in series with the APD, is measured. First the bias voltage across the APD is reduced to a nominal value of 8 V, in turn reducing the APD gain to unity. Therefore, the APD functions as a photodiode. Then the current passing through the APD is measured by observing the voltage across a 10-k\( \Omega \) resistor, in series with the APD. The actual received optical power can be determined by using the following formula:

\[
P_{\text{optical}} = \frac{I_{\text{photodiode}}}{\gamma \cdot A_R}.
\]

In this equation, \( \gamma \) is the responsivity or efficiency of the photodiode.
TABLE I
IMPORTANT PARAMETERS OF INFRARED CHANNEL MEASUREMENT SETUP

<table>
<thead>
<tr>
<th>Measurement Setup Important Parameters</th>
<th></th>
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<td>Operating wavelength</td>
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<td>Frequency range of the measurement system</td>
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<tr>
<td>Average optical output power of laser diode</td>
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<tr>
<td>Area of the receiver APD</td>
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<tr>
<td>Receiver field-of-view</td>
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</tr>
<tr>
<td>APD Gain at operating voltage</td>
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</table>

Fig. 3. For each measurement location, elevation angle of the receiver (θ) is varied from 0° to 180° in steps of 5° and the channel transfer function is recorded in each step. Then the receiver orientation angle (φ) is changed by 45° and the elevation angle is set to 0° and the same set of measurements is repeated. This process is performed four times in each location. Therefore, the orientation angle takes the values of 0°, 45°, 90°, and 135° and the elevation angle takes the values of 0°, 5°, or 180°. Hence, the entire hemisphere above the receiver is covered with 148 recorded transfer functions.

and $A_R$ is its area. Based on the manufacturer’s specifications, the APD in the receiver of measurement setup has a responsivity of $\gamma = 0.5$ and an area of 0.25 cm². Knowing the current passing through the APD, $P_{\text{optical}}$ can be found. The amount of transmitted optical power from the laser diode is then measured by using an optical power detector and without changing the transmitter electrical configuration. Dividing these two values results in the desired $K_{\text{back2back}}$, where $K_{\text{back2back}}$ is equal to the transmitted optical power divided by the received optical power. This value is then normalized to the unit receiver area (1 cm²) in order to remove its dependency on the receiver area in this particular measurement. Knowing $K_{\text{back2back}}$, all the recorded frequency responses can be normalized to find the desired channel transfer function $H_{\text{channel}}(f)$

$$H_{\text{channel}}(f) = H_{\text{rec}}(f)K_{\text{back2back}}/H_{\text{back2back}}(f).$$

Following are the measured values of transmitted optical power levels:

1) received optical power for back-to-back system: 680 nW (back-to-back system uses a lens on top of the laser); 2) transmitted power from source: 180 mW; 3) transmitted power from the diffuse source: 60 mW; 4) transmitted power from the lens (LOS): 95 mW.

B. Channel Parameters

The primary objective of the designer of an infrared link is to achieve a high SNR at the receiver. This is a challenging objective because the link SNR depends on the square of received average optical power [1]. Transmitted optical power is limited by considerations of eye safety and transmitter power consumption. Therefore, the infrared link is mainly a power-limited link, and the average received optical power or channel path loss is the most important parameter. Path loss is defined as the inverse value of dc gain of channel frequency response. That is, path loss can be represented by $1/H(0)$ on a linear scale or $-10^* \log_{10}(H(0))$ on a logarithmic scale in units of dB. As stated before, the received electrical signal is proportional to the area of the receiving photodiode. Therefore, for a given
configuration, increasing the receiver photodiode area increases the received signal power and decreases the channel path loss. To remove this dependency and make the path loss a parameter that describes the channel rather than a combination of channel and receiver, path loss might be normalized for a given receiver area. As an example, a receiver area of $1 \text{ cm}^2$ can be used as the basis for this normalization. This would make the parameter a universal parameter for comparing different channel conditions and different optical receivers. Throughout this paper, values of path loss are all normalized for a receiver area of $1 \text{ cm}^2$.

Another important parameter of an infrared channel is related to multipath propagation of light waves. Reflections of light by objects causes a distortion called *multipath-induced temporal dispersion* or simply *multipath dispersion* in an infrared channel. Optical impulse undergoes several reflections and attenuated replicas arrive at different times, causing an attenuated, spread pulse in time. This distortion causes intersymbol interference (ISI) in the received signal. This added component reduces the noise margin, i.e., it increases the possibility of wrong decisions by closing the eye of the received signal. A useful parameter that quantifies the spread of $h(t)$ is the root mean square (rms) delay spread, defined by [1]

$$
\sigma = \sqrt{\frac{\int_{-\infty}^{\infty} (t - \mu)^2 h^2(t) \, dt}{\int_{-\infty}^{\infty} h^2(t) \, dt}}
$$

where $\mu$ is defined by

$$
\mu = \frac{\int_{-\infty}^{\infty} th^2(t) \, dt}{\int_{-\infty}^{\infty} h^2(t) \, dt}.
$$

This definition accounts for a distribution of $h(t)$ in time and therefore is a suitable definition of spread of impulse response.

For infrared systems, the relation between multipath power penalty and channel rms delay spread depends on the modulation and equalization scheme. It has been shown that there is a strong relationship between $\sigma$ and the power penalty due to ISI for most commonly used infrared digital modulation schemes [10]. In this paper, the value of channel rms delay spread or simply channel delay spread is used as a mean to compare the channel impulse response width and its effect on the transmission system for different configurations.

### III. Receiver Rotation

In this section, we present procedure, results, and conclusions for receiver rotation measurements. The objective of these measurements was to investigate effects of receiver rotation on the properties of an infrared channel. It is clear that an infrared receiver with a small FOV, operating in an LOS configuration, is subject to severe channel changes as it rotates. Receiver FOV is defined as the angle between a normal to receiver surface and the last ray of light that could be detected by the receiver when it comes from the receiver side. When a diffuse configuration is used, the system is less sensitive to rotations. As the receiver FOV increases, changes in channel properties become less noticeable [11]. However, even a wide FOV receiver is subject to major channel characteristics changes because of receiver rotation. This is clearly shown in the results of the sections to come.
A. Measurement Objectives and Procedure

To investigate the effects of receiver rotation on the channel characteristics, nine measurement sites were chosen in CBY. The rooms have different sizes and shapes and contain different objects. For each room, one or two positions for the transmitter and receiver were chosen. For each position, measurements were performed in both LOS and diffuse configurations.

To measure the channel frequency response in a LOS configuration, the spot diffusing technique [9] is used. In our setup, a collimating lens that is used to focus the light onto a diffusing spot on the ceiling introduced a 2.7-dB optical loss. For measurements in a diffuse configuration, a glass diffuser was attached to the laser diode, generating a Lambertian radiation pattern. The diffuser introduces a 4.7-dB optical loss. The infrared source is mounted on an adjustable stand and looks straight up toward the ceiling. Presented results contain necessary normalizations to compensate for losses introduced by the lens and diffuser.

The receiver is mounted on a step motor, fixed to a stand. The step motor is a dc motor controlled by a personal computer. It enables the receiver to rotate by 180° in programmed steps to detect signals from different directions. Custom computer software controls the step motor and collects data from the network analyzer. The computer, the network analyzer, and the power supplies are all placed on a cart. In the measurements, first the locations of the transmitter and receiver are chosen. Then, by instructions, a computer program automatically rotates the receiver in 5° steps, collects frequency response data from the network analyzer, and stores data on a computer hard disk.

For each desired location/configuration, four sets of data are collected. Each set corresponds to a full 180° rotation of receiver. Since rotation is done in steps of 5°, there are 37 recorded frequency responses in each turn. This rotation is done to change the elevation angle of the receiver, as illustrated in Fig. 3. The receiver looks toward one wall at an angle zero, and as the elevation angle increases, the receiver rotates, aiming at the ceiling. When the elevation angle reaches 90°, receiver looks directly toward the ceiling. As the elevation angle increases again, the receiver turns toward an opposite wall, and at 180°, the receiver directly faces the opposite wall. Since rotation is in 5° steps, a total of 37 responses are collected for each 180° rotation. Receiver orientation is changed three times, by 45° each time, to record another set in the same position. This simply changes the receiver orientation, modifying its starting point from facing one wall to facing a room corner and then other walls. Fig. 3 shows the orientation and elevation angle of the receiver. Fig. 4 shows one of the measurement sites called room A (Room E015, CBY building). For each of the two locations in the room, four orientation angles are clearly marked by numbered arrows.

For each configuration at each point, four sets of 37 frequency responses are recorded. The same procedure is followed for both LOS and diffuse configurations. Therefore, for each location in each room, there are \(148 \times 2 = 296\) recorded frequency responses. For our measurements concerning the effects of rotation, 17 positions in the rooms were chosen, resulting in a database of \(296 \times 17 = 5022\) channel frequency responses. This is a very large database of indoor infrared channel measurements and gives us a good base for statistical analysis of recorded data and its parameters. This paper contains the shapes and dimensions of all measurement sites. It also shows the locations and directions of rotations for receivers at measurement sites.

B. Measurement Results and Observations

Fig. 4 shows the location of the source and receiver in room A. This is a typical classroom of size 5.3 × 7.0 m with five rows of chairs (a total of 33 chairs for students). The walls are rough concrete with yellowish color. The ceiling is flat and the same color. Green board extends the entire width of the room. There are 16 flourescent lamps with transparent plastic cover on the ceiling, each 1.2 by 0.3 m. In diffuse measurements where the ceiling is illuminated by infrared radiation, it seems little energy is reflected from these covers and most of the received energy passes through the covers and is absorbed. Most other office and class environments used for measurements have the same type of ceiling. The source is at the room’s center at a height of 1.3
Fig. 6. Channel path loss and its delay spread change when the receiver rotates. Graphs show these changes for both LOS and diffuse configurations for location A1, direction (2).

The receiver is placed at coordinates $A_1 = \{3.8 \text{ m}, 4.6 \text{ m}\}$ and $A_2 = \{1.5 \text{ m}, 1 \text{ m}\}$ and has a height of 1 m.

Fig. 5 shows the effect of receiver rotation on the amplitude of channel frequency response in room A. It can be seen that the shape of the transfer function changes as the receiver rotates. The rotation may cause some nulls in the frequency response and changes its dc value representing channel path loss. This figure also shows the effects of receiver rotation on channel impulse response. Although details of the transfer function shape and changes in the path loss are different in each room, the same trend is observed in all measurement results. Channel path loss and delay spread of the channel change with receiver orientation such that the high values of received optical power correspond to low values of delay spread. The relation between channel path loss (PL) and channel delay spread is studied in more detail in subsequent sections. Fig. 6 shows an example of these changes for both LOS and diffuse configurations at the same location in room A. As the receiver elevation angle $\theta$ increases from zero toward 90°, PL and delay spread decrease. When $\theta$ is between 50° and 130°, channel delay spread is usually very low and PL has its lowest value somewhere in between. Increasing $\theta$ after 130° would increase the path loss and delay spread again. By observing similar curves for other locations, it is clear that the rotation has an almost deterministic effect on the variation of path loss and delay spread.

The lowest value of PL and the angle of lowest PL seem to be quite related to the physical location of the source and receiver. It will be shown that these two important parameters can be predicted by using the physical location information and the receiver relative rotation angle. Fig. 7 shows the relation between the channel path loss and its delay spread in room A, location $A_1$ for diffuse and LOS configurations. It can be seen that the two parameters are linearly dependent on one another when they are plotted on a log scale. Note that the channel path loss is usually reported in log scale by dBo, but the delay spread is usually reported by its value and not its log value. In other words, only when the two variables are expressed in a log scale is the value of the correlation coefficient for the linear regression between them very close to unity. It should be noted that this relationship is a statistical measure of dependence of these two variables. This means that for most cases, a high value of delay spread corresponds to a high value of path loss.

Fig. 7 also shows the result of a linear regression between the two parameters as a solid line on the plot. This relationship can be represented by $PL = \alpha \log_{10}(\sigma) + \beta$, where PL is the path loss and $\sigma$ is the delay spread. This relationship was also observed in all other measurements. Values of $\alpha$ and $\beta$ are not the same in all cases and depend on the location and configuration. However, for most of our results, the values are very close, as can be seen in Table II. This table shows the correlation coefficient between PL and $\sigma$ values for different measurement sites. The parameters of linear fit $\alpha$ and $\beta$ are shown. It is seen that the correlation coefficient ranges between 0.89 to 0.97 for both configurations in all these rooms with a mean value around 0.93. Therefore, we conclude that for a rotating receiver, channel path loss and its delay spread are highly correlated.

From the numerical results obtained, it is seen that the average values for $\alpha$ and $\beta$ are noticeably different for LOS and diffuse configurations. The variances of these variables are also smaller for the LOS case. Using the numerical results reported in this table, it can be concluded that when the receiver rotates, channel delay spread can be approximately estimated from its path loss by using $\sigma \approx 10^{(PL-\beta_{avg})/\alpha_{avg}}$.

The value of $\beta_{avg}$ is approximately 9 (dBo/ns) for diffuse configuration and 8 (dBo/ns) for LOS configuration. The value of $\beta_{avg}$ is approximately 57 dBo for diffuse and 61 dBo for LOS.
configuration. The mean squared error (MSE) for the linear fit in all locations has also been included in this table. The small value of MSE, which is less than 1.5 dBo in most cases, shows that the suggested linear relationship is a very good approximation.

C. Path-Loss Variations Properties

Channel path loss is the most important parameter for an infrared channel. Noting the variation of \(\text{PL}(\theta)\) for all our measurements, it was observed that the variation of this curve has some general properties. For example, the location of the minimum of \(\text{PL}(\theta)\) can be predicted by knowing the physical location of the source and the receiver in a room. In addition, it was found that the variations of this curve are well approximated by a curve-fitting model. This section describes the general characteristics of the received optical power or the channel path loss variation for a rotating receiver.

1) Peak Angle Estimation Algorithm: Fig. 8 shows the physical configuration of an infrared transmitter and an infrared receiver. The line RM is the surface normal line for the receiver and AT is the receiver surface normal line for the transmitter. The receiver \(R\) is rotating such that the angle \(\theta\) changes from 0° to 180° in steps of 5°. Point \(M\) on the ceiling is directly in front of the receiver. In other words, \(M\) is the intersection of the receiver \(R\) surface normal line and the ceiling. Point \(B\) is the origin of a normal line to the ceiling that passes through the receiver. When the receiver rotates, the location of \(M\) changes on the ceiling. The light is emitted from the transmitter and is diffusely reflected by the ceiling, walls, and floor to reach the receiver. Each reflection transmits optical power along with a Lambertian pattern. Reflections are lossy and therefore, among the received optical rays, the set of rays bounced only once carry most of the received optical power.

The channel transfer function is a function of frequency and receiver elevation angle \(\theta\) and can be denoted by \(H(f, \theta)\). The received optical power is the dc component of the transfer function or \(\text{H}(0, \theta)\). Observing the results of measurements, it seems that \(\text{H}(0, \theta)\) has one peak that corresponds to angles in which the receiver is looking toward the ceiling. It decreases almost monotonically as \(\theta\) changes from the peak angle. This characteristic of the transfer function guides us to find a simple mathematical model to find the angle of received peak power using room
TABLE II


<table>
<thead>
<tr>
<th>Room</th>
<th>α_R</th>
<th>β_R</th>
<th>MSE_R</th>
<th>Xcorr</th>
<th>α_cat</th>
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<tr>
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<td>1.5262</td>
<td>2.6098</td>
<td>0.5648</td>
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</tbody>
</table>

Notice that $P_M \propto P_T \cos^m(\alpha) \Omega_M$ and that $d\Omega_M = \cos(\alpha)(A_M/(TM)^2) = \cos(\alpha)((RM)^2d\Omega_{FOV}/(TM)^3 \cos(\beta))$, where $A_M$ is a small area in the vicinity of $M$ seen by the receiver, $P_T$ is the transmitted power from source, $m$ is a Lambertian order of source, and $d\Omega_{FOV}$ is a small receiver FOV. Noting that $TA$ and $RB$ are fixed for a given set of measurements and do not change with $\theta$, it follows that $TM = ((TA)/\cos(\alpha))$. These results can be combined as follows:

$$P_R \propto P_T \cos^m(\alpha) \cos^3(\theta) d\Omega_{R}\Omega_M = P_T A_r d\Omega_{R\Omega_{FOV}} (TA)^2 \cos^{m+3}(\alpha) \cos^{-1}(\beta).$$

The values of $P_T, A_r, d\Omega_{R\Omega_{FOV}}, RB,$ and $TA$ are known and fixed for a given measurement configuration. Therefore, noting that $\beta = 90^\circ - \theta$, it follows that

$$P_R \propto \cos^{m+3}(\alpha) \sin^{-1}(\theta).$$

For most office environments, $n = 1$, and therefore the received power would be proportional to $\cos^{m+3}(\alpha)$.

The assumption of a narrow field-of-view receiver does not hold for receivers designed for diffuse configurations, including the receiver that was used for our measurements. However, the strongest set of rays that are reflected just once and reach the receiver are passing the path of $T \rightarrow M \rightarrow R$. This is evident by noting that other small areas on the ceiling that receive the optical power and have a Lambertian reflection will have an angle with respect to the RM line (the receiver surface normal), and therefore their power would be multiplied by cosine of that angle before it is added to the received power. As the distance between this area and $M$ increases, the reduction will be increased and those areas will contribute less to the first-bounce received power.

Therefore, this simplification is expected to be valid for estimating the peak angle for the $H$ curve. As the results show, the expectation is justified. It should be noted that this approximation is valid to only find the peak of the received power and not all variations of $H(\alpha, \theta)$. As $M$ moves away from the point of maximum, the effects of reflections from other parts of ceiling and walls become more and more important, and a narrow-FOV receiver does not provide a good model to predict the variations in the received optical power for those cases. The peak of the $H(\alpha, \theta)$ curve would be at a point where $\cos(\alpha)$ is maximized. This point will be along the line of intersection between the ceiling plane and the surface specified by the triangle $RBM$.

It is therefore easy to find $M$ for any given configuration by just following this procedure:

1) Pass a plane from the receiver that contains the direction of receiver rotation and is normal to ceiling.
Fig. 9. Variation of the normalized curve $H(0, \theta)$. Solid lines are measurement results. Dotted lines are results obtained from the simulation program. Dash-dot lines are the curves generated by using the peak angle estimation algorithm. Notice the close peak positions for the estimation curves and the measurement curves.

Fig. 10. Estimation error when compared to (a) simulation and (b) measurement results. Top graphs show the error value distribution and bottom graphs show the cumulative distribution of errors. The difference between the estimation algorithm and the measurement is less than 20° in more than 90% of all results (left bottom graph). The error is smaller than 20° 95% of the time when compared to the simulation results (right bottom graph).
Fig. 11. Accuracy of curve fitting in predicting variations of $H(0, \theta)$ curve. Solid line shows the actual measurement results. Star dots represent the estimated curve, obtained by polynomial curve fitting of order 4 to sample points obtained from measurement results. Sample points are chosen uniformly from $\theta = 0^\circ$ to $\theta = 180^\circ$ in steps of $45^\circ$ and are specified by a circle around the star on the graphs.

Fig. 12. Variations of infrared channel PL when receiver changes its elevation angle. For any deviation $\Delta \theta$ from the minimum path loss angle, there is an increase in $\Delta$PL in channel path loss. The value of this increase depends on the room and transceiver configuration.

2) Call the intersection of this plane with the ceiling plane line $BB'$.
3) Pass a line from $A$, orthogonal to $BB'$, and find the intersection. Call that point $M$.
4) Connect $M$ to $R$ and measure the $\theta$ corresponding to $RM$.

The rationale behind this scheme is that $\cos(\alpha)$ is maximized when $AM$ has its smallest value, and therefore the smallest possible $\Delta M$ for a rotating receiver can be found using this algorithm. For implementation of the algorithm, the desired point on the ceiling can be found by tracing the loci of $M$ and finding the point at which (4) is maximized.

2) Peak Angle Estimation Results: The measurement results are recorded for 17 different locations in nine rooms, and at each location, four sets of rotation results are collected. Using the simulation program, transfer functions corresponding to all measurement sets have also been calculated.

The above algorithm has been applied to generate a power estimate curve for each set of collected data. A unity value for $n_{\text{rms}}$ and $n_{\text{ave}}$ is assumed. To generate the results, the $H(0, \theta)$ curves from simulation, measurement, and estimation results were all normalized to a maximum of one to show the location of the peak.

Fig. 9 shows the peak for simulation and estimation results. As can be seen, the estimation method provides very good results for the peak of these curves. In addition, the graphs in Fig. 9 show a very good agreement between the simulation results and measurement results. Not only do the peaks match in almost all cases, but also the shapes of these curves are very similar. It should be noted that for the simulation results, only
two bounces were considered. Increasing the number of bounces used in the simulation would result in excessive computation time and would change the results drastically.

Fig. 10 shows the error distribution for the estimation method with respect to measurement results as well as the simulation results. It can be seen that in almost 90% of cases, the estimation has an error less than 20° when compared to measurement results. Compared to simulation results, the error is less than 20° for 62 sets of results out of 64 simulated cases. This shows a good agreement between the peak angle estimation algorithm and the simulation results for more than 95% of all results.

3) Estimation of Received Optical Power Using Curve Fitting: The variation of received optical power with respect to elevation angle seems to follow a predictable pattern. Traditional curve-fitting algorithms have been used to estimate variations of these curves and have achieved very good results. The idea is to estimate path loss of an infrared channel at all angles in a rotation set (θ ranging from 0° to 180°) by knowing a few samples of the dc value of the transfer function measured at some given values of θ. These samples can be obtained from actual channel measurements or using the simulation program. The measurement database contains more than 130 sets of curves. For each curve in the database, N samples are chosen. A fitting algorithm is then used to fit a G(θ) curve to these samples. The samples are chosen uniformly from θ = 0° to θ = 180°, and the distance between them is 180/(N − 1)°. Several different curve-fitting algorithms of [12], including polynomial curve fitting, spline curve fitting, piecewise linear approximation fitting, and nearest neighborhood curve fitting were tried. The error in curve fitting is defined as the difference between G(θ) and H(0, θ) on a dBo scale. Results show that as N increases, error decreases. In addition, simple curve-fitting algorithms such as polynomial type seem accurate enough for the precision requirements of most communication applications. The best results are obtained when spline curve-fitting algorithms are employed. The figure of merit for comparing different fitting algorithms is the average of the difference between the fitted curve and the measured H(0, θ) for all the measurement results.

Fig. 11 shows an example of curve-fitting results. The curve is obtained by using a polynomial curve-fitting algorithm and using N = 5. It is found that using this value is simple and provides a very good approximation for all our measurements. The worst case average error when curve fitting of an order 4 with N = 5 was applied to the entire collected database of H(0, θ) was about 0.6 dBo. Similar results can be obtained by using a spline curve-fitting algorithm. For N = 4, the results of the spline algorithm provide better accuracy compared to those of polynomial curve fitting. For N = 3 or less, curve fitting does not provide acceptable results for all cases of interest.

Therefore, it can be concluded that variations of channel path loss for a receiver that changes its elevation angle from 0° to 180° can be accurately estimated by measuring (simulating) only five points along the entire rotation path. Applying a fourth-order curve-fitting algorithm to the measured (simulated) results, the variation of path loss versus elevation angle is found with errors of less than 0.5 dBo. This curve can be used to es-
D. Statistical Model of Path-Loss Variation

Consider a rotating receiver when its elevation angle ($\theta$) changes from 0° to 180°. As discussed before, there is an angle $\theta_{\text{min}}$ where the channel PL reaches its minimum during such rotation. As the receiver elevation angle departs from this value, the channel path loss increases. Fig. 12 illustrates a relation between the amount of deviation from $\theta_{\text{min}}$, called $\Delta \theta$, and the increase in path loss $\Delta \text{PL}$. For the case illustrated in this figure, an increase of 30° in elevation angle increases the path loss by about 1 dBo. Obviously, the amount of change in PL is not the same in different scenarios because of the differences in room size, transceiver location, and orientation. However, by collecting the results obtained from all different measurements in all different rooms and considering them together, we can find a general method of estimating the change in the path loss when the receiver moves away from $\theta_{\text{min}}$.

To do this, we find all different values recorded for $\Delta \text{PL}$ for a given value of $\Delta \theta$. Considering all the values of $\Delta \text{PL}$ obtained as samples of a random variable, we might be able to estimate its distribution. Investigating the properties of this distribution has shown that it can be approximated by a Gamma probability distribution function (pdf) in both diffuse and LOS configurations. A random variable with a Gamma distribution has a pdf given by $f(x) = \frac{1}{\beta \Gamma(a)} x^{a-1}e^{-x/\beta}$, where $a$ and $\beta$ are parameters that specify the shape of the distribution.

It is observed that for any given value of $\Delta \theta$, the set of associated values of path-loss changes $\Delta \text{PL}$ can be described with
Fig. 16. Three important parameters that determine the shadowing effect for an infrared channel. These parameters have been changed and their effects on the channel characteristics have been studied.

a given value set \( \{a, b\} \). For example, when \( \Delta \theta = 20^\circ \), the set of all recorded path-loss values can be approximated by a Gamma distribution with parameters \( \{6.72, 0.05\} \) given by

\[
f(\Delta PL) = \frac{1}{5.725^7}\Gamma(6.7)E(\Delta PL)^{5.7-1}e^{-\frac{\Delta PL}{5.7}}.
\]

Fig. 13 illustrates the distribution of \( \Delta PL \) for deviation angles of 5°, 10°, 20°, and 30° in a diffuse configuration. The parameters of corresponding Gamma distributions are shown in the titles of the plots. Fig. 14 illustrates the same set of data when an LOS configuration is used. As expected, results show that for the same deviation angle, diffuse configuration has a smaller average \( \Delta PL \) compared to LOS configuration. For example, for a deviation angle of \( \Delta \theta = 20^\circ \), the average value of \( \Delta PL \) is 0.35 dBo for a diffuse configuration and 0.58 dBo for an LOS configuration. From these results, it is observed that the variation of average \( \Delta PL \) with respect to \( \Delta \theta \) can be modeled with a second-order polynomial. The polynomial that has the best match to the collected results is given by

\[
E\{\Delta PL\} = 0.0005 \times (\Delta \theta)^2 - 0.0117 \times (\Delta \theta) + 0.1603
\]

for an LOS configuration.

These curves have been plotted along with measured values of average \( \Delta PL \) in Fig. 15. We have also included values of Gamma pdf parameters for LOS and diffuse configurations in Table III. It is clear from these results that an LOS configuration is more sensitive to the direction of the receiver because the value of average \( \Delta PL \) is consistently higher than that for a diffuse configuration. The results presented so far can be used to estimate the variations of channel path loss for a rotating receiver under general conditions. To use these results, one would estimate the value of channel path loss in the direction of minimum path loss. This direction can be found using the algorithm presented in Section III-C1. Knowing the direction of minimum path loss, the simulation algorithm can be used to find the channel path loss in that direction. The variation of channel path loss for small variations of the receiver direction can then be obtained by noting that the average \( \Delta PL \) has a second-order

<table>
<thead>
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<th>( \Delta \theta ) (degree)</th>
<th>LOS Mean ( \Delta PL )</th>
<th>Diffuse Mean ( \Delta PL )</th>
</tr>
</thead>
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<tr>
<td></td>
<td>( a )</td>
<td>( b )</td>
</tr>
<tr>
<td>5</td>
<td>0.22</td>
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<tr>
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<tr>
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<td>2.03</td>
</tr>
<tr>
<td>30</td>
<td>0.99</td>
<td>2.52</td>
</tr>
</tbody>
</table>
Fig. 17. Measurement room for shadowing experiments. Receiver was placed at positions indicated by small circles (four positions in each room). For each receiver position, the shadower stood at positions indicated by bars (four shadowing positions and one measurement without shadowing). For each of these receiver–shadower positions, four different responses were recorded, corresponding to four different receiver height values of 60, 80, 100, and 120 cm.

relation with $\Delta \theta$ and has statistical distributions, presented in Table III. Using this table, the average expected change of path loss; its variance, and samples of possible values of $\Delta PL$ can be generated for use in performance simulation programs.

IV. EFFECTS OF SHADOWING ON INFRARED CHANNELS

These measurements were performed to assess changes in the infrared channel characteristics due to shadowing. Infrared light, being very close to visible light in its propagation properties, is subject to shadowing. An infrared source or receiver can be totally blocked by a nontransparent object. Therefore, a worst case for shadowing means no transmission at all. It is desirable to observe the effects of moving objects around an unobstructed infrared communication system and to see how this would affect channel properties.

In practice, the channel can be subject to short time shadowing of source or receiver. A properly designed infrared communications system should be able to tolerate shadowing by transmitting at lower bit rates or by stopping transmission temporarily. It should be able to hold its state in case of a severe shadowing and continue to operate after the communication path becomes clear.

Another factor to consider in the design of indoor infrared communications systems is that the time duration of shadowing is orders of magnitude larger than the bit or symbol duration. Therefore, it is considered a very long-term effect, and its effects are not expected to vary the channel on a symbol-by-symbol basis (assuming bit rates of more than 1 Mbps).

Many factors affect the shadowing. Some of the important factors are the receiver height, the distance between the source and receiver, and the distance of shadowing objects from the receiver.

A human body causes the most common type of path obstruction in a regular office environment. Therefore, this study is focused on effects of shadowing by a person who is called a “shadower” on an infrared receiver, as shown in Fig. 16. Shadowing is more severe when the shadower moves on a line connecting the source and receiver. This is well described by noting the similarity between shadowing of the visible light and infrared light.

A. Measurement Setup

In our measurements, each of the above parameters is changed and the channel transfer function is measured. The shadower is a person with a height of 170 cm and weight of 86 kg who moves on a line between the source and receiver and stands at distances of 25, 50, 75, and 100 cm from the receiver. For each of these points, the height of the receiver was changed from 60 to 120 cm in steps of 20 cm each. Hence, measurement results are recorded for four different heights: 60, 80, 100, and 120 cm. In addition, a reference set with no shadowing was recorded for each of these conditions. This is utilized to assess the shadowing effects in a relative sense. The above set of measurements was repeated for source–receiver distances of 150, 250, 350, and 450 cm to result in $5 \times 4 \times 4 = 80$ sets of transfer functions. This set of measurements is performed for both LOS and diffuse configurations. The measurements were performed in two different rooms in CBY, resulting in $160 \times 2 = 320$ transfer functions. In the first set, named the “room G” set, measurements were performed in a conference room of size 6.0 × 7.8 × 2.3 m. This is a relatively small lounge adjacent to a large conference room. Removable gray full-height partitions on the right-hand side of the room form a wall that separates this lounge from the adjacent conference room. There are 12 chairs around a coffee table in the lounge. The floor is covered with blue carpet, and windows shown on the top and right walls of Fig. 17 cover half the wall’s height. During these measurements, the windows were covered with
shades of color gray. The room’s ceiling has a white flat surface with places for lamps and air conditioning inlets.

The second set of data, labeled “room H” measurements, was collected in an auditorium in the same building. The auditorium has an almost rectangular shape, however, its ceiling height increases from the entrance to an stage. The ceiling surface is edgy and it contains ventilation windows, speakers, local illumination lamps and similar objects typical to an auditorium. Walls are made of brown brick and ceiling is a dark brown rough surface. Fig. 17 shows the locations of the source, receiver, and shadower in these measurements. Note that in room H, the first position of the receiver starts at a 2-m distance from the receiver (instead of 1.5 m in room G). The rest of the setup is the same for both rooms. As before, each transfer function is recorded as 128 complex points in frequency ranging from dc to 400 MHz. The results were normalized to compensate for transmit/receive filtering. Time-domain characteristics of the channel, e.g., channel delay spread, were extracted by converting the transfer function to its corresponding impulse response.

B. Measurement Results and Observations

As before, channel path loss and channel delay spread are two channel properties, extracted from these results. As the shadower gets closer to the receiver, channel path loss increases and impulse response of the channel gets wider, resulting in an increase in channel delay spread. Fig. 18 illustrates variations of the channel transfer function and its impulse response when the shadowing object gets closer to the receiver.

Figs. 19–22 show path-loss results due to changes in the shadowing parameters. Path-loss values are normalized by subtracting the value of $P_{\text{loss}}$ from the results. $P_{\text{loss}}$ is the path loss for a case in which the receiver is closest to the source and there is no shadowing. For example, in room G, $P_{\text{loss}}$ is the path loss for a case when the receiver-to-source distance is 1.5 m, the receiver is at a 60 cm height, and there is no shadowing. This is the lowest recorded path loss for a given room/transmission configuration. The results, after normalization, clearly show the shadowing effects on channel path loss with the source-to-receiver distance and receiver height as parameters. In these figures, each plot corresponds to a certain receiver-to-transmitter distance, as specified in the plot label. For example, the top left plot corresponds to a case where the distance is 1.5 m. In each plot, there are four sets of lines specified by different markers. These lines correspond to different heights of the receiver for that particular measurement. The legend of the graph that specifies that the receiver height is 60 cm, 80 cm, 100 cm, and 120 cm.

C. Observations on Path-Loss Results

We can observe that path loss increases as shadower moves toward the receiver. Shadowing has a stronger impact on path loss when the receiver and transmitter are close. As the distance between the source and receiver increases, the effect of shadowing on path-loss increase becomes less important. For example, considering room G for the diffuse set results, it is seen that the path loss increase due to shadowing is between 3.8–7 dBo, when the source and receiver are at a distance of 1.5 m (lines marked by $\times$). In the same room and under the same conditions, when the distance between the source and receiver is 4.5 m, shadowing effect increases the path loss between 2.5–3 dBo. The same observation is valid for the room H results. Shadowing has a stronger impact on the path loss when the receiver is closer to ground. As the receiver height is changed from 60 to 120 cm, the shadowing effect becomes less important. The graphs show that when the receiver height is 120 cm, path-loss change due to shadowing is smaller than the case where the receiver height is 60 cm. This is seen in the graphs by comparing the lines marked by $\times$ (receiver height $= 120$ cm) with the lines marked by $\times$ (receiver height $= 60$ cm). As an example, in room H, diffuse set results, the maximum change of path loss due to shadowing for a receiver at a height of 120 cm is around 6 dBo. In the same room, variations of up to 9 dBo due to shadowing are observed for a receiver at a height 60 cm.
For an LOS configuration, shadowing is an abrupt process. The path loss changes drastically as a shadow drops on a receiver. However, for a diffuse system, the path loss due to shadowing increases monotonically as a shadower gets closer to the receiver. Abrupt changes in the path loss are not observed in diffuse results. For example, considering the results obtained in room G, it is seen that the path loss changes about 8 dB when the shadower comes 25 cm closer to the receiver in the LOS configuration.
Fig. 21. Normalized path loss in room H using a diffuse configuration. Each plot corresponds to a different distance between the receiver and transmitter, as specified in plot titles. Inside each plot are four sets of lines that correspond to receiver height for each measurement ((*60 cm, (o) 80 cm, (x) 100 cm, (+) 120 cm)).

Fig. 22. Normalized path loss in room H using an LOS configuration. Each plot corresponds to a different distance between the receiver and transmitter as specified in plot titles. Inside each plot are four sets of lines that correspond to the receiver height for each measurement ((*60 cm, (o) 80 cm, (x) 100 cm, (+) 120 cm)).
case (line marked by *). Under the same conditions, a drop in the path loss is less than 1 dBo for diffuse configuration. In fact, there is not a single case in the diffuse shadowing measurements where the drop of power due to shadowing is higher than 3 dBo, when the shadower changes its position by 25 cm. This reduced susceptibility to shadowing is the most important advantage of a diffuse configuration over an LOS configuration.

Transmission is less susceptible to shadowing when the receiver is high above the ground and far away from the source. When the receiver height is 120 cm, maximum change in the path loss due to shadowing is 1 dBo for diffuse and 0.6 dBo for LOS. This is when a shadower is at a distance of 25 cm to the receiver and the result is compared against the same configuration with no shadowing. The worst susceptibility to shadowing happens when a receiver is close to the ground and near the source. When the source-to-receiver distance is 1.5 m and the receiver height is 60 cm, the maximum change in the path loss due to shadowing is 7 dBo for diffuse and 16 dBo for the LOS case. This is when the shadower is at a distance of 25 cm from the receiver with results compared against the same configuration in the absence of shadowing.

D. Relation Between Channel Path Loss and Channel Delay Spread

The delay spread of measured channels has also been calculated. The results show that channel delay spread values are strongly correlated with path-loss values. The graphs in Fig. 23 show the path loss versus delay spread graphs. When the delay spread is represented on a log scale, it shows a linear correlation with path loss. This is very similar to the results obtained previously showing a strong correlation between these two parameters when the receiver rotates.

Parameters for the numerical fit are shown on each graph and are summarized in Table IV. These parameters show the numerical value for a regression line that relates power and delay spread by: $PL = \alpha \log_{10}(\sigma) + \beta$, where PL is the path loss and $\sigma$ is the delay spread. The following observations are made from these graphs.

Fig. 23. Graphs show a correlation between channel path loss and its delay spread for various shadowing conditions. A linear fit with its parameters is also included on each graph. It can be seen from the correlation coefficients that the two variables are strongly correlated.

<table>
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<th>Room</th>
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<th>Line Of Sight Configuration</th>
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<tbody>
<tr>
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<td>$\beta$</td>
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<tr>
<td>Room G</td>
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</tr>
<tr>
<td>Room H</td>
<td>11.9</td>
<td>60.5</td>
</tr>
</tbody>
</table>
E. Observations on Delay Spread Results

For a diffuse configuration, variation of delay spread versus path loss is smooth. As power drops, delay spread increases and a strong correlation is seen between the delay spread and path loss. The top two graphs in Fig. 23 show the results for the diffuse configuration. It is clearly seen that the distribution of points is continuous across the regression line.

For LOS configurations, there are two regions on the graphs. One region with very small values for the delay spread corresponding to no shadowing and another region with results corresponding to shadowing, which includes large values for the delay spread. The linear relationship between the two variables on the log scale is clearly seen on the graph.

In LOS, values of delay spread have a higher dynamic range. When the path between the transmitter (spot on the ceiling) and receiver is not blocked, delay spread is very low, and when it is blocked, delay spread is very high.

V. CONCLUSION

Infrared links are sensitive to direction the transceivers face. A set of measurements have been designed and performed to investigate the effects of rotation on the characteristics of an indoor infrared channel. The results of these measurements have been reported. Using these measurement results, it was shown that variations of channel path loss are smooth and a simple curve-fitting algorithm can be used to accurately interpolate the intermediate values. It was shown that for a receiver changing its elevation angle from 0° to 180°, five points along the entire path are sufficient to predict variation of channel path loss for an entire rotation range. The results also demonstrate correlation between channel delay spread and channel path loss for both diffuse and LOS configurations. A simple formula can provide an estimate of channel delay spread for a known path loss of a given configuration. It was demonstrated that the variations of channel path loss for small changes of receiver rotation can be described by a Gamma distribution. This enables generation of samples of channel path loss under general conditions for system-level simulation algorithms. Measurements have also been performed to investigate the effects of shadowing on the indoor infrared channel characteristics. Shadowing reduces the received optical power and increases the channel delay spread. Some important parameters that specify the impact of shadowing on the channel characteristics were included in the measurement plans. Therefore, the performed measurements include different scenarios to investigate the effects of receiver height, receiver-to-shadower distance, receiver-to-source distance, and configuration type (LOS versus diffuse) on shadowing. The variation of channel path loss due to shadowing and due to these parameters was studied and detailed results were presented. It was shown that channel path loss can increase by up to 8 dB in the worst case shadowing scenarios in a diffuse configuration. This happens when the source and receiver are very close, the receiver is very close to the ground, and the shadower is 25 cm away from the receiver. For an LOS configuration, shadowing has a much more important effect and can increase the channel path loss by more than 16 dB, as presented by the results.

It was shown that shadowing increases the channel delay spread. For the measured shadowing results, channel path loss and delay spread are correlated and their relationship can be expressed by

$$\text{PL} = \alpha \log_{10}(\sigma) + \beta.$$  

REFERENCES


M. R. Pakravan, photograph and biography not available at the time of publication.
for Information and Communications Technology Research. During 1997–1998, he was also the CTO and a Vice President at TeleBeam Inc., State College, PA. He visited, as an academic Visitor (Consultant), Lucent (Bell Labs), in the summer of 1999. He is a Consultant to industry. His research contributions have been in the fields of satellite communications, fixed radio communications, portable and mobile radio communications, atmospheric laser communications, fiber-optic communications, and fiber-optic networks. His current research interests are in broadband wireless communications systems and networks and optical fiber communications systems and networks. He has received funding from the National Science Foundation (NSF), NSERC-Canada, Telecommunications Research Institute of Ontario, Canadian Institute for Telecomm. Research, Pennsylvania’s Ben Franklin Technology Center, ARL-PSU, Pittsburgh Digital Greenhouse, and many industries. He has supervised to completion several doctoral dissertations. He has published more than 250 refereed papers and several book chapters and has received several patents in these areas. His professional activities include being on the Advisory Committee of the Department of Electrical Engineering at Worcester Polytechnic Institute (WPI), Worcester, MA, and serving as a Reviewer and Panelist for the National Science Foundation. He has chaired review panels for NSERC-Canada and served as a Reviewer for multiple technical journals and conferences.

Prof. Kavehrad received three Exceptional Technical Contributions awards while working at Bell Laboratories for his works on wireless communications systems; the 1991 TRIO Feedback award for his patent on a “passive optical interconnect”; and five Best Paper Awards and a Canada NSERC Ph.D.-Thesis award, jointly with his graduate students, for their work on optical networking. He was elected by the Canadian Parliamentary Secretary to the Minister of Industry as a Leader in the development of Canada’s information highway to serve in Canada’s first Community Center for Information Access in March 1994. Presently, he is on the Editorial Board of the International Journal of Wireless Information Networks. He has chaired, organized, and been on the advisory committee for several international conferences and workshops. He is a former Technical Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS, IEEE COMMUNICATIONS MAGAZINE, and the IEEE MAGAZINE OF LIGHTWAVE TELECOMMUNICATIONS SYSTEMS.