ABSTRACT
This paper presents results from an experiment that used a variety of antennas inside two buildings. A profound result is that directional circularly-polarized (CP) antennas reduce rms delay spreads when compared with omni-directional and directional linearly-polarized (LP) antennas at identical locations. The variation of rms delay spread over distances of several wavelengths is also greatly reduced when CP antennas are used in place of LP antennas with similar gains.

I. INTRODUCTION
This paper presents results of wide band path loss and rms time delay spread measurements using omni-directional linear polarized antennas, directional linear polarized antennas, and directional CP antennas. Previous measurements by the authors used a variety of transmit and receive antenna heights and showed there is little difference in path loss or rms delay spread between the 1.3 GHz and 4.0 GHz bands inside buildings [1]. The measurement system and preliminary path loss and time dispersion statistics inside five dissimilar buildings were given in [1]. This new work shows how antenna polarization and antenna directivity impact path loss and time delay spread in indoor radio channels.

II. EFFECTS OF ANTENNA GAIN AND POLARIZATION ON DELAY SPREAD AND PATH LOSS
Since publication of [1], new measurements were conducted in a six story partitioned office building, denoted as Site D, and in a large single-story grocery store, denoted as Site E. Measurements in Site D were made along corridors and around corners of main hallways on the second and third floors. As in [1], the transmitter was moved to several measurement locations for each receiver base station location. In Site D, nine measurement locations were used for one second floor base station, and seven measurement locations were used for one third floor base station. Measurements in Site E used one base station located in a corner of the shopping area and sixteen measurement locations throughout the store.

At each measurement location, eight different power delay profiles were measured at 1.3 GHz using different combinations of transmitter (mobile) and receiver (base) antennas. The linear polarized omnidirectional discone antennas had gains of 1.5dBi; the directional CP helical antennas had gains of 9 dBi; and 3 dB beamwidths of 30 degrees. The eight antenna and polarization configurations are listed in Table 1.

a. Linear Polarized Antenna Results
Measurements using discone antennas showed that the sense of LP did not significantly change the value of time delay spread. The median value of \( \sigma_n \) for both polarizations (VV and HH in Table 1) was 30 ns, although median rms delay spread increased to 35 ns for cross-pol antennas (VH). Scatter plots of path loss using horizontal, vertical, and linear cross-pol omnidirectional antennas showed that the best-fit path loss exponent was also not a strong function of polarization when transmitter and receiver antennas were co-polarized. The calculated values of the path loss power law exponent \( n \) for all measurements were 2.50 and 2.23 for VV and HH configurations, respectively. The standard deviations \( \sigma \) about the \( d^2 \) path loss model were 8.6 dB and 10.4 dB for vertical and horizontal polarizations, respectively. The cross-pol measurements (configuration VH), however, showed greater path loss with distance, as \( n=2.63 \) and \( \sigma=7.1 \) dB. The increase in path loss when orthogonal linear antenna polarizations are used at base and mobile suggests that indoor channels offer some polarization isolation.

Figure 1 shows the amount of polarization isolation offered at each measurement location, and plots the cross-pol discrimination at each location as a function of co-pol path loss. Each point on the scatter plot indicates the increase in path loss using cross-pol antennas (VH) as compared with the average path loss measured when linear co-pol antennas (VV and HH) were used at the same location. For example, the largest cross-pol discrimination shown on Figure 1 occurred at a LOS measurement location where the measured cross-pol path loss was 17 dB greater than the average co-pol path loss at the same location. The average co-pol path loss at that location was measured to be 20 dB greater than a 1 meter free space reference measurement. Average co-pol path loss was computed as the average of the two path loss values measured using VV and HH antenna configurations.
Mean values of cross-polar discrimination for LOS and OBS topographies are 8.3 dB and 2.8 dB, respectively. Figure 1 suggests that in LOS environments, the received signal is dominated by the LOS component, which does not depolarize during propagation. Conversely, in OBS topographies, the propagation mechanisms of reflection, diffraction, and scattering tend to depolarize the transmitted signal. In [3], measurements showed negative cross-polar discrimination in OBS channels. Note for LOS channels, however, Figure 1 shows cross-polar discrimination is much better than reported in [3], which suggests that in LOS channels, CP could offer reductions in delay spread due to the preservation of the polarization of the LOS signal. This is shown subsequently by measurements. The standard deviation of cross-polar discrimination is 3.4 dB for LOS topographies and 2.5 dB for OBS topographies, although Figure 1 shows that for most LOS channels, cross-polar discrimination is clustered between 5 and 10 dB.

b. Circularly Polarized Antenna Results

Figure 2 compares the distribution of rms delay spread for CP on Axis (C1 from Table 1), CP 45° Off Axis (C2 & C3), Base Circular to Mobile Linear (CH & CV), and LP (VV & HH) antenna configurations for all LOS channel measurements. When compared with omnidirectional LP antennas, CP directional antennas result in a significant reduction of $\sigma_T$. For example, Figure 2 shows in LOS channels, worst case $\sigma_T$ is 45 ns for linear omnidirectional antennas at base and mobile, 25 ns for a directional CP transmitter antenna and an omnidirectional receiver antenna, and only 8 ns for CP directional antennas at both base and mobile. Even when one of the CP antennas is pointed 15 degrees off-axis, it can be seen there is a substantial decrease in $\sigma_T$ as compared with the omnidirectional LP antennas. In OBS channels, CP directional antennas consistently reduced rms delay spread by at least 20% (and usually more than this) when compared with omnidirectional LP antennas at all measurement locations.

Figures 3a and 3b show scatter plots that compare measured path loss for directional CP (On Axis) and omnidirectional LP antennas in LOS and OBS topographies. To provide fair comparison of path loss measurements using antennas with different radiation patterns, the maximum (on-bore sight) antenna gains were subtracted out of the link budget before computing path loss from measured data. Although delay spread decreases when directional CP antennas are used, wide band path loss becomes greater. In LOS channels, the best fit path loss exponents are 1.74 and 1.54 for CP and LP antennas, respectively. In OBS topographies, path loss exponents are 3.50 and 2.70 for CP and LP, respectively. The path loss difference is more severe for OBS topographies since propagation in such environments is typically via many paths from many directions, whereas in LOS environments the power delay profile is typically dominated by the direct LOS component [4],[5]. Thus, when a directional antenna is pointed in a particular direction, multipath power arriving from other directions will not be received and consequently will not add to received power.

III. CP ANTENNAS REDUCE DELAY SPREAD VARIABILITY

Additional measurements in Site D compared propagation parameters using directional LP log-periodic antennas (with gains of 7 dBi and 3 dB beamwidths of 50 degrees), directional CP helical antennas, and omni-directional LP antennas. By introducing the directional log-periodic antennas into the experiment, we hoped to determine whether the rms delay spread reduction in Figure 2 was due to antenna directivity or antenna polarization. Measurements were conducted at six hallway locations in Site D: three LOS locations along a main hallway and three OBS locations where the transmitter and receiver were placed in different hallway corridors. At each measurement location, ten power delay profiles were recorded at $\lambda/4$ spacings over a measurement distance of 2.5\lambda [2]. Although the CP helical antennas offered slightly more gain than the LP log-periodic antennas, Site D had 200/c values of cross-pol discrimination for CP (On-bore sight) channel. Additional data can be found in [2] and is similar to Figure 4. The figure shows that the variation of $\sigma_T$ is greatly diminished when CP antennas are used in place of omnidirectional or directional LP antennas as a receiver moves over a local area. It should be possible to exploit the smaller delay spread offered by CP antennas for improved high data rate transmission and other implementation aspects of indoor wireless systems.
REFERENCES


Figure 1. Cross-polarization discrimination as a function of co-polarized path loss for all Site D and E locations. Cross-pol discrimination is significantly greater in LOS than OBS environments. Co-pol path loss was computed as the average of path loss (in dB) measured using V-V and H-H antenna configurations. Frequency = 1.3 GHz.

Figure 2. CDF of rms delay spread as a function of polarization for LOS topography. CP refers to helical antennas at transmitter and receiver. Notice that CP offers some robustness to delay spread when there is a 45 degree pointing error. Frequency = 1.3 GHz.

Figure 3a. Path Loss vs. Log T-R Separation

Figure 3. Scatter plot of path loss for CP antennas pointed on-axis and omni-directional LP antennas for (a) LOS and (b) OBS topographies. This figure shows higher path loss for CP antennas in OBS topographies. Maximum (on-boresight) antenna gains have been factored out of the path loss calculation. Frequency = 1.3 GHz.
Figure 3. Scatter plot of path loss for CP antennas pointed on-axis and omni-directional LP antennas for (a) LOS and (b) OBS topographies. This figure shows higher path loss for CP antennas in OBS topographies. Maximum (on-boresight) antenna gains have been factored out of the path loss calculation. Frequency = 1.3 GHz.

Figure 4. Variation of rms delay spread over a 2.5λ track for LP omni-directional (VV and HH), LP directional (VV and HH), and CP directional, for a typical OBS channel. Frequency = 1.3 GHz.
VV - Base Station and Mobile using Vertical Polarization.

HH - Base Station and Mobile using Horizontal Polarization.

VH - Base Station using Vertical Polarization, Mobile using Horizontal Polarization. Commonly referred to as Linear Cross-polar.

CV - Base Station using Circular Polarization with the helical always pointed in the direction of the Mobile, Mobile using Vertical Polarization.

CH - Base Station using Circular Polarization with the helical always pointed in the direction of the Mobile, Mobile using Horizontal Polarization.

C1 - Base Station and Mobile using Circular Polarization with both helical antennas always pointed in the direction of each other. Will be commonly referred to as CP - On Axis

C2 - Base Station and Mobile using Circular Polarization. Mobile helical pointed in the direction of the Base Station; Base Station helical pointed ~ 45° to the right of directly toward the Mobile.

C3 - Base Station and Mobile using Circular Polarization. Mobile helical pointed in the direction of the Base Station; Base Station helical pointed ~ 45° to the left of directly toward the Mobile.

Table 1. Descriptions of the eight antenna and polarization configurations used in this experiment.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_1$(ns)</th>
<th>$\sigma_2$(ns)</th>
<th>$\sigma_3$(ns)</th>
<th>$\sigma_4$(ns)</th>
<th>$\sigma_5$(ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omni LP - Vert.</td>
<td>6.2</td>
<td>13.6</td>
<td>4.0</td>
<td>8.1</td>
<td>2.3</td>
</tr>
<tr>
<td>Omni LP - Horiz.</td>
<td>15.0</td>
<td>19.6</td>
<td>6.3</td>
<td>4.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Directive LP - Vert.</td>
<td>12.1</td>
<td>9.3</td>
<td>3.5</td>
<td>3.7</td>
<td>2.2</td>
</tr>
<tr>
<td>Directive CP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOS - 9.40 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOS - 15.2 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOS - 31.1 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OBS - 13.6 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OBS - 31.7 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OBS - 34.1 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Comparison of rms delay spreads measured with LP omni-directional (vertical and horizontal), LP directional, and CP directional antennas at both transmitter and receiver. All directional measurements were made with antennas directed toward each other (on-axis).