Indoor Radio WLAN Performance
Part II: Range Performance in a Dense Office Environment

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Abstract - This paper discusses indoor WLAN DSSS radio range testing relating antenna type, radiated power, and transmitter/receiver separation to the IEEE 802.11 compliance range at the 2.4 GHz ISM band frequencies. Indoor range performance is shown to depend not only on transmit power and transmission rate, but on the product's response to multipath and obstructions in the environment along the radio propagation path. Consequently, a comparison of the effects of propagation with respect to a WLAN printed antenna and a dipole are investigated in the dense office environment. Finally, to understand propagation effects, a basic overview is presented.

1.0 INTRODUCTION

To realize the limitations in performance of WLAN products in dense office environments it is necessary to provide an overview of how signals propagate. The following is a mini-tutorial of the basic propagation mechanisms with reference to indoor scenarios.

Shown in Fig. 1 is a simulation of the RF signal energy distributed within a typical office. This view is a cross-section of the office at desktop level. As shown, RF signal dispersion for indoor wireless areas is highly disturbed [1]. Reflection, diffraction and scattering of the RF signal is dynamic and difficult to predict. Small changes in position or direction of a receiver (relative to a transmitter) may result in wide variations in signal strength. Within office structures, RF propagation is dependent on office dimensions, obstructions, materials, and signal frequency. Consequently, WLAN range data performance is highly dependent upon the surrounding physical environment. The physical environment can also be classified into both static and dynamic elements. Static elements comprise a variety of natural and manmade materials, geometrical boundaries, and spatial configurations. Dynamic elements comprise mobile objects (oscillating fans, people, and cars seen through windows.).

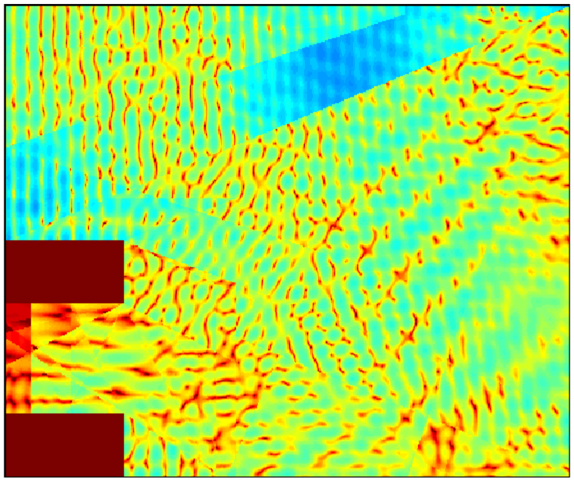

Fig. 1 Indoor Office Signal Intensity Map

2.0 WLAN PROPAGATION OVERVIEW

The main problem that exists for indoor environments is that the signal propagated from the transmitter antenna will experience many different signal transformations and paths with a small portion reaching the receiver antenna. Awareness of this process will assist the user to better understand radio performance limitations. Much research and study is dedicated to the characterization of the signal environment (Often referred to as channel characterization). A few propagation fundamentals are reviewed in the following text.

2.1 Indoor Propagation Mechanisms

The propagated electromagnetic signal in the indoor environment can undergo three primary physical modes. These are reflection, diffraction, and scattering [2]. The following definitions assume small signal wavelength, large distances (relative to wavelength) and sharp edges for a typical indoor scenario. As shown in equation (2) below, the free space wavelength at 2.4 GHz is 4.92 inches. This wavelength relative to flat surfaces is sufficiently small for wave propagation mechanisms to hold true. Typically, the distances between walls, floors and ceilings are on the order of 10 feet or greater, and the office environment contains many vertical and horizontal edges and surfaces.

Reflection: The propagated signal striking a surface will either be absorbed, reflected, or be a combination of both. This reaction depends on the physical and signal properties. Physical properties are the surfaces' geometry, texture and material composition. Signal properties are the arriving incident angle, orientation, and wavelength.

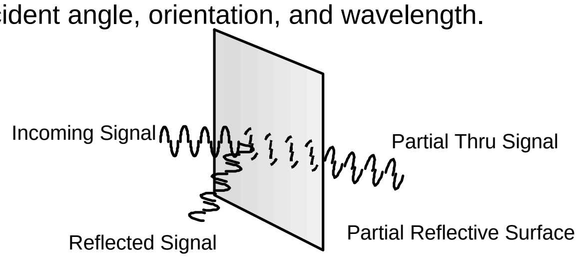

Fig. 2 - Reflected Signal

Perfect conductors will reflect all of the signal. Other materials will reflect part of the incident energy and transmit the rest. The exact amount of transmission and reflection is also dependent on the angle of incidence, material thickness and dielectric properties. Major contributors to reflection are walls, floors, ceilings and furniture.

Diffraction: As shown in Fig. 3. a diffracted wave front is formed when the impinging transmitted signal is obstructed by sharp edges within the path.

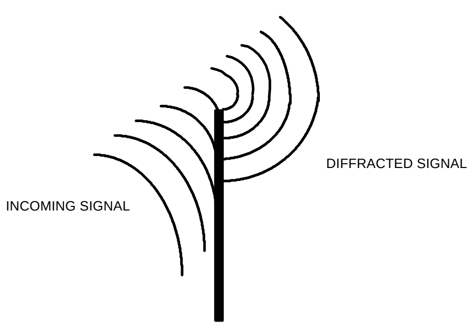

Fig. 3 - Diffraction of a Signal

Diffraction occurs when obstacles are impenetrable by the radio waves. Based on Huygen's principle, secondary waves are formed behind the obstructing body even though there is no line of site [3]. Indoor environments contain many types of these edges and openings, both orientated in the vertical and horizontal planes. Thus the resultant diffracted signal is dependent on the geometry of the edge, the spatial orientation, as well as dependent on the impinging signal properties. Such as amplitude, phase and polarization. The result of diffraction of a wave at an obstacle edge is that the wavefront bends around and behind the obstacle edge. Diffraction is best demonstrated by the radio signal being detected close to the inside walls around corners and hallways. This phenomenon can also be attributed to the waveguide effect of signals propagating down hallways.

Scattering: If there are many objects in the signal path, and the objects are small relative to the signal wavelength, then the propagated wavefront will break apart into many directions. The resultant signal will scatter in all directions adding to the constructive and destructive interference of the signal that is illustrated in Fig. 4. Most modern office construction contains pressed steel I-beams throughout the wall supports. Furthermore, construction materials such as conduit for electrical and plumbing service can add to the scattering effect.

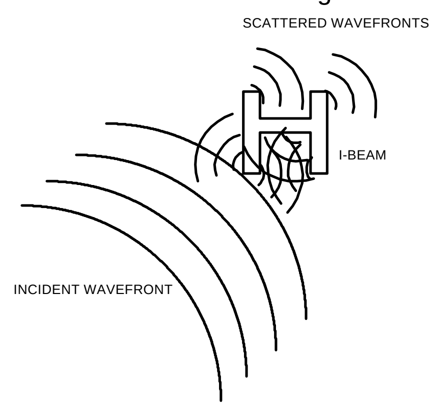

Fig. 4 - Scattered Wavefront on an I-beam

2.2 Indoor Path Loss

Path loss is difficult to calculate for an indoor environment. Again, because of the variety of physical barriers and materials within the indoor structure, the signal does not predictably lose energy. The path between receiver and transmitter is usually blocked by walls, ceilings and other obstacles [4]. Depending on the building construction and layout, the signal usually propagates along corridors and into other open areas. In some cases, transmitted signals may have a direct path (Line-of-Site, LOS) to the receiver. LOS examples of indoor spaces are; warehouses, factory floors, auditoriums, and enclosed stadiums. In most cases the signal path is obstructed.

Free Space Loss

Fundamental to indoor path loss analysis is the free space loss. If the transmitting antenna were ideally a radiating point source in space, the propagated surface wave front will exit the point source in a spherical pattern as shown in Fig. 5. The spherical signal energy reduces as the square of the distance. Free Space Path Loss (FSPL) is defined as:

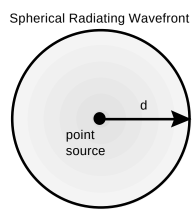

Fig. 5- Free Space Radiating Point Source

$$FSPL = (4\pi d/\lambda)^2 \qquad (1)$$

Where d is distance in meters between the transmitter and receiver, and λ(lambda) is the wavelength in meters. This equation also implies that as the frequency increases the loss will be proportionally higher. Relating frequency to wavelength:

$$\lambda = c/f \qquad (2)$$

Where c is the speed of light, c = 3×10^8 m/s, and frequency, f = cycles per second. For example, the wavelength of the 2.4 GHz sinusoid is:

$\therefore$ λ=.125 meters, λ=12.5 centimeters or λ=4.92 inches.

Free space loss defined in decibels is :

Free Space Loss = 10•log(FSPL) (3)

Where FSPL is from equation 1.

$\therefore$Free Space Loss (FSL) = 40 dB @ 1 meter

$\therefore$Free Space Loss (FSL) = 60 dB @ 10 meter

Therefore, the free space loss 1 meter away from the transmitter is 40 dB! Thereafter, the signal attenuates at a rate of 20 dB per decade

Line Of Site Path Loss

For a LOS office scenario, the path loss is given by:

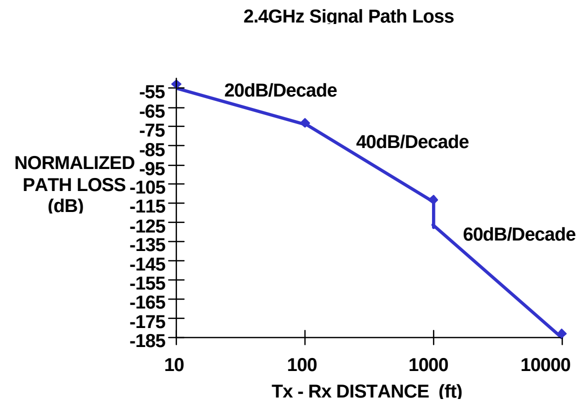

Fig. 6 - 2.4GHz Typical Path Loss

$$PL = FSL_{ref} + n_1 \bullet 10 \bullet \log(d_{tr}) \qquad (4)$$

Where FSL_{ref} is the free space loss in dB determined in the far field of the antenna. Usually for indoor environments, this is calculated to be 1 or 10 meters as shown in equation (3). "d_{tr}" is the distance between the receiver and transmitter. The symbol "n_1" is a scaling correction factor which is dependent on the attenuation of the propagation environment. In this case, equation 4 is for large indoor spaces. The n_1 factor has been determined from empirical data collected and can be found in the excellent references by; [2] T. Rappaport and [3] A. Santamaria, Lopez-Hernandez. For line of site application in hallways the n_1 factor has been determined to be less than 2. This is due to the waveguide effect provided by properties of hallways or corridors.

Figure 6 shows the free space attenuation in dB for a typical indoor application. The curve represents various LOS path losses. The first segment represents the path loss due to free space. The second and last segments represent a more lossy path. The instantaneous drop demonstrates the loss due to obstruction of the LOS path.

Obstructed Path Loss

Obstructed path loss is much more difficult to predict, especially for the myriad of different indoor scenarios and materials. Therefore, different path loss models exist to describe unique dominant indoor characteristics. Based on free space loss and the three propagation phenomenon, the path loss models also account for the effects of different building types. Examples are multi-level buildings with windows, or single level buildings without windows.

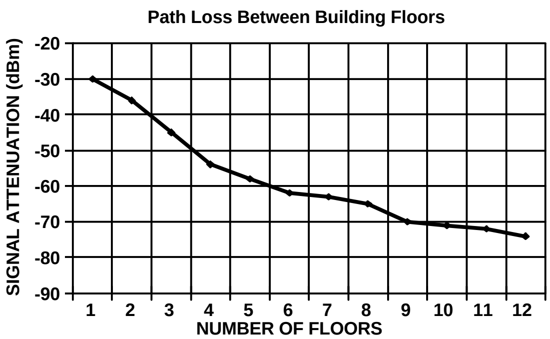

Fig. 7- Multiple Floor Indoor Path Loss

It has been shown (See Fig. 7) that the propagation loss between floors begin to diminish with increasing separation of floors non-linearly. The attenuation becomes less per floor as the number of floors increases. This phenomenon is thought to be caused by diffraction of the radio waves along side of a building as the radio waves penetrate the building's windows. Also, a variety of different indoor configurations can be categorized for buildings with enclosed offices, or office spaces consisting of a mix of cubicles and enclosed rooms. Examples of attenuation through obstacles for various materials are shown in the table below.

Table 1 - 2.4 GHz Signal Attenuation

Window Brick Wall	2 dB
Metal Frame Glass Wall into Building	6 dB
Office Wall	6 dB
Metal Door in Office Wall	6 dB
Cinder Block Wall	4 dB
Metal Door in Brick Wall	12.4 dB
Brick Wall next to Metal Door	3 dB

Indoor path loss has been shown to be exponential as shown in Fig. 6. In specific cases the models can show deterministic limits. However, in majority of the cases the obstructed path loss is determined through empirical means followed by corresponding refinements to the mathematical model.

Multipath and Fading Effects

As a transmitted radio wave undergoes the transformation process presented in the indoor environment it reaches the receiving antenna in more than one path, thus giving rise to multipath. Relating multipath to propagation models and path loss employs stochastic theory and probability distribution functions (pdf). A somewhat understated view of the multipath effect is; signal variations within a building, where there are no clear line of site signal paths between the receiver and transmitter, approximate a Rayleigh distribution. For receivers and transmitters that have line of site signal paths, the distribution is Rician.

A Rayleigh distribution function describes a process where a large number of incident rays (as seen at the receiver antenna) add randomly with respect to amplitude and time. A Rician distribution is similar to a Rayleigh pdf except that a Rician pdf contains a strong dominant component. Usually the dominant component is the direct line of sight or ground reflection ray [5].

Multipath introduces random variations in the received signal amplitude over a frequency bandwidth. Multipath effects also vary depending on the location of the antenna as well as the type of antenna used. The observed result of random signal distributions, as seen by the WLAN radio receiver, will be the "in and out" variation (fading) of the signal (See Fig. 8). Variations as much as 40 dB can occur. Fading can be very rapid or slow. This depends on the moving source and the propagation effects manifested at the receiver antenna. Rapid variations over short distances are defined as small-scale fading. With respect to indoor testing, fading effects are caused by human activities and usually exhibit both slow and fast variations. Sometimes oscillating metal bladed fans can cause rapid fading effects.

Applications of the WLAN radio indoors can either be fixed or mobile. Thus, small-scale fading

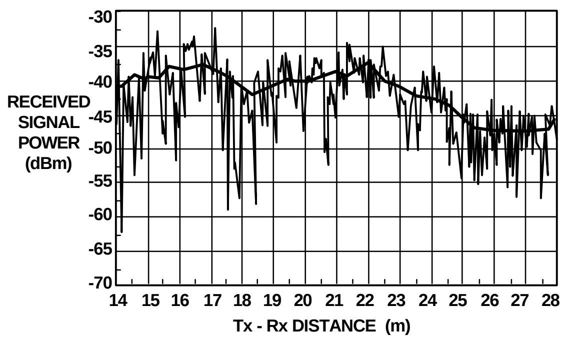

Fig. 8 - Small Scale Fading

effects can be further described using multipath time delay spreading. Since the signal can take many paths before reaching the receiver antenna, the signals will experience different arrival times. Thus, a spreading in time (as well as frequency) can occur. Typical values for indoor spreading are less than 100 nano-seconds. Different arrival times ultimately create further degeneration of the signal.

Finally, those who are involved in the wireless discipline whether as a designer or a user, must be aware of construction materials, interiors and exteriors, and locations of a building to best position WLAN radio equipment. For optimal performance the user should also consider work activities. Ultimately, the WLAN user needs to understand the relationship between indoor propagation effects and how WLAN performance is affected.

3.0 INDOOR WLAN RADIO RANGE TESTING

The number of different WLAN products is increasing, and consequently, so is the demand for more indoor radio WLAN range metrics and benchmarks. Especially in comparison of Frequency Hopping (FH) and Direct Sequence (DS) radio systems. Furthermore, the usage of the WLAN radio dictates the performance of the radio in network applications. For example, the user may be connected in a point-to-point or peer group (Ad-Hoc) situation or connected via a centrally controlled group intranet through an Access Point (AP).

In peer group applications the user is connected with another user independent of the local ether. This scenario represents the worst case radio performance. This is because the radios' orientation and separation can be in the fringe areas of the signal, and therefore be more susceptible to effects of multipath, fading, and attenuation.

WLAN radios in the network group configuration are usually within the range of the access point cells. The coverage of the cells overlap allowing roaming capability to the user. Consequently, centrally controlled networks are not at the same risk as an ad-hoc network and are not discussed.

3.1 Range Testing Description

The objective of testing is to determine the range extent of a point-to-point DSSS radio link governed by the recently adopted IEEE 802.11 WLAN standard in a dense office environment. Range tests were evaluated at an effective power of 16 dBm, 10 dBm, and 0 dBm for both a printed circuit antenna and a high quality dipole antenna. Only 16 dBm data is discussed in this paper. The presentation will elaborate more on test results and antenna considerations in the data analysis section.

The IEEE 802.11 standard specifies the receiver minimum and maximum input levels for Frame Error Rates (FER) not to exceed $8x10^{-2}$ at a MAC Protocol Data Unit (MPDU) length of 1024 bytes.

The distance in which the 8 percent FER occurs is not an absolute. For instance, the effective 802.11 range distance between the receiver and transmitter measured in a hallway will not be the same for different obstructed views, even with the same output power and antenna. Therefore, a robust measurement technique must account for and mitigate the office propagation characteristics to accurately establish the 802.11 effective range. The following range test attempts to accomplish this task.

3.2 Building Layout

Shown in Fig. 9 is the layout of the office complex where the range tests are conducted. The layout is typical of offices on the Harris campus, comprising long hallways and contiguous enclosed offices without windows.

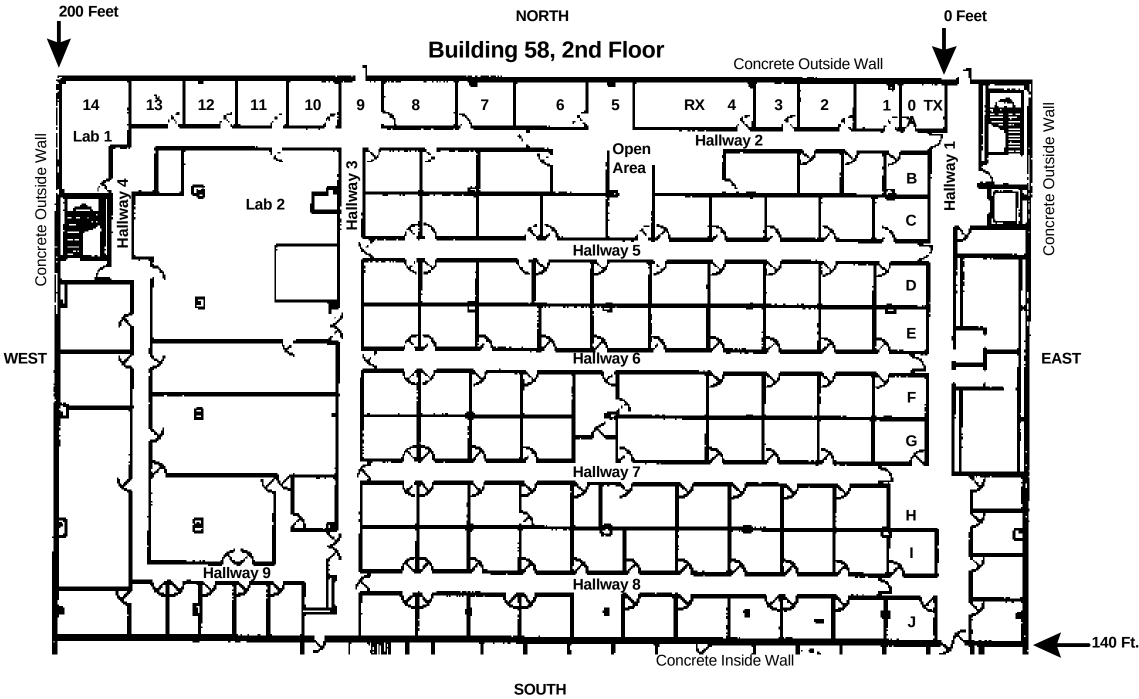

Fig. 9- Range Test Office Layout

Construction: All outside walls are constructed of heavy cinder block and concrete headers. Internal office walls are constructed of thin, removable vinyl covered plaster boards mounted on thin stamped I-beam 2 by 4's. The ceilings are standard dropped ceiling tiles. The roofing structure above the tiles are metal trusses and large concrete pre-fabricated reinforced panels. The space between the dropped ceiling and roof contain conduit, cables, and air ducts. Floors are concrete covered with durable carpet, and office doors are fabricated with wood.

Offices: The rooms contain standard steel office furniture with formica tops. Most offices are occupied by one person accompanied by a typical assortment of books, computer equipment, knick knacks, and limited number of lamps, and fans. Some of the walls hold pictures, dry erase and cork boards.

3.3 Test Setup

(2)-WLAN PCMCIA DSSS radios. Initially, each contain a printed circuit antenna and Harris PRISM™ integrated DSSS RF chipset and baseband processor. The cards were replaced with dipole versions for the second part of the test. The radio is setup for 2 Mbit/s data rates using Differential Quadrature Phase Shift Keying (DQPSK) per the 802.11 specification. The initial output power is set to +18 dBm [6]

(2)-Dell Latitude Pentium 150 MHz Laptop computers configured with LAN software drivers and test evaluation software. The test software allows the user the capability to evaluate the performance of the Physical Layer of the radio in terms of Packet Error Rate (PER) and to load MAC executable into the Flash device on the PCMCIA radio card [7]. Note: The combination of the laptop and PCMCIA radio is defined as the radio, receiver, transmitter, or antenna depending on the usage reference.

(2)-Non-conductive mobile carts with 1 inch thick wood and formica table top. The carts are used to transport the receiver radios throughout the building. The transmitter remained in a fixed location.

(1)-Hewlett Packard Power meter and sensor; used for power measurement at the antenna feed point. Measurements were taken after a fifteen minute warm-up time.

The DSSS transmitter, is configured for 2 Mbit/s data rates, channel 6, 1024 packets per frame, and continuous broadcast data transfer mode. A complete transmit field consists of a preamble, a 16-bit length field, a 32-bit field, 1024 data bytes, and a 32-bit CRC. The data in the packets is randomized as well as protected by a CRC. In addition, each packet transmitted has a sequence number and the receiver can determine missed packets. The receiver software calculates the PER based on the number of missed packets. All parameters can be controlled and monitored by the real-time software utility.

The transmitter card output power is reset to 16 dBm and allowed to stabilize before preceding with the test.

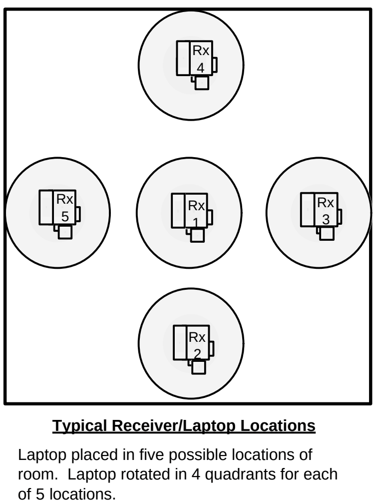

Fig. 10 - Receiver Measurement Locations

3.4 Test Method

The transmitter is located in a fixed position (location 0,A) as shown on the reference building layout. The position of the laptop is such that the integrated printed circuit antenna is orientated towards the north.

To alleviate multipath and propagation effects, the laptop/receiver/antenna combination is rotated 90 degrees for each sample measurement period, until one revolution is complete. The receiver is then moved to another location within the measurement area. For a typical office, 5 locations are selected as illustrated in Fig. 10. Each respective location repeats a four quadrant measurement. The dwell time for each measurement period averages 3 minutes. Thus each measurement location can take approximately 12 minutes, and for an average room approximately 1 hour.

Data Analysis

The collected data for each receiver/transmitter pair is logged and entered into Microsoft Excel spreadsheet and graphed. The graph in Fig. 11 is the averaged PER for the printed circuit antenna with an output power of +16 dBm.

The PER at approximately 100 feet is of interest because the propagated signal exits hallway 2 and spreads into the open area. This area contained metal book cases and desks. Shadowing and fading effects were observed in this measurement area. After 135 feet, the PER increased fairly abruptly. However, hot signal spots could be located by moving the cart around in the fringe areas.

Interpolation of Fig. 11 shows that the average IEEE 802.11 8 % PER range is approximately 120 feet, well below what was expected. Analysis of the WLAN card revealed that the printed circuit antenna E-field polarization was dominant in the azimuthal (horizontal) plane. Signals propagating in the horizontal plane largely account for the unexpected discrepancy in range distance. The printed circuit antenna was tested in a full anechoic chamber while mounted in the laptop. The elevation tests in the chamber indicated that the antenna look angle was more sensitive to slightly above the horizon with horizontal polarization. This could account for a lower range since there were more obstructions at this level. Also, the peak gain of the printed circuit antenna was approximately 0 dBi (dB relative to an isotropic antenna).

Analysis of the dipole antenna configuration shown in Fig. 12, produced more expected results for this environment. The same shadowing effects were seen at the 100 foot measurement location, with half the packet errors of the printed circuit antenna. The interpolated 802.11 compliance range for the dipole configuration was approximately 200 feet. Even at the 802.11 compliance range the throughput was 1462 kbps.

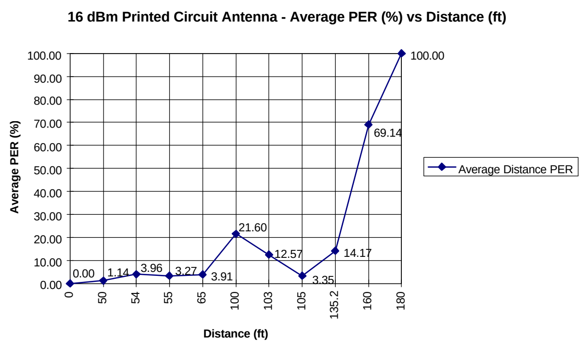

Fig. 11 - Printed Circuit Antenna 802.11 Range

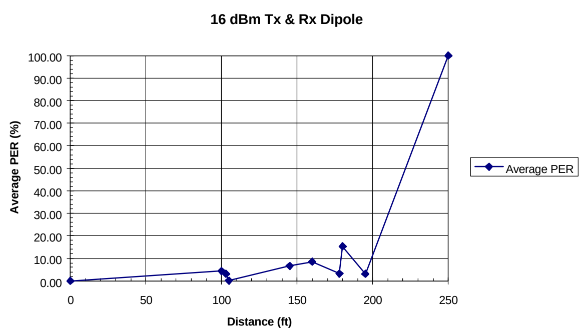

Fig. 12 - Dipole Antenna 802.11 Range

4.0 CONCLUSIONS AND OBSERVATIONS

Analysis of the data showed that the dipole antenna outperformed the printed circuit antenna almost 2 to 1 in range distance. Range performance along the North concrete wall was slightly less than along the inside office groups, towards the South and West. Since the interior of the building is relatively uniform in construction the 802.11 range was similar in all directions. The range distance down hallway 1 and 2 were the only exceptions.

The characteristics of the antenna can make a dramatic difference in range performance. This is also true regarding the sensitivity to propagation and fading. For instance, since the dipole characteristics make the antenna more uniformly sensitive to the ambient signal energy, the radio also exhibited more sensitivity to fading.

The biggest impact to range performance in dense office environments therefore can be the choice of the antenna. With a properly selected antenna the effects of multipath can be reduced and the range improved. A good tutorial and reference on embedded antennas is listed below by David L. Thomas [8].

NEW DEVELOPMENTS

Printed circuit antennae are attractive alternatives to external antennae; however, this convenience comes at both an engineering and performance cost. With the advent of sophisticated radio chip solutions (i.e. Harris' PRISM™), radio designs have become easier. This is not the case for designing printed circuit antennae to the on board circuitry. However, there are new smaller, high performance antenna designs that promise to make the job easier, in addition to being low in cost and easy to implement.

New antenna developments using fractal principles are being designed by Fractal Antenna Systems, Inc. in Fort Lauderdale. Fractal antennas provide more flexibility in design with improved performance than traditional patches. Small ceramic antenna chip solutions by Murata allow for flexible design solutions and performance optimization. TOKO offers a ceramic monopole puck antenna that can achieve near dipole range and performance. Both are currently being used in PCS communications and WLAN products. One of the most promising new technologies comes from U.S. Navy research. Developers call it the Contra-wound Toroidial Helical Antenna. This antenna can provide up to 300 percent improvement in performance or reduction in size. Because of circular polarization properties of the antenna, fading is not a problem, and it is nearly isotropic in direction.

In conclusion, no new technology is a panacea unless it is proven in the field. Future efforts to integrate the antenna to the radio and perform range testing is on the agenda.

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