Indoor propagation issues for wireless LANs

It looks good on paper, but the actual variations of propagation caused by absorption, scattering and multipath make for large variations in path loss from the free space.

By Dan Dobkin

Wireless local area networks (WLANs) are rapidly gaining popularity. These networks are primarily targeted for indoor use, and are most often based on either the IEEE 802.11 Ethernet-type protocols or the Bluetooth Special Interest Group (SIG), both using the unlicensed bands at 2.4 to 2.5 GHz (IEEE 802.11b – "WiFi" — and Bluetooth) or at 5.15 to 5.85 GHz (IEEE 802.11a – "WiFi5"). The European HiperLAN standard is also designed for operation around 5.2 to 5.8 GHz.

It is often said that the higher-frequency unlicensed national information infrastructure (U-NII) band at 5.15 to 5.85 GHz will be intrinsically limited to shorter ranges than the industrial/scientific/medical (ISM) band due to higher path loss, limiting the utility of 802.11a relative to that of 802.11b.

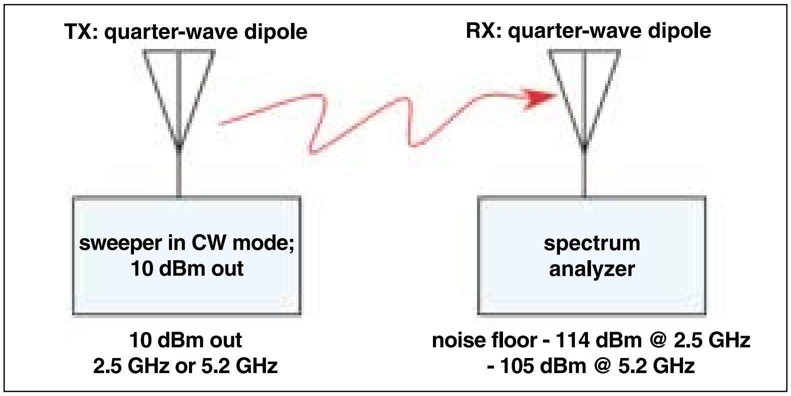

Figure 1. Measurement schematic.

The purpose of this investigation was to examine that claim. It was found, at least in the test environment discussed in this article, to be unfounded.

Experimental method and results

The propagation of a continuous-wave (CW) signal at either 2.5 or 5.2 GHz from place to place within a typical light industrial environment was measured. The 10 mW signal was generated using a sweeper in CW mode and radiated from a fixed vertically oriented $\lambda/4$ dipole constructed from a coaxial line with exposed center conductor of appropriate length, soldered to a copper ground plane 15 cm on a side.

The signal was received by an identical dipole and monitored with a spectrum analyzer. The receive antenna was moved to various locations throughout the facility. At each nominal location, at least five measurements were taken, in which the exact position was moved randomly in 10 to 20 cm increments to sample possible signal variations due to shadowing and multipath fading. Nominal locations were the same for the 2.5 and 5.2 GHz measurements to within about 1 meter.

The experimental setup is shown schematically in Figure 1, and the measured points in Figures 2(a) and (b). The transmitter was located on the second floor (the red dot in Figure 2(a)) and receive locations on both floors 1 and 2 were tested. The building is typical of Silicon Valley construction, with an open central area occupied by cubicles or engineering test benches, offices and conference rooms along the perimeter, and a thin steel-supported concrete floor. The cubicle adjacent to the transmitter contained several large sheet-metal bookshelves, acting as the sort of internal obstacle one might typically expect to encounter in an indoor environment.

Short distance measurements (0.6 ±0.05 and 1.2 ±0.05 meters) provide a rough calibration for the longer distances, because multipath effects are generally minimal at these distances. Distance from transmitter to receiver was estimated from building plans to the nearest meter, accounting for the 3 meter height of the floor 1 ceiling when applicable.

Figure 3 shows the results for both frequencies and both floors. The dots connected by a bar represent the highest and lowest values measured at the same nominal location. It is seen that local fades of anywhere from 5 to 25 dB are common, with one instance of 45 dB. Average values fall as much as 30 dB below ideal free-space [$1/r^2$] propagation. Finally, it is apparent that there is little statistically significant distinction between the path loss for the 2.5 and 5.2 GHz signals.

To further emphasize this point, a joint fit to all of the data points was performed, finding a best-fit propagation model as defined by:

$$\text{model signal (dBm)} = -38 - \left[10\log(\mathit{distance})\right] - 8.95\begin{Bmatrix}1 \text{ if floor } 1\\ 0 \text{ if floor } 2\end{Bmatrix} \qquad (1)$$

Figure 2. Transmit and receive locations overlaid on a building layout.

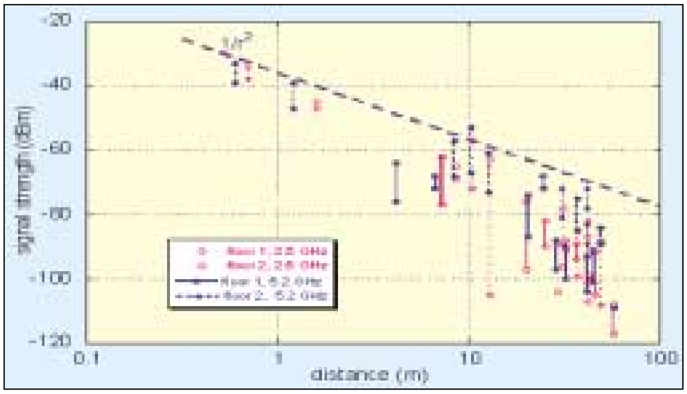

Figure 3. Results of propagation measurements, floors 1 and 2, 2.5 and 5.2 GHz.

(That is, the propagation exponent is about 3.0 and the floor loss about 9 dB.)

The results for each measured data point from the modeled value for that nominal location for 2.5 and 5.2 GHz, is shown in Figures 4(a) and (b) as histograms. While there is a modest difference in the exact shape of the distributions, the difference of the averages (1.7 – 1.4 = 0.3) is much less than the standard deviations of the distributions. There is no statistically significant difference between 2.5 and 5.2 GHz link losses in the facility.

A bit more detail

• *Free Space* — It is a common misconception that free space propagation is wavelength-dependent. It is timely to examine how this misunderstanding arises.

The signal strength received by an ideal receiving antenna from an ideal transmitting antenna over a free-space distance "*d*" can be expressed as:

$$P_{rec} = P_{trans}\left(\frac{1}{4\pi d^2}\right)g_{trans}A_{rec} \qquad (2)$$

where *P*s are transmitted and received powers, g_{trans} is the directivity of the transmitting antenna, and A_{rec} is the effective collecting area of the receiving antenna. Note that there is no explicit dependence of the propagation on wavelength[1].

The received signal strength is, however, more often written in terms of antenna directivity[2]. To arrive at this form one must impose the reciprocity condition : *transmitting from antenna 1 to antenna 2 should give the same result as transmitting from antenna 2 to antenna 1 in free space* (that is, space is isotropic, at least in the absence of an overall magnetic field and orbiting charges) by:

$$P_{trans}\left(\frac{1}{4\pi d^2}\right)g_1A_2 = P_{trans}\left(\frac{1}{4\pi d^2}\right)g_2A_1 \qquad (3)$$

And, a bit of algebra shows that:

$$g_1A_2 = g_2A_1 \rightarrow \frac{g_1}{g_2} = \frac{A_1}{A_2} \qquad (4)$$

That is, the directivity is monotonically related to the effective collecting area of the antenna. An ideal isotropic radiator (directivity = 1) has an effective collecting area proportional to the square of the wavelength, therefore:

$$A_{iso} = \frac{\lambda^2}{4\pi} \rightarrow A_{rec} = g_{rec}\left(\frac{\lambda^2}{4\pi}\right) \qquad (5)$$

Substituting this in the link loss expression gives the more commonly observed form:

$$P_{rec} = P_{trans}\left(\frac{1}{4\pi d^2}\right)g_{trans}g_{rec}\left(\frac{\lambda^2}{4\pi}\right) \qquad (6)$$

Note that, although the term in wavelength is often folded into the term in distance for dimensional convenience, it is actually a statement about antenna size. A nearly isotropic antenna must get smaller as the wavelength shrinks. It is the reduced collecting area of the receiving antenna, not any mysterious wavelength-dependent propagation behavior, that causes free-space link losses to increase with frequency when antennas of a given directivity are specified.

Therefore, higher frequencies induce one to use not shorter ranges, but more directional antennas with larger collection area to maintain a constant link budget.

• *Indoor propagation* — The situation is, of course, more complex in practical indoor environments, where numerous objects may scatter, diffract, reflect, and absorb radiation.

Numerous experimental and theoretical studies of indoor propagation have been performed ([3], and [6 – 11]). The effects of the environment are often absorbed into a modified propagation exponent, ranging from 2.7 to 5, and a floor loss factor of 3 to 12 dB, generally in agreement with the empirical expression we arrived at for our data.

However, there does not seem to exist a specific comparison of unlicensed frequencies, under identical circumstances, such as that reported above, or any suggested analytic approximation for the effects of frequency on path loss

• *Scattering* — The effects of scattering and diffraction have been studied for many years. It is well-known that objects whose dimensions are small compared to a wavelength act as weak scattering centers, with effective scattering cross-section proportional to the fourth power of the impinging wavelength (Rayleigh scattering)[4]. Objects much larger than a wavelength can be treated by the familiar approach of phase-insensitive ray tracing learned in classical optics, and encountered every day in our visual world: they absorb, reflect and cast geometric shadows.

The dominant scatterers in indoor environments fall into neither of these simplistic categories: their typical sizes are from 2 to 3 cm to human dimensions of 2 to 3 meters vs. wavelengths of roughly 12 cm in the 2.4 to 2.5 GHz ISM band and around 5.5 cm in the 5.2 to 5.8 GHz UNII band. Most of these objects fall into the Mie scattering

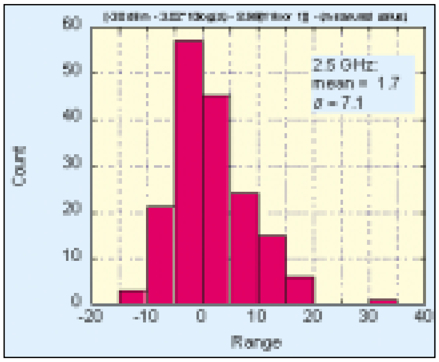

Figure 4(a). 2.5 GHz data vs. joint model.

regime from 1 to 10 wavelengths, in which complex behavior depending on the shape and characteristics of the scatterer is expected[5]. Obstacles much smaller than a wavelength “disappear” from view. Thus FM at 100 MHz (λ = 3 meters) is undisturbed by cars and people, but suffers reflections and diffraction from buildings. This leads to multipath fade in urban environments. The situation is depicted qualitatively in Figure 5, showing scattering cross-section as a function of size for a perfectly reflecting sphere, for frequencies of 2.45 and 5.2 GHz.

It is expected to find a strong monotonic wavelength dependence in indoor propagation when there are important scatterers at sizes between the cutoffs of the high and low frequency waves.

For example, if the environment were populated with lots of metal spheres (ball bearings) of 2 cm diameter, a 5.2 GHz transmission would be scattered 10 times more effectively than a 2.45 GHz transmission. However, a quick look around an office environment will disclose that human beings mostly populate their world with larger objects; the “disappearance” of 2-cm scattering centers at ISM band relative to UNII band has

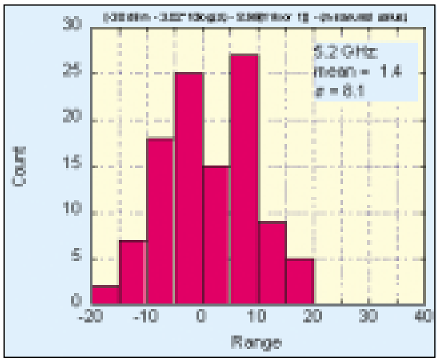

Figure 4(b). 5.2 GHz data vs. joint model.

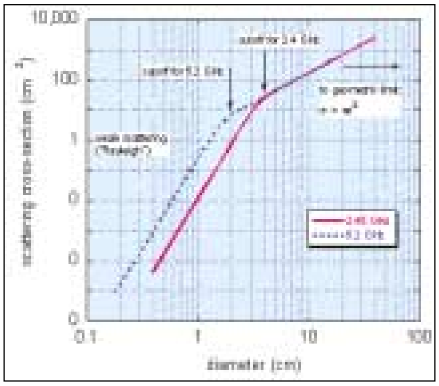

Figure 5. Scattering cross-section vs. diameter for perfectly reflecting spheres, after[5].

little effect on the overall path loss. For larger objects (of size larger than a wavelength), the diffracted intensity must be examined in more detail. Investigation of a typical two-dimensional obstacle of short dimension 0.5 meter, located 5 meters from a source of either 2.4 or 5.25 GHz radiation, was performed using the Fresnel integrals. The diffracted minima at e.g. 12 meters from the obstacle, are 5 dB deeper at 5.25 GHz than at 2.4 GHz, though only 30 cm wide; the on-axis maxima only differ by about 2 dB between the high and low frequencies. Based upon this rationale, it can be concluded that the experimental results are reasonable and may be typical of indoor environments.

- *Multipath and delay spread* — Multipath propagation leads both to fading and to variations in path delay of transmitted signals. Delay spread and number of significant paths increase gradually with distance in indoor environments; a typical range appears to be about 20 to 80 nsec for 5 to 15 meter distances at 5 GHz[8].

An 802.11a signal contains 48 active carriers[12]. At the minimum overall data rate of 6 Mb/s each carrier has a data rate of 125 Kb/s or a bit time of 8 µseconds. Even during the PLCP preamble, signal transmission uses 12 subcarriers for an effective rate of 500 KHz. It seems unlikely that the bit error rate would be extremely sensitive to the 10 to 30 nanosecond variations in the multipath delay distribution that one would expect at these ranges.

While there has been no explicit examination of the effects of multipath propagation, it can be noted that the magnitude of multipath propagation should be reflected in the variation about the mean of path loss (see Figures 4(a) and (b)). Similar standard deviations for CW propagation suggest qualitatively similar multipath / delay effects.

Conclusions

As a result of this experiment, it is suggested that no intrinsic impairment exists in 5.2 to 5.8 GHz propagation vs. 2.4 to 2.5 GHz propagation in office/light manufacturing environments. Thus, no intrinsic impediment to roughly equivalent deployment of 802.11a and 802.11b wireless LAN systems exists.

Note, however, that this does not imply equivalence of practical systems: higher frequencies suffer higher losses in cables and circuit boards, and low-cost devices may suffer from reduced gain or lower output power at higher frequencies. Further, to achieve equivalent collecting area, higher-frequency antennas become more directional, which may be inconvenient for end-users.

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The author would like to acknowledge the assistance of colleagues including Eric Frick, Marc Abramson, Mike Johnston, Andy Graven, and Tuan Nguyen in this work.