Indoor Propagation and Wavelength

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Abstract: In this article we examine the propagation of frequency bands relevant for wireless local area networks – IEEE 802.11, Bluetooth, and HiperLAN -- in typical indoor environments. We show that the simplistic quadratic dependence of link loss on wavelength generally employed is related to antenna characteristics, with free-space propagation being wavelength-independent as it must be to conserve energy. The actual variations of propagation due to absorption, scattering, and multipath cause large variations in path loss from the free space result; our experimental data in a typical indoor environment shows that these variations are much larger than the modest difference arising from the distinction between 2.4 and 5.2 GHz wavelengths. The UNII band has no intrinsic disadvantage of range for indoor use, at least with respect to path loss, but the choice of bands may influence the optimal choice of antennas.

Introduction

The use of wireless local area networks (WLANs) is rapidly growing in 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 SIG, both using the unlicensed bands at 2.4-2.5 GHz (IEEE 802.11b – "WiFi" -- and Bluetooth) or at 5.15-5.85 GHz (IEEE 802.11a – "WiFi5"). The European HiperLAN standard is also designed for operation around 5.2-5.8 GHz.

It is often said that the higher-frequency UNII band at 5.15-5.85 GHz will be intrinsically limited to shorter ranges than the ISM band due to higher path loss, limiting the utility of e.g. 802.11a relative to that of 802.11b. The purpose of this investigation was to examine that claim; we showed that it is, at least in our test environment, unfounded, although there are important practical issues in radio design which may in the end produce a similar result.

Experimental Method and Results

We measured 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 (WJ Communications' facility in San Jose, CA). The 10 mW signal was generated using a sweeper in CW mode and radiated from a fixed vertically-oriented quarter-wave 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 through the facility; at each nominal location, at least 5 measurements were taken, in which the exact position was moved randomly in 10-20 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, since multipath effects ought to be 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.

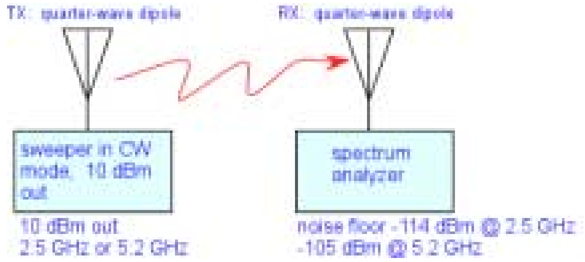

Figure 1: Measurement schematic

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

In figure 3 we show 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. We see 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 we performed a joint fit to all the data points, finding a best-fit propagation model:

$$\text{model signal (dBm)} = -38 - 3.02\left[10\log(\mathit{distance})\right] - 8.95\begin{Bmatrix}1 \text{ if floor } 1\\ 0 \text{ if floor } 2\end{Bmatrix}$$

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

We then subtracted each measured data point from the modeled value for that nominal location and present the results for 2.5 and 5.2 GHz as histograms in figures 4(a) and (b). 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 our facility.

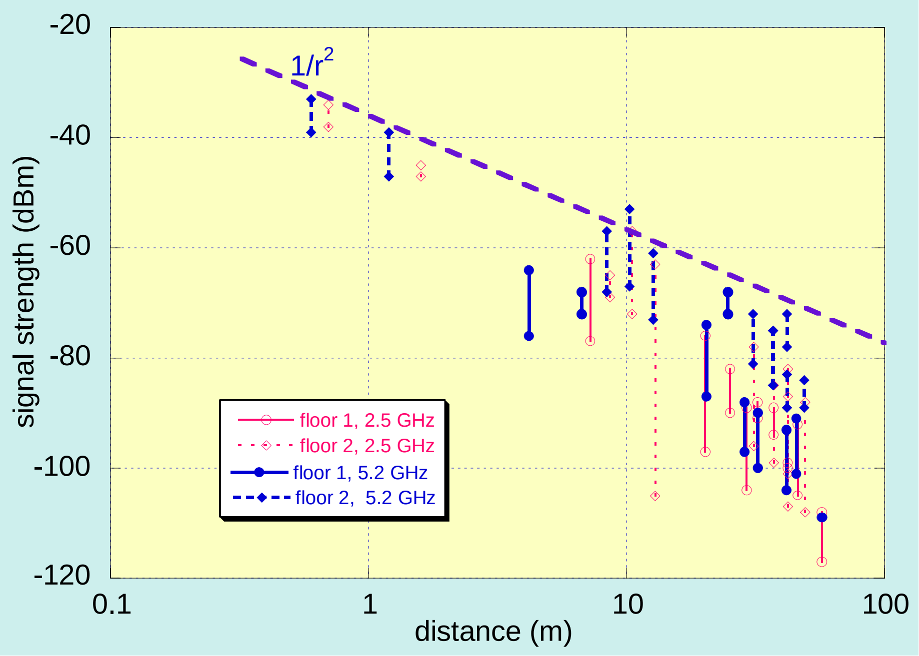

Figure 3: Results of propagation measurements, floors 1 and 2, 2.5 and 5.2 GHz

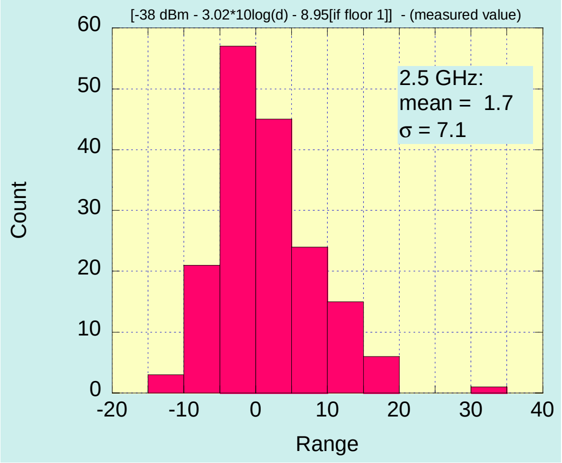

Figure 4(a): 2.5 GHz data vs. joint model

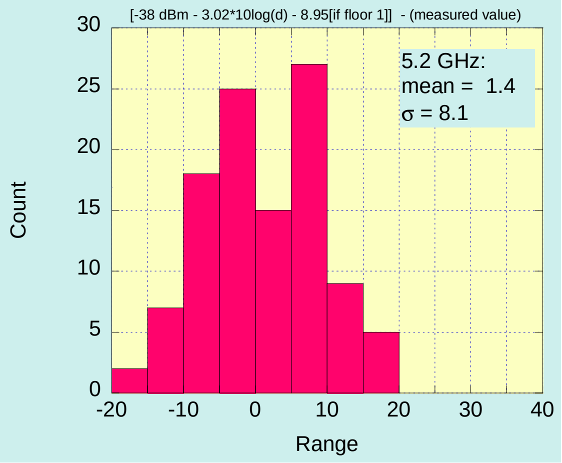

Figure 4(b): 5.2 GHz data vs. joint model

Discussion and Conclusions

Free Space:

It is a common misconception that free space propagation is wavelength-dependent. Let us 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:

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

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]. In order to arrive at this form, we begin by imposing 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):

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

A bit of algebra shows that:

$$g_1A_2 = g_2A_1 \rightarrow {}^{g_1}\!/_{g_2} = {}^{A_1}\!/_{A_2}$$

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

$$A_{iso} = {}^{\lambda^2}\!/_{4\pi} \rightarrow A_{rec} = g_{rec}\left({}^{\lambda^2}\!/_{4\pi}\right)$$

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

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

or

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

Note that, although the term in wavelength has been 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 employ not shorter ranges but more directional antennas with larger collection area, in order 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 references therein,[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 3-12 dB, generally in agreement with the empirical expression we arrived at for our data. However, we have been unable to find a specific comparison of unlicensed frequencies in 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 2-3 cm to human dimensions of two to three meters, vs. wavelengths of roughly 12 cm in the 2.4-2.5 GHz ISM band and around 5.5 cm in the 5.2-5.8 GHz UNII band. Most of these objects fall into the Mie scattering regime regime from 1 to 10 wavelengths, in which complex behavior depending on the shape and characteristics of the scatterer is expected [5]. Obstacles of size much less than a wavelength "disappear" from view. 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.

We would expect 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 little effect on the overall path loss.

For larger objects of size several times larger than a wavelength, the diffracted intensity must be examined in more detail. We have estimated the intensity distribution for a two-dimensional obstacle by numerical integration of the Fresnel integrals [13] using Mathcad 2000 Professional. Some results are shown in figure 6. We have treated a typical obstacle of short dimension 0.5 meter, located 5 meters from a source of either 2.4 or 5.25 GHz radiation, and examined the intensity profiles at observation distances of 4, 12, and 32 meters. Depicted in the figure is the radiation intensity normalized to unimpeded free space propagation loss. The nulls are about 4 dB deeper for the high-frequency radiation, but the averages differ very little, as shown in table 1.

Table 1: Average normalized intensity

Observation distance (m)	**2.4 GHz illumination**	**5.2 GHz illumination**	**<I(5.2)/<I(2.4) [dB]**
4	0.87	0.88	0
12	0.77	0.76	0
32	0.29	0.38	1.2

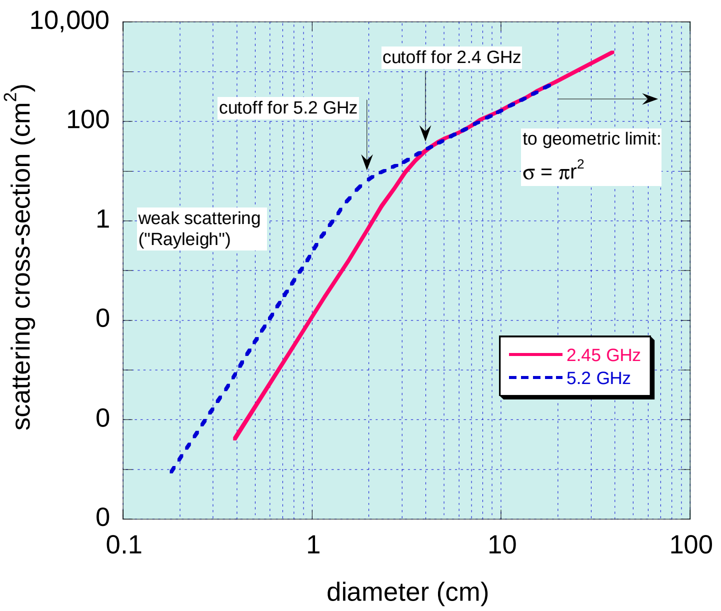

Figure 5: Scattering cross-section vs. diameter for perfectly reflecting spheres, after [5]

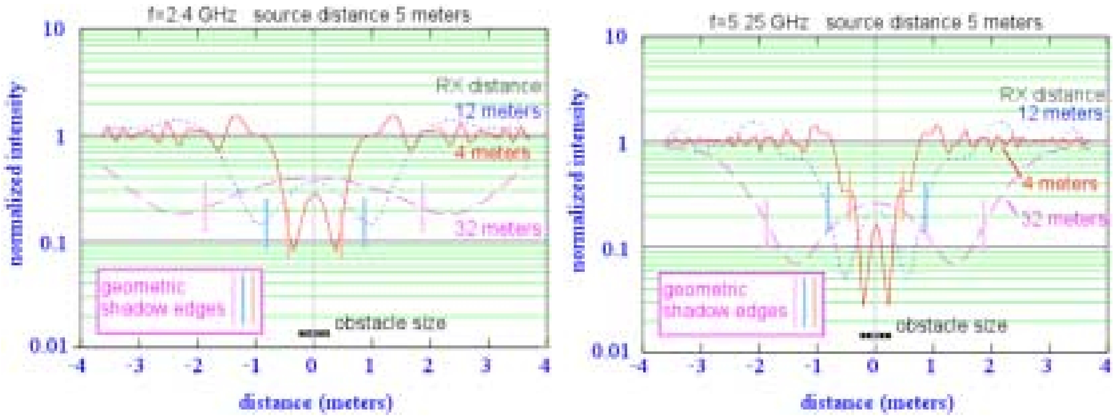

Figure 6: intensity (normalized to free space propagation) for a two-dimensional obstacle 0.5 meters wide, illuminated by a source 5 meters distant; measured in the plane perpendicular to propagation at 4, 12, and 32 meters from the obstacle. The vertical lines denote the extent of the geometric shadow at each observation distance.

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 20-80 nsec for 5-15 meter distances at 5 GHz [8]. An 802.11a signal contains 48 active carriers [12]; at the minimum overall datarate of 6 Mbps each carrier has a datarate of 125 Kbps or a bit time of 8 microseconds. Even during the PLCP preamble, signal transmission employs 12 subcarriers for an effective rate of 500 KHz. It seems unlikely that the bit error rate would be extremely sensitive to the sub-microsecond variations in the multipath delay distribution that one would expect at ranges of a few tens of meters.

Absorption:

Absorption loss in normal dry air is less than 0.01 dB/km below 10 GHz [14], and thus negligible indoors. Dielectric loss in *liquid* water is both frequency- and temperature-dependent; near room temperature the loss at 5 GHz is around 30% higher than at 2.5 GHz, with the peak around 15 GHz [15]. Little liquid water is present in most indoor environments. Loss tangents for many common materials are roughly constant with frequency [16], implying absorption is linear in frequency; to the extent that absorption is significant relative to scattering, we would expect a 3 dB increase in absorption for 5.2 GHz radiation vs. 2.4 GHz. Our results are consistent with the assertion that scattering is more important than absorption in indoor environments.

Conclusions

We suggest that there is no intrinsic impairment of 5.2-5.8 GHz propagation vs. 2.4-2.5 GHz propagation in office/light manufacturing environments, and thus no intrinsic impediment to roughly equivalent deployment of 802.11a and 802.11b wireless LAN systems. 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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