Making OFDM Work for High-Performance Wireless Network Applications

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1. Introduction

Automobiles have been with us now for many decades and in a general sense they are all very similar, all requiring 4 wheels, an engine and fuel system, a chassis, etc. However, no one would mistake a Ferrari for a Jeep because their intended use, design and costs differ greatly. In the same way, wireless networks for the home and office have been with us for at least the past 10 years, but delivered performance can differ greatly depending upon the objectives in mind.

The most dominant wireless networking standard of the day is IEEE802.11b which was originally designed approximately 10 years ago for data-only based communications. In order to make the networking protocol as simple and scalable as possible, a carrier-sense-multiple-access (CSMA) medium-access control (MAC) protocol was adopted. With the advent of a wide spectrum of new consumer electronic (CE) applications like high-definition television (HDTV), MP3 players, digital cameras and camcorders, personal video recorders (PVRs), cable modems, 1394 applications, satellite television, etc., the limited capabilities offered by 802.11b networks have been dramatically surpassed and newer wireless technology is greatly needed.

Enter Air5™, an OFDM-based wireless networking technology that offers the information throughput rate, communication reliability and quality of service (QoS) that is needed by this host of new CE devices and applications. Comparing Air5 to existing IEEE802.11b networks is not that different than the earlier automobile comparison, and in the balance of this article, some of these important differences will be made more clear.

Perspective has been very key in the development of Air5. Magis' lead investors mandated in mid-1999 when the start-up company was founded that the wireless technology developed be capable of "delivering multiple streams of high-quality video simultaneously" within the home and office along with other less demanding services like voice and data. At the same time, the technology had to be affordable if it had any chance of succeeding in the CE marketplace, and standards would also be an important issue. Although the IEEE802.11a wireless standard had been released in the late 1990's, careful technical assessment of the standard showed that it alone would be unable to deliver the level of performance needed. Rather than completely abandon IEEE802.11a for an entirely new system design however, it was found that improvements could be made to the OFDM baseline system design that would permit the modified system to achieve the needed objectives and Air5 was consequently born. Some of the factors that make Air5 the unprecedented superior wireless vehicle for delivery of video, voice and data are discussed in the sections that follow.

It should be understood from the outset that high-QoS video delivery is the most demanding of all possible services, and that although many references to the video case will be mentioned in this memorandum, this in no way should convey that Air5 is meant for video alone. Rather, the same high QoS and throughput necessary for video benefits the wireless delivery of voice and data as well.

This paper primarily addresses the physical layer (PHY) and medium access control (MAC) layer innovations and considerations that were developed in order to make the OFDM-based system work and work extremely well at 5 GHz.

2. Misconceptions Regarding the 5 GHz Wireless Channel

Many different opinions have been offered about propagation over the 5 GHz channel in recent months. Some quantitative insight into this important question is offered in the following sections.

2.1 Propagation Differences at 5GHz Compared to 2.4GHz

It is common practice to estimate propagation loss over a free-space channel using the Friis[1] formula which gives the receive signal-to-noise ratio (SNR) as

$$SNR_{dB} = 10Log\left[P_T G_T G_R \left(\frac{\lambda}{4\pi R}\right)^2\right] - 10Log\left(kT\ BW\ NF\right) \qquad (1)$$

where

P_T	Transmit power in Watts
G_T	Numerical transmit antenna gain[2]
G_R	Numerical receive antenna gain
λ	Wavelength, meters
R	Range, meters
k	Boltzmann constant
T	Absolute temperature, taken to be 290K
BW	Bandwidth of modulation, Hz
NF	Noise factor of receiver[3]

For use with indoor communications where flat losses due to walls and other materials are present along with multipath-related issues, this equation is normally modified to

$$SNR_{dB} = 10Log\left[P_T G_T G_R \left(\frac{\lambda}{4\pi}\right)^2\right] - 10nLog(R) - 10Log(kT\ BW\ NF) - L_{dB} \qquad (2)$$

where the “range loss exponent” is given by n, and L_{dB} is the bulk loss (in dB) due to absorption by walls, etc. For free-space propagation, n≡2 and L_{dB} is 0 dB. The primary quantities of interest for the indoor channel are of course the loss exponent n and the bulk loss L_{dB}.

A second straight-forward model that has been considered from time to time within Magis is that by Medbo [2]. This model assumes an additional flat dB-per-meter loss represented by α in (3) but is otherwise the free-space model of Friis.

$$SNR_{dB} = 10Log\left[P_T G_T G_R \left(\frac{\lambda}{4\pi R}\right)^2\right] - 10Log(kT\ BW\ NF) - \alpha R \qquad (3)$$

In (3), R is the range in meters and α has the units of dB/meter having a value of approximately 0.44 dB/m.

All of the channel propagation loss models just mentioned exhibit a square-law decrease in SNR as the RF frequency is increased. If all other factors are left unchanged in the foregoing equations, the SNR for a signal at 5.25 GHz rather than 2.4 GHz will be reduced by $20Log(5.25/2.4) = 6.8\,dB$. If we were dealing with a strictly line-of-sight (LOS) channel without multipath using ***omni-directional antennas***, the discussion would be over. However, for a LOS-link at 5 GHz, this 6.8 dB difference could be easily made up by the increased antenna gain available at 5.25 GHz as compared to 2.4 GHz with the same size antenna. The presence of significant multipath with the indoor wireless channel changes the picture dramatically though, especially as the data rate is increased beyond several Mbps, and these simplistic models are inadequate to reveal the entire story.

2.1.1 Propagation Losses Through Common Building Materials at 2.4 GHz and 5 GHz[4]

Additional propagation losses beyond that experienced in free-space are due primarily to (i) reflections caused by spatial impedance discontinuities encountered by the signal wavefront as it propagates through space and (ii) ohmic losses that occur from propagation through materials other

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[1] D.C. Hogg, “Fun with the Friis Free-Space Transmission Formula”, IEEE Antennas and Propagation Magazine, Vol. 35, No. 4, August 1993 G.W. Collins, “Wireless Wave Propagation”, Microwave Journal, July 1998

[2] Numerical Gain= $10^{0.1Gain_{dB}}$

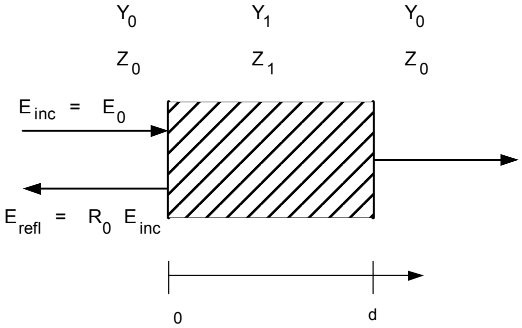
[3] Noise Factor = $10^{0.1NoiseFigure_{dB}}$

[4] Magis Networks Report, [3]

than free-space. Since the impedance of free space is $Z_o = \sqrt{\mu_o / \varepsilon_o} = 377\,\Omega$, any impedance change due to walls, floors, etc. encountered by the propagating signal will result in reflections that lead to frequency-selective fading due to the multipath.

For measuring the scattering parameters of a dielectric material in free space, the relative permittivity of the material can be calculated as described here by assuming a planar incident wavefront and an infinite plane-parallel plate dielectric slab. Imposing boundary conditions at the interface of the dielectric material, that is, that the tangential components of the electric and magnetic fields must be continuous, leads to a system of equations relating the transmission and reflection coefficients of the system, the electric fields, and the dielectric properties of the material. These quantities are described graphically in Figure 1 and the equations that follow

Figure 1 Electric Field Components for a Plane Electromagnetic Wave Incident on an Infinite Plane Dielectric Slab in Free-Space



$$
\begin{aligned}
&\mathrm{E}_0(1+\mathrm{R}_0) = \mathrm{E}_1(1+\mathrm{R}_1)\\
&\frac{\mathrm{E}_0}{Z_0}(1-R_0) = \frac{E_1}{Z_1}(1-R_1)\\
&E_1\left(e^{\gamma_1 d} + R_1 e^{-\gamma_1 d}\right) = T_0 E_0\\
&\frac{E_1}{Z_1}\left(e^{\gamma_1 d} - R_1 e^{-\gamma_1 d}\right) = T_0 \frac{E_0}{Z_0}
\end{aligned}
\qquad (4)
$$

where $\gamma_i = j(2\pi/\lambda_0)\sqrt{\tilde{\varepsilon}_{ri}}$, $Z_i = \dfrac{\gamma_0}{\gamma_1} Z_0$, $\tilde{\varepsilon}_{ri}$ is the complex relative permittivity of medium "i" and Z_i is the impedance of medium "i". The solutions in terms of R_0 and T_0 for this system of equations are given in [1] as

$$
\begin{aligned}
R_0 &= \frac{\left(\gamma_0^2 - \gamma_1^2\right)e^{-\gamma_1 d} - \left(\gamma_0^2 - \gamma_1^2\right)e^{\gamma_1 d}}{\left(\gamma_0 + \gamma_1\right)^2 e^{-\gamma_1 d} - \left(\gamma_0 - \gamma_1\right)^2 e^{\gamma_1 d}}\\
T_0 &= \frac{4\gamma_0\gamma_1}{\left(\gamma_0 + \gamma_1\right)^2 e^{-\gamma_1 d} - \left(\gamma_0 - \gamma_1\right)^2 e^{\gamma_1 d}}
\end{aligned}
\qquad (5)
$$

The power transmission and reflection coefficients are then given by

$$
\begin{aligned}
T &= \left|T_0^2\right|\\
R &= \left|R_0\right|^2
\end{aligned}
\qquad (6)
$$

and $T + R + A = 1$, where A is the power coefficient of absorption.

Representative transmission and reflection results from [3] are provided here in Table 1. As shown there, most of the losses are very similar between 2.3 GHz and 5.25 GHz except for red brick and cinder block where the 5.25 GHz signal losses are higher.

Table 1 Transmission and Reflection Coefficients at 2.3GHz and 5.25GHz [3]

Material	T (dB)			R (dB)		
	2.3 GHz	5.25 GHz	Δ	2.3 GHz	5.25 GHz	Δ
Plexiglass (7.1mm)	-0.3560	-0.9267	0.5707	-12.23	-5.65	-6.5753
Plexiglass (2.5mm)	-0.0046	-0.2041	0.1994	-21.69	-13.25	-8.4470
Blinds (closed)	-0.0016	0.0020	-0.0035	-30.97	-20.39	-10.578
Blinds (open)	0.0137	0.0315	-0.0178	-44.23	-46.95	2.7210
Red brick (dry)	-4.4349	-14.621	10.186	-12.53	-8.98	-3.5459
Red brick (wet)	-4.5119	-14.599	10.087	-12.52	-9.41	-3.1185
Carpet (back)	-0.0361	-0.0318	-0.0044	-25.19	-15.8	-9.4080
Carpet (weave)	-0.0271	-0.0056	-0.0214	-26.94	-18.7	-8.2710
Ceiling tile	-0.0872	-0.1795	0.0923	-21.07	-18.7	-2.3470
Fabric	0.0216	0.0133	0.0083	-41.70	-30.1	-11.570
Fiber-glass	-0.0241	-0.0340	0.0099	-39.40	-28.8	-10.581
Glass	-0.4998	-1.6906	1.1908	-11.29	-4.9	-6.3446
Drywall (12.8mm)	-0.4937	-0.5149	0.0211	-12.11	-11.5	-0.6390
Drywall (9mm)	-0.5095	-0.8470	0.3376	-12.03	-8.87	-3.1596
Light cover (front)	-0.0040	-0.0533	0.0494	-28.47	-20.0	-8.4490

Material	T (dB)			R (dB)		
	2.3 GHz	5.25 GHz	Δ	2.3 GHz	5.25 GHz	Δ
Light cover (back)	-0.0070	-0.0532	0.0462	-28.07	-18.8	-9.2390
Linoleum (back)	-0.0186	-0.1164	0.0977	-26.05	-17.3	-8.7610
Linoleum (front)	-0.0198	-0.1278	0.1081	-23.69	-16.0	-7.6690
Fir lumber	-2.7889	-6.1253	3.3364	-17.45	-14.8	-2.6890
Particle Board	-1.6511	-1.9508	0.2997	-8.59	-14.1	5.5359
Plywood	-1.9138	-1.8337	-0.0801	-9.05	-30.5	21.422
Stucco (back)	-14.582	-13.906	-0.6760	0.62	0.04	0.5785
Stucco (front)	-14.863	-13.235	-1.6280	-2.38	-9.24	6.8587
Tiles	-2.2163	-1.4217	-0.7946	-6.24	-14.9	8.6093
Tar paper	-0.0956	-0.1341	0.0385	-28.88	-17.8	-11.067
Cinder block (dry)	-6.7141	-10.326	3.6119	-7.67	-6.13	-1.5324
Cinder block (wet)	-7.3527	-12.384	5.0313	-5.05	-7.55	2.5080
Diamond mesh	-20.985	-13.165	-7.8200	-0.53	0.89	-1.4216
Wire lath (paper)	-1.2072	-0.7044	-0.5028	-6.38	-10.9	4.6015
Wire lath	-1.2136	-0.3404	-0.8732	-8.01	-21.8	13.764

It is worthwhile to point out that signals reflected from many of the materials including glass and plexiglass in Table 1 are less attenuated at 5 GHz than at 2.4 GHz. This fact translates into richer multipath characteristics at 5 GHz than at 2.4 GHz which can be advantageously exploited to improve non-LOS links within indoor environments if desired.

***Key Point:** Propagation losses through most building construction materials are very similar at 2.3 GHz and 5.25 GHz. Reflections are however more prevalent at 5 GHz leading to richer multipath characteristics that if advantageously exploited, can lead to very substantial improvements in link throughput and reliability.*

2.2 Time-Varying Multipath

The short wavelengths involved at both 2.4 GHz and 5.25 GHz lead to multipath characteristics that can vary fairly quickly with time. At the same time, nearly time-static multipath fading characteristics have also been observed that span seconds or even minutes. This latter phenomenon makes the use of large data buffers to introduce time diversity with standard IEEE802.11a implementations questionable at best because even very long buffers (e.g., 90 seconds) can be over-run. The issue being addressed within this section pertains more to the question of how quickly the channel multipath characteristics can change rather than how long they may persist.

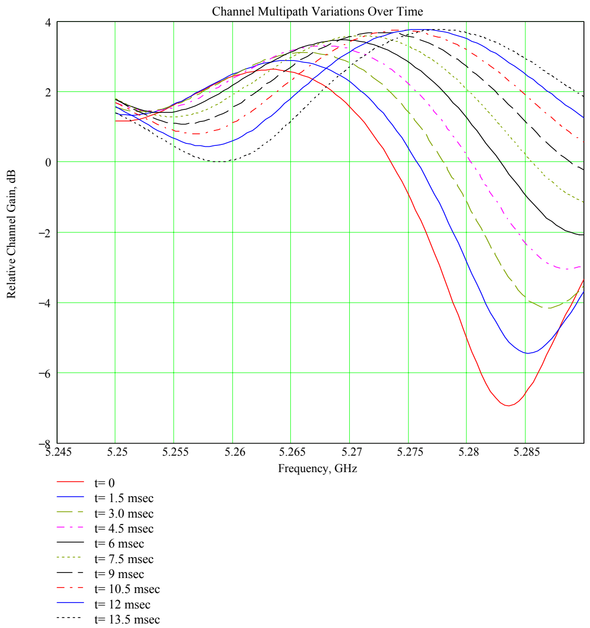
In order to facilitate this discussion, it is helpful to consider a simple 3-ray multipath model that can be represented mathematically with a channel transfer function given by

$$H(f) = 1 + A_1 e^{-j2\pi f(\tau_1+\tau_m)\tau_1} + A_2 e^{-j2\pi f(\tau_2+\tau_m)} \qquad (7)$$

where A_1 and A_2 are the relative strengths of the two multipath rays, τ_1 and τ_2 are the relative path length time differences compared to the direct-ray, and τ_m is a hypothesized additional time-dependent path delay due to user movement. As this model stands, it can exhibit channel loss or channel gain above the normal free-space channel path loss. Selection of different parameter values is fairly non-critical in showing the time-varying behavior of the multipath characteristics that result.

In free-space, signals travel approximately 11.8 inches per nanosecond. If the user movement is assumed to be V_{user} in feet-per-second orthogonal to the receive signal wavefront, then $\tau_m(t) = 12 V_{user} t / 11.8$ nsec. The sensitivity of the observed frequency-selective fading shown in Figure 2 to path delay changes in (7) is incredible in that even 0.1 nsec represents 1.18 inches which is almost a half-wavelength. In the case of Figure 2, the example parameter values chosen were A_1= 1, A_2= 0.40, A_3= 0.23, τ_1= 21.85 nsec, τ_2= 32.34 nsec and τ_3= 53 nsec and the user was assumed to be moving at 5 feet per second which is equivalent to about only 3 miles per hour.

Figure 2 Example Channel Multipath Characteristics Over Time

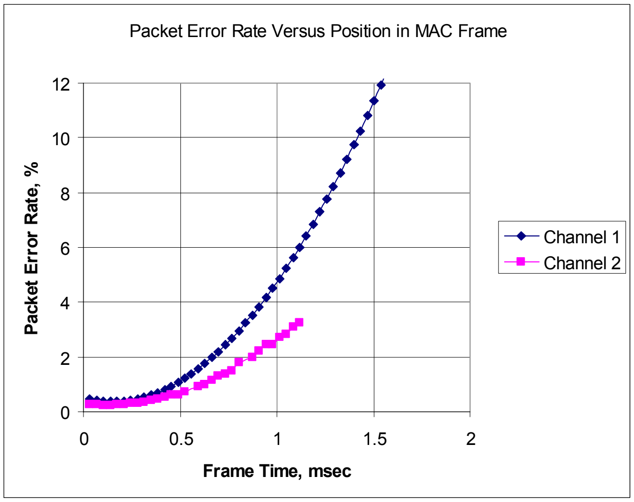


As shown in this simple example, a small amount of motion introduced into the wireless channel can result in a wide 10 dB frequency-selective impairment that could break the wireless link along the edge of coverage.

In order to explore the channel coherence issues involved with communication over the 5 GHz channel, the Air5 system was purposely modified to use longer MAC frames over several different channel conditions and histograms of the data packet error rate (PER) were computed. The channel estimates that were used were based upon single-shot estimates using the T1-T2 long-symbol portion of the IEEE802.11a standard preamble. The channel that was considered was the large conference room area at Magis which is a large open-area having large metallic window blinds along two walls, an approximately square perimeter having about 1500 square feet of floor space, 8 foot ceiling in an industrial multi-story steel-reinforced concrete building. The wireless link was set up across a distance of about 25 feet in an area to the side of the audience seating area where refreshments were served during a company meeting. The "channel 1" conditions occurred while approximately 40 people were milling around getting refreshments and directly disturbing the line-of-sight link. The "channel 2" conditions are actually a long-term average over the entire length of the meeting that was held in the conference room thereby including a substantial amount of time during which most of the staff was seated. The measurement data was post-processed to compute the PER as a function of the cell location within each MAC frame and the results are shown in Figure 3. As fully expected, the "channel 1" conditions with many people moving within the conference room exhibited considerably worse PER than the more benign conditions that involved far less people activity on the average.

The point of this channel coherence discussion is primarily that the operating point of the entire system must be managed carefully in order to deliver good QoS performance. Good QoS performance without using large data buffers and their accompanying time delay limits the number of packet re-transmission attempts that can be used. If the PER is too high and the number of re-transmissions for a given packet are exhausted, that packet would be dropped and artifacts introduced if operating in video mode. The results here are specific to the implementation details of the Air5 system, but the same kind of factors must be considered in any other system design also.

Figure 3 Packet Error Rate Versus Packet Location Within MAC Frame for 64-QAM Rate= ¾



Several summary points are worth noting with regard to the time-varying nature of the frequency-selective fading / multipath that is present on most 5 GHz indoor channels:

Key Points:

- *With a free-space wavelength of only about 2 inches, very slight positional displacements can change the frequency-selective fading characteristics dramatically;*
- *Even very modest movement of either the wireless terminals or other objects within the propagation volume can lead to significant changes in the frequency-selective fading characteristics;*
- *Without some form of channel adaptation, use of long MAC frames will be very difficult due to channel coherence losses, particularly at 36 Mbps and higher. The PER must be closely administrated if high QoS performance is desired.*

2.2.1 Pedestrian-Induced Fading at 5 GHz

A recent paper considered the effects of pedestrian traffic on indoor 5 GHz channels [5] ***based upon simulation***. Fading profiles were reported for a point-to-point link in a 150-m^2 open-plan environment with moderate pedestrian traffic conditions. The fading depths reported ranged from 31 dB to 36 dB and the results were Rayleigh-distributed despite the presence of a direct-ray for the majority of the simulated scenarios. The floor plan used for the simulation study is shown here in Figure 4. The pedestrian-induced fading episodes that this simulation study predicted are shown in Table 2. Many factors are not included in this simulation model including the modulation bandwidth and the role of frequency-selective fading versus a complete flat fade across the entire modulation bandwidth. In this respect, experimental results using the IEEE802.11a waveform would probably be more useful. Even so, if the below-threshold percentages that are reported in Table 2 are representative of the channel behavior involved, this level of performance may be quite adequate for data-only applications whereas it is not acceptable for the high QoS demands posed by video.

Figure 4 Floor Plan for Simulation Study Regarding Pedestrian Traffic at 5 GHz

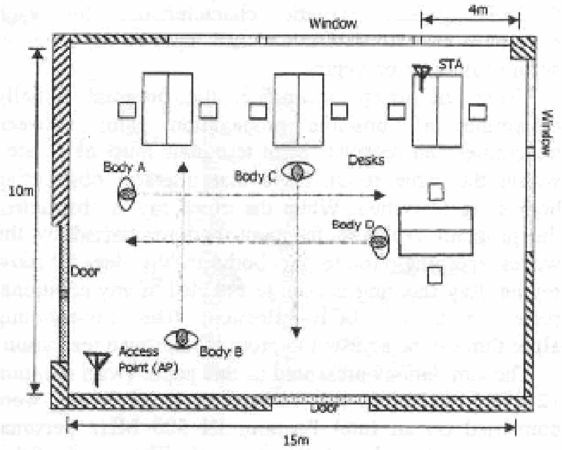


Table 2 Pedestrian-Induced Fading Episodes at 5.7 GHz

Threshold Level Relative to Mean (dB)	% of Time Below Threshold
0	66.6
-5	21.1
-10	5.8
-15	1.1
-20	0.1

Key Point: *If the below-threshold probabilities are viewed as video-outage probabilities, pedestrian traffic must be a major consideration in the system design in the context of high-quality video delivery. Short of using very large video buffers, no one wants to receive only 94.2% of their 2 hour HDTV movie error free.*

2.2.2 Generalized Space-Time Processing to Combat Channel Multipath

Channel delay-spread associated with channel multipath often limits the range performance of IEEE802.11b systems rather than inadequate signal strength, particularly at the higher data throughput rates. Since multipath is really interference of one's own signal with oneself, severe multipath can actually be more problematic for smaller distances than for larger distances.

Space-time coding (STC) and its many variants is one of the most active research areas in wireless communications. Generally, the primary motivation for STC is to increase the overall system capacity in terms of bits/Hz. Unfortunately, these systems are still quite expensive and in the most degenerate channel cases, very limited capacity improvement may be achieved.

STC systems take advantage of the transmit and receive signal wavefronts in the time, spatial and coding dimensions to ideally deliver greater throughput. A far less aggressive perspective has been employed for many years through traditional diversity methods which were developed in part to improve channel reliability in the wake of channel multipath. Traditional diversity systems employ a wide range of techniques including spatial, frequency, time and polarization methods in order to combat channel multipath as well as other channel impairments.

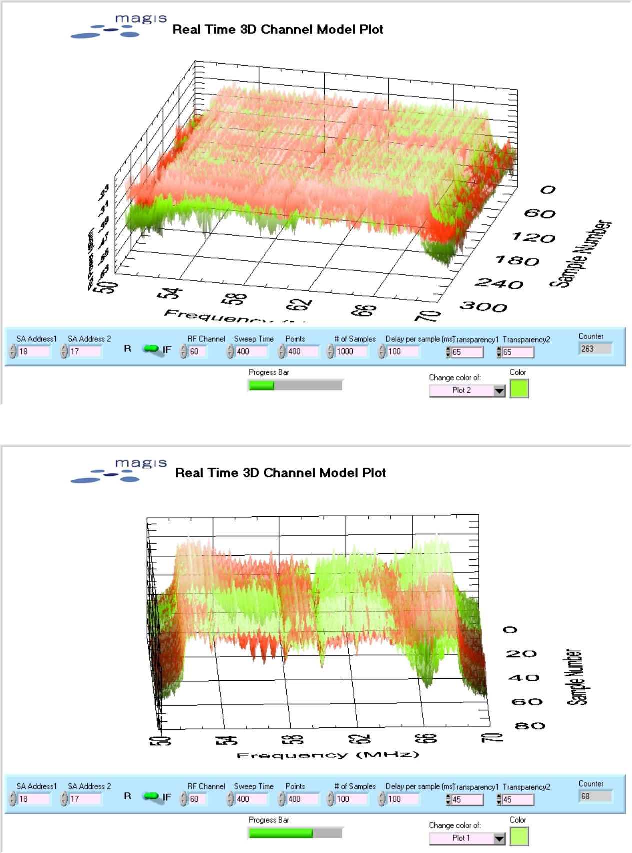
Most if not all of the primary channel loss models that are used throughout the wireless industry are related in some way to a power-law range dependency as discussed earlier in Section 2.1. All of these formula rely on local CW signal strength measurements that are made over a specified spatial region and then averaged. This time and position averaging eliminates almost all of the spatial and frequency domain structure present. Take for instance the discussion of the measurement techniques used in a recent paper[5] on this topic:

"Halfwave dipole (2 dBi) antennas and directional patch antennas (7 dBi, 90° x 70° beamwidth) were used in the measurements. The transmitted signal was a continuous wave at 5.2 GHz and of about 30 dBm power. At the receiver, a spectrum analyzer (HP8595E) with a low noise amplifier was used. The sensitivity[6] of the receiver chain was about -130 dBm. For each measurement point a spatial average of received power was obtained by taking the median of 401 samples on a horizontal circle of about 0.5 m diameter."

As clearly stated, spatial signal strength variations of the signal wavefront are purposely averaged out. Therefore, if one specific spatial location exhibits very good signal strength, even though the system could benefit greatly if it somehow chose to receive the signal at that location, the power-law assessment averages all of this detail away. Furthermore, our own experience at Magis has shown that the spatial profile of the signal strength can change dramatically unless "all" of the measurements are made very nearly at the same instant in time.

Many channel sounding assessments were done in the Magis building two years ago to more fully understand the propagation problem more thoroughly. A typical result from one of these assessments is the time-frequency domain chart provided here in Figure 5. During this effort, a wide-band CDMA signal source was used having a modulation bandwidth of about 20 MHz. Signal interception software was developed in a laptop computer environment for ease of mobility and a pair of simple half-wave patch antenna were used to capture the signal wavefront at two points in space simultaneously. As shown in Figure 5, the receive signal structure is clearly time-varying with many rich features. In each plot, two traces are overlaid corresponding to the signal received by the two different patch antennas separated a specified distance apart.

Figure 5 Example Receive Signal Assessment where Signal Amplitude is Plotted Against Time and Frequency



SA Address1: 18
SA Address 2: 17
RF Channel: 60
Sweep Time: 400
Points: 400
# of Samples: 1000
Delay per sample (ms): 100
Transparency1: 65
Transparency2: 65
Counter: 263
Change color of: Plot 2

SA Address1: 18
SA Address 2: 17
RF Channel: 60
Sweep Time: 400
Points: 400
# of Samples: 100
Delay per sample (ms): 100
Transparency1: 45
Transparency2: 45
Counter: 68
Change color of: Plot 1

Although colorful, this previous perspective of the time-varying frequency-selective fading channel is not sufficiently quantitative to be that useful. A second-generation channel instrumentation setup was put together with the collection patch antenna hosted on a pair of plastic micrometers as shown in Figure 6. Care was taken to make sure that

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[5] Medbo, J., Jan-Erik Berg, "Simple and Accurate Path Loss Modeling at 5 GHz in Indoor Environments with Corridors", VTC2000

[6] Although not stated, if we assume that the measurement system noise figure is 8 dB, this translates into a resolution bandwidth of about 4 kHz.