Antenna Guidelines For Use With Magis Air5^{TM}

Optimizing System Performance Over Difficult Multipath Communication Channels

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Advance Information

This product is in a formative or design state. The document contains design target specifications for product development.

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1. Introduction

Delivery of high-throughput, high-Quality-of-Service (QoS) information over a wireless 5 GHz indoor communication channel is very challenging, due to the severe amount of frequency-selective fading that is generally present. Although the Magis Air5™ system has been designed to deal with multipath in an optimal manner, the overall performance of the system can be significantly affected by the choice of antennas used in the system.

Antenna choice for a specific product depends on a wide range of factors, including cost, product form-factor, ultimate throughput and QoS required, and data type. No single antenna design can be optimal for all cases. The antenna recommendations presented in this memorandum are intended to exhibit the Magis Air5 chipset performance at its best, with no serious regard for size or form factor.

This memorandum presents a number of guidelines that should be helpful in matching the Magis Air5 chipset technology with the antenna technology best suited for most applications.

2. Situation Overview

The indoor 5 GHz communication channel that uses the IEEE802.11a signaling rates can be severely compromised by frequency-selective multipath. Contrary to popular belief, frequency-selective fading can very often cripple even the most robust physical layer mode (6 Mbps, BPSK, R=½). Deep, flat fading that extends across the entire 20 MHz modulation bandwidth can often occur. Unlike mobile channels, once a single antenna falls into a serious fading condition, that condition may persist for seconds or even minutes, unless there is motion present within the propagation volume that changes the existing multipath characteristics. For this reason alone, a multi-antenna (MA) methodology must be employed for indoor networking to deliver high-QoS services.

The Magis Air5 system optimally combats the serious effects of frequency-selective multipath by using advanced MA signal processing techniques. These techniques are most effective when the multiple antennas involved have statistically independent “looks” at the incoming signal wave front, becoming less and less effective as the signals delivered to each individual antenna become more and more similar. It is this aspect of the antenna array design for the Magis Air5 system that is complicated. It is not sufficient to simply design a “good” antenna element; rather, the antenna elements used in the array must work in unison to deliver the maximum channel capacity[1] achievable under the wide range of multipath channel conditions possible.

3. Basic Questions

The Magis Air5 hardware approach is noticeably different in that it uses up to six antennas simultaneously. It is worthwhile to address a number of basic questions regarding the Magis Air5 approach before the more detailed subject matter is presented.

3.1 Why Six Antennas?

Communication over a fading wireless channel involves mathematical probability. If the fading degrades the Bit Error Rate (BER) performance of the system, the impairment is typically measured in dB. On the other hand, if the fading phenomenon crushes the communication link for small intervals of time, the impairment is discussed more in terms of the probability of a link outage. In either case, the rate of information exchange through the wireless channel is impaired.

Both channel impairment types are serious when high-quality video transmission is involved. When video is involved, the data throughput rate is also reasonably high. As a result, there is often little excess system throughput capacity available to deal with a problematic channel.

The following example illustrates how frequency-selective multipath is particularly problematic. Assume that the ideal receive signal spectrum is as shown in Figure 1 (a) but, due to multipath, one antenna at the distant end of the link receives the signal spectrum shown in Figure 1 (b). Clearly, the signal-to-noise (SNR) ratio varies across the modulation bandwidth, dipping to very low levels in the spectral null region. The situation can be further amplified by considering the generalization shown in Figure 1 (c). Assume that the forward error correction (FEC) being used is rate (R) ¾. This

[1] Channel capacity is in the context of information theory in this usage. It can be estimated using channel cutoff rate, as discussed later in this memorandum.

means that one quarter of the coded bits sent over the channel form the FEC redundancy. If the deep frequency null in Figure 1 (c) eliminates more than one quarter of the total modulation bandwidth present, information is unquestionably lost over the wireless channel. In any practical system, the FEC would “break” well before this much damage is impressed on the received spectrum.

Assume further that the probability that a single antenna receive spectrum is damaged in this manner (or worse) is p. If the system is using a single antenna, the probability that the communication link breaks is simply p. If, on the other hand, there are N statistically independent receive antennas, each processing different signal wave fronts of the same incident signal, the probability that the link breaks in the same manner is reduced to p^N. Therefore, if the probability p is 0.03 for each of the N antennas considered separately, the probability that the link would be broken when using five such antennas under the same conditions is $(0.03)^5 = 0.000000024$, which is dramatically better.

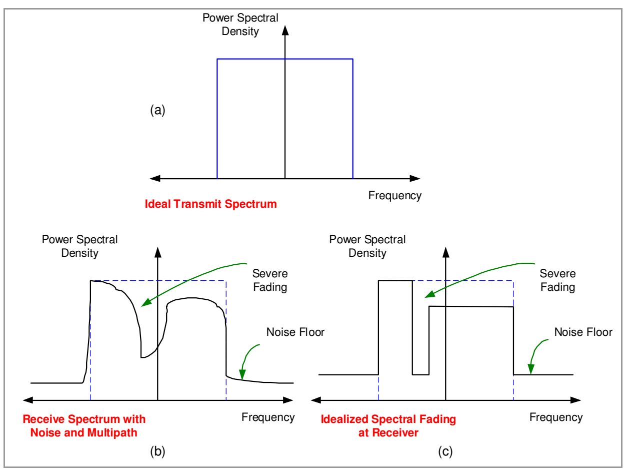

Figure 1: Frequency-Selective Fading at the Receive End of the Link

The Magis Air5 system was purposely designed to deliver multiple simultaneous streams of high-quality video. This fact alone mandates that the link robustness be made orders of magnitude better than that customarily used for simple data transfer. Consumers do not want their video program to break up randomly during a two-hour movie. If the link is not adequately robust, the only way to circumvent the problem is to use very large data buffers at the receive end, hoping that the buffers are not emptied before better link conditions return. This is particularly problematic for indoor communication links because, once a (single-antenna) link is in a serious fading condition, that condition may persist for seconds or even minutes. In the case of very long fading intervals, even large amounts of data buffering will not be sufficient, and consumers will experience a loss of video.

Even in data-only communication, link robustness is important. It is not uncommon for conventional IEEE802.11a systems that use a carrier-sense-multiple-access (CSMA) medium-access-control (MAC) layer to retransmit dropped data packets 10 or even 20 times. This amount of retransmission consumes channel capacity very rapidly, resulting in very inefficient use of the precious wireless bandwidth available. Since only four RF channels are presently available in Japan at 5 GHz (and 8 channels in the U.S.), efficient use of the spectrum resources is a necessity.

3.2 Are There Other Alternatives to Multiple-Antenna Processing?

As discussed in Section 3.1, frequency-selective fading can lead to prolonged link outage intervals in single-receive antenna systems that are operating in the indoor multipath environment. Data buffering can alleviate this problem in single-antenna systems as long as the outage is for a short time. However, in general, the multiple-antenna receive systems can provide far superior performance. Simply put, if a single-receive antenna system has its one antenna situated in a severe multipath fade, there is no signal other than noise to process.

3.3 Why More Receive Antennas than Transmit Antennas?

This question really pertains to the advantages of transmit diversity as compared to receive diversity. Advanced multiple-input-multiple-output (MIMO) systems use multiple transmit and multiple receive antennas in space-time coded systems to deliver very high spectral efficiency throughput. Whether MIMO-type signal processing is attempted or more traditional diversity methods are used, a number of factors favor receive-end multiple-antenna (MA) processing over transmit-end, especially when cost and power consumption are important.

Focusing on IEEE802.11a type signaling (i.e., excluding space-time-coded waveforms), if MA signal processing is used at only the receiver-end of the link, no feedback over the channel is required to deal with the frequency-selective fading, since all the computations can be done locally. The computational burden is, therefore, distributed rather than localized within the access point (AP). The handling of receive-signal levels in the MA processing is also much easier than dealing with the signal levels normally associated with transmitter operation.

If MA technology is used at only the transmit end, multiple power amplifiers are needed, resulting in additional cost and current consumption. It is also much more difficult to prevent unwanted coupling between the different transmitter outputs. This coupling normally leads to additional spectral regrowth and other problems. If the transmit antennas are to be shared with the receive function, very linear RF switches are required, thereby posing additional issues.

The Magis Air5 system terminals use one transmit antenna and up to five receive antennas. This architecture addresses the difficulties associated with having more than one transmit antenna in any terminal, while providing the MA signal processing that is mandatory at the receive end to address frequency-selective fading.

3.4 Can Fewer Receive Antennas Be Used?

Fewer than five receive antennas can be used in any terminal, but the link-outage probability will increase correspondingly, as discussed earlier in Section 3.1. Additional tradeoffs can be made regarding link robustness and the number of receive antennas used, as discussed in Section 5.

3.5 How Serious Is Attenuation Between the Receive Antennas and the RF Electronics?

The indoor wireless channel is a fading channel. In contrast with a typical satellite channel, where fractions of a dB matter significantly, the indoor fading channel poses dramatically different constraints on the design and operation of a wireless system.

Consider the following two scenarios:

1. Use all five receive antenna ports, cable loss to each antenna spanning from 3–5 dB.
2. Use only three receive antenna ports, cable loss to each antenna <1 dB.

Assuming the two scenarios represent the same bill-of-material cost[2], which scenario would deliver better performance on the average over the indoor multipath channel? The lower coaxial cable loss would result in a correspondingly lower system noise figure and, therefore, better system sensitivity. The greater number of receive antennas in scenario #1 could, of course, provide more independent looks at the incident signal wave front than scenario #2.

Answer: Scenario #1 is generally far superior to scenario #2, as far as the indoor wireless channel is concerned, because of fading and the reasoning presented earlier in Section 3.1. While it is true that less coaxial loss results in better receiver sensitivity, if severe frequency-selective fading is present, the penalty there can easily be 20 dB, or the link may simply not work at all.

3.6 Doesn't OFDM Eliminate Most of the Multipath Problems?

In the case of a complete flat-frequency fade for a single-antenna system, no amount of signal processing can recover the desired signal, because only noise is present. This question really only applies to frequency-selective fading like that shown in Figure 1 and Figure 3, where only a portion of the modulation spectrum experiences severe nulling. Even in these situations though, hardware performance constraints limit the degree to which Orthogonal Frequency Division Multiplexing (OFDM) alone can resolve the problem.

Even in strong signal conditions, where the frequency nulled spectrum region is still well above the ambient noise floor at the antenna input, the finite performance limits of the radio electronics affect the degree to which the received spectrum can be effectively repaired. This is due to two reasons. First, receiver linearity sets an additive-type intermodulation noise floor that to first-order competes with the desired signal and fills in the spectral nulls if they are deep enough. Second, the receiver's own phase-noise performance also limits the signal-to-noise ratio (SNR) achievable through the receive chain. Receiver linearity alone limits the achievable SNR through the receiver to roughly 35 dB, although in the case of 64-QAM R=¾, the system sensitivity $SNR_{Sens} \cong 25$ dB is required,

[2] Scenario #1 might use higher loss coax to connect antennas, because there are five of them, whereas scenario #2 could use better antennas with more expensive coax connections.

thereby leaving a fade-depth margin of perhaps 10 dB. In the case of local-oscillator phase noise alone, the phase noise pedestal causes spreading of adjacent OFDM frequency bins into adjacent bins, thereby also setting limits on the achievable SNR through a practical receiver. Therefore, the channel estimate (based on the long-symbol portion of the IEEE802.11a standard preamble) is not sufficient to recover spectral nulls that are deeper than perhaps 10 dB for 64 QAM operation. This concept is shown in Figure 2. Additional measures, like MA signal processing, must be employed at each receiver to deal with the performance limitations of any practical low-cost, low-power receiver.

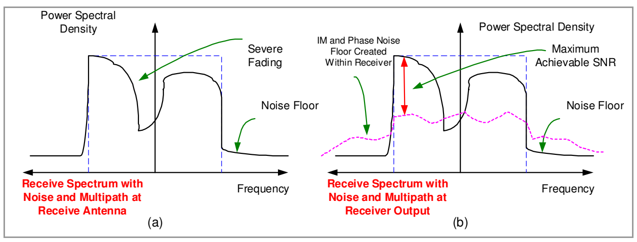

Figure 2: Illustration of Already Disadvantaged Signal at Receiver Input due to Frequency-Selective Multipath is Further Impaired by Finite Receiver Linearity and Phase Noise Performance

4. Indoor Channel Multipath Characteristics

Indoor frequency-selective fading in the 5 GHz channel exhibits both very fine and coarse characteristics. Since a quarter-wavelength at 5.25 GHz is only 0.562 inches, almost every metal object within the propagation volume participates in the creation of multipath signals. The most common frequency-selective fading that occurs is like that shown in Figure 3, where portions of the received spectrum are reduced in amplitude, but there is also one or more spectral nulls present. In the case of OFDM, signaling information that is present in the frequency-null region will be compromised unless the received SNR is high. Error correction coding that is present in the IEEE802.11a signaling[3] will combat some of the spectral loss shown in Figure 3. However, if the spectral null is too wide or multiple nulls are present, the error-correction coding may be broken. This information theory aspect is developed at greater length in Section 10.

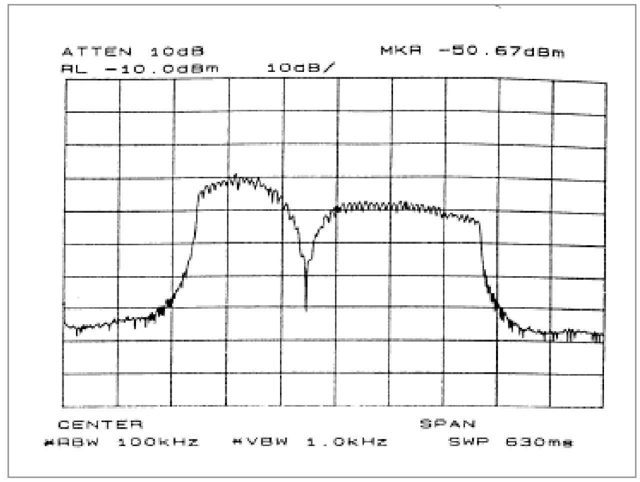

Figure 3: Modulation Spectrum Plot with Frequency-Selective Multipath[4]

A second type of frequency-selective fading that has been observed frequently in the office environment is a large flat-fade that severely attenuates the entire 20 MHz modulation bandwidth. Movement of the receive antenna by only a few tenths of an inch can move the received signal spectrum in and out of this complete signal fade. This observation alone makes it mandatory to include some form of receive diversity in the system, since indoor frequency-selective fading can often be quite stationary over time, thereby destroying the communication link. Several representative measurements of frequency-selective fading over the indoor office channel are discussed in Section 11.

In general, frequency-selective fading effects on the indoor 5 GHz channel can be extremely bad. Since multipath results from interference from one's own time-delayed signal, the effects of multipath can often be worse over shorter distances than longer ones. In multipath-limited links, moving the receiver closer to the transmitter may in fact worsen communications rather than improve them.

5. Tradeoffs Between Antenna Arrays, System QoS, and Data Buffering

A number of high-level system performance parameters are linked together in the Magis Air5 system simply due to the laws of physics. Although this memorandum is intended to address the

[3] Viterbi convolutional coding. Magis Air5™ also includes Reed-Solomon FEC.

[4] From M10203, "A 20 Mbp/s OFDM Demonstrator at 5 GHz: System Design, Implementation and Experimental Results", Robert Castle, Alan Jones, Hewlett-Packard Laboratories, HPL-98-24, February 1998.

antenna question specifically, it is important to point out these conceptual linkages.

As developed in later sections, the Magis Air5 MA technology works best when all the receive antennas have independent (i.e., uncorrelated) looks at the receive-signal wave front. When the wave fronts seen by the antennas are independent, the likelihood that all the antennas are simultaneously in a flat-frequency fade is correspondingly much smaller. This is the conceptual basis for diversity in general.

To illustrate the coupling between these different system-level parameters, assume that all of the antennas momentarily have the same frequency-selective spectral notch shown in Figure 3. Assume further that the spectral notch is severe enough to cause data cells to be received in error. As a first line of defense, the system automatic repeat request (ARQ) function flags the errant data cells during each MAC burst, causing them to be retransmitted during a subsequent MAC burst. These retransmissions require (i) additional system throughput over the channel to support and (ii) additional time to get the errant data cells across the channel without error, which affects the time jitter (QoS). If the spectrum-notch conditions persist over time, multiple retransmission attempts may be required to get the errant data cells communicated across the channel. However, due to specific QoS constraints, the maximum number of attempts (TTL)[5] must be limited.

In the case of MPEG2 video, the maximum allowable time jitter between MPEG2 blocks that are delivered out of the receiver is very small (on the order of microseconds), whereas the length of each MAC frame is 1 to 2 msec. A smoothing buffer is, therefore, required in order to smooth out the occasionally intermittent delivery of MPEG2 packets over the wireless channel (due to ARQ activities). The depth of this buffer depends on the maximum TTL value that is used by the system. If a large TTL value is permitted, the smoothing buffer must be that much deeper, to avoid going empty before good MPEG2 packets are received over the channel.

For a given multipath scenario, the system packet-error-rate (PER) can be expressed as a function of the receive conditions $\underline{C}$ and the correlation between the receive antennas $\underline{\rho}$. (Both are vectors because up to five receive antennas are involved.)

$$PER = f(\overrightarrow{C}, \overrightarrow{\rho}) \tag{1}$$

For a real data-throughput rate *D* in Mbps, the average channel throughput rate required due to the overhead loss associated with (unlimited) data retransmissions is given by

$$D_{With\_ARQ} = \frac{D}{1 - PER} \tag{2}$$

If TTL= N_{ARQ}, then the probability that an errant cell does not get delivered error free is given by

$$P_{TTL\_Drop} = PER^{N_{ARQ}} \tag{3}$$

The mean-square number of transmission attempts required for a given PER is given by

$$\sqrt{\mathrm{E}\left(n^2\right)} = \sqrt{\frac{3PER - PER^2}{(1 - PER)^2} + 1} \tag{4}$$

The TTL value required to keep the overall system BER less than a specified level Λ_{BER} in spite of a PER and channel bit error rate (after FEC) p is given by

$$TTL \geq \frac{\log_e\left[(1 - PER)\frac{\Lambda_{BER}}{p}\right]}{\log_e(PER)} \tag{5}$$

This relationship is shown plotted for two different values of channel bit error rate p in Figure 4 and Figure 5. In all these cases, the presumption is that the PER and channel bit error rate p are statistically independent from burst-to-burst and bit-to-bit. If a serious spectral fade persists over multiple MAC bursts, this assumption will of course be violated.

[5] TTL= time to live, in terms of number of total transmission attempts allowed.

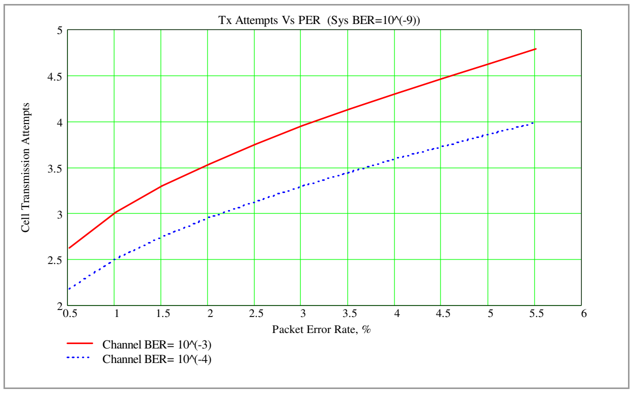

Figure 4: Transmission Attempts Required Versus Packet Error Rate for a Net System BER of 10^{-9}

A complete analysis of the interactions between the channel PER, choice of TTL parameter, and smoothing-buffer depth is beyond the scope of this memorandum. For the purposes of antenna array design, however, the array should ideally be constructed to deliver maximally independent looks at the received signal wave front, thus minimizing the system's reliance on a large number of retransmissions (i.e., large TTL) and, consequently, the need for a large smoothing buffer.

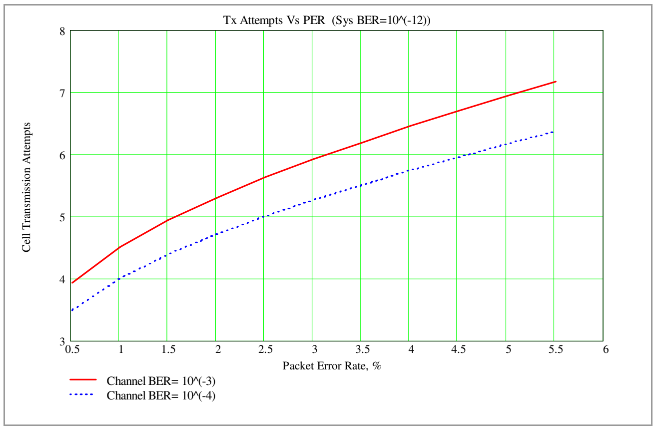

Figure 5: Transmission Attempts Required Versus Packet Error Rate for a Net System BER of 10^{-9}

6. Multiple Antenna Signal Processing: Technical Background

A great deal of activity is presently occurring in the areas of MIMO systems, space-time coding, hybrid modulation/coding techniques, diversity processing, smart antennas, and low-cost antenna design, etc., in order to facilitate 3G/4G cellular activities, as well as new initiatives like wireless home networking. Differentiating between practical product solutions and science projects is crucial in order to address consumers' performance and cost demands.

In the material that follows, technical discussions are presented to provide support for the antenna recommendations that are provided in Section 8.

6.1 General Comments

A myriad of different antenna design methodologies and design material choices can be found in the available literature. Product form factors, as well as customers' prior experience with wireless products, are all considerations when it comes to choosing the type of antenna technologies that are deemed acceptable. Although some comments and discussion will be provided concerning individual antenna elements, most of the attention will be addressed to design of the antenna array and the desirable properties that the array should deliver.

The Magis Air5 system is based on a *reasonable* amount of advanced multiple-antenna signal processing technology. This point cannot be overstated. Many technologies that are presently being pursued in academic circles may well deliver outstanding performance. However, cost, complexity, size, and/or power consumption make them simply unsuitable for the present-day consumer electronics marketplace.

Other technical solutions, while applicable for a single point-to-point link, are impractical to implement in a centralized network that ideally has a single access point. The processing burden on the AP that must communicate with all of the networked RTs can easily become prohibitive. In this respect, practical solutions must distribute the computational load across the field of RTs as much as possible, rather than rely on "unlimited" computational power in the AP. Unlike cellular telephone base stations that are very expensive and serve potentially hundreds of user terminals, a typical home installation is likely to have perhaps one to three RTs with a single AP, at least to begin with. In this respect, the AP must be almost as cost effective as the RTs, because there is little cost elasticity in the set-top box or other host device to defray more cost in the wireless AP electronics.

6.2 Receive Antenna Array Performance Objectives

The fundamental purpose behind the Magis Air5 multiple (receive) antenna approach is to deliver statistically independent looks at the incoming signal wave front, thereby avoiding (i) severe frequency nulls in the received signal spectrum and (ii) large flat-frequency fading that completely eliminates the received signal in serious multipath situations. This theme is central to all MIMO theory, whether “old-style” simple diversity techniques or advanced space-time coding in nature.

Antenna gain is also a serious consideration because the antenna gain enters into the Friis equation (19) directly, having a direct influence on communication range in power-limited, high-attenuation channels.

It is possible to design an antenna array that works exceptionally well in high-multipath situations, but performs miserably in low-multipath channel situations, and vice versa. The end-product designer who uses the Magis Air5 solution needs to understand these factors and either provide different antenna solutions specifically tailored for these different scenarios, or provide a single solution that is perhaps not completely optimal in all cases, but is sufficiently general purpose in nature.

6.3 Correlation Between Multiple-Receive Antenna Elements

As pointed out in Section 6.2, one of the important objectives that needs to be achieved in the array antenna design is the correlation between the multiple-receive antenna elements. The unwanted correlation can occur due to either mutual coupling between the antenna elements, because they are simply spaced too closely together, or because the antenna elements are not sufficiently spaced so as to have independent looks at the incident electromagnetic wave fronts.

6.3.1 Receive Antenna Element Spacing for Low Correlation

As developed in [1], the spatial correlation between two linear antenna elements when the multipath scatters form a two-dimensional, omni-directional diffuse field is given by[6]

$$\rho(d) = J_0\left(\frac{2\pi d}{\lambda}\right) \qquad (6)$$

where $J_0(.)$ is the zero-order Bessel function of the first kind and d is the antenna separation. The correlation function for this case is computed in Figure 6. As shown there, the first two zeros of the correlation coefficient occur with an antenna spacing of approximately 0.8 inches and 2.0 inches, respectively.

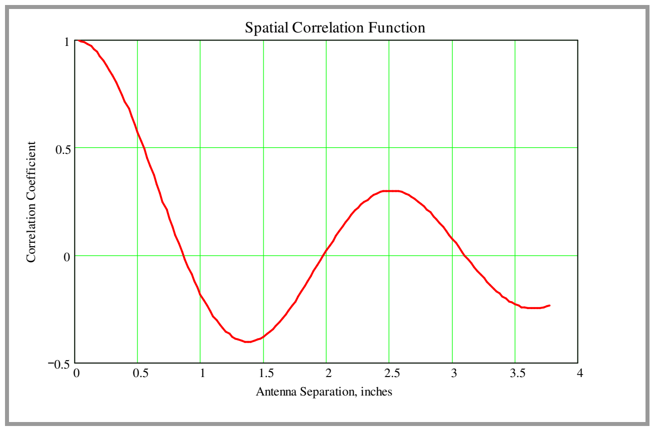

Figure 6: Spatial Correlation for Two Linear Antenna Elements in the Presence of Scatters that Form a Two-Dimensional Omni-Directional Diffuse Multipath Field

In the case where a linear array of receive antennas is used as shown in Figure 7, the antenna elements can be considered a pair at a time. Clearly, the adjacent neighbor elements will present the highest degree of correlation.

[6] Also see [6,7,9,10].

A linear array like that shown in Figure 7 may be adequate in situations where a preferred direction of communication is known, but this is not generally the case with the AP. In the AP case, a direction-insensitive antenna array is normally required, like that shown in Figure 8. In the circular array, the symmetry clearly favors no specific direction in azimuth.

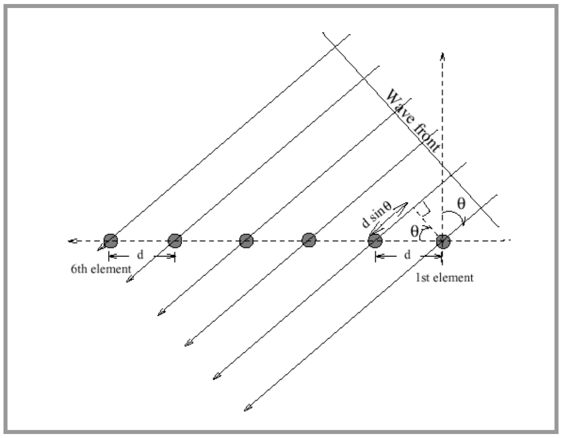

Figure 7: Linear Array of Diversity Antenna Elements [7]

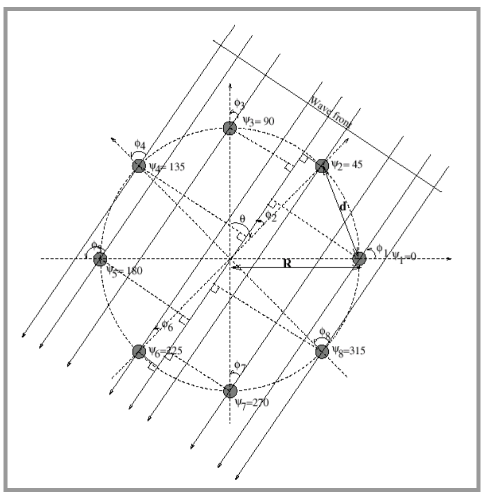

Figure 8: Circular Array of Diversity Antenna Elements [7]

In the Magis Air5 system, a maximum of five receive antennas are available. In order to preserve the desired symmetry, they should be arranged in a pentagonal shape, as shown in Figure 9. Due to the symmetry, every antenna is separated from every other antenna by either distance *d* or distance 1.618d. This observation makes it convenient to consider the antenna correlation question one pair at a time.

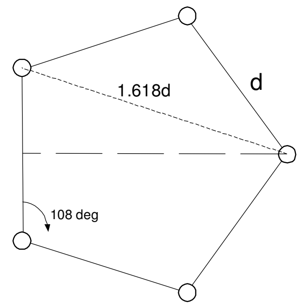

Figure 9: Pentagon Antenna Array Arrangement for Use with Five Receive Antennas

Based on this perspective, ideally, the correlation relationship given by (6) can be made close to zero for both lengths *d* and 1.618d. The two correlation functions are plotted in Figure 10, along with a third curve that represents the sum of the absolute values of the two correlation coefficients versus antenna parameter *d*. As shown in Figure 10, both pair-wise antenna correlation coefficients are near zero if the spacing parameter d is made approximately 2 inches.

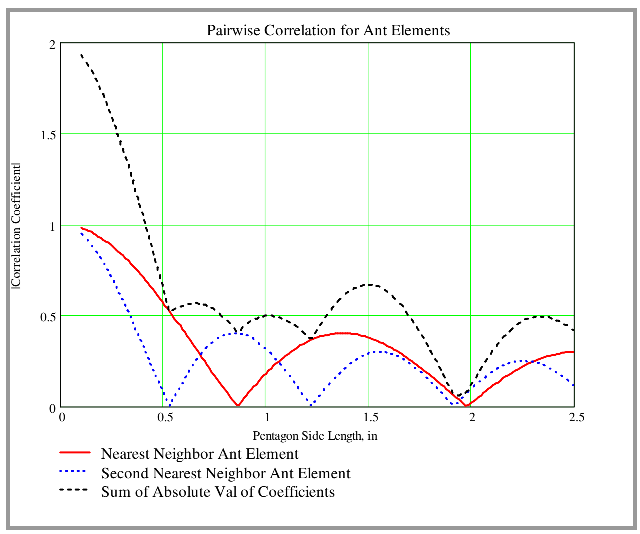

Figure 10: Pair-Wise Antenna Correlation for Pentagonal Antenna Element Arrangement

6.3.2 Other Antenna Array Geometries

Several other antenna array geometries are considered in [3], specifically those shown in Figure 11. The figure of merit used to analyze the geometries was based on a comparison of the diagonality properties of the array-correlation matrices. Although the differences reported were fairly small, the lowest correlation properties were achieved for the uniform linear antenna array, and the worst for the zigzag array. According to these results, the size of the antenna array aperture seen from different directions is strictly related to the correlation between antenna array-elements (i.e., bigger aperture implies lower correlation).

It is also insightful to know that broadside linear antenna arrays (element spacing *d*) in the context of space-time MIMO systems can deliver considerably more channel capacity than a five-or-six-element circularly arranged array having the same antenna element spacing *d* [31]. This is primarily because the linear broadside array presents the larger total width between the two geometries.

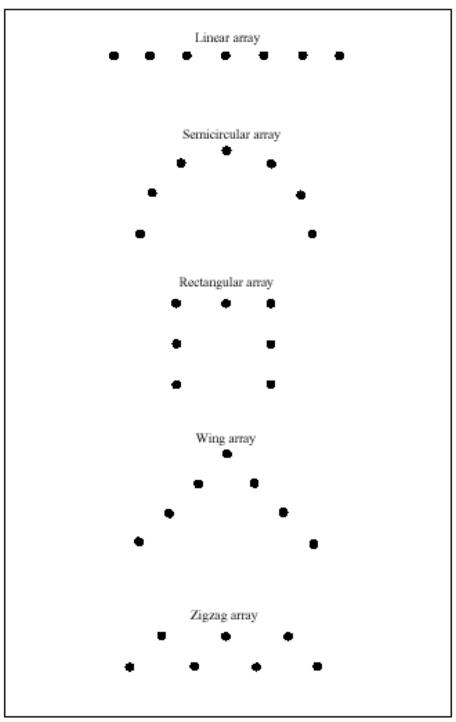

Figure 11: Investigated Antenna Array Configurations [3]

6.3.3 Two-Dimensional, Omni-Directional Scatters Angular Extent on Pair-Wise Antenna Correlation

If the two-dimensional, omni-directional scatters occupy an azimuth range that spans from 0 to 2π radians in extent, the pair-wise antenna correlation function is properly given by (6). In moderate multipath channel scenarios, the azimuth extent of such omni-directional scatters will unquestionably be reduced to a lesser extent. If the azimuth extent of the scatters is assumed to have a Gaussian distribution, the pair-wise antenna correlation can be shown to be approximately given by [36]

$$\rho(d,\theta_o,\sigma_\theta) = \left| \int_{-\pi+\theta_o}^{+\pi+\theta_o} \exp\left[j\frac{2\pi d}{\lambda}\sin(\theta) \right] \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp\left[\frac{(\theta-\theta_o)^2}{2\sigma_\theta^2} \right] d\theta \right| \quad (7)$$

where θ_o is the nominal off-normal wave front angle of incidence and σ_θ is the rms angular width of the scatters field in radians. The finite azimuth extent is conceptually shown in Figure 12 [17].

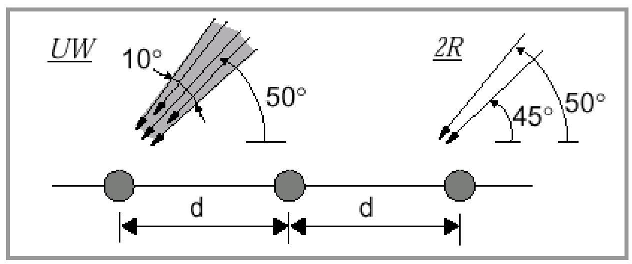

Figure 12: Linear Array Diversity Element Correlation With Localized Scatters in Azimuth

The main-lobe angular beam-width of an antenna is directly tied to the antenna gain delivered in normal passive antennas. As a direct result, an antenna gain of +6 dBi still corresponds to a main-lobe angular width on the order of 90 degrees, which is quite broad. Whether the Gaussian angular-width shaping present in (7) is due to the finite angular extent of the omni-scatters or due to the directive antenna gain pattern effect on the otherwise uniformly distributed two-dimensional omni-scatters, the correlation coefficient between antenna elements remains very low for d=2 inches over a wide range of angular extent parameter σ_θ (see Figure 13). This result supports using some antenna gain over isotropic, particularly at the RT end where some directional preference to the AP can in most cases be easily accommodated.

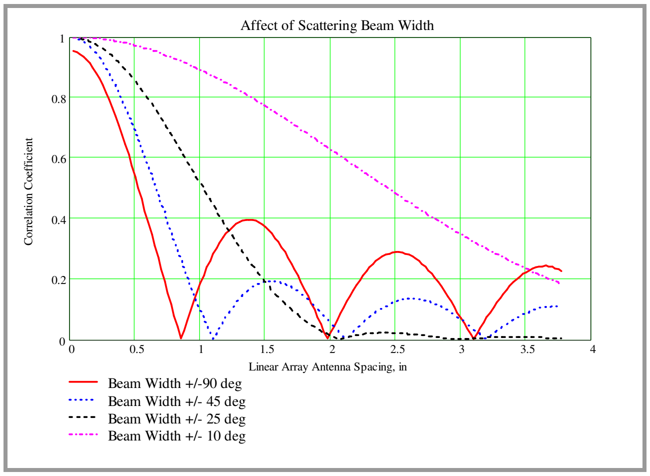

Figure 13: Effect of Narrow Angular-Width Two-Dimensional Scatters on Antenna Correlation

Large antenna gain can pose degraded performance issues for the high-multipath case. Too much antenna directivity may result in strong signals actually being attenuated, if they correspond to direction of arrivals that do not correspond to the bore sight of at least one receive antenna. If all the receive antennas have high gain, the gain patterns may not overlap significantly. As a result, uncorrelated antenna outputs may be produced as desired, in principle, but no receive antenna may sufficiently intercept the available incident signal wave front, and the net performance will be quite poor.

Dual-selection-diversity SNR performance in a spatially correlated scattering environment, assuming correlated Rayleigh fading is considered in [5]. The typical scenario where all signals arrive at the receiver within ±Δ degrees at the angle θ is shown in Figure 14. For a two-dimensional, uniform, limited azimuth field with certain beamwidth (θ-Δ, θ+Δ), the spatial correlation is given by

$$\rho(d) = \sum_{m=-\infty}^{+\infty} e^{jm\left(\frac{\pi}{2}-\theta\right)} \frac{\sin(m\Delta)}{m\Delta} J_m\left(\frac{2\pi d}{\lambda}\right) \qquad (8)$$

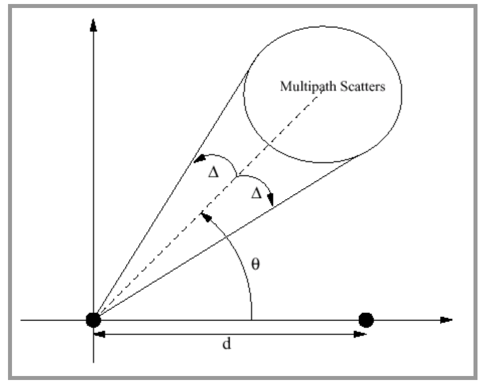

Figure 14: Typical Scenario Where All Signals Arrive at the Receiver Within ±Δ Degrees at Angle θ.

In Figure 15 and Figure 16, the results are presented in terms of the minimum antenna separation required, in order to achieve 90% of the available average SNR that dual-selection diversity can provide. The diversity effectiveness is a direct result of the quantity d sin(θ), which represents the projected extent of the spacing as viewed from the direction of the scatters. For the material presented here, if the beam-width of the scatters and the angle of arrival are both greater than 30 degrees, then 1.3λ is sufficient antenna separation to deliver 90% of the available dual-antenna selection diversity gain. If the beam-width of the scatters is at least 30 degrees and the angle of arrival is at least 40 degrees, only λ spacing is required to deliver the same 90% diversity benefit.

6.3.4 Antenna Correlation Impact on MA Processing Gain

To first order, the processing loss associated with correlated antennas can be roughly estimated with the guidelines provided in [28]. In the case of only two receive antennas, the performance reduction is approximately given by

$$\Delta R = -5\log_{10}\left(1-\rho^2\right) \qquad (9)$$

In the case of three correlated receive antennas with the same correlation value between any two channels, the performance loss is approximately

$$\Delta R = -3.33\log_{10}\left[(1+2\rho)(1-\rho)^2\right] \qquad (10)$$

These results are for straightforward Rayleigh-fading channels based on simple SNR arguments.

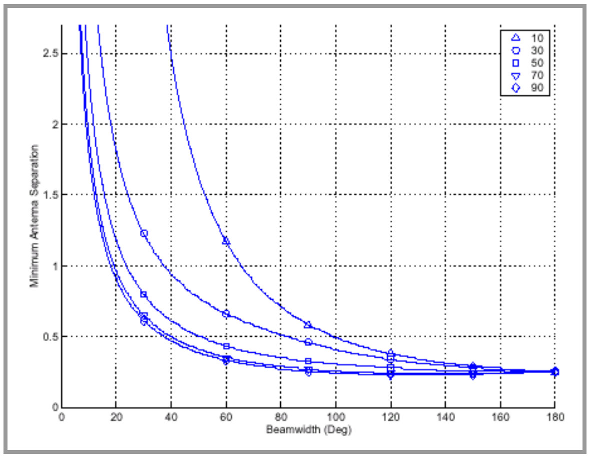

Figure 15: Minimum Dual-Antenna Separation Required (in Wavelength) to Achieve 90% of the Available Average SNR Dual Selection Diversity Gain. (Angle of Arrival θ= {10, 30, 50, 70, 90} deg.)

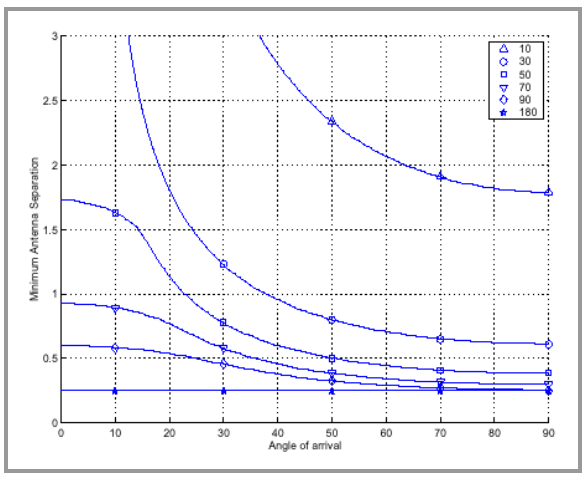

Figure 16: Minimum Dual Antenna Separation Required (in Wavelength) to Achieve 90% of the Available Average SNR Dual Selection Diversity Gain. (Angle of Arrival θ= {10, 30, 50, 70, 90, 180} deg.)

6.3.5 *Mutual Coupling Between Closely Spaced Antenna Elements*

Significant coupling between antenna elements with a subsequent unwanted increase in antenna element correlation can occur if the antenna elements are too closely spaced together. In general, spacing antenna elements closer than about λ/4 can lead to some compromises in this area. This may be a dated measure, however, if advanced high-dielectric constant materials, etc., are used in the antenna fabrication.

The mutual-coupling impedance has been analyzed in the case of linear half-wave antennas that are either spaced in a colinear manner or broadside, as shown in Figure 17 and Figure 18.

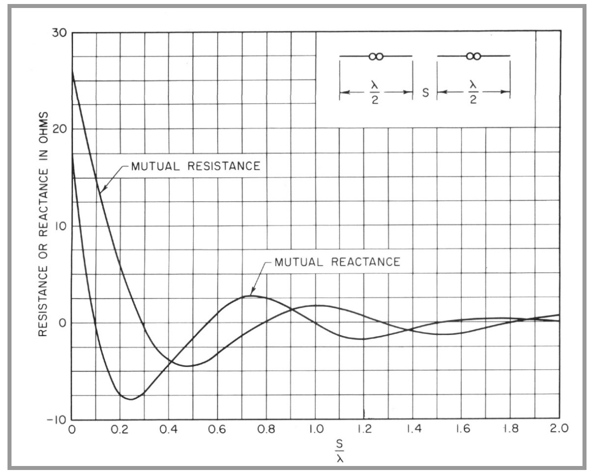

Figure 17: Mutual Impedance Between Colinear Half-Wave Antennas [25]

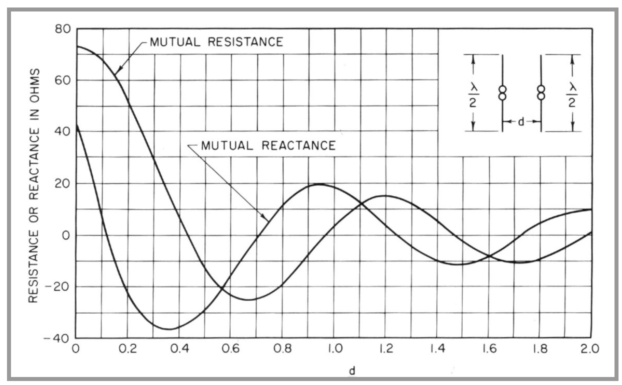

Figure 18: Mutual Impedance Between Broadside Half-Wave Antennas [25]

In the case where the antennas are λ/4 monopoles that are parallel to each other, this situation has been studied in [16]. In this case, the self-impedance of each monopole is given by

$$z_{ii} = 36.6 + j22.6\Omega \qquad (11)$$

and the mutual impedances are given by [16]

$$r_{ij} = 15\left[2C_i(\beta d) - C_i\left(\beta\sqrt{d^2+L^2}+\beta L\right) - C_i\left(\beta\sqrt{d^2+L^2}-\beta L\right)\right] \qquad (12)$$

$$x_{ij} = -15\left[2S_i(\beta d) - S_i\left(\beta\sqrt{d^2+L^2}+\beta L\right) - S_i\left(\beta\sqrt{d^2+L^2}-\beta L\right)\right]$$

where L= λ/2, β= 2π/λ, and $C_i(x)$ and $S_i(x)$ are the Sine and Cosine integrals, respectively. Following the guidance provided in [16], let v_i be the received voltage on the i^{th} antenna, i_i the current on the i^{th}

antenna, z_L be the load impedance, and v_S, i_S, and z_{iS} be the source voltage, current, and impedance. The direction of the currents is chosen such that $v_i = -z_L i_i$. Using Kirchoff's laws,

$$\begin{bmatrix} v_1 \\ \ldots \\ v_N \end{bmatrix} = \begin{bmatrix} z_{11}i_1 + z_{12}i_2 + \ldots + z_{1S}i_S \\ \ldots \\ z_{N1}i_1 + z_{N2}i_2 + \ldots + z_{NS}i_S \end{bmatrix} \quad (13)$$

where z_{ij} is the mutual impedance between antenna element i and j. Without loads being present, the currents i_i are all zero. The received voltages in this case are $s_i = z_{iS} i_S$. The source vector with and without antenna coupling is defined as

$$\begin{aligned} V &= [v_1 \quad \ldots \quad v_N]^t \\ S &= [s_1 \quad \ldots \quad s_N]^t \end{aligned} \quad (14)$$

and $V = Z^{-1} S$ where Z is the coupling matrix that is given by

$$Z = \begin{bmatrix} 1 + \frac{z_{11}}{z_L} & \ldots & \frac{z_{12}}{z_L} \\ \frac{z_{21}}{z_L} & \ldots & 1 + \frac{z_{22}}{z_L} \end{bmatrix} \quad (15)$$

The source vector obtained without coupling is given by

$$S(\varphi) = g(\varphi)\left[1 \quad e^{j2\pi\frac{d}{\lambda}\cos(\varphi)}\right]^t \quad (16)$$

whereas the source vector with coupling is given by $V(\varphi) = Z^{-1} S(\varphi)$. Under these conditions with $z_{11} = z_{22}$ and $z_{12} = z_{21}$ where $Z^{-1} = \begin{bmatrix} a & b \\ b & a \end{bmatrix}$, the individual antenna gain patterns are given by

$$\begin{aligned} v_1(\varphi) &= g(\varphi)\, a\left[1 + \frac{b}{a} e^{-j2\pi\frac{d}{\lambda}\cos(\varphi)}\right] \\ v_2(\varphi) &= g(\varphi)\, a\left[\frac{b}{a} + e^{-j2\pi\frac{d}{\lambda}\cos(\varphi)}\right] \end{aligned} \quad (17)$$

In the two-monopole antenna case, the antenna directivity patterns are as shown in Figure 19. As expected, if the antenna elements are closely spaced (e.g., λ/10), the two antenna elements are tightly coupled and, although some pattern deformation occurs, both patterns are very similar. For the larger λ/2 spacing, pattern directivity begins to set in as expected.

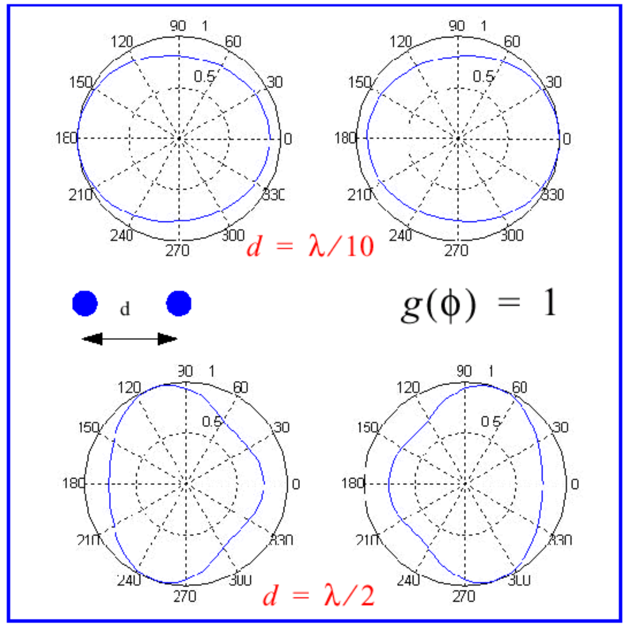

Figure 19: Deformation of the Radiating Pattern of Two Monopole Antennas Due to the Mutual Coupling Between Antennas [16]

Almost all references advocate using antenna spacing no less than λ/4; many references advise that a spacing of λ/2 is sufficient to reduce the antenna element mutual-coupling adequately. One such reference is [23].

6.3.6 Coupling Between Co-Polarized Antenna Apertures in a Common Flat Ground Plane

The mutual-coupling question has been addressed in [24] for the case of co-polarized antenna apertures in a planar array. Quoting from [24],

> "Previous observations have shown that the mutual coupling between widely spaced apertures in a common ground plan varies inversely as the separation distance in the E-plane and inversely as the square of the separation distance in the H-plane, with a phase variation that is linear with separation. The fields near a radiating source vary inversely as the cube of the distance away from the source."

For a fixed separation, the mutual coupling varies in a sinusoidal manner with a relative angular position.

Powerful E&M software design tools can be used to look at this question, but the material presented in [24] can assist in the analysis stage with considerably less effort required. An example result from [24] for rectangular apertures that are 0.8λ x 0.4λ in size is shown in Figure 20, with the parameter definitions as provided in Figure 21.

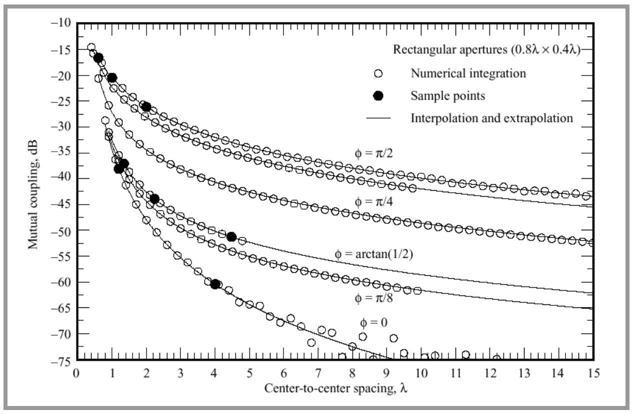

Figure 20: Mutual Coupling Between Two Rectangular Apertures 0.8λ x 0.4λ in Size

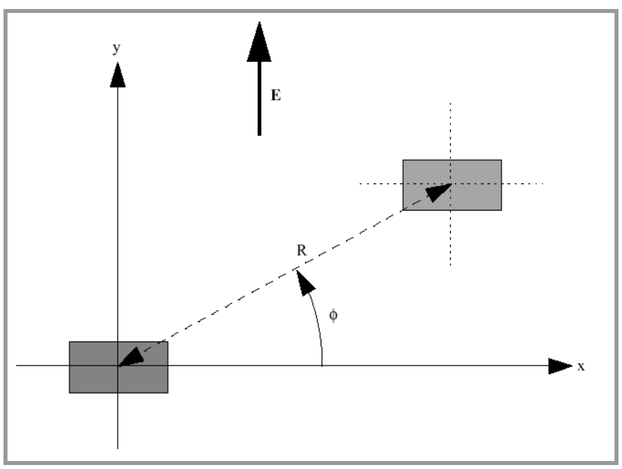

Figure 21: Geometry of Two Identical Apertures in Ground Plane

6.4 Multipath Channel Characteristics

The indoor multipath channel is very complicated. The indoor multipath channel is not time-stationary, and it is virtually impossible to reproduce the same exact channel characteristics from one hour to the next, let alone one day to the next. At 5 GHz, everything counts, from furniture placement, to people movement, to the relative humidity of the air, and air temperature. Add to these conditions the unprecedented aspirations to move data at throughputs as high as 54 Mbps reliably enough to support video (without large data buffers), and every detail matters.

Due to all of these complications, the Magis Air5 system design has been based far more on mathematical probabilities than a published channel model or other theoretical models that have not been rigorously tested. The large variability of the channel normally dictates that field measurements be heavily averaged in order to see trends and dependencies. This same averaging can also obscure important channel features.

6.4.1 Delay Spread

Since multiple signal paths are involved in propagation over the indoor channel due to signal reflections, different signals arrive at the distant receiver at different times, the span of the delay times being termed “delay spread.” The size of the delay spread is directly related to the coherence bandwidth of the channel and other key quantities.

Although many papers have been written on the subject of indoor delay spread, one of the simplest results that quantify this important measure for indoor channels can be found in [27] and is given by

$$DelaySpread(ns) = k\sqrt{FloorArea_{meters}} \qquad (18)$$

where k depends on the reflectivity of the enclosing walls. In metal-walled rooms, k ranges from 3 ns/m to 4 ns/m, whereas in brick/stone-walled rooms it is approximately 1.5 ns/m.

6.4.2 Frequency-Selective Fading

Frequency-selective fading can be extremely severe, particularly in office environments where a great deal of metal is present in the building structure and many planar metal surfaces are present that reradiate incident RF energy. A glimpse at some of the channel data that has been collected within the Magis building (three stories, steel-reinforced concrete) is provided in Section 11. As shown there, the frequency-selective fading profile can dramatically change by moving a receive antenna only ¼ inch. This kind of rich multipath structure can only be combated with MA-type technology.

Propagation down long, narrow corridors that have substantial conductive surface content can be particularly difficult, as far as multipath is concerned. Some recent results are provided in [21], although the results presented are based strictly on a single-antenna system, which, consequently, has none of the advanced MA technology that is used in the Magis Air5 system.

6.4.3 Wave Front Direction of Arrival

In low-multipath channel scenarios, the main signal direction of arrival (DOA) is understandably very much LOS and, therefore, very tractable. In denser multipath scenarios, strong incident signal wave fronts can originate from virtually any direction (see Section 6.3). A number of references, including [30], [33], [32] as well as Magis' own field measurements, support the conclusion that the primary wave front DOAs in high-multipath channels are primarily specular rather than diffuse in nature. DOAs, as well as time of arrivals (TOA), appear to be very clustered. The clustering of the DOAs can be so tight as to make it impractical to selectively choose a single DOA "hot spot," if smart antenna technology were to be employed, for example. Even if one such "hot spot" could be singled out from the rest, there is absolutely no guarantee that the recovered signal would not exhibit severe frequency-selective fading itself.

Owing to the wide range of DOAs that can result with indoor channels, omni-directional antennas are generally preferred in dense multipath cases. Although omni-antennas can lead to more delay spread, overly directive antennas may well exclude DOAs that contain the best signal energy.

6.4.4 Summary Comments on Channel Multipath

One of the more concise summaries of indoor channel multipath is given in [11]. Drawing from that reference, consider the following points:

1. Delay Spread:
    a. Circular and linear polarized signals have similar delay spreads for both LOS and obstructed paths (OBS).
    b. Omni-directional transmit and receive antennas produce higher delay spreads, especially for channels with large geometric aspect ratios (e.g., a corridor).
    c. Delay spread increases as the degree of depolarization increases.
2. Basic Transmission Loss:
    a. Circular polarized signals have greater basic transmission loss than linear polarized signals in both LOS and OBS paths.
    b. Omni-directional transmit antennas provide stronger signal coverage than directional transmit antennas for OBS paths.
    c. Basic transmission loss increases as the degree of depolarization increases.
3. Depolarization:
    a. Circular polarized signals are depolarized more than linear polarized signals.
    b. The indoor channel significantly depolarizes transmitted signals.

7. Candidate Antenna Elements

The individual antenna elements used in the antenna array can take on a very wide range of form factors using a wide range of materials. This section is provided only to present some of the many options that are possible.

A slotted-array style antenna is shown in Figure 22. This could be realized as a metallized plastic frame around a product or a hollow metal frame. At 5 GHz, the waveguide dimensions would be quite small. In Figure 23, metal or metallized plastic vanes are used to create segmented directional gain patterns that exhibit low coupling between adjacent antenna elements. Although this architecture would perform reasonably well in dense multipath scenarios, it would probably exhibit difficulties in lighter multipath cases, where, in many cases, only one or two of the elements would have significant incident RF signal. Many creative, low-cost microstrip architectures are possible, as suggested in Figure 24 and Figure 25. In Figure 26, a circular array of simple monopoles is used for the array, the tilt angle and separation set to reduce coupling and increase angular coverage. A partial summary of possible planar antenna structures is shown in Table 1.

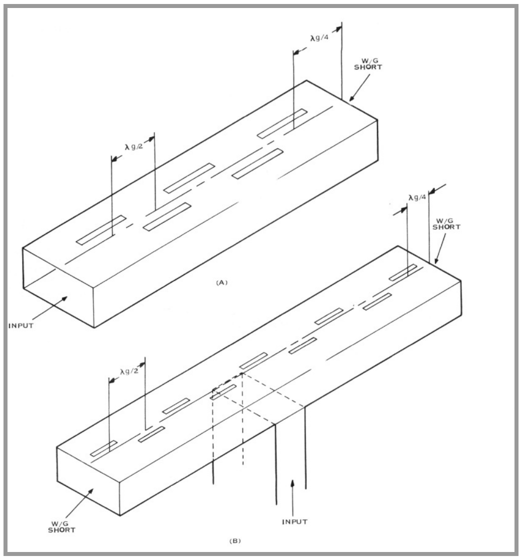

Figure 22: Linear Resonant Slotted-Array Antenna (a) End-Fed, (b) Center-Fed [25]

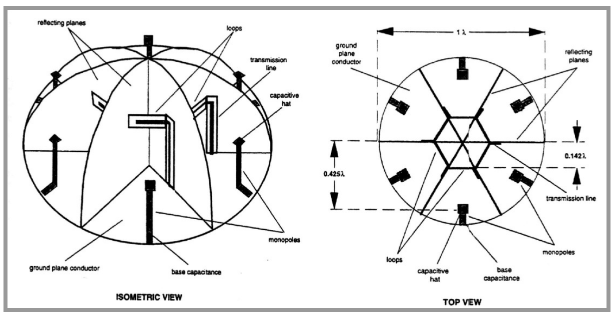

Figure 23: Multi-Port Antenna Concept [26]

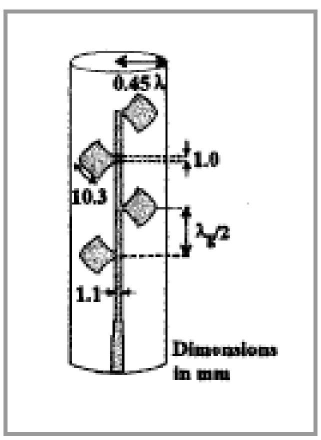

Figure 24: Printed-Patch, Phased-Array Antenna [13]

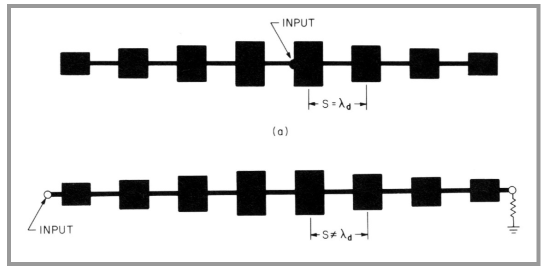

Figure 25: (a) Resonant Series-Fed Microstrip Array and (b) Traveling-Wave Series-Fed Microstrip Array

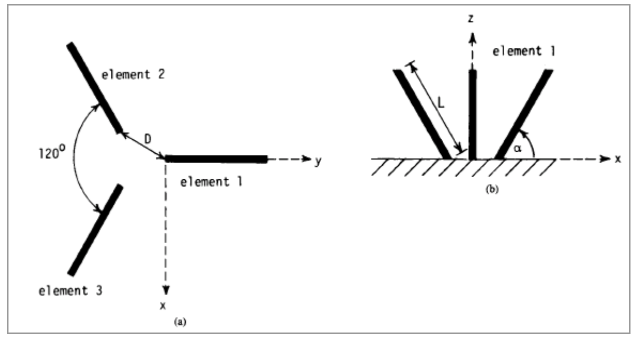

Figure 26: Circular Array of Outward Sloping Monopoles for Vehicular Diversity Antennas [14]

Table 1: Possible Planar Antenna Structures [22]

		Pattern	*Directivity*	*Polarization*	*Bandwidth*	*Comments*
Patch		Broadside	Medium	Linear/Circular	Narrow	Easiest design
Slot		Broadside	Low/Medium	Linear	Medium	Bi-directional
Ring		Broadside	Medium	Linear/Circular	Narrow	Feeding complicated
Spiral		Broadside	Medium	Linear/Circular	Wide	Balun & Absorber
Bow-Tie		Broadside	Medium	Linear	Wide	Same as Spiral
TSA(Vivaldi)		Endfire	Medium/High	Linear	Wide	Feed transition
Yagi Slot		Endfire	Medium	Linear	Medium	Two layer design
Quasi Yagi		Endfire	Medium/High	Linear	Wide	Uniplanar, Compact
LPDA		Endfire	Medium	Linear	Wide	Balun, Two Layer
Leaky-Wave		Scannable	High	Linear	Medium	Beam-steering, Beam-tilting

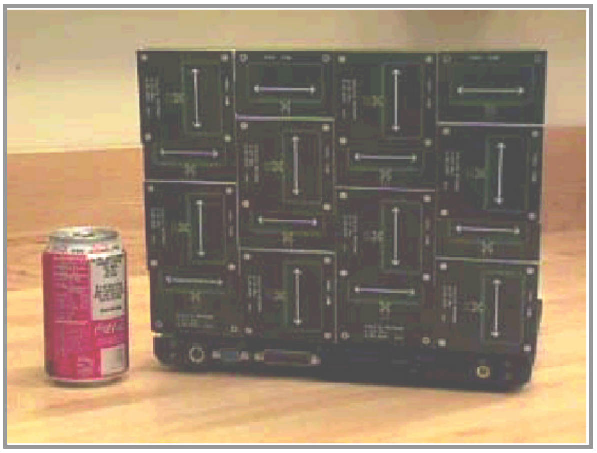

Figure 27: Multiple Antennas Integrated into Back of Laptop Computer (Lucent BLAST Technology)

Figure 28 shows one of the most attractive and low-cost antenna designs that easily deliver gain. This antenna style is being studied further for use within the RT's antenna array.

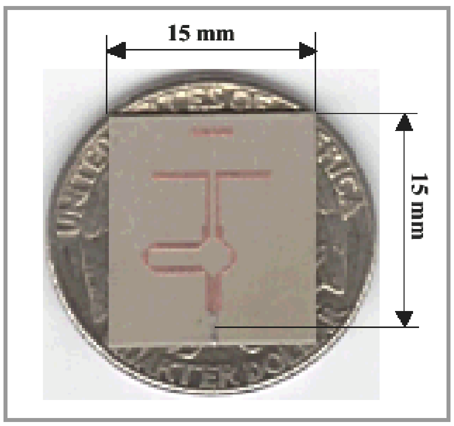

Figure 28: Small Size of a 10 GHz Quasi-Yagi Antenna

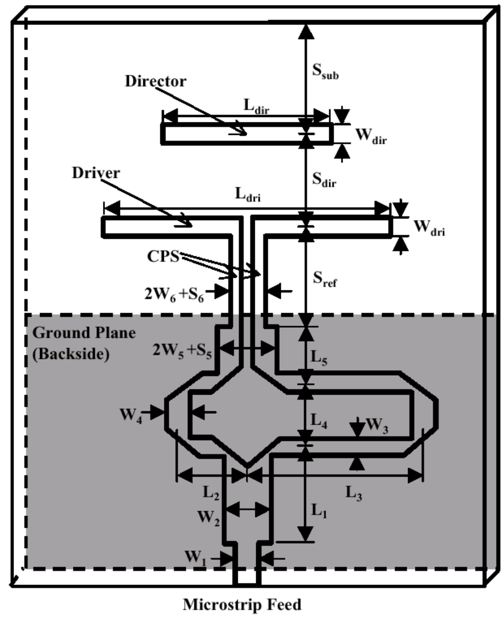

Figure 29: Detailed Dimensions of Quasi-Yagi Antenna [22]

The performance results for a single antenna element should not be extrapolated to that antenna element type used in an array. Surprisingly strong interaction can occur between some antenna element types when placed in an array even with λ-spacing. It is *highly recommended* that candidate antennas be characterized individually, as well as in their final array configuration, before being adopted for a final design.

8. Antenna Recommendations

As alluded to earlier, no single antenna array is optimal for all link scenarios. In cases where very little or no multipath is present (e.g., outdoor LOS), directive antennas will display the best performance. On the other hand, indoor links that have substantial multipath present generally perform better when omni-directional antenna elements are used. These perspectives are developed in greater detail in the following sections.

8.1 Antenna Regulatory Limits

The FCC has set limits on the effective isotropic radiated power (EIRP) allowed in the different segments of the 5 GHz U-NII frequency bands. These limits are provided below in Table 2 for easy reference. (See Section 12 for exact FCC declarations.)

Table 2: Summary of FCC Transmit Limitations for 5 GHz UNII Bands

Frequency Span, GHz	Maximum Transmit Antenna Gain Allowed, dBi	Maximum Transmit Power Allowed for 802.11a Waveform, dBm	Maximum EIRP, dBm
5.15 – 5.25	6	16.2	22.2
5.25 – 5.35	6	23.2	29.2
5.725 – 5.825	6	29.2	35.2

If a transmit antenna gain in excess of 6 dBi is used in any frequency band, the maximum transmit power must be reduced by the same excess amount in dB.

Whereas the transmit antenna gain is effectively limited to +6 dBi, there is understandably *no limitation* on receive antenna gain. This fact can be used quite effectively in point-to-point outdoor links, where high-gain helix antennas, etc., can be adopted to increase the receive antenna gain to easily 20 dBi or more.

8.2 Minimal-Multipath Channels

Channels that have very little multipath must contend with the fact that propagation at 5 GHz is substantially LOS. If the LOS path is obstructed by someone or something, the propagation path loss is correspondingly higher. In the case of human intervention, the increase in path loss can be substantial, since propagation losses through human tissue will be very high at 5 GHz. The Magis Air5 system has been purposely designed to exploit multipath (in the home and small office), thereby lessening direct LOS issues. These techniques are of course ineffective if no multipath is present in the channel.

Directional antennas are recommended for the best performance over minimal-multipath channels. More specifically, the guidelines in Table 3 are recommended for greatest range and link robustness.

Table 3: Antenna Guidelines for Best Link Range/Robustness Over Minimal-Multipath Channels

Terminal	Point-to-Point Link	General Coverage
Access Point: Transmit	Use +6 dBi antenna; polarization not an issue. (Assumes that AP can use full legal transmit power levels.)	Use an omni-directional antenna; polarization not an issue.
Access Point: Receive	Use any antenna gain desired for link range and robustness. Polarization should match that used by the RT transmitter.	Several options depending on link range and robustness desired. Must compute link margins to decide. ▪ Single omni-directional receive antenna, polarization matching that of AP transmitter. ▪ Sectorized (n ≤ 5) directional antennas providing required azimuth and elevation coverage.
Remote Terminal: Transmit	Two options, depending on whether the RT transmit power is constrained less than regulatory limits: ▪ If power constrained, use any antenna gain desired (≤ +6 dBi) for link range and robustness. Polarization should match that used by the AP receive antenna(s). ▪ If not power constrained, use +6 dBi antenna. Polarization should match that used by the AP receive antenna(s).	Use an omni-directional antenna; polarization not an issue.
Remote Terminal: Receive	Use any antenna gain desired for link range and robustness. Polarization should match that used by the AP transmitter.	Several options, depending on link range and robustness desired. Must compute link margins to decide. ▪ Single omni-directional receive antenna, polarization matching that of AP transmitter. ▪ Sectorized (n ≤ 5) directional antennas providing required azimuth and elevation coverage.

In the absence of multipath along with the flexibility to use any reasonable receive antenna gain desired, free-space communication range can be quite substantial with the Magis Air5 technology. The classical Friis[7] range equation for free-space propagation is given as

$$SNR_{dB} = 10Log\left[P_T G_T G_R \left(\frac{\lambda}{4\pi R}\right)^2\right] - 10Log\left(kT\ BW\ NF\right) \qquad (19)$$

where:

P_T Transmit power in Watts

G_T Numerical transmit antenna gain ($10^{0.1Gain_{dB}}$)

G_R Numerical receive antenna gain

λ Wavelength in meters

R Range in meters

k Boltzmann constant

T Absolute temperature, taken to be 290K

NF Noise factor of receiver ($10^{0.1NoiseFigure_{dB}}$)

In the Magis Air5 Core Module configuration, 5 GHz filtering and antenna cabling losses are higher than what will normally be seen in a finished, integrated product, so the noise figure should be taken as approximately 10 dB. The transmit- and receive-antenna gains, along with the maximum transmit power adopted, are up to individual customers' objectives. Assuming a channel bit error rate[8] (after FEC but without benefits of ARQ) of 10^{-4}, the required receive SNR per signaling rates for the Magis 61XX family are as provided in Table 4.

[7] D.C. Hogg, "Fun with the Friis Free-Space Transmission Formula." IEEE Antennas and Propagation Magazine, Vol. 35, No. 4, August 1993. See [29].

G.W. Collins, "Wireless Wave Propagation", Microwave Journal, July 1998. See [38].

[8] Although much higher BER levels have been thoroughly evaluated and fall on the anticipated waterfall curves, this BER has been internally adopted based on MPEG2 QoS guidelines and is uniformly used within Magis as the defined "system sensitivity" operating point.

Table 4: SNR Requirements at Sensitivity Versus Throughput Rate

Rate, Mbps	Signal Constellation	Viterbi Coding Rate	Required SNR at 10^{-4} BER, dB[9]
6	BPSK	½	3.3
9	BPSK	¾	5.7
12	QPSK	½	5.9
18	QPSK	¾	8.4
24	16QAM	½	12.1
36	16QAM	¾	16.4
54	64QAM	¾	23.0

Based on a transmit power level of +16 dBm, a total system receive noise figure of 10 dB, the SNR required at sensitivity from Table 4 and a range of receive antenna gains, the free-space communication range versus channel signaling rate for a point-to-point link can be computed from (19) as provided in Table 5.

Table 5: Free-Space Range for Point-to-Point Links at Sensitivity for Different Receive Antenna Gains (meters) Using P_{Tx}= +16 dBm

Data Rate, Mbps	Reqd SNR, dB	Rx Ant Gain= 0 dBi	Rx Ant Gain= 3 dBi	Rx Ant Gain= 6 dBi	Rx Ant Gain= 21 dBi
6	3.3	1,506.6	2,128.1	3,006.0	16,904.1
9	5.7	1,142.9	1,614.3	2,280.3	12,823.1
12	5.9	1,116.8	1,577.6	2,228.4	12,531.2
18	8.4	837.5	1,183.0	1,671.1	9,397.1
24	12.1	547.0	772.7	1,091.4	6,137.5
36	16.4	333.4	471.0	665.3	3,741.0
54	23	156.0	220.3	311.2	1,749.8

As Table 5 shows, substantial point-to-point link range can be realized with the Magis Air5 technology with increasing receive antenna gain, even at the transmit power level of +16 dBm.

[9] Based on Magis report.

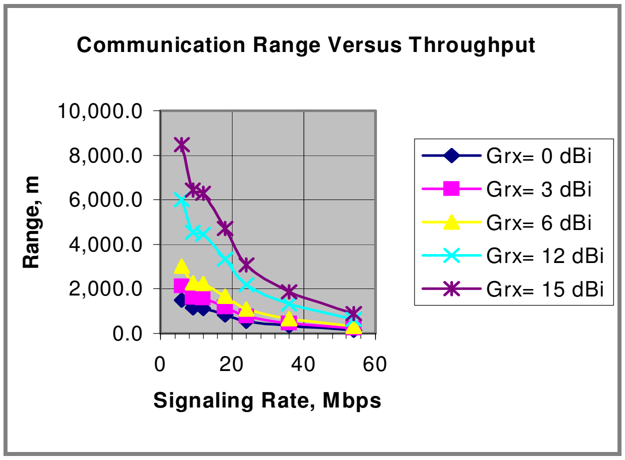

Figure 30: Communication Range for Point-to-Point Links at Sensitivity Versus Channel Signaling Rate and Receive Antenna Gain (Corresponding to Table 5)

8.3 Moderate-Multipath Channels

Most homes generally fall into the moderate-multipath channel case. Although homes also exhibit frequency-selective fading, the number of walls, bookshelves, cabinets, and general amount of wood content involved (at least in U.S. homes) leads to signal absorption losses playing a significant role in the area of achievable throughput versus range.

Many papers have been written on the subject of expected loss over these kinds of channels, but none of the prior research adequately addresses the role of Magis-style MA processing with the kind of signal bandwidths used in the Magis Air5 system.

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

$$SNR_{dB} = 10Log\left[P_T G_T G_R \left(\frac{\lambda}{4\pi}\right)^2\right] - 10nLog(R) - 10Log(kT\ BW\ NF) - L_{dB} \quad (20)$$

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 straightforward model that has been considered within Magis is that by Medbo [21]. This model assumes an additional flat dB-per-meter loss represented by α in (21) but is otherwise the free-space model of Friis.

$$SNR_{dB} = 10Log\left[P_T G_T G_R \left(\frac{\lambda}{4\pi R}\right)^2\right] - 10Log(kT\ BW\ NF) - \alpha R \quad (21)$$

In (21), R is the range in meters, and α has the units of dB/meter having a value of approximately 0.44 dB/m.

All such channel models that are "power-law based" necessarily make a number of simplifying assumptions in order to condense massive amounts of measurement data into a meaningful empirical result. However, this same measurement process obscures most of the signal wave front information that must be exploited at 5 GHz (or at 2.4 GHz) in order to deliver high-throughput reliable wireless links.

Most, if not all, power-law based propagation loss models use extensive measurement averaging in the data-reduction process. Medbo[10] describes a modeling approach that is very similar to that presented by Keenan-Motley[11] and Devasirvatham[12] in which the measurement process is described as follows:

> "Halfwave diple (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 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 in diameter."

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[10] Medbo, "Simple and Accurate Path Loss Models at 5 GHz for Indoor Environments with Corridors," VTC 2000.

[11] J.M. Keenan, A.J. Motley, "Radio Coverage in Buildings," British Telecom Technology Journal, Vol. 8, No. 1, January 1990, pp. 19-24.

[12] Devasirvatham, *et al.*, "Multi-Frequency Radiowave Propagation Measurements in the Portable Environment," IEEE Intl. Conf. On Communications, 1990, pp. 1334-1340.

Being single-frequency in nature, this measurement collection method is blind to the frequency-domain correlation in the fading. Similarly, using a single antenna element that is averaged over such a large region also makes this collection technique blind to the spatial-frequency structure present in the multipath wave front. Although this data collection technique is attractive[13] for its simplicity and relative independence of antenna choice and other signal processing involved, it cannot provide adequate insight into the signal propagation wave fronts that exist in a multipath environment and how they might be exploited for improved indoor communications. Nonetheless, these are some of the deficiencies of the current technical literature that is available.

Based on the materials provided in this report, the recommended antenna guidelines over moderate multipath channels are given in Table 6.

Table 6: Antenna Guidelines for Best Link Range/Robustness Over Moderate-Multipath Channels

Terminal	**Antenna Choice**
Access Point: Transmit	Use omni-directional antenna, linear polarization. (Assumes that AP can use full legal transmit power levels.)
Access Point: Receive	Omni-directional elements, N=5, linear polarization, pentagon antenna array arrangement with d=2 inches
Remote Terminal: Transmit	Omni-directional linear-polarized antenna (can choose to go to up to +6 dBi antenna gain, if desired).
Remote Terminal: Receive	Omni-directional (or up to gain of +6 dBi) elements, N=5, linear polarization, broadside linear antenna array arrangement with d=2 inches.

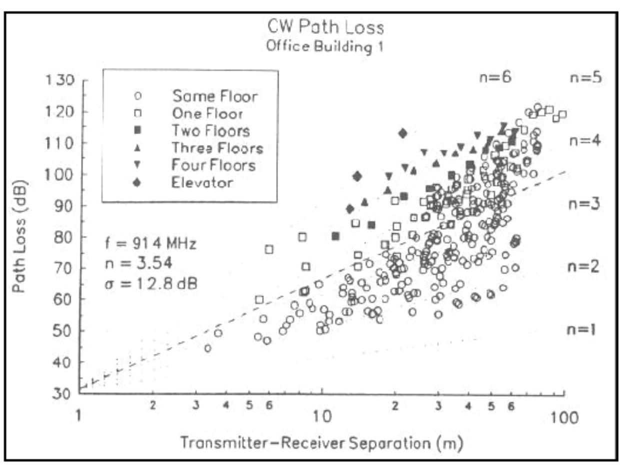

Figure 31: Example of Collected Data Superimposed with Power-Law Modeling[14]

8.4 Dense-Multipath Channels

The dense-multipath scenario is expected to be more typical of industrial/office situations where significant metal structures and furnishings are present. In large open-room areas, it is not unusual for the propagation losses to be considerably less than the loss associated with the distance in free space, since the room behaves very much like a waveguide. Most IEEE802.11a systems are more multipath limited under these circumstances than signal-strength limited.

Table 7: Antenna Guidelines for Best Link Range/Robustness Over Dense-Multipath Channels

Terminal	**Antenna Choice**
Access Point: Transmit	Use omni-directional antenna, linear polarization.
Access Point: Receive	Omni-directional elements, N=5, linear polarization, pentagon antenna array arrangement with d=2 inches.
Remote Terminal: Transmit	Same as AP transmit.
Remote Terminal: Receive	Same as AP receive.

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10. Appendix: Theoretical Basis for Magis Air5 Multiple-Antenna Signal Processing

In large areas where multipath is particularly extreme, the propagation loss can be considerably less than expected, based on free-space predictions. As reported elsewhere[15], propagation losses through most common building materials are almost the same at 5 GHz as they are at 2.4 GHz.

One of the first investigations carried on at Magis was to develop a thorough understanding of what communication theory limits applied to the indoor wireless channel and then, given that understanding, determine what cost-complexity solution could be designed and built to achieve the end objectives. To this end, the Magis team built a multi-antenna array signal-capturing system.

The IEEE802.11a standard uses a standard k=7 Viterbi convolutional encoder that primarily encodes across the 48 data-bearing OFDM frequency bins. Adequately severe frequency-selective fading will break the code, thereby causing burst-errors to occur. In order to assess the potential viability of different solutions, a cutoff-rate-based scoring metric was used in conjunction with the antenna array signal capturing system, thereby permitting the assessments to be done without a fully operational IEEE802.11a system in hand.

The channel cutoff rate is shown versus E_b/N_o for several square QAM signal constellations in Figure 32 as given by (22) for square-QAM signal constellations.

$$R_o\left(N_o\right) = -Log_2\left[\frac{1}{M^2}\sum_{ki}\sum_{kj}\exp\left(-\frac{\left\|S_{ki}-S_{kj}\right\|^2}{4N_o}\right)\right] \quad (22)$$

This relationship for R_o can be summed over all of the OFDM bins in the modulation bandwidth, including the effects of frequency-selective fading in order to assess the impact of a given fading characteristic on the information capacity of the impaired channel.

Severe multipath can be very damaging to a wireless network because moving terminals closer together (thereby increasing the received signal power in principle) can often make the multipath problem even worse.

[15] Magis report on propagation at 5 GHz.

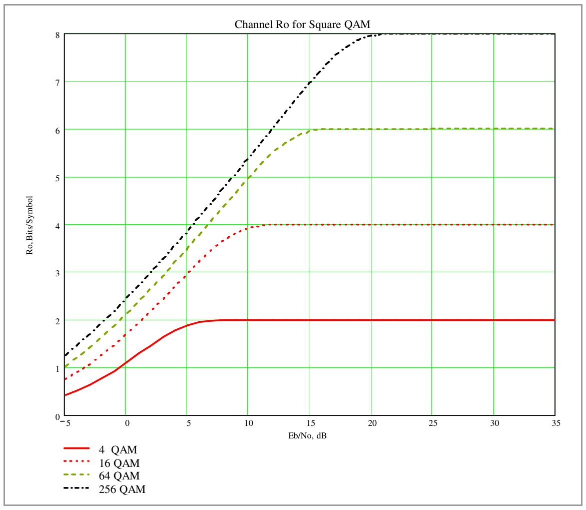

Figure 32: Channel Cutoff Rate R_o for Several Square QAM Signal Constellations in AWGN

One channel sweep in which the signal strength versus frequency for four elements of the antenna array is simultaneously plotted is shown in Figure 33 through Figure 35. The overall channel R_o was then calculated based on assuming different maximum C/N_o levels across modulation bandwidth. High-level assessments like this allowed the Magis system team to determine plausible engineering solution paths (i) while using the actual real propagation channel, and (ii) prior to expending the extraordinary effort required to build a complete hardware prototype of our Magis Air5 system.

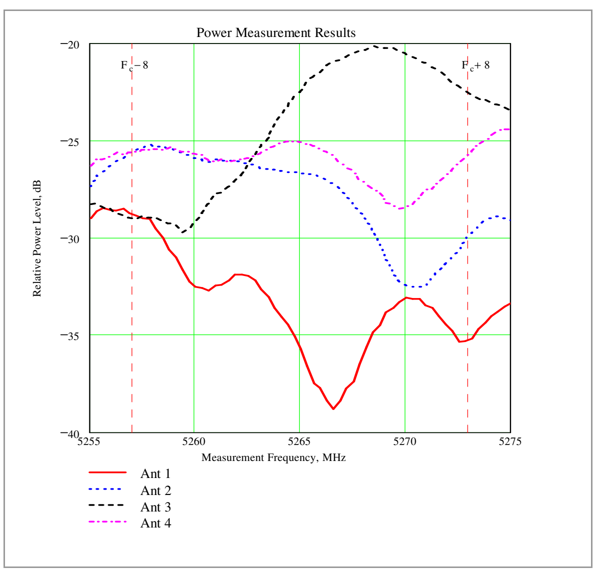

Figure 33: Baseline Multi-Element Array Channel Sweep (Only Four Elements Shown)

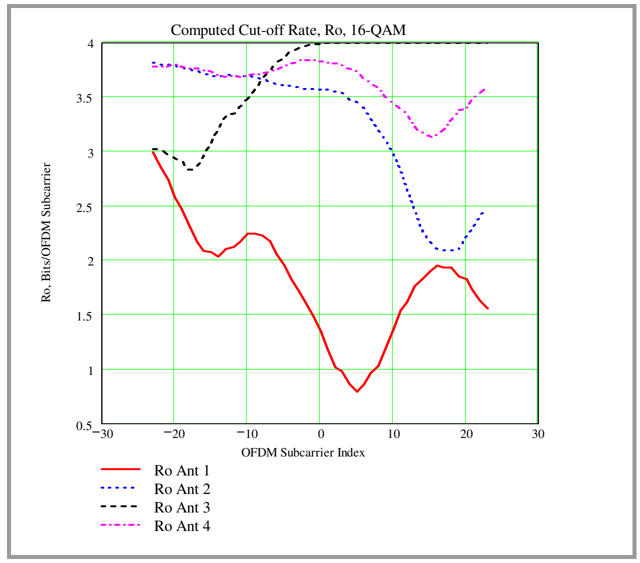

Figure 34: Computed R_o Using the Baseline Sweep from Figure 33 Assuming C/N_o= 20 dB Maximum.

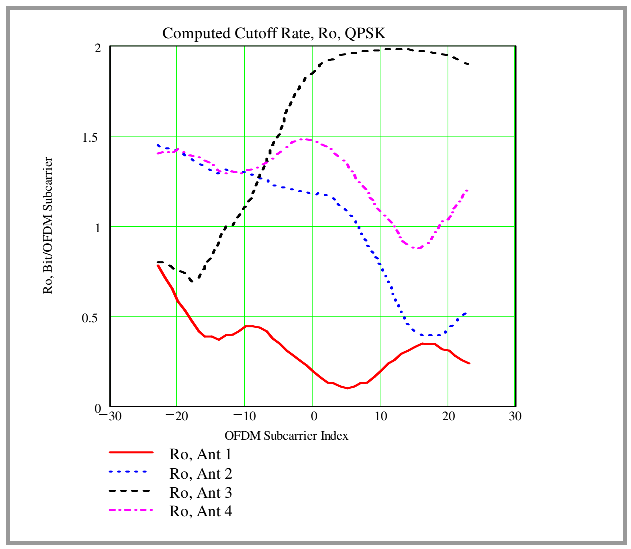

Figure 35: Computed R_o Using the Baseline Sweep from Figure 33 Assuming C/N_o= 10 dB Maximum

11. Appendix: Frequency-Selective Fading Characteristics in the Indoor Channel

A number of additional propagation channel soundings were made within the Magis office building to investigate the dense-multipath case. Figure 36 presents a floorplan of the 3rd floor.

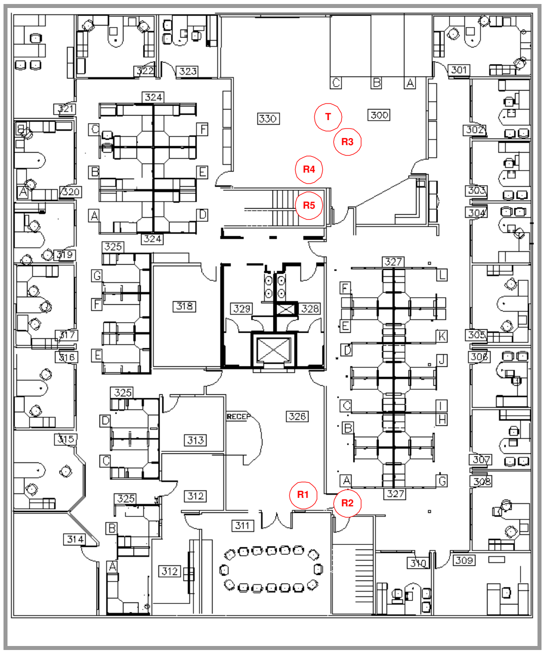

Figure 36: Floor Plan for Magis 3rd Floor (Maximum Length Dimension Approx. 110 Feet)

Figure 38: Portion of Antenna Gain Pattern Assessment Equipment Setup

Figure 39: Simple Microstrip Patch Antenna Used to Examine Local 5 GHz Signal Energy. X- and Y-Axis Plastic Micrometers Are Used to Accurately Position the Antenna for Each Measurement

Only limited equipment is needed to conduct an exploratory examination of the wireless channel propagation characteristics at 5 GHz (see Figure 37 and Figure 38). A simple microstrip, half-wave patch antenna is shown mounted with two plastic micrometers for x- and y-axis positioning in Figure 39. A wideband CDMA signal source can be used to create a broadband signal source at 5 GHz, and a spectrum analyzer equipped with an external low-noise amplifier (LNA) can be used to capture the received signal strength at each measurement point. This simple test setup was used to measure the received signal strength in many locations throughout the Magis building. A few representative measurements are provided in Figure 41 through Figure 44.

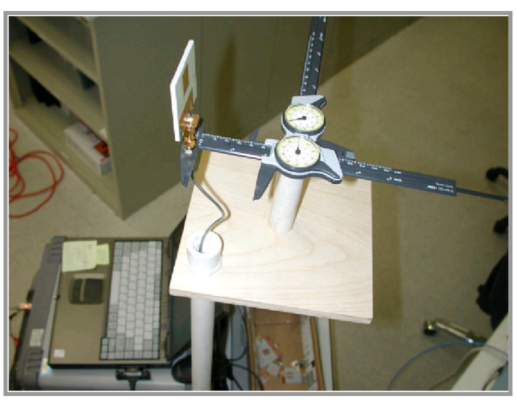

Figure 37: Antenna Probe Assembly

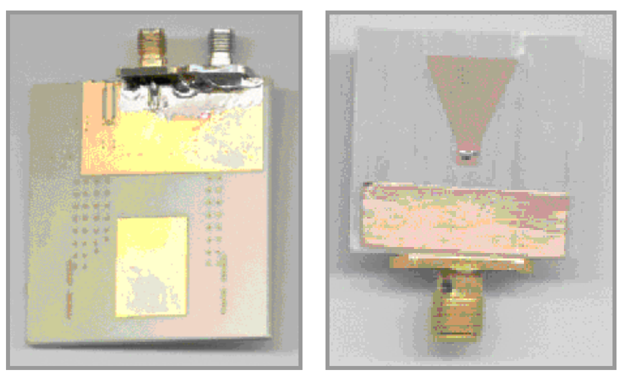

Figure 40 Two of the many different types of antennas that have been studied at Magis (a) Half-wave microstrip patch antenna, (b) microstrip omni-antenna

Referring to Figure 41 through Figure 43, the fine structure location of the frequency selective fading varies rapidly when moving the patch antenna across a distance of only 1 inch using the antenna and plastic micrometer setup shown in Figure 37 and Figure 38. As shown by comparing these figures, a few tenths of an inch cause the frequency-selective fading to move appreciably across frequency. Through the many measurements conducted, several simplistic observations can be immediately drawn:

- Frequency-selective characteristics can change significantly in only a few tenths of an inch.
- Small location differences often simply shift a frequency-selective notch a little lower or a little higher in frequency.
- Frequency-selective null patterns are more often than not very slow changing for the indoor channel. This implies that, once a frequency null comes into play, it can remain stationary for many tens or even hundreds of seconds.

Based on these measurement observations, several high-level conclusions were made regarding the Magis Air5 system design:

- A practical engineering solution that can deliver the throughput and channel reliability demanded by video had to be immune and in fact exploit the fine-structure (e.g., tenths of an inch variation) multipath present with many indoor wireless channels.
- Simple switched-antenna diversity cannot defeat the multipath problem, because the frequency-nulling present at one antenna position was often just shifted to a different portion of the same nominal 20 MHz channel, thereby delivering no benefit.
- Unlike mobile applications that benefit from movement to keep terminals out of sustained frequency-fades, very-fine-structured dead-zones are commonplace over the 5 GHz indoor channel.

In these very crucial respects alone, the IEEE802.11a standard provides no guidance whatsoever.

Motivated in part by the recent work done with space-time coding involving antenna arrays, different antenna arrays were constructed to investigate the frequency-spatial correlation presented by indoor multipath channels. The amount of data collected can quickly become overwhelming, making the true value of the investigation depend entirely on the ability to post-process the collected data. Some example 3-dimensional plots are shown here in Figure 46 and Figure 47 corresponding to a 110 foot non-line-of-sight indoor channel within the Magis building[16]. This particular channel exhibits very heavy multipath and almost wave-guide-like behavior, with propagation losses that are much less than those exhibited in free-space for the same link distance.

To make the data presentation tractable, only two inputs are plotted versus time and frequency in Figure 45 and Figure 46. Each input corresponds to a different element of the antenna array used during the signal collection process. As shown in these two figures, the fine structure of the multipath-related fading is a complex function of time and frequency.

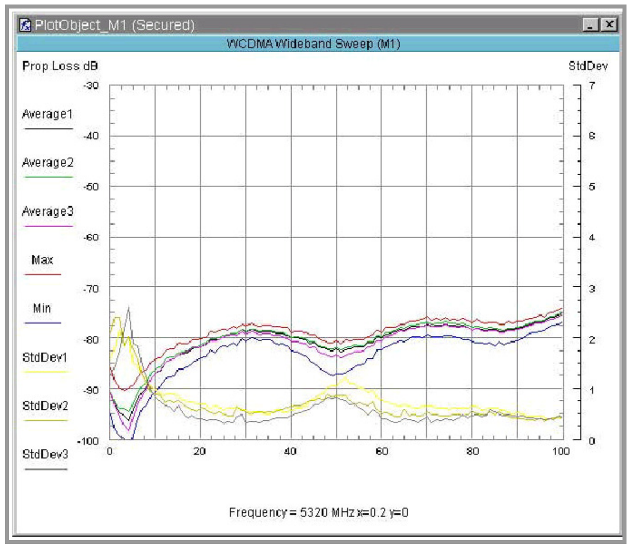

Figure 41: 20 MHz Frequency Sweep Centered at 5.23 GHz, X= 0.20, Y= 0.0 (in.)

[16] The Magis building is a 3-story, steel-reinforced concrete building with aluminum wall studs, a massive steel-lined elevator shaft up through the center of the building, and corrugated steel sheeting as part of each story's sub-flooring. The ceilings all contain steel framing for false ceilings also and all of the windows are generally covered by metal venetian blinds.

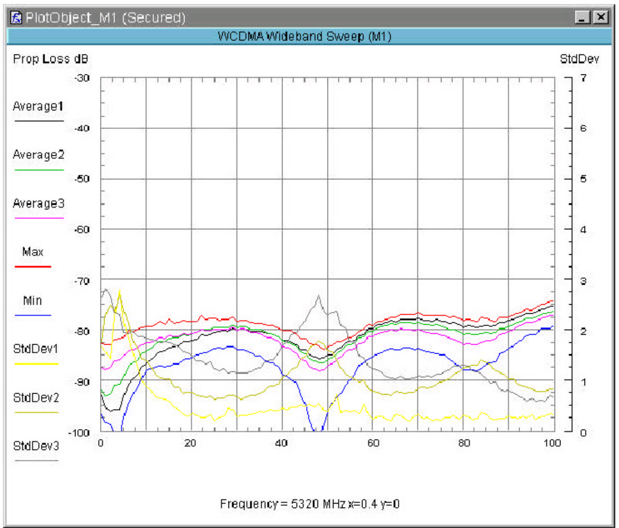

Figure 42: 20 MHz Frequency Sweep Centered at 5.23 GHz, X= 0.40, Y= 0.0 (in.)

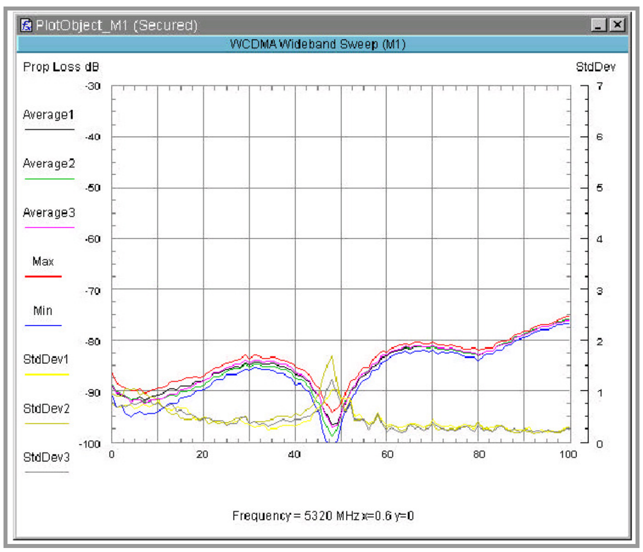

Figure 43: 20 MHz Frequency Sweep Centered at 5.23 GHz, X= 0.60, Y= 0.0 (in.)

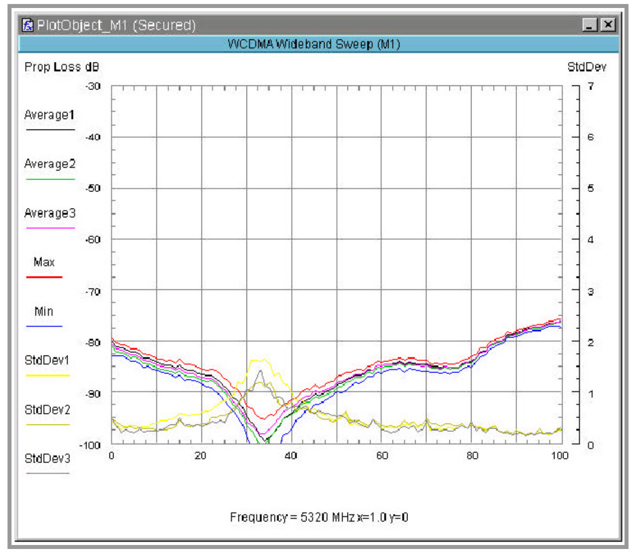

Figure 44: 20 MHz Frequency Sweep Centered at 5.23 GHz, X= 1.0, Y= 0.0 (in.)

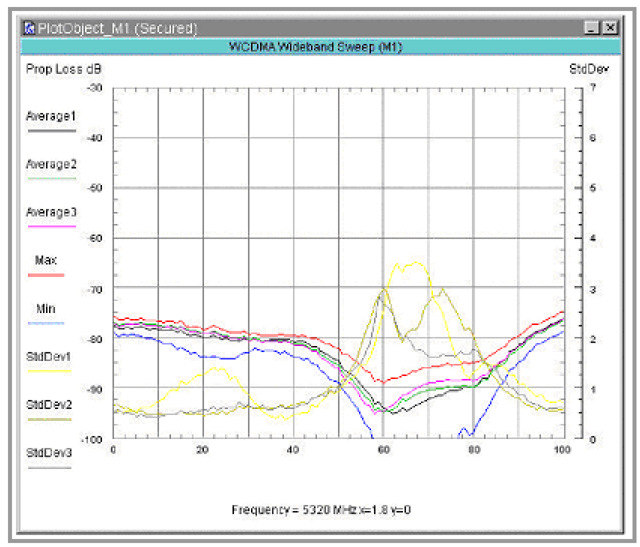

Figure 45: 20 MHz Frequency Sweep Centered at 5.23 GHz, X= 1.8, Y= 0.0 (in.)

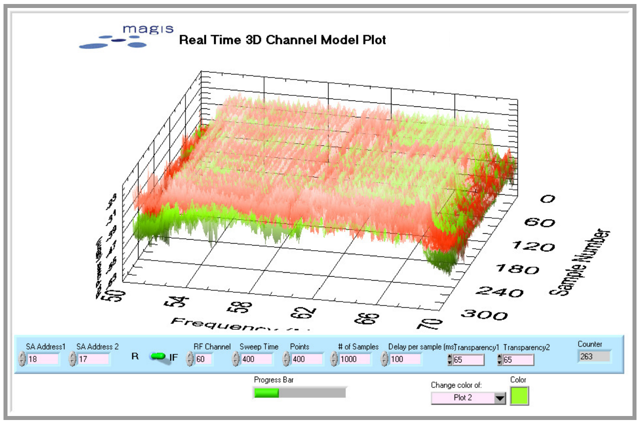

Figure 46: 3-D Channel Plot Corresponding to 110 Foot Non-Line-of-Sight Channel[17] Using Two Simultaneous Looks at the Received Spectrum (Centered at 60 MHz)

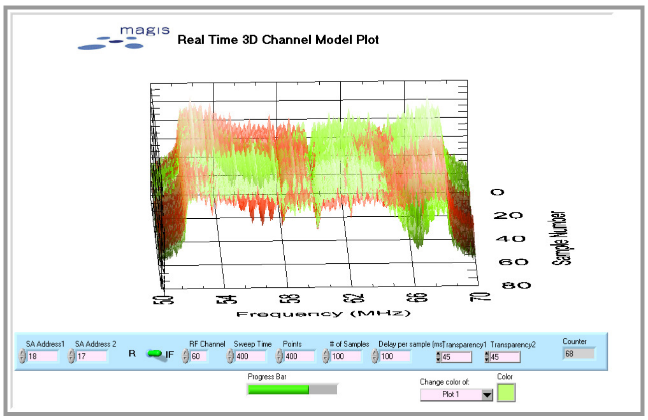

Figure 47: 3-D Channel Plot Equivalent to Figure 46, Except That Distant Office Door Now Open Rather Than Closed[18]

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17 Magis report, "Channel Model Investigation," Figure 9.

18 Magis report, "Channel Model Investigation," Figure 12.

12. Appendix: FCC Transmitter Limits

Sec. 15.407 General technical requirements.

(a) Power limits:

(1) For the band 5.15–5.25 GHz, the peak transmit power over the frequency band of operation shall not exceed the lesser of 50 mW or 4 dBm + 10logB, where B is the 26-dB emission bandwidth in MHz. In addition, the peak power spectral density shall not exceed 4 dBm in any 1-MHz band. If transmitting antennas of directional gain greater than 6 dBi are used, both the peak transmit power and the peak power spectral density shall be reduced by the amount in dB that the directional gain of the antenna exceeds 6 dBi.

(2) For the band 5.25–5.35 GHz, the peak transmit power over the frequency band of operation shall not exceed the lesser of 250 mW or 11 dBm + 10logB, where B is the 26-dB emission bandwidth in MHz. In addition, the peak power spectral density shall not exceed 11 dBm in any 1-MHz band. If transmitting antennas of directional gain greater than 6 dBi are used, both the peak transmit power and the peak power spectral density shall be reduced by the amount in dB that the directional gain of the antenna exceeds 6 dBi.

(3) For the band 5.725–5.825 GHz, the peak transmit power over the frequency band of operation shall not exceed the lesser of 1 W or 17 dBm + 10logB, where B is the 26-dB emission bandwidth in MHz. In addition, the peak power spectral density shall not exceed 17 dBm in any 1-MHz band. If transmitting antennas of directional gain greater than 6 dBi are used, both the peak transmit power and the peak power spectral density shall be reduced by the amount in dB that the directional gain of the antenna exceeds 6 dBi. However, fixed point-to-point U-NII devices operating in this band may employ transmitting antennas with directional gain up to 23 dBi without any corresponding reduction in the transmitter peak output power or peak power spectral density. For fixed, point-to-point U-NII transmitters that employ a directional antenna gain greater than 23 dBi, a 1 dB reduction in peak transmitter power and peak power spectral density for each 1 dB of antenna gain in excess of 23 dBi would be required. Fixed, point-to-point operations exclude the use of point-to-multipoint systems, omni directional applications, and multiple collocated transmitters transmitting the same information. The operator of the U-NII device, or if the equipment is professionally installed, the installer, is responsible for ensuring that systems employing high gain directional antennas are used exclusively for fixed, point-to-point operations.