VIDEO54

MIMO and Smart Antenna Techniques for 802.11a/b/g

INTRODUCTION

Convenience and affordability have made Wi-Fi the dominant home networking technology. Its popularity, in turn, has raised the awareness of current Wi-Fi limitations, spurring a rush to market of alternative technologies such as next generation Powerline and UWB. With the combined advantage of mobility, ubiquity and massive volume, the chances of dislodging Wi-Fi's reign in the home are remote, especially since 802.11n, the standard body for next generation Wi-Fi, is already working on addressing many of the current shortcomings.

The .11n proposals have centered on a wireless technology called MIMO (Multiple-In, Multiple-Out), and proprietary MIMO chipsets are already available in the market for experimentation. Video54's BeamFlex™ technology applies the principles of MIMO to enhance today's 802.11a/b/g networks in the most cost effective way. This paper will discuss today's wireless LAN problems and how MIMO addresses them. It will also examine the important implementation choices for MIMO devices and the Video54 BeamFlex approach.

WHAT'S THE PROBLEM?

The most frequent complaints about Wi-Fi home networks are inadequate range and spotty coverage. Performance fluctuations, often masked by the burstiness of data applications such as web surfing, become immediately apparent when the network is asked to support latency and throughput sensitive applications such as online gaming and video streaming where instantaneous and uninterrupted bandwidth is critical. Eventually, as broadband access speeds are upgraded to multi-megabits, the need for higher data rates than the current physical layer maximum of 54 Mbps will also become important.

THE WI-FI WOES

Signal strength and noise levels, commonly expressed in the form of signal-to-noise ratio (SNR),

WHAT IS MIMO?

"MIMO wireless refers to the use of multiple antennas at both ends of a radio link, and is emerging as an important technology to enhance wireless performance. MIMO has evolved (and is still evolving), since its early beginning in 1993, with contributions from hundreds of researchers around the world. Some aspects of MIMO have already entered wireless standards, and many more standards efforts are ongoing.

The multiple antennas at each end of a MIMO link can be used in different modes such as transmit-receive diversity, beamforming, antenna subset selection and spatial multiplexing. Each of these modes further has several internal options. Which mode or option actually maximizes performance depends on the channel condition, SNR and QoS requirements, among other factors. For example spatial multiplexing can perform poorer than transmit-receive diversity under certain scenarios. Different aspects of MIMO will find their unique niches in the plethora of products now entering the market."

Dr. A. Paulraj
Professor at Stanford University, Supervisor of the Stanford Smart Antenna Research Group since 1993 and a renowned pioneer in MIMO technologies.

"MIMO refers to any technology that uses multiple antennas on both sides of the link. There are a variety of different transmission and reception methods that make use of multiple transmit and receive antennas - all are considered MIMO techniques."

Dr. Robert W. Heath Jr.
Assistant Professor at University of Texas at Austin and head of its Wireless Systems Innovations Laboratory (WSIL) conducting active research program in all aspects of MIMO communication including antenna design, signal processing algorithms, channel feedback, and prototyping.

are the key determinants of wireless performance and range. (See Sidebar 1). It is well known that radio signals weaken with distance and impediments in the signal path. For example, an 802.11g data network in a typical home loses performance to the point of being unusable at about 70 to 100 feet (23-33 meters), especially if there are intervening materials such as walls and doors that absorb or scatter the Wi-Fi signals. (See Sidebar 2). But even the strongest signals can become undecipherable in the presence of "loud" noise, (nearby noise is always "loud"), resulting in receive errors and retransmissions. Beside the thermal and electromagnetic noise that exists in all homes, other major sources of noise are radio frequency (RF) interference, co- and adjacent-channel interference and multipath interference.

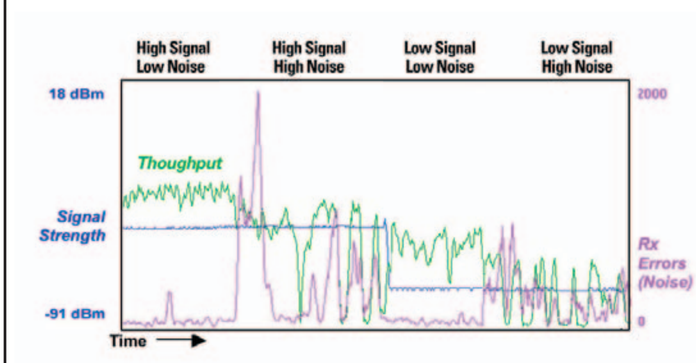
RF interference comes from RF devices operating in the same frequency band as the Wi-Fi network. Well known culprits that interfere with 802.11g in the 2.4 GHz band are cordless telephones, Bluetooth devices and microwave ovens.

Co- and adjacent-channel interference occurs in dense Wi-Fi environments such as multi-tenant apartment buildings where one network's information signals become noise to another network (co-channel interference). Even when the neighbor networks are assigned to different frequency channels, signals can leak into adjacent channels and raise their noise levels (adjacent-channel interference).

Multipath interference results when radio signals are reflected by physical objects such as ceilings and walls as well as people, creating multiple signal paths between the sender and the receiver. Signal waves thus arrive at the receiver out of phase, creating a condition called multipath fading that manifests itself in reduced and unpredictable signal strength, coverage holes and packet errors. Multipath fades ebb and flow with the movements of people and objects in a home.

Devices compensate for weak or noisy signals by automatically lowering their transmission rate which has the undesirable side effect of decreasing throughput and reducing total network capacity.

SIDEBAR ONE



The above snapshot demonstrates the impact of signal strength and noise on Wi-Fi throughput.

The **blue** line represents the signal strength levels recorded by the measuring station's RSSI (Receive Signal Strength Indicator) at two different locations.

The **pink** line represents RF noise (indicated by receive-error counts). High noise levels were created by powering up the microwave oven.

The **green** line shows the measuring station's throughput under varying signal and noise conditions. The throughput rate at any individual moment is impacted by the signal-to-noise ratio at that moment as well as other factors not shown in the snapshot, such as the transmit data rate used by the NIC or the AP.

The snapshot demonstrates declined throughput under low signal strength and/or noisy conditions. Note also the dramatic performance swings under reduced SNR conditions.

The Impact of Signal Strength and Noise on Network Performance

SIDEBAR TWO

Interior Wall Material	Reduction in Signal Strength
Drywall (Gypsum), Playwood board, Veneer board	Less than 20%
Glass Typical interior door	30-60%
Double-glazed window Concrete or brick wall	90-95%
Metal	100%

Wi-Fi Signal Penetration Losses

Brute force solutions for boosting signal strength such as high gain antennas or stronger power amplifiers are ineffective since they lack the agility to deal with the variability of the RF environment. Smart antenna technologies capable of automatically adapting to dynamic changes in the environment to maximize the availability of quality signal paths have become the focus of next generation Wi-Fi solutions.

MIMO TO THE RESCUE

"MIMO is an antenna technology for wireless communications in which multiple antennas are used at both the transmitter and the receiver. The antennas at each end of the communications circuit are combined to minimize errors and optimize data speed," [1]. MIMO operates in two modes: Diversity and Spatial Multiplexing.

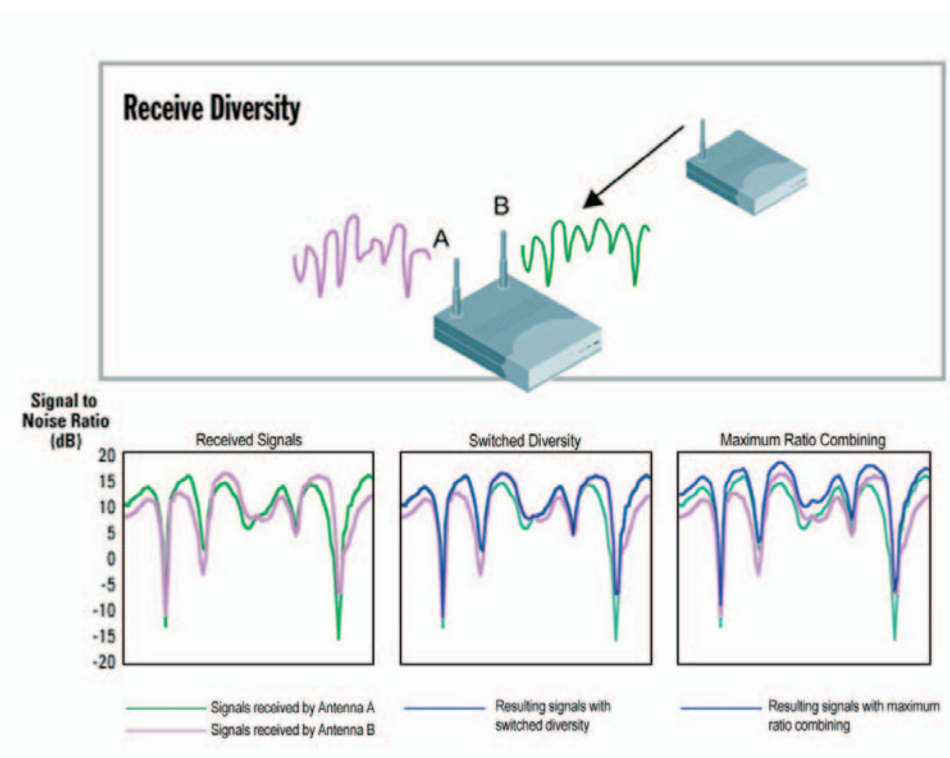
Diversity Mode

Fundamentally, Diversity refers to the use of multiple antennas to increase the probability of a high quality signal path between the sender and the receiver. Diversity can be implemented at the transmit end, the receive end or at both ends of the wireless link.

Simple receive diversity involves the use of two (potentially more) antennas that are spaced sufficiently apart such that they can receive signals from independent signal paths. A basic way to select the optimal receive antenna output is switched diversity, whereby the receiver simply switches antenna whenever it detects weak signals or a high noise level from the current receiving antenna. More sophisticated diversity techniques such as Maximum Ratio Combining (MRC) receive on multiple antennas simultaneously and apply advanced signal processing algorithms to combine the different versions of the received signals to maximize SNR. Switched diversity and MRC can be implemented on just the receive side of a link. (Figure 1).

Transmit Diversity is more complicated because the sender needs prior knowledge of the receiver in order to optimize the transmit path(s). The simplest scheme is to use the antenna from which information signals

Figure 1
Receive diversity maximizes SNR: Comparing Selection Combining and Maximum Ratio Combining



have arrived successfully from the target receiver before. More advanced techniques transmit multiple copies of the same information stream out of the antennas for added redundancy. In this scenario, the same information signals must first be transformed into different RF signals to avoid interference with one another. Sophisticated signal transformation techniques require the receiver to implement a corresponding "de-transformation" algorithm whereas simple signal transformation such as Cyclic Delay Diversity can be implemented on only one side of the link.

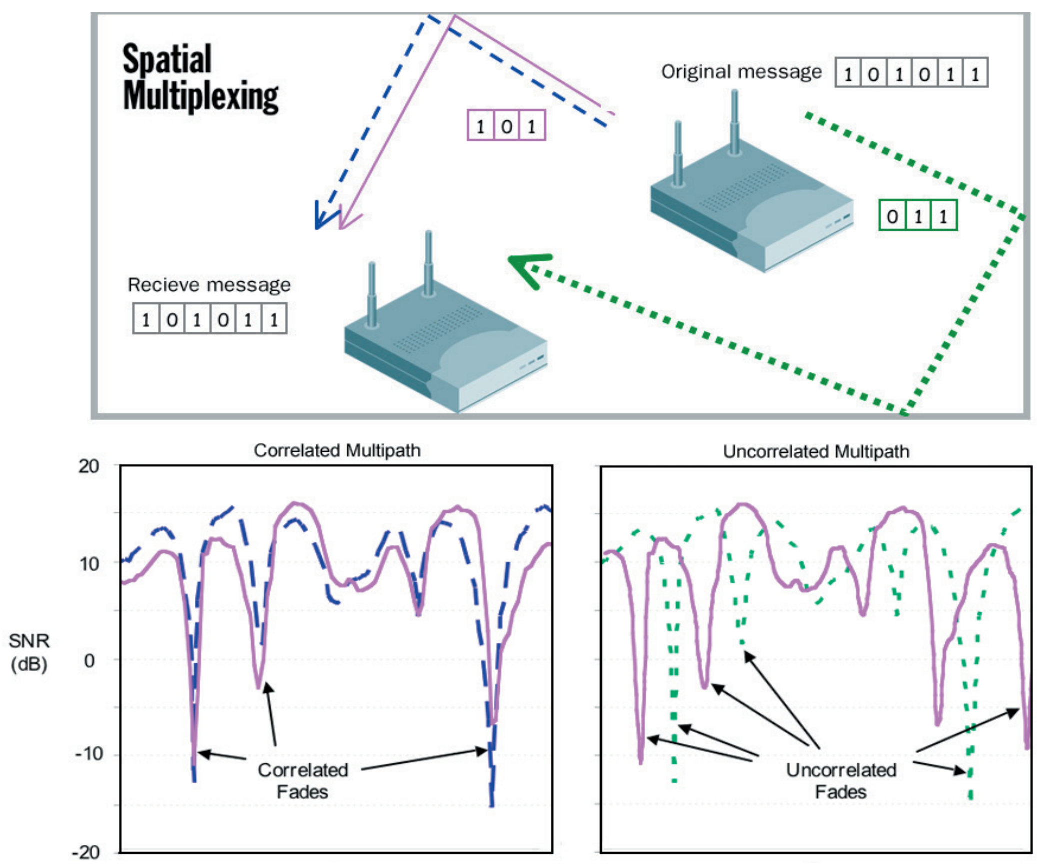
Diversity maximizes wireless range and coverage. It also increases network throughput by finding quality signal paths such that devices can communicate using the highest data rates and avoiding signal paths that are likely to produce packet errors and retransmissions. Generally, the number of uncorrelated antennas used, or the diversity order, produces a logarithmic gain in performance.

Spatial Multiplexing Mode

In rich multipath environments with multiple uncorrelated signal paths, (see figure 2), Spatial Multiplexing (SM) allows the sender to transmit different portions of the user data on multiple paths in parallel to increase capacity. The target receiver must implement a corresponding de-multiplexing algorithm to recover the original information stream from its receive antennas. In an ideal multipath environment, SM can increase the capacity of a single frequency channel linearly with the number of SM antennas used. However, the achievable performance is highly dependent on the RF environment.

SM requires uncorrelated multipaths. Since multipath fades change moment by moment with motion, there is no assurance that uncorrelated signal paths can always be found. Furthermore, SM does not work well in low SNR environments ([2], [3]) where signals are weakened by distance or the noise level from RF and channel interference is high. Such impairments make it more difficult for

Figure 2
Spatial multiplexing over uncorrelated multipaths



the sender and receiver to identify the uncorrelated signal paths. When the SM mode is not possible, a MIMO system reverts to diversity mode.

It should be noted that SM by itself does not provide any range improvements; in fact, its dependence on a high SNR reduces its operating range. In order to improve both range and throughput, a MIMO implementation needs to support some form of diversity scheme in addition to Spatial Multiplexing.

MIMO AND SMART ANTENNA IMPLEMENTATION ISSUES

MIMO promises to address both the coverage and performance shortcomings of today's Wi-Fi networks. However, before a standard is well defined, the choices made in a MIMO implementation, i.e., which diversity methods, how many antennas, what multiplexing algorithms, etc, have profound interoperability and cost implications.

Interoperability

Spatial Multiplexing requires the same multiplexing algorithm on both sides of a communications link. Therefore it is not interoperable with existing 802.11a/b/g devices. Until 802.11n is defined, only SM client and SM network devices from the same vendor can communicate with each other. In contrast, switched diversity and Maximum Ratio Combining are diversity techniques that can be implemented on just one side of a communications link; therefore they can benefit all existing 802.11a/b/g devices.

Cost

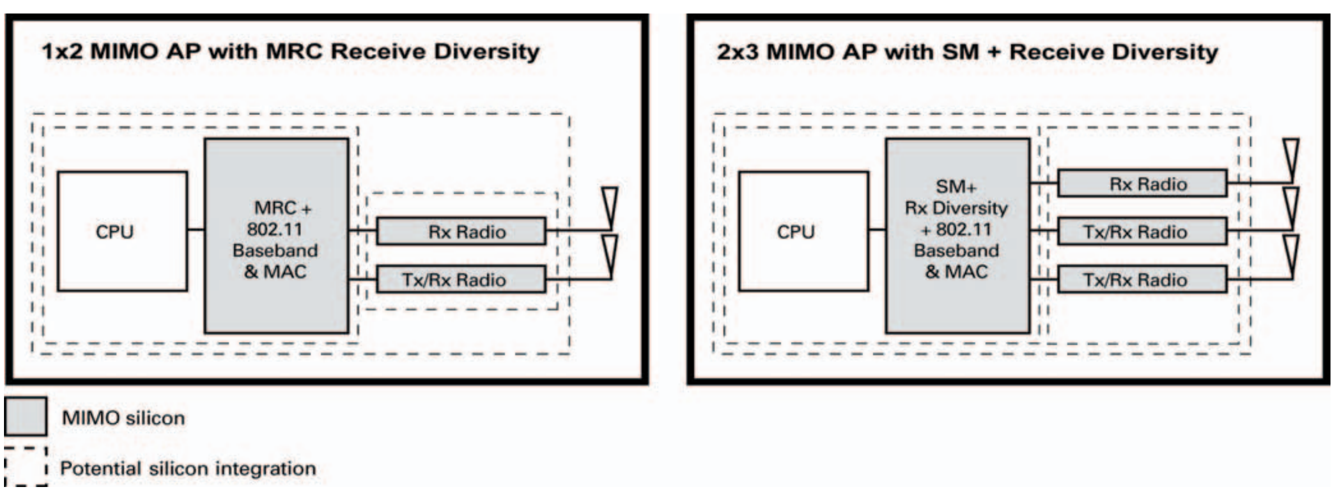
MRC and SM require complex signal processing which must be integrated into a new generation of Wi-Fi chipsets. While single chip integration of the Media Access Control (MAC), baseband, radio and host processor functions is now driving 802.11b/g System-on-Chip (SoC) prices to less than $10, MIMO chipsets will not reach this price range until 802.11n standardization, technology maturity and unit volume approach a similar level.

Furthermore, both MRC and SM require one radio chain per antenna, (see figure 3). A radio chain consists of analog elements such as amplifiers, analog-to-digital converters, mixers, etc, which consume power and are relatively expensive; unlike digital chips, they do not follow Moore's law. The cost of the radios will constitute a growing percentage of the total system cost even as MIMO silicon hits critical volumes.

Performance

While a large body of research has demonstrated the theoretical capacity improvements possible with SM, there are also studies that show antenna selection diversity producing better performance than SM in the presence of low SNR, RF or channel interference [2], [3]. This would imply that a good diversity technique may be more effective than Spatial Multiplexing for long range coverage and in dense urban dwellings.

Figure 3
Functional blocks for MIMO AP systems



VIDEO54'S BEAMFLEX

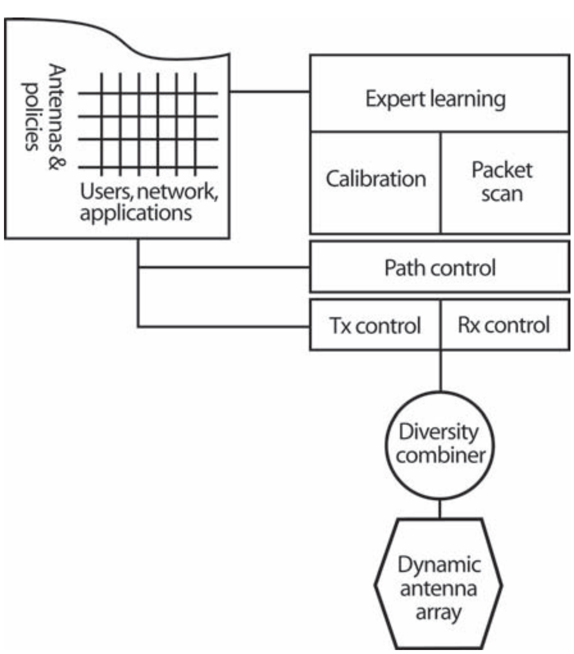
BeamFlex, a smart antenna technology, delivers MIMO's diversity benefits to 802.11a/b/g devices today and can be integrated in future 802.11n devices to further increase diversity gain and scale Spatial Multiplexing performance at minimal incremental costs.

Smart Antennas with Unmatched Agility

Central to BeamFlex is an agile antenna array with multiple antenna elements that can be combined in real time to offer an exponential increase in diversity order. With N number of high-gain, directional antenna elements, a BeamFlex antenna array provides 2^N-1 unique radiating patterns to maximize range and coverage in a home. A Diversity Combiner composed of low cost, software-controlled circuitry allows the BeamFlex software to manage antenna combining in real time.

The "smarts" of the BeamFlex antenna system reside in its control software. At its core is an expert system that constantly learns the environment – the RF conditions, communicating devices, network performance and application flows. A Path Control module uses the knowledge to select optimum antenna combinations on a per packet basis to ensure a quality signal path to each receiving station. The Transmission Control module sets the transmission policies including data rate and queuing strategy based on application and station knowledge, (see figure 4). The BeamFlex software interfaces to the 802.11 MAC layer and is compatible with standard 802.11 chipsets. Residing in the host processor, it adds minimal incremental CPU load and memory utilization.

Figure 4
Video54 BeamFlex architecture



A Systems Approach to MIMO Diversity

BeamFlex takes a systems approach to maximize signal coverage, application throughput and network capacity. It makes critical use of physical (L1), data-link (MAC/L2), network (L3), transport (L4) and application layer (L7) information to assist in the joint optimization of the antenna structure and transmission policies. This, in combination with the massive order of diverse path options offered by the agile antenna array, ensures consistent and uninterrupted bandwidth for real time applications such as video streaming and online games. (See BeamFlex Performace Charts in Appendix B)

Standards Compliance

Until there is a consensus on the 802.11n specification, any ASIC-based implementation of Spatial Multiplexing mode will most likely be obsolete by the time 802.11n arrives. By implementing large-scale diversity at the antenna and software levels, BeamFlex is compatible with any standard-based 802.11 chipset, today and tomorrow.

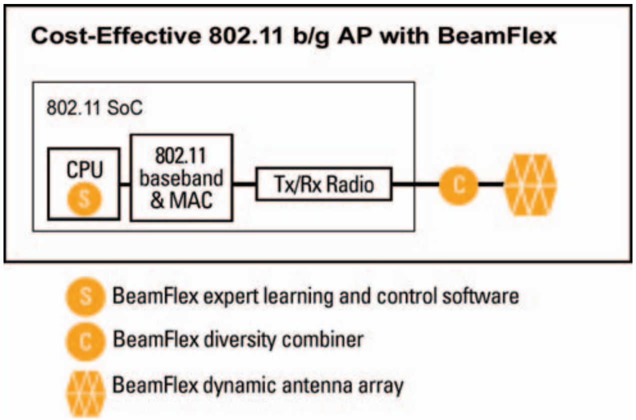
Enhancing Installed Wi-Fi Devices

SM is not interoperable with installed 802.11a/b/g devices. Only the diversity techniques that do not require dual-end coordination can benefit existing Wi-Fi devices. BeamFlex offers substantial improvements to the Wi-Fi installed base even when implemented on only the access point or the station; when it is integrated on both, BeamFlex provides full transmit and receive diversity to deliver another order of optimization.

Most Cost Effective

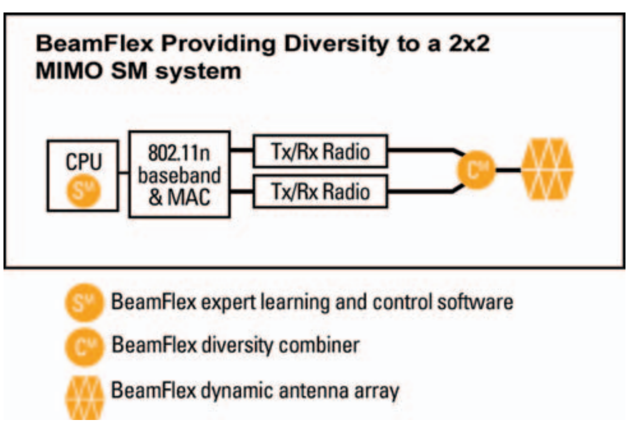
The cost of antenna material is minuscule compared to the cost of a radio chain. By using a nimble, software-combinable antenna array to achieve large-scale diversity without additional radios and by leveraging commoditized, mass market Wi-Fi chipsets, BeamFlex produces performance and range improvements at a better price/performance ratio than pre-standard MIMO chipsets with multiple radios, (see figure 5, next page).

Figure 5
Functional blocks for BeamFlex-based AP system



Recent research has started focusing on reducing MIMO's complexity, power consumption and cost by employing fewer radio chains and optimally allocating each chain to one of a larger number of antennas controlled via an antenna selection scheme, [4], [5]. As an example, a minimum MIMO implementation that provides both SM and receive diversity requires 3 sets of antennas and radios for single band and twice as many for dual-band support. With BeamFlex providing diversity coverage, a 2x2 MIMO implementation can achieve improved Spatial Multiplexing and provide diversity gains at the same time with only 2 (single band) or 4 (dual band) radio chains, reducing cost, power consumption and space. (See figure 6).

Figure 6
Functional blocks for 2x2 MIMO AP with spatial multiplexing and transmit/receive diversity



Manufacture-Friendly

Physical antenna design has received relatively little attention in MIMO research although antenna arrays are fundamental to MIMO. As MIMO implementations scale, adding radio chains and spatially separated antennas can quickly become a nightmare from the perspective of power dissipation, real estate and manufacture assembly. The BeamFlex dynamic antenna array makes efficient use of limited physical space to create a large number of antenna patterns without additional power or radio chain requirements. Furthermore, antenna placement is designed-in, resulting in a single small internal antenna assembly. An internal antenna array also reduces the number of movable parts, hence lowering the risk of product returns.

SUMMARY

MIMO will enable Wi-Fi to continue its dominance in home networking technologies but standardization is essential to ensure multi-vendor interoperability and protect consumers' investment. In the meantime, a subset of MIMO techniques can be implemented without risking compatibility with 802.11a/b/g devices today and 802.11n systems in the future. BeamFlex offers the most cost effective, standards-based implementation of MIMO's diversity mode to maximize performance and coverage for the vast installed base of 802.11a/b/g networks. It is also uniquely positioned to complement MIMO silicon solutions by reducing cost, power requirements, system size and manufacturing complexity while providing a practical way to scale performance to an even higher level.

Sources and References

[1] searchMobileComputing.com, http://searchmobilecomputing.techtarget.com/sDefinition/0,,sid40_gci1025328,00.html

[2] Andreas F. Molisch and Moe Z. Wi, "MIMO Systems with Antenna Selection – An Overview", copyright Mitsubishi Electric Research Laboratories, Inc., 2004, 201 Broadway, Cambridge, Massachusetts 02139, TR-2004-014, pp. 10, 18, Mar 2004.

[3] Jon W. Wallace and Michael A. Jensen, "MIMO Capacity Variation with SNR and Multipath Richness from Full-wave Indoor FDTD Simulations", Department of Electrical and Computer Engineering, Brigham Young University.

[4] Bedri Artug Cetiner, Hamid Jafarkhani, Jiangyuan Qian, Hui Jae Yoo, Alfred Grau, Franco De Flaviis, "Multifunctional Reconfigurable MEMS Integrated Antennas For Adaptive MIMO Systems", University if California, Irvine.

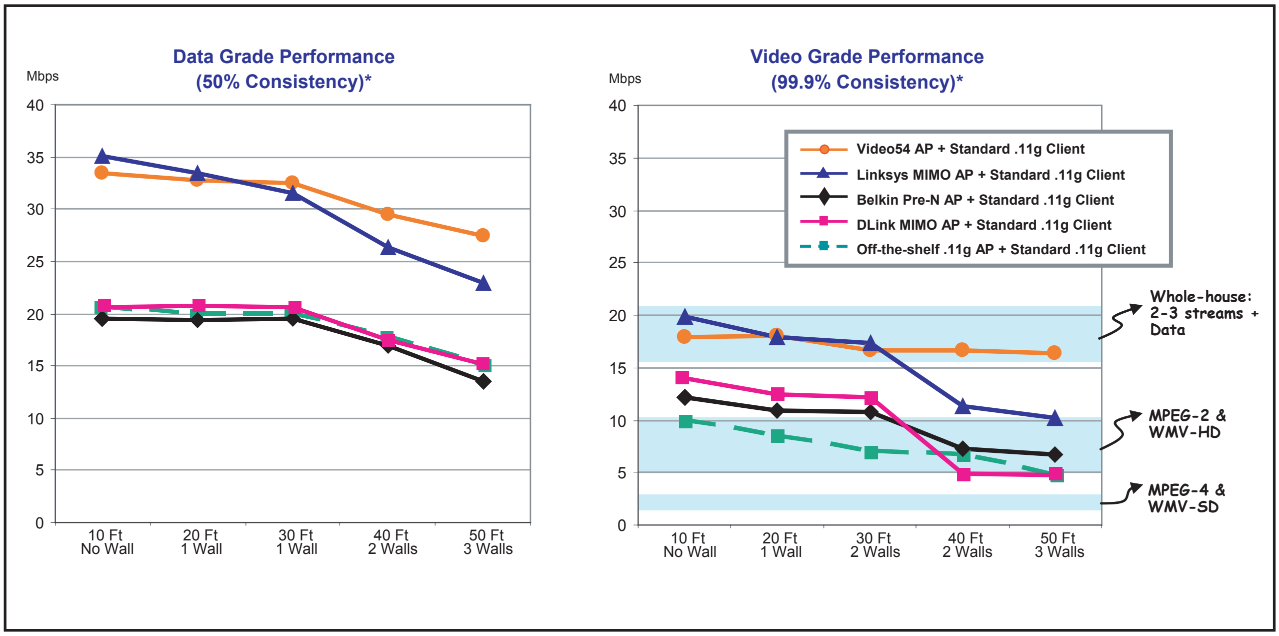
[5] Michael A. Jensen and Jon W. Wallace, "Antenna Selection for MIMO Systems based on Information Theoretic Considerations", Brigham Young University, 2003.

APPENDIX(A): Comparison of MIMO/smart antenna techniques

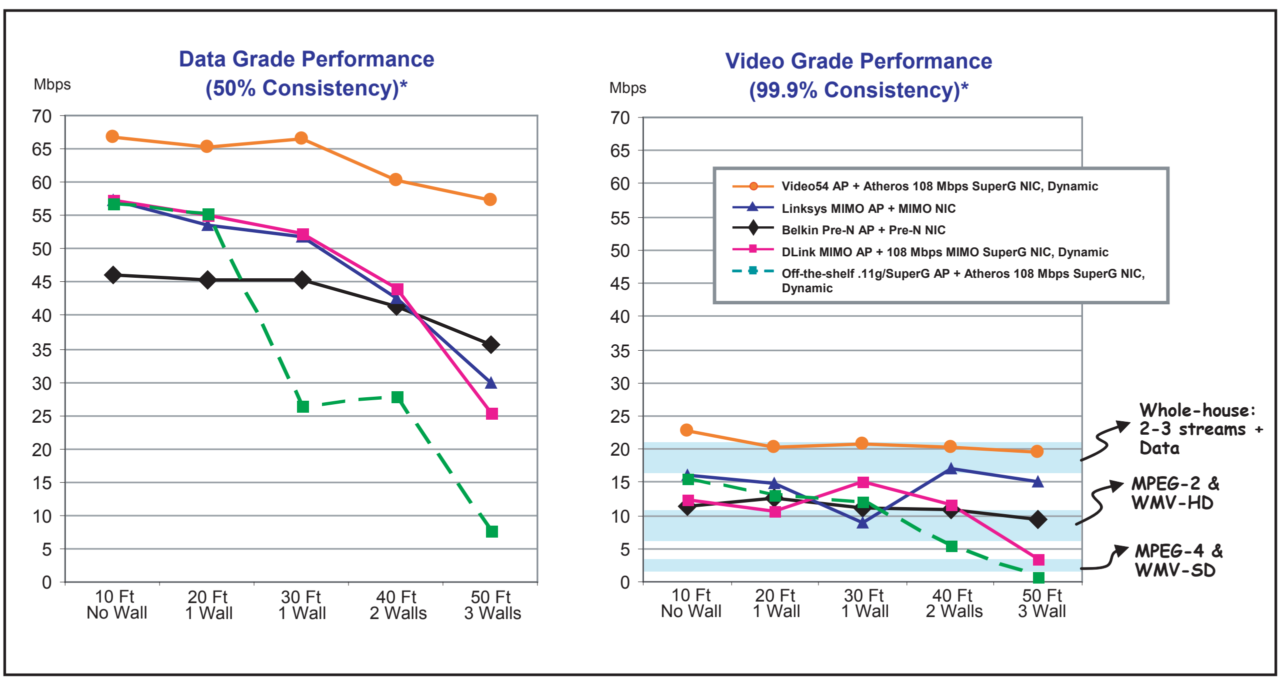
	Maximum Ratio Combining (MRC)	Cyclic Delay Diversity	Spatial Multiplexing (SM)	Video54 BeamFlex
Type of enhancement	Rx diversity	Tx diversity	Tx/Rx multiplexing	Tx/Rx diversity
Increases range?	Yes	Yes	No	Yes
Increases PHY rate/ theoretical capacity?	No	No	Yes	No
Increases achievable throughput?	Yes	Yes	Yes	Yes
Enhances 802.11a/b/g?	Yes	Yes	No	Yes
Dual-end solution required?	No	No	Yes	No
Silicon requirements	Requires new chip support	Requires new chip support	Requires new chip support	No on-chip requirements; compatible with all Wi-Fi chipsets
Number of radio chains required	2 or more	2 or more	2 or more	1 or more

APPENDIX(B): Performance comparisons of MIMO/Smart Antenna implementations in a real world home with high noise levels

54 Mbps (802.11g) comparisons



108 Mbps comparisons



Test Environment
- 1,200 SQ FT apartment in large complex
- Noise from 12+ active APs in neighborhood
- UDP echo test
- 10,000 measurements per AP, per position

% Consistency Definition