Mimo and Smart Antenna Techniques for 802.11a/b/g Networks

INTRODUCTION

Convenience and affordability have made Wi-Fi the dominant home networking technology. Its popularity has also raised the awareness of current Wi-Fi network limitations, spurring a rush to productize alternative technologies such as next generation HomePlug 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 next generation Wi-Fi standard body, 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. This paper will discuss the wireless LAN problems and how MIMO addresses them. It will also examine the important implementation choices in MIMO and the 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 real-time applications such as online gaming and video streaming where instantaneous and stable bandwidth is necessary. 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

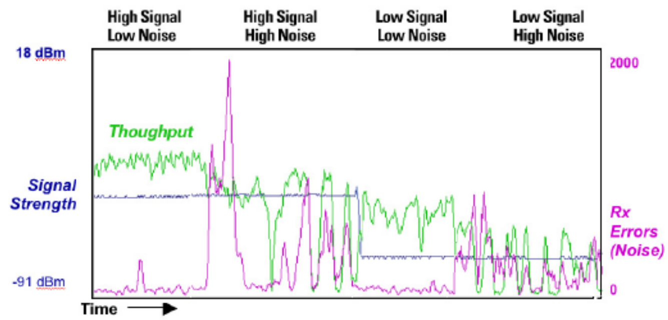
Signal strength and noise level are the key determinants of wireless performance and range, (see Sidebar 1). It is well known that radio signals weaken with distance and impediments in the signal path. For example, an 802.11g network in a typical home loses performance to the point of being unusable 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, next page). 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 typical 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 oven.

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.

SIDEBAR ONE



The above throughput test snapshot demonstrate 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). The high noise levels at the right hand side of both pictures were created by powering up the microwave oven.

The **green** line shows the throughput trends under various signal and noise conditions. Note that the throughput rate at any individual moment is impacted by the SNR as well as other factors, such as the transmit data rate used by the NIC or the AP.

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

The Impact of Signal Strength an 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

Wi-Fi devices compensate for weak or noisy signals by automatically lowering the transmission rate which has the undesirable side effect of decreasing throughput and reducing total network capacity. Many optimization schemes focus on maximizing the Signal to Noise Ratio (SNR) between the sender and receiver. 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

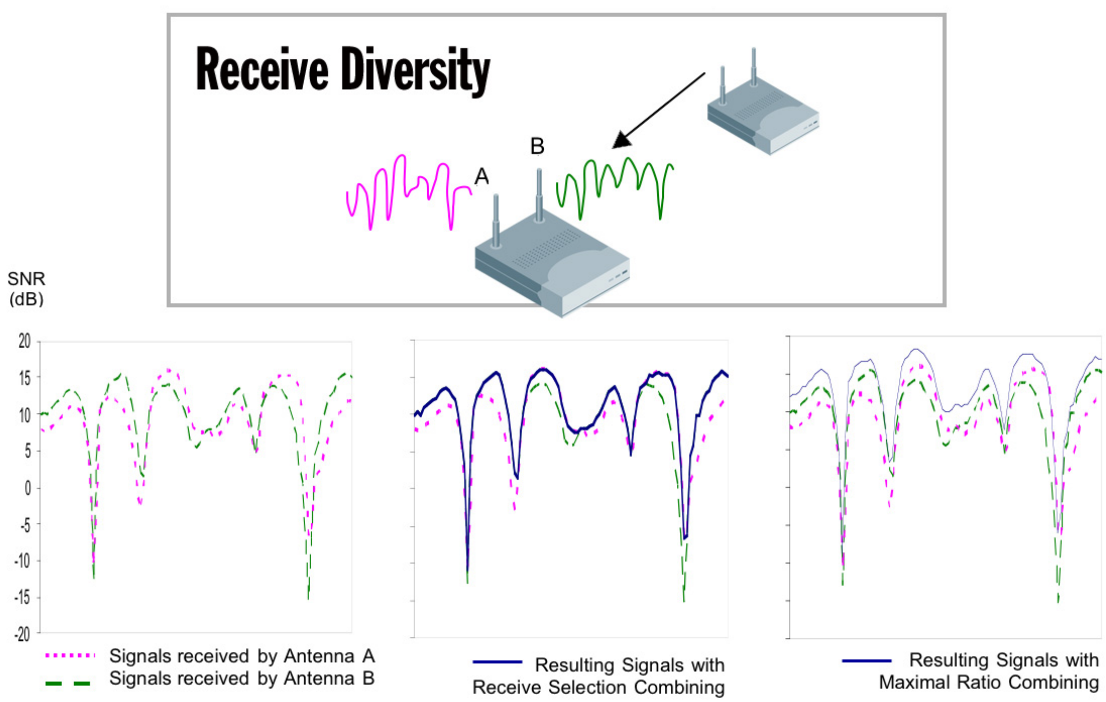
"MIMO is an antenna technology for wireless communications in which multiple antennas are used at both the transmitter and the receiver. The antennas at each end of the communications circuit are combined to minimize errors and optimize data speed," [1]. MIMO operates in two modes: Diversity or Spatial 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 or more antennas that are spaced sufficiently apart such that they can receive signals from independent signal paths. A basic way to select an optimal receive antenna from an array of antennas is Selection Combining, whereby the receiver switches to another antenna whenever it detects weak signals or a high noise level from the current receiving antenna. More sophisticated 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 and minimize receive errors. Selection Combining and MRC can be implemented on just the receive side of the link, (figure 1).

Figure 1
Receive diversity maximizes SNR: selection combining and maximum ratio combining



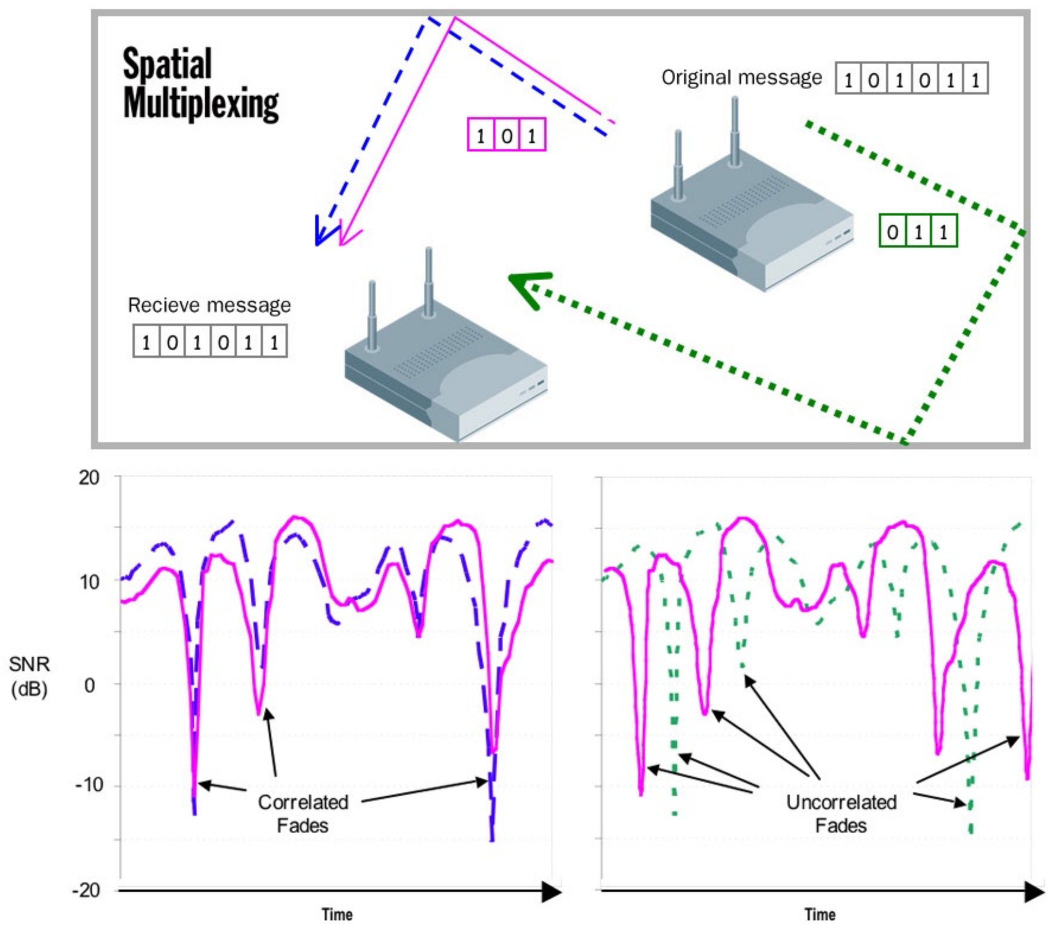
Transmit Diversity is more complicated because the sender needs prior knowledge of the receiver in order to optimize the transmit path(s). The simplest scheme is to use the antenna from which information signals have been received successfully from the target receiver before. More advanced techniques 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 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 multiple antennas. In an ideal multipath environment, SM can increase the capacity of a single frequency channel linearly with the number of transmit antennas used.

Figure 2
Spacial diversity over uncorrelated multipaths



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 weak due to distance or the noise level is high because of RF and channel interference. Such impairments make it more difficult for the sender and receiver to identify the uncorrelated signal paths. When the SM mode is not possible, MIMO 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 SM's 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.

Beamforming

While some people may argue that Beamforming is not MIMO, it is a smart antenna technology that is currently being considered as part of 802.11n. Beamforming uses multiple, closely spaced antennas to transmit the same phased signals to maximize radiation toward a particular direction while canceling interference from other directions. The result is a higher SNR towards the intended receiver. Beamforming is highly effective in line-of-sight (LOS) situations; in non-LOS (NLOS), multipath environments, it may require more than two antennas to be equally effective.

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.

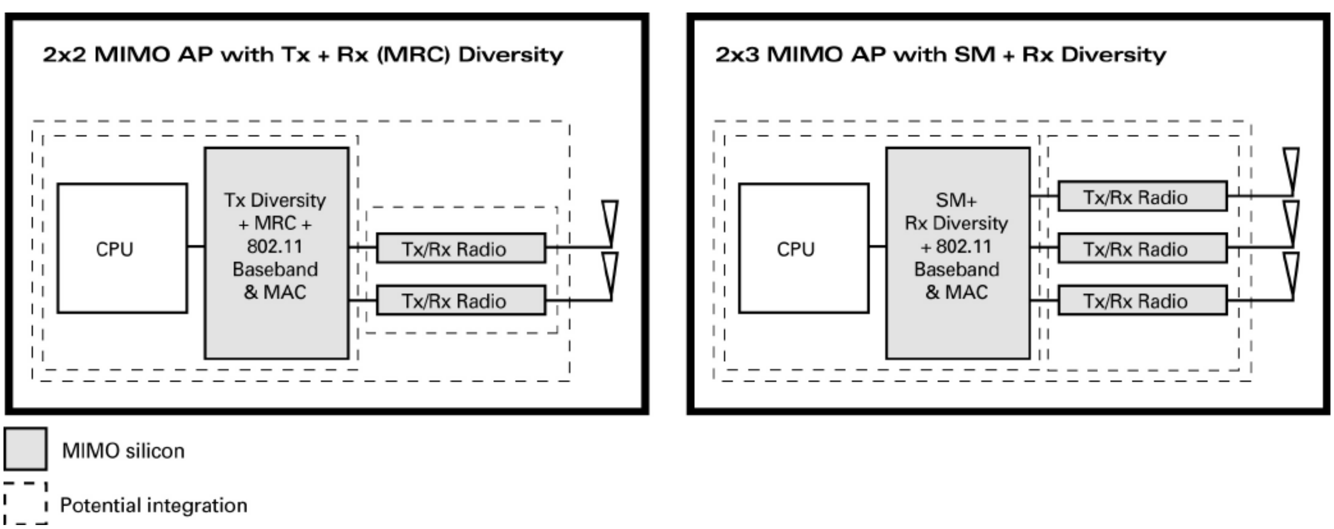
Interoperability

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, Selection Combining 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 even when diversity is only implemented on the Access Point.

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),

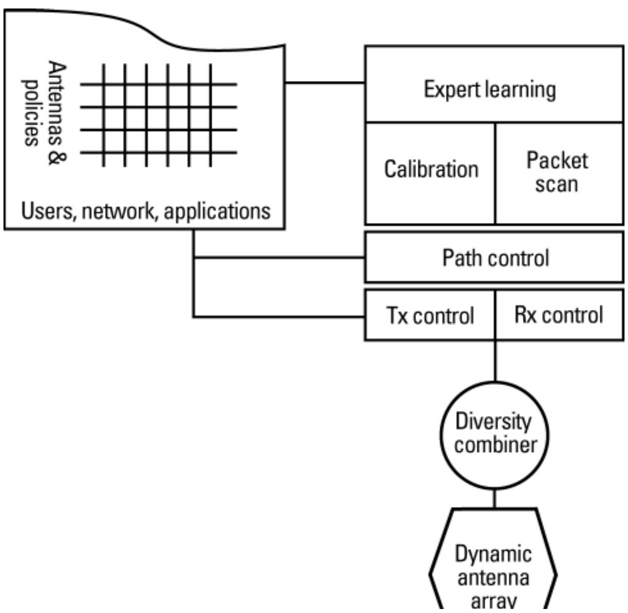
Figure 3
Functional blocks for MIMO AP systems



Baseband, radio and host processor functions is now driving 802.11b/g System-on-a-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, MRC and SM require one radio 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

Figure 4
Video54 BeamFlex architecture



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 co-adjacent 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.

VIDEO54'S BEAMFLEX

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

Smart Antennas with Unmatched Agility

Central to BeamFlex is an agile antenna system 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 2N-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 core of the BeamFlex software is an expert system that constantly learns the environment – the RF conditions, communicating devices, network performance and application flows. A Path Control module selects optimum antenna combinations on a per packet basis to ensure a quality signal path to each receiving device. 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.

A Systems Approach to MIMO Diversity

In addition to offering a massive order of diverse path options, joint optimization of the antenna structure and transmission policies based on real time, multi-disciplinary knowledge allows BeamFlex to maximize signal coverage, throughput, network capacity, (figure 5), and ensure consistent and instantaneous bandwidth delivery to real time applications such as video and online games (figure 6).

Standards Compliance

Until there is a consensus on the 802.11n specification, any ASIC-based implementation of Spatial Multiplexing mode will likely become 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 existing 802.11b/g/a devices. Only the diversity techniques that do not require dual-end coordination can deliver benefits to 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 diversity without additional radios and by leveraging commoditized, mass market Wi-Fi chipsets, BeamFlex produces performance and range optimization at a better price/performance ratio than pre-standard MIMO chipsets with multiple radios (figure 5, next page).

Figure 5
Functional blocks for BeamFlex-based AP system

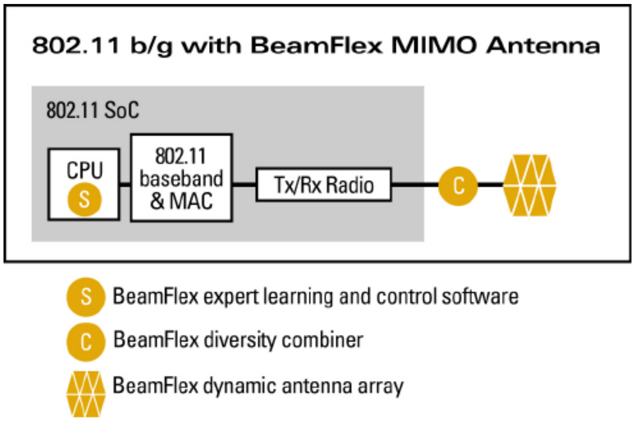
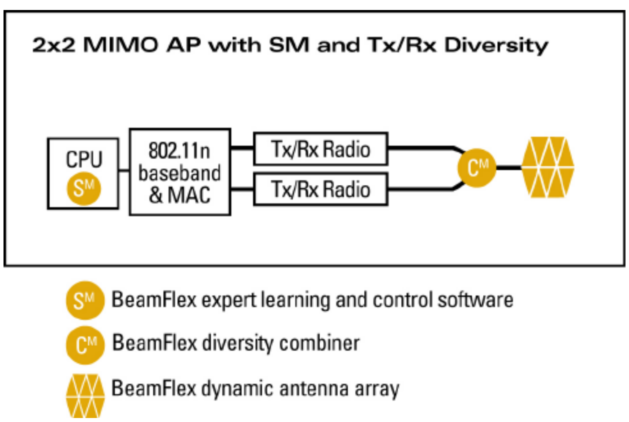


Figure 6
Functional blocks for 2x2 MIMO AP with spatial multiplexing and transmit/receive diversity



Recent research has started focusing on reducing MIMO's complexity, power consumption and cost by employing a reduced number of 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 6 sets for dual-band (2.5 and 5 GHz) support. With BeamFlex providing diversity coverage, a 2x2 MIMO implementation can achieve improved Spatial Multiplexing and diversity gains at the same time with only 2 radios for single band and 4 radios for dual-band support, reducing cost, power consumption and space. (Figure 6)

Manufacture-Friendly

Physical antenna design has received relatively little attention in MIMO research although antenna arrays are critical to the idea of MIMO. A single-band (2.4 GHz or 5 GHz), 2X3 MIMO access point requires 3 radios and antenna elements; a dual-band design requires 3 dual-band antennas and 6 radios. This quickly becomes a nightmare from the perspective of power dissipation, real estate and manufacture assembly. The BeamFlex configurable antenna array makes efficient use of limited physical space to create a large number of antenna patterns without additional power requirements. In addition, antenna placement is handled in the design phase 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 a 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

APPENDIX: Comparison of MIMO/smart antenna techniques

	Maximum Ratio Combining (MRC)	Cyclic Delay Diversity	Spatial Multiplexing (SM)	Beamforming	Video54 BeamFlex
Type of enhancement	Rx diversity	Tx diversity	Tx/Rx multiplexing	Tx SNR optimization	Tx/Rx diversity
Increases range/ coverage?	Yes	Yes	No	Yes	Yes
Increases PHY rate/theoretical capacity?	No	No	Yes	No	No
Increases achievable throughput?	Yes	Yes	Yes	Yes	Yes
Enhances 802.11a/b/g?	Yes	Yes	No	Yes	Yes
Dual-end solution required?	No	No	Yes	No	No
Silicon requirements	Requires on-chip support	Requires on-chip support	Requires on-chip support	Requires on-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	2 or more	1 or more