Getting the Most out of MIMO:

Boosting Wireless LAN Performance with Full Compatibility

OVERVIEW

Multiple-input/multiple-output (MIMO) technology offers tremendous performance gains for wireless LANs (WLANs) at relatively low cost. Any system with multiple inputs into the receiver and multiple outputs to the transmitter is a MIMO system, but implementing such a system involves several distinctly different radio techniques. Some of these techniques are beneficial and fully compatible with today's standard WLAN equipment, while others do not improve performance when used with existing equipment.

Because industry standards for MIMO techniques will take many years to finalize, WLAN users and equipment vendors who want MIMO's benefits now must choose between MIMO techniques fully compatible with today's equipment and proprietary MIMO techniques that work with a single vendor's equipment. By taking advantage of MIMO techniques fully compatible with today's standards, users see immediate range/throughput benefits, even with existing laptop computers and other WLAN-enabled devices.

Atheros' VLocity™ MIMO technology uses fully compatible MIMO techniques. MIMO products based on this technology provide better performance at a far lower overall cost than products using proprietary MIMO techniques. A fully compatible MIMO approach offers straightforward choices for both WLAN users and equipment vendors.

These choices come at a time when greater throughput and range are vital for users who want to stream multimedia content wirelessly throughout large homes and other buildings. Streaming multi-megabit HDTV signals across a large home without dropouts or "dead spots" demands that a WLAN keep throughput high even in challenging areas and at ranges normally be seen as extreme. MIMO techniques are ideal for meeting such performance goals.

This paper explains the background and tradeoffs involved in using MIMO techniques and shows how Atheros' VLocity technology achieves today's best MIMO performance while maintaining full compatibility with existing 802.11 standards.

THE ORIGINS OF MIMO

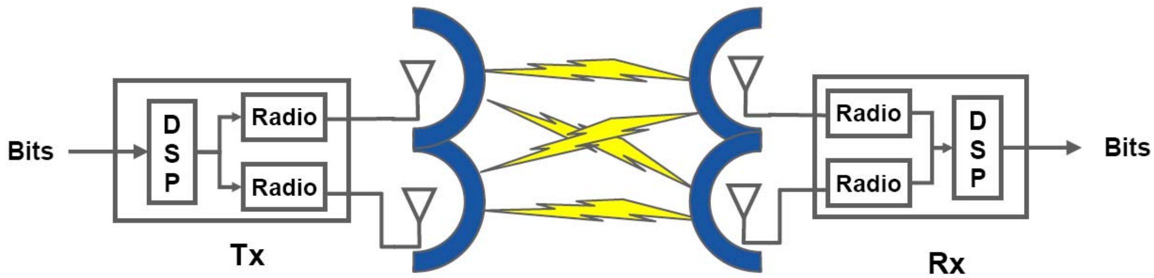
MIMO concepts have been under development for many years for both wireless and wire-line systems. One of the earliest MIMO-to-wireless communications applications came in 1984 with groundbreaking developments by Jack Winters of Bell Laboratories. This MIMO pioneer described ways to send data from multiple users on the same frequency/time channel using multiple antennas at the transmitter and receiver. Since then, several academics and engineers have made significant contributions in the field of MIMO.

Many WLAN, Wi-Max, and cellular companies offer (or are planning to offer) MIMO-based solutions. Existing applications include multiple-antenna systems, Code Division Multiple Access (CDMA) systems used in 3G cellular systems, and even Digital Subscriber Lines (DSL) with multiple telephone lines experiencing crosstalk.

MIMO MULTIPLIES POWER

In MIMO, "multiple in" means a WLAN device simultaneously sends two or more radio signals into multiple transmitting antennas. "Multiple out" refers to two or more radio signals coming from multiple receiving antennas (see Figure 1).

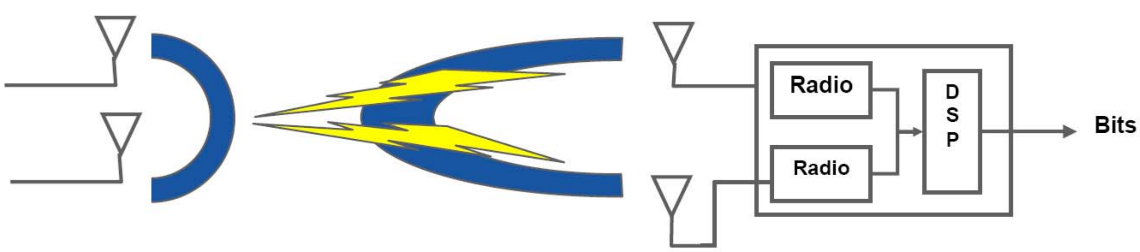
Figure 1 Any system with multiple inputs into the receiver and multiple outputs to the transmitter is a multiple-input/multiple-output (MIMO) system. On a practical level, several techniques are involved in implementing a MIMO system.



These views of "in" and "out" may seem reversed, but MIMO terminology focuses on the system interface with antennas rather than the air interface. Whatever the terminology, MIMO's basic advantage seems simple: multiple antennas receive more signal and transmit more signal.

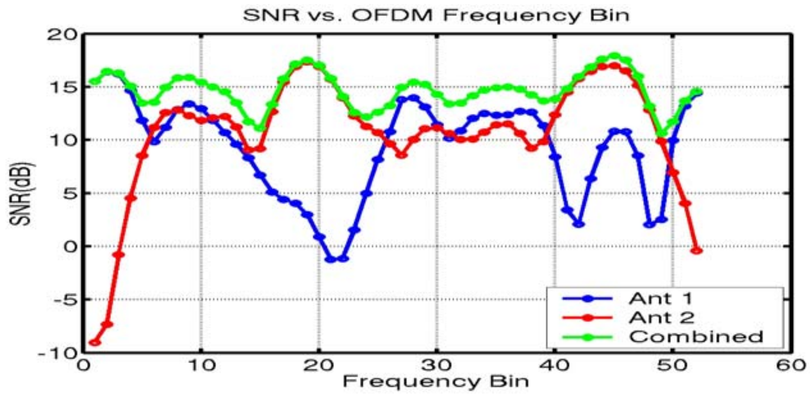
In fact, there is much more to MIMO than that. On the receive side (see Figure 2), for example, having multiple receivers not only increases the amount of receive power, but also reduces multipath problems by combining the received signals for each frequency component separately.

Figure 2 Maximal receive combining takes the signals from multiple antennas/receivers and combines them in a way that significantly boosts signal strength. This technique is fully compatible with standard 802.11abg devices.



This process is called subcarrier-based maximal receive combining. It significantly improves overall gain, especially in multipath environments. In such environments, signals pass through and reflect from various objects so that different signal characteristics reach the two receiving antennas. Some frequencies tend to be attenuated at one antenna but not the other, as shown by channel measurements in a multipath environment (see Figure 3).

Figure 3 Different antennas usually see different signal characteristics at various frequencies due to multipath effects between transmitter and receiver. Subcarrier-based maximal receive combining intelligently combines the strongest signal at each frequency for best overall signal strength.



By combining signals from the antennas at each frequency, maximal receive combining increases signal power. At frequencies where signals have similar strength, the receiver selectively combines their signal strength, thus more than doubling the signal power even when using only two antennas.

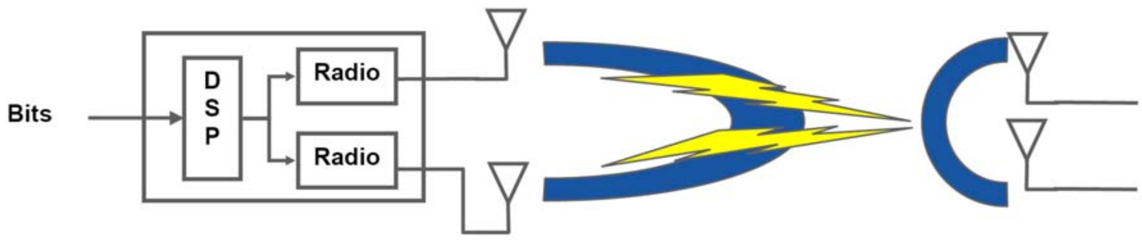
Receive combining should not be confused with antenna diversity. The latter does not involve selecting signal components based on strength at different frequencies or the addition of the signal strength from multiple antennas. A receiver with antenna diversity chooses one antenna that provides the best average performance and ignores the other antenna(s). It is possible to implement this technique using an antenna array with control algorithms that select the best-performing antenna from moment to moment based on sophisticated performance criteria. Systems may use this form of antenna diversity, like basic either/or diversity, in addition to maximal receive combining.

Note that the transmitter does not need MIMO technology to take advantage of a receiver's receive combining capability. Transmitters in existing devices such as hot spot access points and home gateways, laptop, and desktop computers are fully compatible with this MIMO technology, which applies equally well to 2.4- and 5-GHz bands to improve performance for all standard 802.11a, 802.11b, and 802.11g devices. Unlike some other techniques, receive combining increases performance on even one end of a wireless connection.

MULTIPLYING TRANSMIT PERFORMANCE

Using multiple power amplifiers and antennas implements the other half of the MIMO equation (see Figure 4). A phase-shifting algorithm allows the transmitter to drive multiple antennas in a way that focuses most of the radio's power towards the target receiver. This approach can increase effective transmit power by the square of the number of transmit antennas. With two transmit antennas, for instance, the system effectively quadruples transmit power.

Figure 4 Using multiple transmitters and antennas is a MIMO technique that improves performance in two ways. First, it puts more signal power into the air. Second, it enables transmit beamforming to focus the radio energy toward the intended receiver. Both of these techniques are fully compatible with standard 802.11abg devices.



This increase has two components: power gain and array gain. The power gain results from multiple transmit antennas delivering more power into the air, thus increasing the total amount of energy by the number of antennas. A two-transmitter MIMO system delivers twice the power, for example. The array gain results from focusing the delivered energy in the direction of the receiver—beamforming—so that less is wasted in other directions. With two transmit antennas, the fraction of total energy sent in the desired direction doubles. Thus the combination of these two effects results in a net increase in effective transmit power of up to four times.

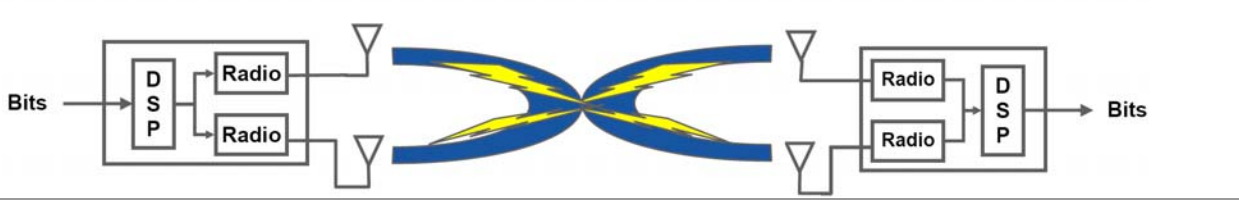
This focusing process can be highly adaptive to the frequency characteristics of the transmission channel. If the beamforming system has received at least one packet from the target device, the system knows the channel response, as illustrated in Figure 3. (The same channel response applies to both transmit and receive directions.) The beamforming system can therefore adjust the phase of the signals sent from the two antennas such that they constructively add at the receive antenna(s) for each set of frequencies. This technique reduces the effects of multipath, even when transmitting to non-MIMO devices.

The MIMO transmitter dramatically improves the range over which a receiver can obtain a high-bandwidth signal, so MIMO offers better coverage for large homes or offices. The MIMO transmitter also makes WLAN setup easier because users can pick up a usable signal even at extreme ranges.

COMPATIBILE MIMO

Obviously, the most powerful MIMO approach is to use all the techniques discussed so far—maximal receive combining, multiple power amplifiers and transmit beamforming—to multiply the gain of a WLAN link several fold (see Figure 5). This MIMO approach uses the three transmitter and receiver techniques to send the same, coherent 802.11 signal used by all existing wireless LAN devices. Together, the three compatible techniques achieve dramatic improvements in range/throughput while also improving performance with WLAN devices that do not use MIMO techniques.

Figure 5 Using the techniques illustrated in Figures 2 and 4 on both sides of the radio link results in a WLAN system that improves performance dramatically. At the same time, these techniques offer significant performance gains with existing 802.11abg devices.



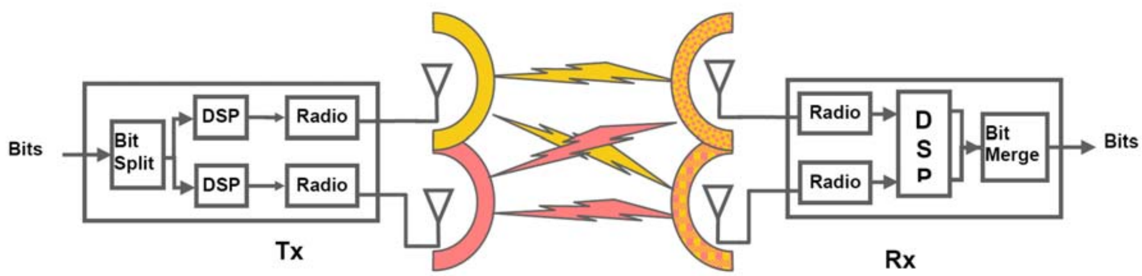
PROPRIETARY MIMO

The information on VLocity MIMO described in this paper shows exactly how successful the compatible MIMO techniques are at improving performance. Before looking at this performance data, however, consider a MIMO technique that does not improve performance with standard 802.11abg devices.

The previously described MIMO techniques send and receive the same data stream through multiple antennas. Some signal gain achieved by this approach comes from the fact that the signals from the multiple antennas travel over different spatial paths. The multipath signals shown in Figure 3 indicate this effect. The same data stream transmits from multiple antennas, and multiple antennas receive these streams with slightly different frequency characteristics.

It turns out that multiple antennas can send entirely different data streams over separate spatial channels, and multiple receiving antennas can recover these data streams (see Figure 6).

Figure 6 Spatial multiplexing is a MIMO technique in which multiple data streams transmit at the same frequency but over different spatial channels. Standard 802.11abg devices cannot demultiplex these data streams, and thus cannot improve throughput with this technique.



This scheme is called spatial multiplexing because one data stream is multiplexed (divided) between multiple transmitting antennas and sent over separate spatial channels. The receiver then demultiplexes the spatial streams to recover the original data. The multiplexed signal can only be demultiplexed by a device using the same proprietary MIMO implementation.

This MIMO approach holds great promise for increasing future channel bandwidth, but the approach is incompatible with today's 802.11abg devices. That is, a spatial-multiplexing transmitter can still communicate with a standard 802.11abg receiver, but not using spatial multiplexing techniques. Such products must fall back to single- transmitter/single-receiver mode when used with standard 802.11 devices. In these cases, the benefits of spatial multiplexing MIMO are lost.

Spatial-multiplexing products are therefore beneficial only for users who buy all-new WLAN devices based on the same proprietary MIMO technology. Many devices that have integrated WLAN capability will not be able to take advantage of this MIMO technology, including notebook computers (Centrino-based notebooks, for example) and consumer electronics equipment such as digital media players and PDAs. Given the price of new equipment, users who install the proprietary MIMO products are likely to be disappointed with the performance when used with most 802.11 products.

MIMO STANDARDS

Spatial multiplexing could be useful if all WLAN vendors implemented the technique in a compatible way. IEEE 802.11n will eventually provide an industry standard for such implementations. The IEEE 802.11 Task Group N is still in the process of selecting a base proposal that the task group will then need to refine. A standard will probably not be ratified until late 2006 or early 2007.

Spatial multiplexing products introduced now thus have two drawbacks: They cannot provide spatial multiplexing benefits to legacy devices and will most likely be incompatible with the eventual MIMO standard specified in 802.11n.

Rushing to implement spatial multiplexing now makes little sense because there is an alternative MIMO approach that offers full compatibility, with dramatic performance gains for all 802.11abg devices. On a practical level, Atheros compatible MIMO (combining transmit beamforming with maximal receive combining) plus Super G® technology meets or exceeds the performance of spatial-multiplexing products in most cases, as shown later in this paper.

In addition to MIMO techniques, 802.11n will undoubtedly include several other performance-enhancement techniques. All of the proposals that have been under consideration by the IEEE 802.11 Task Group N include support for packet bursting and fast frames, along with 20/40-MHz mode (known as Turbo Mode in Atheros products). All three of these techniques have long been part of Atheros' Super G and Super AG technology.

THE POWER OF VLOCITY MIMO

Atheros' VLocity MIMO technology implements all of the compatible MIMO techniques described here. As noted previously, these techniques boost performance many times over, even when only one VLocity MIMO device communicates with a non-MIMO 802.11abg device.

Placing a VLocity MIMO device on both sides of the link achieves more dramatic improvements. Measuring these improvements involves tests in two different environments: a free-space environment (measuring the line-of-sight performance between the two devices) and an environment that includes the multipath characteristics of the typical home or office. The test results show the benefit of the VLocity MIMO technology compared to non-VLocity MIMO devices, with link improvement values given in decibels. A value of 3 dB equates to a doubling of apparent power (i.e. a 100-mW transmitter would appear to provide 200 mW of signal power). Table 1 summarizes the VLocity MIMO test results.

Table 1: VLocity MIMO Performance Gains (dB)

Scenario	Two-Power-Amplifier-Gain	Beamforming/ Receive Combining Gain	Total
VLocity MIMO → VLocity MIMO (line-of-sight)	3	6	9
VLocity MIMO → VLocity MIMO (home/office)	3	6-9	9-12
VLocity MIMO → Legacy (line-of-sight)	3	3	6
VLocity MIMO → Legacy (home/office)	3	3-6	6-9
Legacy → VLocity MIMO (line-of-sight)	0	3	3
Legacy → VLocity MIMO (home/office)	0	3-6	3-6

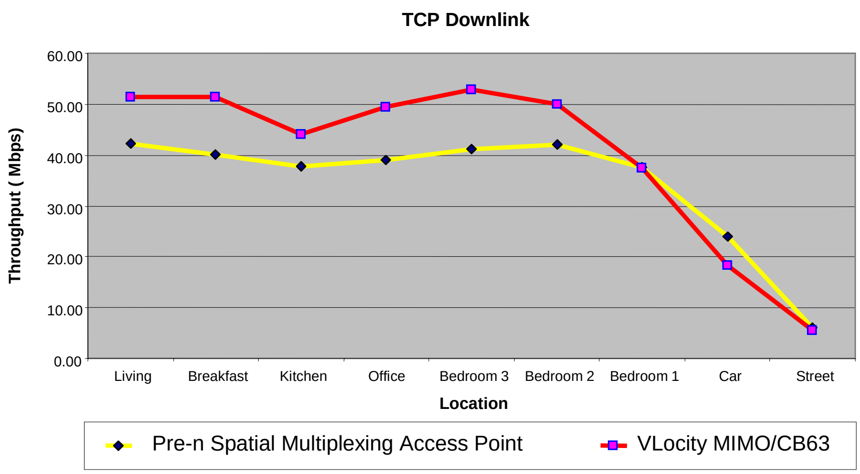
When VLocity MIMO devices are at both sides of the link in a free space environment, measured results show that the effect is additive while maintaining full 802.11abg compatibility. The total link improvement is 9 dB. Of this total, 3 dB comes from maximal receive combining, 3 dB from beamforming, and 3 dB from the use of two power amplifiers that coherently deliver twice the power in a single signal.

In home or office environments with variable amounts of multipath, the link improvement is the same or even greater. VLocity MIMO still gets 3 dB of improvement from the two power amplifiers plus 6-9 dB improvement from beamforming and maximal receive combining. Thus, using VLocity MIMO technology on both sides of a typical home or office link shows improvements as great as 12 dB—more than 1000 mW of equivalent transmitter power.

COMPARING VLOCITY MIMO WITH SPATIAL MULTIPLEXING

To compare the performance of VLocity MIMO products and current spatial multiplexing designs, Atheros measured TCP downlink throughput for various locations in and near a 3000-square-foot home (see Figure 7).

Figure 7 Throughput measurements of Atheros VLocity MIMO devices and spatial multiplexing devices show that the Atheros devices provide superior performance for almost all locations in and around a large home. The Atheros devices use MIMO techniques that are fully compatible with non-MIMO 802.11abg devices.



The VLocity MIMO throughput was superior in most locations and only exceeded by the spatial multiplexing system in one location. Current spatial multiplexing products fail to provide justification for using proprietary technology to gain a significant performance advantage.

In both tests and wide-ranging simulations that cover many possible conditions, VLocity MIMO's maximum TCP/IP throughput exceeds that of spatial multiplexing products by 20 percent or more, and VLocity MIMO products cost significantly less.

COMPATIBLE MIMO NOW

For users of business and home WLANs who need additional range and/or throughput, MIMO can offer the desired improvements immediately. To see those improvements with existing WLAN stations still in place, however, users must leverage the fully compatible MIMO techniques—maximal receive combining, multiple power amplifiers and phased-array adaptive transmit beamforming.

Atheros' VLocity MIMO products implement these MIMO techniques using sophisticated methods to obtain a high-performance, cost-effective solution. Long before MIMO standards become available, Atheros is providing fully compatible technology that improves performance with any 802.11abg device.

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