

## Leveraging MIMO in Wide-Area Networks

November 18, 2005



*©2005 ArrayComm LLC, All Rights Reserved*



## Leveraging MIMO in Wide-Area Networks

A growing number of current and prospective wide-area wireless network operators are adopting strategies that include mobile broadband access and rich multimedia services. These strategies present significant challenges to their wireless networks — requiring large improvements in network capacity, subscriber data rates, range, and coverage quality in order to build and sustain viable business models. The potential performance gains offered by smart antenna technologies such as MIMO are of increasing interest to operators as they grapple with these challenges to network economics. The promise MIMO has shown in the wireless LAN field, combined with recent advances in client device technologies, have prompted much exploration of wide-area MIMO application.

Many inherent characteristics of local-area networks that have driven MIMO success in that domain differ substantially in wide-area environments, so the technology transfer must be handled with care. In the following brief overview of wide-area MIMO application, we highlight interference and limited scattering as the most important of these differences and recommend key considerations in implementation. The good news for wireless operators is that a large portion of the theoretical gains from MIMO can indeed be achieved in the wide area by network-aware solutions designed to minimize interference in multi-cell environments and maintain robust operation in limited-scattering situations. We also note that as these performance gains can be achieved without changes in underlying wireless protocols, MIMO for wide-area networks may be closer to realization than generally understood.

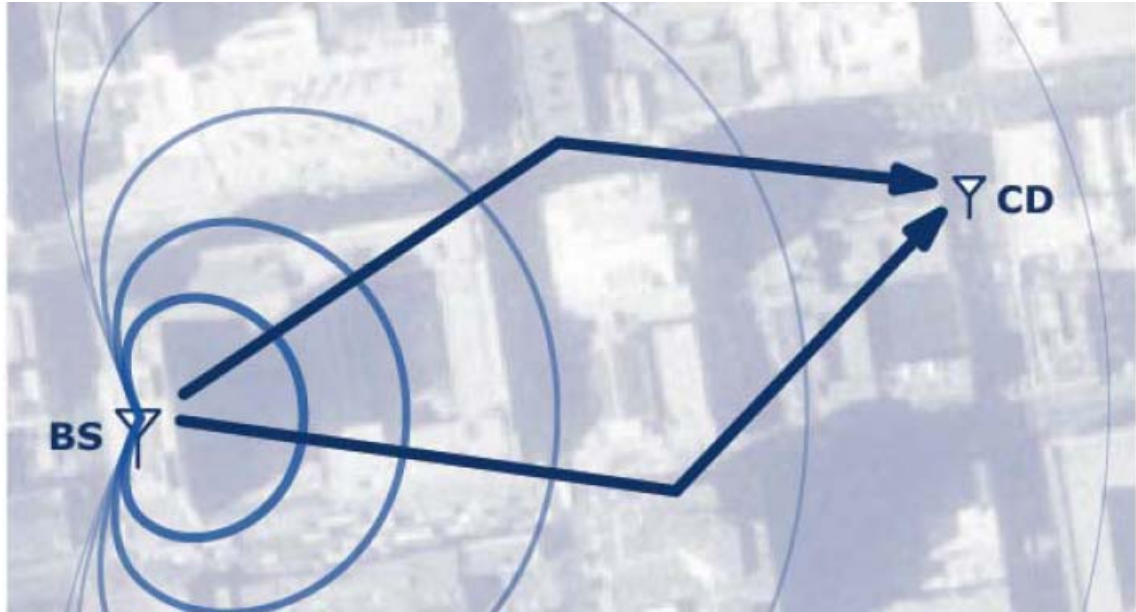
## Defining MIMO Technology

Smart antenna deployments in commercial wide-area networks to date have used multiple antennas only on the base station side of the link, with a single antenna on the client device, due largely to significant cost sensitivity on the subscriber end. As pressure to improve wide-area network economics has continued to rise, and as increased chipset integration for client devices has reduced the marginal cost of adding smart antenna processing there, interest in solutions with smart antennas on both ends of the link has risen as well. Multiple antennas at both ends allow for many new transmission techniques that are not possible in systems with multiple antennas at only one end, with additional performance gains in many situations. The industry's current dialog on smart antennas includes widely varying definitions of the terms used for a range of different implementations, so it's worth stepping through a brief overview of how the taxonomy fits together.

We start with the simplest case. Consider a system with a single antenna at each end of the link. Although the signal is transmitted in all directions (typically within a 120° sector), a particular wireless channel may only have two dominant paths, as illustrated in Figure 1. We show here an example of an elevated base station communicating with a mobile handset (or more generically, a "client

device”, since it could be a mobile computing platform) down at street level, where the bulk of the received signal comes from reflections off neighboring buildings. This corresponds to a single-input single output (SISO) channel. [Note that in the industry’s chosen nomenclature, “input” and “output” are defined in these terms from the frame of reference of the channel itself, rather than the perspective of the devices on either end.]

**Figure 1**  
A wireless channel with two dominant propagation paths between a base station (BS) and client device (CD), represented by the arrows, overlaid on the base station’s nominal 120°-sector transmission pattern.



Here we can introduce the simplest and currently most common form of smart antennas. If the receiver has more than one antenna, it can intelligently combine the signals from the different antennas and recognize that the signal indeed is arriving from two main directions. It can do this because the two paths have different spatial characteristics or different spatial signatures. Since the receiver recognizes that there are two different spatial signatures, it can combine the signals from the two antennas such that they add coherently resulting in a stronger combined signal. This corresponds to a single-input [to the channel], multiple-output [from the channel] (or SIMO) scenario and this is the well known case of receiver diversity. Receive diversity is used widely in 2G and now 3G cellular networks on the base station side of the link.

If instead the transmitter has multiple antennas while the receiver has only one antenna, the signal still travels along the same paths since the physics are the same (the buildings are still there). This corresponds to a multiple-input single-output (MISO) scenario. The main difference compared to SIMO is that the combining has to be done at the transmitter instead of the receiver. By weighting the transmit antennas appropriately, the two paths can be made to add coherently in the same way as for the SIMO case. This approach is used widely in PHS and HC-SDMA systems with multiple antennas on the base station side, for both receive (working in SIMO mode) and transmit (working in MISO mode).

Providing multiple antennas at both ends of the link corresponds to a MIMO (multiple-input, multiple output) scenario. In this case, we can exploit the two paths much more efficiently — as we illustrate in Figure 2. The transmitter can

weight its antennas so that one stream of information, shown in blue, is sent along the first path (i.e., spatial signature) and another stream of information, shown in orange, on the other path. Since the receiver also has multiple antennas it can separate the two streams by detecting that they have different spatial signatures. In this case, two entirely different data streams can be sent, potentially doubling the data rate seen by the subscriber. This offers a material advantage in the best case over what can be achieved with MISO or SIMO processing alone. This MIMO advantage can be achieved without requiring extra bandwidth or power. The multi-path propagation which generally impairs the performance of single-antenna links is instead exploited in the MIMO case to increase the channel efficiency and quality.

**Figure 2**

A communication channel with two dominant propagation paths being used to double the subscriber's data rate through MIMO. Note the beam shaping enabled by multi-antenna processing that directs signal along the channel of interest and the absence of signal along the other dominant channel.

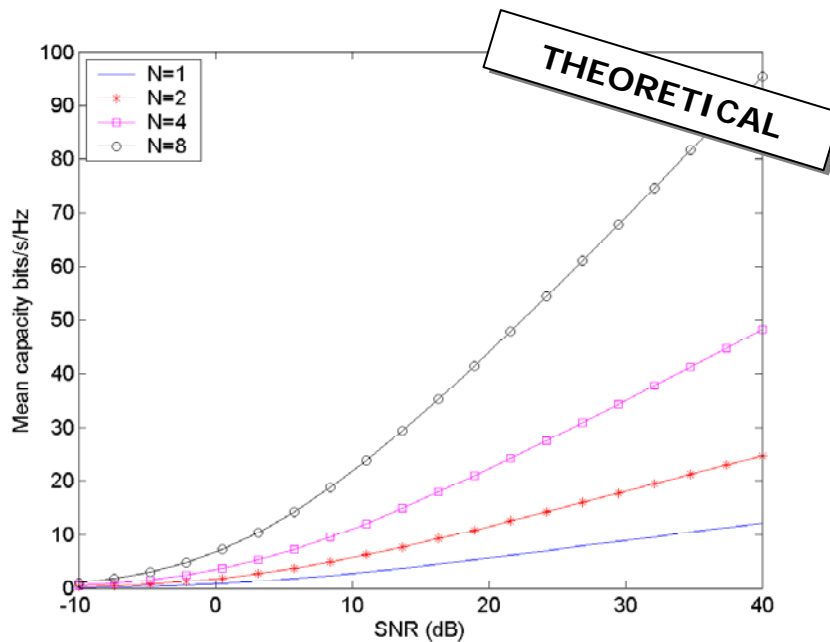


It is important to understand that MIMO systems exploit multi-path propagation provided that these spatial dimensions exist in the propagation environment. In the figures above, there are four antennas and only two dominant paths. Hence, in this case only two data streams can be formed even though there are four antennas. Therefore, the performance of MIMO is closely related to the multipath richness of the environment where the system is employed. Fortunately, in many environments there is enough scattering and multipath to support several parallel data streams.

Results from information theory suggest that the system capacity, which represents an upper bound on the data rate, grows linearly with the number of antennas (under certain channel assumptions and holding total power constant) if multiple antennas are used at both ends. In Figure 3, the *theoretical* capacity for different MIMO systems with equal number of transmit and receive antennas is shown. The capacity for the 8 x 8 MIMO system (i.e. with 8 antennas on each end of the link) can be up to eight times the capacity of a single antenna system. When all network opex and capex costs are taken into account, MIMO techniques offer substantial net performance and economic benefits over single antenna systems. Especially for high-data-rate services such as true broadband access, IPTV, and large file transfers, where limited bandwidth poses a severe problem,

MIMO techniques are a promising solution. Increasing levels of component integration in client devices of the past few years have significantly reduced the marginal cost of adding multi-antenna processing on the subscriber end of the link, making consideration of MIMO applications more practical in many situations.

**Figure 3**  
Theoretical average capacity versus SNR for MIMO systems with N transmit and receive antennas, holding total transmit power constant.



The predictions in Figure 3 only characterize the performance limits of an ideal system. Information theory does not provide a great deal of practical guidance for how to achieve these limits. Practical systems face the challenge of how to use the spatial dimensions provided by the channel to best advantage. In principle, three main ways of exploiting the channel have been proposed, the first two focused on individual link performance and the third on overall network performance:

- Increased data rate.** The previously described technique (illustrated in Figure 2) is usually referred to as *spatial multiplexing*. For channels with a rich scattering environment it is possible to increase the data rate by transmitting separate information streams on each antenna. Using sophisticated receiver technology, the different streams can be separated and decoded. For example, using four transmit and four receive antennas, four times the capacity of a single antenna system can be achieved.
- Improved quality of service through diversity.** Conversely, by transmitting the same signal over multiple antennas over multiple symbols, the *reliability* of the transmission can be improved instead of the data rate. Essentially, this technique provides space-time diversity by sending multiple copies of signal over different antennas and time instants. This technique of spreading or coding the information symbols over both space and time is called space-time coding.

- **Achieving a mix of both higher data rate and improved quality of service through interference mitigation.** Another alternative exploitation of the spatial dimensions in a MIMO system, suitable to more interference-rich environments, is optimizing the distribution of radio energy in the system overall, to minimize creation of and sensitivity to co-channel interference in the network. Described in more detail in our final section, this solution meets the objectives of higher data rates and more robust links through higher SINR (which enables higher modulation classes and therefore higher data rates in the link) and classic diversity (which increases link stability). As with the MISO system, the multiple spatial channels are used by the base station to create a coherent combination of energy at the client device. They are used by the client device to improve its effective sensitivity in those spatial 'directions' (as in a SIMO system), reducing the power required on transmit by the base station. The reverse is done on uplink. The base station and client device work automatically in concert to reduce the level of interference in the system. As we will discuss in the next sections, overall network performance is a critical dimension for wide-area system optimization, and interference is a dominant driver of broadband network performance.

Research labs throughout the world have demonstrated the practical feasibility of MIMO techniques in the initial and most promising application, wireless LANs, by achieving capacities close to those predicted theoretically in their labs using both spatial multiplexing and space-time coding. Due to the large performance gains shown in that initial application, MIMO techniques have quickly left the research labs and into WLAN products.

## Early MIMO Success with WiFi

The most widely publicized implementations of MIMO have been in fixed, local-area wireless environments where the primary benefit of MIMO is to increase individual client device throughput. In particular, WLANs (a.k.a. WiFi networks) in home and enterprise applications exhibit several characteristics that make them ideal candidates for initial adoption of MIMO:

- **Rich scattering.** Most WiFi systems are deployed in environments with rich scattering such as indoor or dense urban settings. In these environments, there are usually several propagation paths or spatial dimensions that can be exploited to form multiple streams. In fact, the indoor environment closely matches the conditions necessary to achieve the linear increase in capacity with increased number of antennas shown in Figure 3.
- **Independent deployment.** Another key element for a rapid deployment is that WiFi equipment usually is purchased by the end-users and is deployed independently in their own network. Interoperability of different MIMO WiFi solutions is not critical, as indicated by the success of IEEE 802.11n products before a common MIMO standard has been agreed upon. This has allowed a very rapid deployment of MIMO without waiting for a standard to be formed.
- **Limited interference.** Also key is that the WiFi environment is closely matched to the theoretical assumptions under which MIMO techniques have been studied. Due to the short range of WiFi networks, MIMO receivers generally operate without significant levels of co-channel interference. The performance of these solutions degrades quickly if operated with significant levels of uncompensated co-channel interference in a network of multiple access points.

The successful deployment of MIMO in WiFi demonstrates that the potential performance improvements made possible by MIMO are real. The fact that it has moved from promising lab results to WiFi products in just a few short years suggests a tempting opportunity for operators of wide-area wireless networks to replicate this success.

## The Challenge for Wide-Area Networks

The same performance benefits that enabled the successful adoption of MIMO in WiFi products do make MIMO a good potential candidate for the mobile environment in wide-area wireless. However, the mobile, multi-cell environment is fundamentally different from the WiFi radio environment in some ways that make a straightforward deployment challenging.

- **Interference.** The wide-area environment experiences significant levels of interference due to dense deployments and large cells. In such environments, rejection of interference and high throughput are both necessary. Hence, in order to extend MIMO's WLAN success to wide-area networks and mobile broadband data services, new MIMO solutions are necessary that take into account both interference and data rate.
- **Limited scattering.** The wide-area scattering environment can in some cases be limited with only one or two dominant paths. For instance, if there is line-of-sight (LOS) there is only one dominant propagation path which limits the use of spatial multiplexing techniques.
- **Interoperability.** In a wide-area network, all the users need to communicate with the base stations seamlessly throughout a large network (spanning both geographies and operators), which makes interoperability a necessity. Solutions such as those outlined above that use spatial multiplexing or space-time codes require protocol changes that can increase the time-to-market for MIMO solutions significantly in the wide-area domain. For example, the receiver needs to know the space-time code that the transmitter is using in order for it to decode the data. Work is already under way in several standardization bodies to include MIMO in mobile systems such as the IEEE 802.16e standard, but there is still some time before robust commercial products will begin to appear.

These factors make adoption of MIMO more challenging in a wide-area network than in WiFi. New solutions that account for the specific properties of a large, multi-cell network are necessary. Successful implementations of MIMO in wide-area networks will share two key attributes:

- **Interference suppression.** In the wide-area case the additional degrees of freedom available through the antenna arrays at both ends of the link should be used at least in part to reduce interference. Interference mitigation at both the transmitter and receiver can dramatically reduce network interference compared to systems with only interference rejection at one end.
- **Robust solutions.** Solutions can be developed that account for a limited number of dominant propagation paths. Significant performance gains can still be achieved through coherent combining at both the transmitter and receiver even in channels with limited scattering. Recent research shows that even for channels with only one dominant propagation path, the so called key-hole channels, substantial gains can be achieved using smart antenna techniques at both ends of the link.

## MIMO for Wide-Area Networks

A significant portion of the ultimate MIMO gains can be achieved now in existing wide-area networks without changes to existing protocols and without waiting for completion of new protocols. Substantial performance improvements can be achieved with adaptive array processing techniques at the base station combined with similar processing at the mobile terminal — the third basic MIMO approach outlined above. In fact, theory indicates that this is the optimal approach under many of the channel conditions common in wide-area networks. These gains both in terms of signal strength and also in interference suppression are critical for the evolution of wide-area networks, in support of operators' increasingly broadband and multimedia service objectives. As Robert Syputa, Senior Analyst at Maravedis Telecommunications Research, recently noted, "To live up to the promise of providing metro/wide area network coverage at true broadband data rates, both WiMAX and future versions of 3GPP must adopt MIMO and AAS technologies."

A solution that balances interference rejection and throughput can be achieved in the following way. The base station calculates combining weights for its antenna array that minimize interference from the base station point of view. Similarly, the mobile terminal uses its antenna array to minimize interference from the handset point of view. Since no special coding in the link is required at either the base station or the client device, the MIMO processing can be implemented and operated completely independently on each device. The result is a self-organizing and self-optimizing system that continually adapts to the changing interference environment and to the changing service needs of the user. The independence of each end of the link in this MIMO approach provides robust performance even in the case of a heterogeneous network or one in an upgrade transition — where not all base stations and client devices are equipped with multiple antennas. Single-antenna endpoints simply participate using SIMO (in transmit) or MISO (in receive) channels with their multi-antenna counterparts. The overall network benefit of this interference-minimizing MIMO approach would be an increasing function of the penetration of multi-antenna devices in the system.

In addition to maintaining more robust performance in loaded networks than would be possible with "plain vanilla" MIMO techniques adopted directly from the WiFi domain, the interference-optimized MIMO approach we describe has an additional benefit in wide-area application. In these networks with relatively large cells and stringent indoor-coverage service objectives, there are many cases at cell edges and deep indoor locations where client devices must operate with very poor channels — where SNR is too low to employ the more complex MIMO techniques. The adaptive antenna processing inherent to an interference-optimized MIMO approach will allow the network to serve users more effectively in these low-SNR cases by "devolving" from the complex MIMO modes to the more classic adaptive antenna approach (often referred to by the oversimplified term "beamforming").

## Conclusion

The performance gains provided by MIMO techniques show great promise of fueling the next chapter in the ongoing revolution in wireless communications. Already MIMO equipment is providing performance gains to the WiFi market and wide-area networks will soon be next. However, the radio environment in a

wide-area, mobile wireless system is very different from the WiFi domain, with interference posing the most significant challenge. Fortunately, there are wide-area MIMO solutions available now based on adaptive antenna processing that provide tremendous gains over single-antenna systems. These solutions balance interference and throughput requirements by exploiting through multiple antennas the spatial dimensions inherent in the channel. A significant portion of these gains can be achieved without changes to protocols and can be deployed in the near future. Hence, wide-area MIMO applications may be closer to realization than is generally understood.

---

*For more information on how these concepts are being put into practice in commercial systems, please contact ArrayComm via [info@arraycomm.com](mailto:info@arraycomm.com)*