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Datacomm Research Company

USING MIMO-OFDM TECHNOLOGY TO BOOST WIRELESS LAN PERFORMANCE TODAY

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Using MIMO-OFDM Technology to Boost Wireless LAN Performance Today

This White Paper describes how MIMO-OFDM (Multiple Input Multiple Output-Orthogonal Frequency Division Multiplexing) technology delivers significant performance improvements for wireless LANs, enabling them to serve existing applications more cost-effectively as well as making new, more demanding applications possible. It also explains how manufacturers and end-users can profit by deploying MIMO-OFDM products today without sacrificing any benefits of the anticipated IEEE 802.11n standard tomorrow.

There are three basic parameters that completely describe the quality and usefulness of any wireless link: speed, range and reliability. Prior to the development of MIMO-OFDM, the three parameters were interrelated according to strict rules. Speed could be increased only by sacrificing range and reliability. Range could be extended at the expense of speed and reliability. And reliability could be improved by reducing speed and range. MIMO OFDM has redefined the tradeoffs, clearly demonstrating that it can boost all three parameters simultaneously. While MIMO will ultimately benefit every major wireless industry including mobile telephone, the wireless LAN industry is leading the way in exploiting MIMO innovations.

The market for wireless LANs, particularly in the consumer and small business segments, has skyrocketed. By all accounts, annual growth in wireless LAN device shipments has increased from threefold to fivefold since 2001[1]. With huge opportunities for wireless LANs looming in home entertainment, Voice over IP (VoIP), and public access, the biggest market growth may yet lie ahead.

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[1] Gartner, *Wireless LAN Semiconductors: Worldwide 2002-2007* (1/30/04);
IDC, *Worldwide WLAN Semiconductor Forecast and Analysis 2004-2008* (July 2004); and
The Linley Group*, A Guide to Wireless LAN Chipsets* (June 2004)

Products based on existing wireless LAN standards often fail to meet the range requirements encountered in homes, small businesses, retail stores, and other business locations. For example, a consumer may be frustrated to discover that a wireless LAN cannot reach both an upstairs bedroom and a home office in a corner of the basement. A small business may be disappointed to discover that it needs three or four access points interconnected via a wire backbone to cover its modest-sized premises. And an enterprise may learn that a location beyond the reach of wire is also difficult to reach wirelessly.

Existing wireless LAN standards also lack the throughput levels required by emerging and potentially huge applications such as home entertainment. For example, a single High Definition TV (HDTV) stream requires at least 20-24 Mbps of sustained throughput throughout the home. A wireless LAN's advertised data speed is usually the "raw" link rate—a significant fraction of which is reserved for protocol overhead (commands, status messages, and error control mechanisms). Plus, the capacity of a wireless LAN may be shared between multiple users and applications. Though today's wireless LAN standards promise speeds up to 54 Mbps, actual user throughput often drops into the single digits near the edge of the home coverage area—if a connection can even be maintained—making "wired quality" streaming video impractical using wireless LAN devices based on existing standards.

Fortunately, these limitations are surmounted using a combination of MIMO and OFDM technologies. That is why MIMO-OFDM is the foundation of all proposals for the IEEE 802.11n standard. However, the standard is not expected to be finalized until 2006; the first products conforming to the standard probably won't appear until 2007.

Several commentators advise manufacturers and end-users to avoid the MIMO-OFDM solutions available now and wait for products based on the upcoming standard. Some argue that end-users should always reject solutions that are not based on recognized industry standards—no matter how innovative or beneficial. Others suggest "pre-standard" solutions may prove financially injurious to end users, could disrupt the operation of existing wireless LANs, and may be misrepresented as compliant with or easily upgraded to the yet-to-be-defined 802.11n standard.

However, it's possible to support standards and also recognize that "pre-standard" solutions often possess time-to-market advantages. The "pre-standard" solution may be the best choice for customers with immediate needs. Plus, pre-standard products may be fully compatible with, or even enhance the performance of, products based on existing standards. As long as device manufacturers don't promise more than they can guarantee (such as software upgrades to the not-yet-defined 802.11n standard and interoperability tests), there is little risk of sowing confusion among consumers (see "What Pre-Standard, MIMO-Enhanced Wi-Fi Products Can and Can't Guarantee," below.)

What is MIMO?

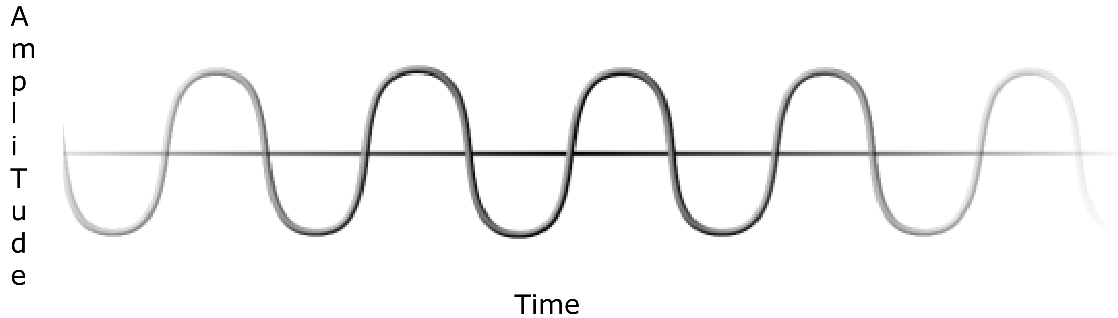
Multipath propagation is a feature of all wireless communication environments. There is usually a primary (most direct) path from a transmitter at point "A" to a receiver at point "B." Inevitably, some of the transmitted signal takes other paths to the receiver, bouncing off objects, the ground, or layers of the atmosphere.

Signals traversing less direct paths arrive at the receiver later and are often attenuated. A common strategy for dealing with weaker multipath signals is to simply ignore them—in which case the energy they contain is wasted. The strongest multipath signals may be too strong to ignore, however, and can degrade the performance of wireless LAN equipment based on existing standards.

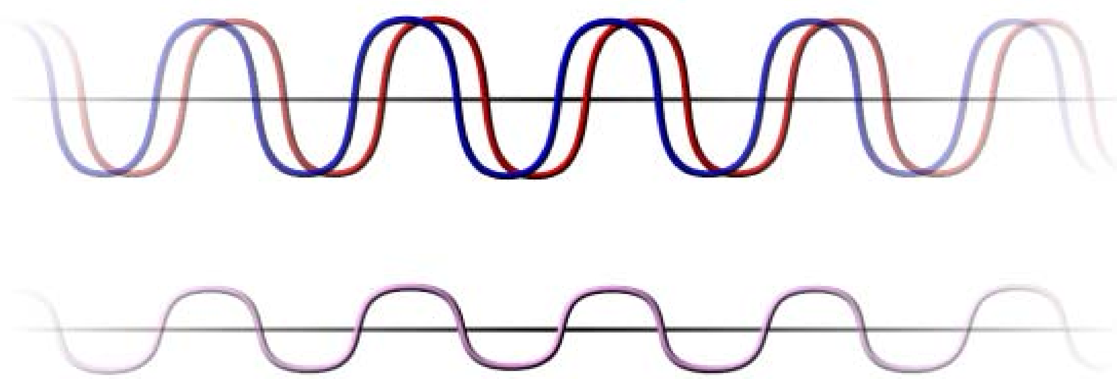
Radio signals can be depicted on a graph with the vertical axis indicating amplitude and the horizontal axis indicating time as sine waves. See **Figure 1, a**. When a multipath signal arrives slightly later than the primary signal, its peaks and troughs are not quite aligned with those of the primary signal, and the (combined) signal seen by the receiver is somewhat blurred. See **Figure 1, b**. If the delay is sufficient to cause the multipath signal's peaks to line up with the primary signal's troughs, the multipath signal will partially or totally cancel out the main signal. See **Figure 1, c**.

Traditional radio systems either do nothing to combat multipath interference, relying on the primary signal to out-muscle interfering copies, or they employ multipath mitigation techniques. One mitigation technique uses multiple antennas to capture

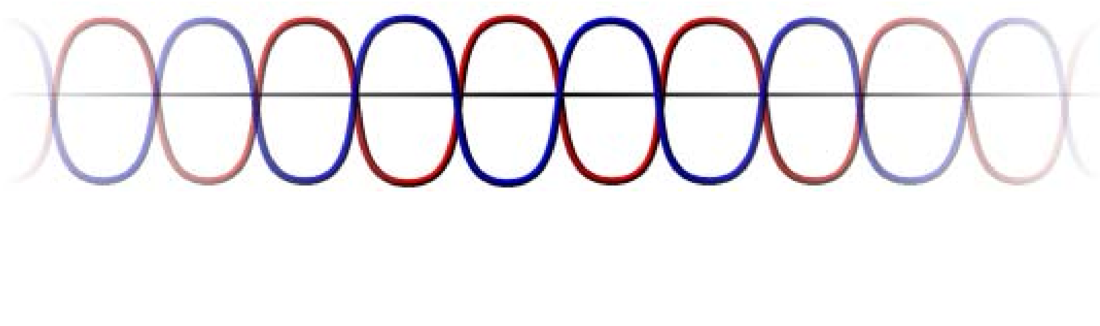
Figure 1: How multipath propagation affects radio signals



a. A radio signal may be represented as a sine wave



b. Multipath signals arriving slightly out-of-phase combine at the receiver to create a somewhat weaker and less distinct signal



c. In the extreme case, multipath signals arriving 180° out-of-phase will cancel each other out the strongest signal at each moment in time. Another technique adds different delays to received signals to force the peaks and troughs back into alignment. Whatever the mitigation technique, all assume multipath signals are wasteful and/or harmful and strive to limit the damage.

MIMO, in contrast, takes advantage of multipath propagation to increase throughput, range/coverage, and reliability. Rather than combating multipath signals, MIMO puts multipath signals to work carrying more information. This is accomplished by sending and receiving more than one data signal in the same radio channel at the same time. The use of multiple waveforms constitutes a new type of radio communication—communication using multi-dimensional signals—which is the only way known to improve all three basic link performance parameters (range, speed and reliability).

Because MIMO transmits multiple signals across the communications channel (rather than the conventional system's single signal), MIMO has the ability to multiply capacity (which is another word for "speed"). A common measure of wireless capacity is spectral efficiency—the number of units of information per unit of time per unit of bandwidth—usually denoted in bits per second per Hertz, or b/s/Hz. Using conventional radio technology, engineers struggle to increase spectral efficiency incrementally (i.e. one b/s/Hz at a time). By transmitting multiple signals containing different information streams over the same frequency channel, MIMO provides a means of doubling or tripling spectral efficiency.

MIMO can also be thought of as a multi-dimensional wireless communications system. Conventional radio systems try to squeeze as much information as possible through a one-dimensional pipe. In order to do that, engineers must adapt their designs to the noise and other limitations of a one-dimensional channel. MIMO empowers engineers to work in multiple dimensions, creating opportunities to work around the limitations of a one-dimensional channel.

Greater spectral efficiency translates into higher data rates, greater range, an increased number of users, enhanced reliability, or any combination of the preceding factors. By multiplying spectral efficiency, MIMO opens the door to a variety of new applications and enables more cost-effective implementation for existing applications.

An interesting sidelight: Guglielmo Marconi demonstrated the first non line-of-sight (NLOS) wireless communications system in 1896 by communicating over a hill. From that day forward, engineers viewed multipath signals as an annoyance at best and serious problem at worst. The first paper describing wireless MIMO's capacity multiplying capability was published 100 years later in the 1996 Global Communications Conference proceedings[2].

How Does MIMO Differ from the Smart Antenna?

MIMO and "smart antenna" systems may look the same on first examination: Both employ multiple antennas spaced as far apart as practical. But look under the hood, and you will see that MIMO and smart antenna systems are fundamentally different[3].

Smart antennas enhance conventional, one-dimensional radio systems. The most common smart antenna systems use *beamforming* (a.k.a. *beam switching*) to concentrate the signal energy on the main path and *receive combining* (a.k.a. *diversity*) to capture the strongest signal at any given moment. Note that beamforming and receive combining are only multipath mitigation techniques, and do not multiply data throughput over the wireless channel. See **Figure 2**.

That's not to say beamforming and receive combining aren't useful. Both have demonstrated an ability to improve performance incrementally in point-to-point applications (e.g., outdoor wireless backhaul applications). However, while beamforming and receive combining are valuable enhancements to conventional radio systems, MIMO is a paradigm shift, dramatically changing perceptions of and responses to multipath propagation. While receive combining and beamforming increase spectral efficiency one or two b/s/Hz at a time; MIMO multiplies the b/s/Hz.

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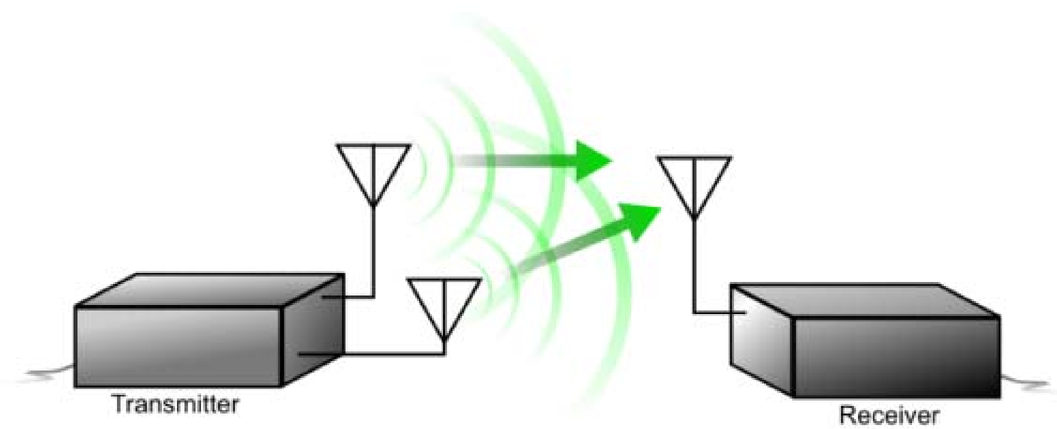
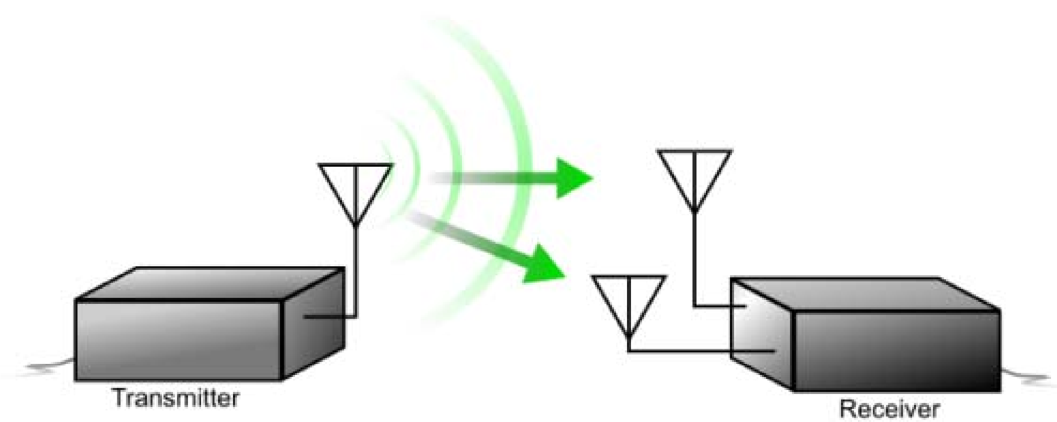
[2] *Spatio-Temporal Coding for Wireless Communications,* Raleigh, G.G.; Cioffi, J.M. Global Telecommunications Conference, 1996: vol. 3, 18-22 Nov. 1996, pp. 1809-1814

[3] *MIMO Technology is Today's Most Significant Advance in Wireless Communications--but not all MIMO Claims are Accurate*, Datacomm Research Company, Research Alert, February 8, 2005

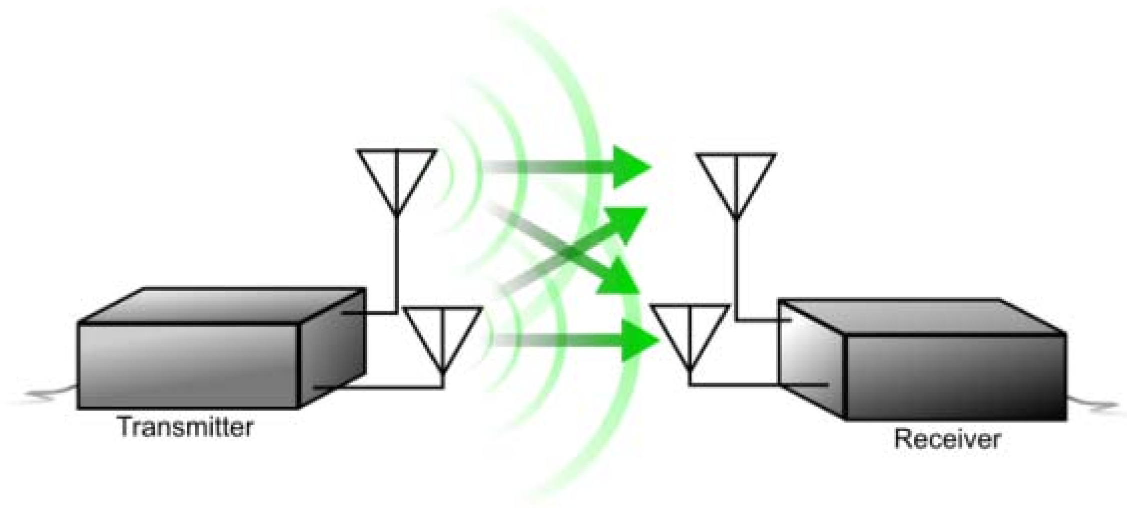
Figure 2: Comparing smart antenna schemes (a, b, and c) with MIMO (d)



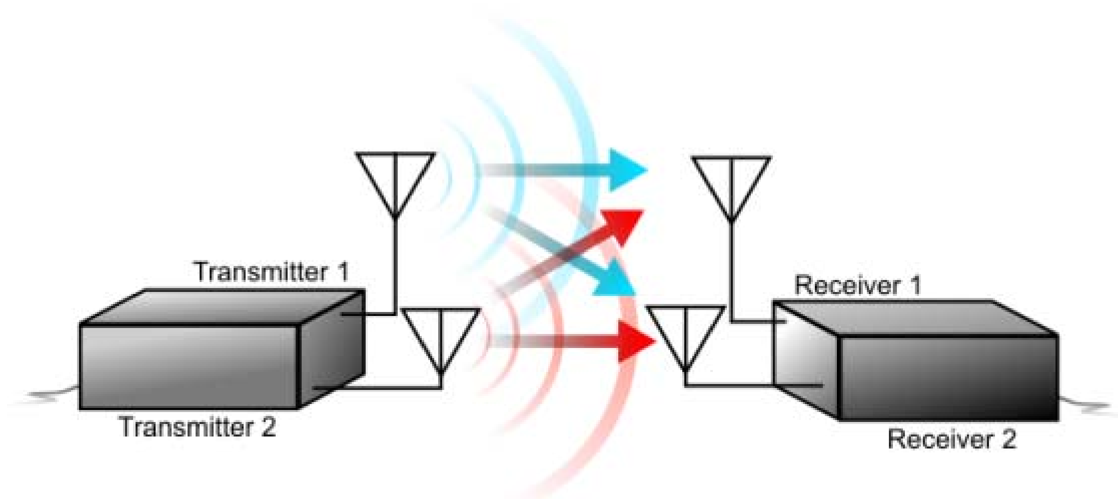
a. Beamforming (beam steering) employs two transmit antennas to deliver the best multipath signal



b. Diversity (receive combining) uses two receive antennas to capture the best multipath signal



c. There may be a physical resemblance between radio systems using a combination of beam steering and diversity and MIMO systems. Note, however, that with the beam steering/diversity approach, only one signal is sent over the channel.



d. MIMO uses multiple transmitters, receivers and antennas to send multiple signals over the same channel, multiplying spectral efficiency.

What is Channel Bonding and Where Does it Fit?

Another performance-enhancing technique is *channel bonding*. Channel bonding multiplies throughput by combining two or more radio channels. Assuming the channels are available, channel bonding is one of the most direct methods of increasing throughput. But there is a significant price associated with channel bonding: increased bandwidth consumption.

In some cases, channel bonding may not be an option because the target frequencies have been allocated to other users or services. In other cases, the performance benefits may not outweigh the technical challenges. In all cases, channel bonding must be implemented carefully to minimize the interference problems that may arise when using more bandwidth.

Both MIMO and channel bonding can multiply throughput. But there are two key differences between the approaches. Though channel bonding increases throughput and capacity, it may reduce range slightly. MIMO enhances all three performance attributes simultaneously. And while channel bonding increases throughput by consuming more bandwidth, MIMO increases spectral efficiency, multiplying throughput in the same bandwidth.

Smart antennas and channel bonding are important and useful technologies but they must not be confused with MIMO technology. If everything else is equal, MIMO-based products will outperform smart antenna- and channel bonding-based products. However, the different technologies are not necessarily adversaries: MIMO-based products can make judicious use of smart antennas and channel bonding to offer even more benefits.

Why MIMO-OFDM?

MIMO can be used with any modulation or access technique. Today, most digital radio systems use Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), or Orthogonal Frequency Division Multiplexing (OFDM).

Time division systems transmit bits over a narrowband channel, using time slots to segregate bits for different users or purposes. Code division systems transmit bits over a wideband (spread spectrum) channel, using codes to segregate bits for different users or purposes. OFDM is also a wideband system, but unlike CDMA which spreads the signal continuously over the entire channel, OFDM employs multiple, discrete, lower data rate subchannels.

MIMO can be used with any modulation or access technique. However, research shows that implementation is much simpler—particularly at high data rates—for MIMO-OFDM. Specifically, MIMO-OFDM signals can be processed using relatively straightforward matrix algebra.

What is the Best Way to Deliver Wireless LAN Innovations?

One of today's biggest high-tech controversies is how best to encourage and deliver technology innovations. Everyone agrees that standards play an important role in ensuring interoperability and cost reduction (through volume production of key components). Not everyone agrees, however, about what makes some standards more successful than others. In particular, there is difference in opinion regarding whether standards drive innovation or innovation drives standards.

Each year, thousands of standards are published. Some standards are extremely successful; many achieve limited success. But the majority are simply overtaken by events. The Global Systems for Mobile Communications (GSM) is an example of an extremely successful standard. Internet Protocol Version 6 (IPv6) is almost universally recognized as the Internet's next generation protocol, but it has made little headway in replacing IPv4. The Internet was built on TCP/IP, a protocol developed by two engineers, instead of the highly-touted Open Systems Interconnection (OSI) protocol developed by the International Standards Organization (ISO).

Successful standards often codify market-proven innovations. Ethernet, like Token Ring, began life as a proprietary local area networking (LAN) standard. Vendors have learned over time that it's better to control 20% of a very large market than

100% of a small market with a doubtful future. That's why most vendors are anxious to offer a proprietary innovation as the foundation for an open standard.

To wit, most successful standards start with a technology that has gained market traction and open it to wider participation. Standards for proven markets deserve and receive more attention and urgency. Participants are more amenable to compromise, recognizing that neither vendors nor users benefit from lengthy delays.

Some commentators and vendors warn that bringing innovations to market before relevant standards have been published hinders market development. However, this claim is not supported by the facts. Today, there are many successful standards that started as proprietary innovations with clear end-user benefits. But there are few if any examples of markets that failed to develop simply because such innovations were introduced prematurely.

Another common complaint is that proprietary and "pre-standard" products are harmful to customers. Specifically, it is asserted that these customers will wake up one day to learn that the products they invested in are not compatible with the published standard. However, this argument overlooks several important points. Many customers buy proprietary or pre-standard products because they have specific, urgent requirements addressed by such solutions. Standards usually take a minimum of 1-2 years to develop, and products conforming to those standards usually require another year before they are commercially available; many customers routinely replace computer and communications equipment every few years to take advantage of further developments.

More importantly, vendors have become more sophisticated about introducing innovative technology. For example, wireless LAN products incorporating MIMO-OFDM technology (often called "pre-standard, MIMO-enhanced Wi-Fi" because MIMO-OFDM is central to the forthcoming 802.11n standard) are fully compatible and interoperable with existing 802.11b, 802.11g, and 802.11a devices on the same network at the same time. (In fact, MIMO-OFDM products enhance the performance of the existing standards as we explain in the next section.)

Plus, it's not unusual for vendors that sell pre-standard enhancements to introduce products incorporating both standard and pre-standard modes once the standard has been finalized, providing their customers a bridge between the two environments. For example, in the late 1980s dial-up modem maker US Robotics offered a proprietary high-speed mode; once the V.32 high-speed standard was published, US Robotics introduced what it dubbed its "dual standard" product.

The upshot is that innovation drives standards—not the other way around. Proprietary and pre-standard enhancements play a pioneering and positive role. The vision of hordes of customers left stranded by vendors of proprietary or pre-standard enhancements is a myth. The more successful a pre-standard enhancement is, the more incentive for the vendor to continue supporting it by developing products that include both pre-standard and standard modes.

How MIMO-OFDM Benefits Products Based on Existing Standards

The fact that products incorporating pre-standard MIMO-enhanced Wi-Fi look the same on the outside as products with smart antennas hints at another benefit. The pre-standard MIMO products have the antennas and other circuitry needed to provide smart antenna functionality when operating in a mode based on existing standards.

In fact, this smart antenna functionality boosts performance even when present on just one end of a link. Thus, pre-standard MIMO products are not only fully compatible with existing Wi-Fi standards; they also enhance the performance of those standards.

This demonstrates in yet another way that pre-standard MIMO enhancements can be designed to complement rather than thwart standards. Thus, while customers may purchase pre-standard MIMO-enhanced Wi-Fi products to take advantage of MIMO-OFDM's superior performance, some may discover that merely adding these devices to a standards-based network does the job for them, rendering moot concerns about "non-standard" modes[4].

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[4] "MIMO products boost 802.11g nets," Craig Mathias, *Network World*, 03/21/05

MIMO-OFDM Enables New Wireless LAN Applications and Markets

Wireless LANs scored their first major success in vertical industrial applications—primarily warehouse and retail floor inventory management. The market exploded as wireless LANs were embraced for PC networking and sharing broadband access in small businesses and homes.

This success has positioned wireless LANs to drive the development of three new markets with huge growth potential: home entertainment networking, cordless Voice over IP (VoIP), and a variety of machine-to-machine (M2M) applications.

Currently, tens of millions of wireless LAN nodes are shipped annually. Home entertainment applications present the opportunity to sell hundreds of millions of nodes per year—one for every television, stereo system, DVD player, remote screen, remote speaker, and portable record/playback device shipped.

Cordless VoIP represents an even greater prospect. Assuming a significant fraction of private and public wireless LANs are modified to handle VoIP traffic, a market for integrating Wi-Fi with mobile phones will emerge. There are currently 1.5 billion mobile phone subscribers, with more than 500 million handsets sold annually.

And there is more to cordless VoIP than first meets the eye; for example, cordless VoIP could enable strategic alliances between mobile phone and cable network operators. Major cable operators are entering local phone markets, creating opportunities for mobile carriers to offer handsets that serve as cordless phones in the home—a single phone for all of users' telephone service needs.

The potential number of wireless LAN nodes needed for machine-to-machine applications is mind boggling. For example, the average home security system could easily use a dozen nodes for door and window sensors, motion detectors, and video cams. Other major wireless M2M applications include telematics, asset monitoring, mobile commerce, healthcare, real-time enterprise communications, and homeland security[5].

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[5] As described in Datacomm Research's report, "Wireless Machine-to-Machine: an In-depth Study of Applications and Vertical Markets," published July 16, 2004.

MIMO-OFDM could prove to be a key enabler in all of these markets. Home entertainment will require wireless networks capable of transmitting high-speed data (actual user data rates of 50 Mbps and higher) throughout the entire home. Cordless VoIP calls for low latency, wide coverage, and reliable operation while walking about. Wireless M2M applications require both high-speed and excellent coverage. High-speed will be critical as imaging becomes a preferred data gathering method in specific market segments, and coverage will be a requirement as many remote nodes are embedded in other devices or machines.

What Pre-Standard, MIMO-Enhanced Wi-Fi Products Can and Can't Guarantee

Pre-standard, MIMO-enhanced Wi-Fi products can guarantee superior performance in MIMO-enhanced mode, 100% compatibility with existing standards, and even improved performance in standards-based modes.

But vendors can't guarantee that pre-standard, MIMO-enhanced Wi-Fi products will be software or firmware upgradeable to the future 11n standard. No responsible supplier can make such a claim. It is impossible to guarantee interoperability under the 802.11n standard until the final specification is ratified and interoperability tests are certified by a body such as the Wi-Fi Alliance (WFA). At the time of this writing, the 802.11n standard had not even reached draft status.

Pioneers of MIMO-based wireless LAN products

A number of individuals, university research labs, and corporate R&D departments have contributed to the development of MIMO technology. Some of the earliest work was performed at Lucent Technology's Bell Labs and Stanford University during the 1990s.

Airgo Networks, Inc. (Palo Alto, California) was first to enable MIMO-based wireless LAN products priced within reach of consumers. Airgo's "True MIMO" chipset solution has been adopted by top wireless LAN manufacturers including Belkin, Buffalo Technology, Linksys (the market leader), Netgear, and SOHOware. Perhaps the real proof that MIMO has arrived, however, is that these products now occupy a substantial share of precious shelf space in retail stores catering to the booming home networking market.

Meanwhile, the consensus in the wireless LAN industry is that MIMO is the core technology for the next-generation standard being developed by the IEEE 802.11n working group. With MIMO-based products already on the market—and more models no doubt on the way—the working group needs to expedite development of a specification that is both acceptable to the majority of vendors and harmonious with the rapidly growing installed base of MIMO-based products.

Interestingly, one of the biggest challenges confronting Airgo Networks is misuse of the term "MIMO." Given Airgo's time-to-market lead, and mounting evidence that MIMO will soon become a required home wireless networking feature, some vendors hope that calling smart antenna solutions "MIMO" will buy them time while they develop actual MIMO products.

At every step of the 802.11n standards process—starting with the draft standard vote, continuing with incorporation of comments, and ending with the final standard ratification—changes will be made that are likely to require hardware modifications in the MIMO chipsets. Even after the final standard is fully ratified, any supplier's chipsets may require further hardware changes to ensure interoperability. Today, many WFA tests require features that are not specified in the relevant 802.11 standard because, realistically, such standards are almost never sufficient to ensure that any two devices will interoperate.

Thus, it is impossible for a chipset supplier to guarantee that a software or firmware upgrade to an OEM product will be sufficient to achieve 802.11n interoperability with devices based on other suppliers' chipsets. It will be approximately two years before the WFA is able to certify 802.11n interoperability. In the meantime, OEMs and consumers should not make purchase decisions based on claims concerning a not-yet-defined standard and set of interoperability tests. Instead, purchases of pre-standard, MIMO-enhanced Wi-Fi devices should be based on the application requirements, the performance and cost of the MIMO-enhanced products, and the investment protection afforded by backwards compatibility with existing 802.11a/b/g standards.

Customers contemplating purchase of pre-standard, MIMO-enhanced Wi-Fi products may also want to consider whether the vendor promises that its future, certified interoperable 802.11n standard products will be backwards-compatible with its current pre-standard MIMO products. Unlike promises of easy upgrades to future, not-yet-defined standards, the backwards compatibility of future products with existing products is something vendors can guarantee. Such guarantees serve as an investment protection program, allowing customers to continue using pre-standard client devices alongside future 802.11n standard client devices by replacing only the access points with dual-mode models.

MIMO: A Rising Star

MIMO-OFDM technology is more than the latest technical improvement for wireless LANs. MIMO-OFDM is a major technology upgrade enabling demanding new applications with huge market potential and facilitating significant growth in existing applications. Though the IEEE 802.11n task group is developing a standard for

MIMO-OFDM wireless LAN devices around which the entire industry should rally, the delivery of pre-standard MIMO enhanced Wi-Fi devices today can only boost development of a robust market for MIMO-OFDM wireless LAN devices.

