INVITED PAPER

MOBILE WiMAX – FOURTH-GENERATION WIRELESS

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Abstract—*Mobile WiMAX™ has been positioned as a 4G wireless WAN technology. For mobile WiMAX to become a serious 4G contender, there must be a substantial improvement in some combination of its performance, capacity, and economics, compared with that of other contenders. In this respect, the IEEE 802.16e standards that define mobile WiMAX provide considerable flexibility. This paper is a high-level survey of the more distinctive technologies that, together, have the potential of creating the improvements that will make mobile WiMAX successful. The paper suggests that mobile WiMAX will be successful only when the potential technological improvements permitted by the standards are aggressively adopted. While intended for decision makers and others who require only a general understanding of mobile WiMAX, the paper does include references that will lead designers to appropriate sources.*

Key Words—*4G, fourth generation, mobile WiMAX, WAN, wireless*

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INTRODUCTION

Mobile worldwide interoperability for microwave access (WiMAX™) offers a new set of wireless protocols that, when implemented in cellular radio systems, is intended to provide broadband wireless access with improved performance, capacity, and economics (all of which are interrelated) compared with existing wireless access. Mobile WiMAX is intended to provide data rates in excess of 1 Mbps to fixed, portable, and mobile subscribers over wide areas at costs far lower than those of existing approaches. Mobile WiMAX is synonymous with the IEEE 802.16e suite of standards. These standards have a high level of generality; they function, in fact, as a family of protocols. Further, because of demanding objectives and because existing technologies already approach theoretical upper limits of performance, the IEEE 802.16e standards are exceedingly complex, arguably more so than the standards for any previous wireless interface. The flexibility and complexity of mobile WiMAX will challenge equipment manufacturers that wish to offer interoperable and economical equipment and systems. But hundreds of companies, including operators and component and equipment manufacturers, as well as tens of thousands of engineers, are already participating in making mobile WiMAX a reality. Mobile WiMAX *will* happen, although its timing, performance, and degree of market penetration are conjectural.

This paper provides a high level description of the technologies that make mobile WiMAX unique. These technologies may be loosely described as relating to orthogonal frequency division multiplexing (OFDM) and multi-antenna signal processing (MAS). Each of these areas is treated very flexibly in the standards—so much so that it may be impossible to build a system that accommodates so much flexibility and is still interoperable with all other such systems. While it is not the intent of this paper to resolve this complex issue, it does include value judgments about which approaches best serve the needs of operators and end users.

The complexity of the mobile WiMAX standards is indicated by the list of 118 acronyms provided with a technical overview prepared by the WiMAX Forum™ [1]. A rather abbreviated list appears in this paper. More complete lists and more comprehensive descriptions are available from the resources listed in the references.

THE WiMAX MODULATION STRATEGY

It is the nature of the real-world radio frequency (RF) environment that radio channel quality is highly variable. This variability may be caused by

ABBREVIATIONS, ACRONYMS, AND TERMS

4G	fourth generation
AAS	adaptive antenna system (adaptive array smart antenna technology)
AMC	adaptive modulation and coding (permutation method)
FDD	frequency division duplex
FUSC	full usage subcarrier (permutation method)
MAS	multi-antenna signal processing
MIMO	multiple-input, multiple-output—use of multiple antennas on both base station and subscriber station
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiple access
PUSC	partial usage subcarrier (permutation method)
QAM	quadrature amplitude modulation
QoS	quality of service
QPSK	quadrature phase-shift keying
RF	radio frequency
SDMA	spatial division multiple access
SINR	signal-to-interference-and-noise ratio
STC	space-time coding
subcarrier	an individual OFDM FFT discrete frequency element (a.k.a. tone)
subchannel	frequency dimension of RF bandwidth allocation unit
TDD	time division duplex
tone	an individual OFDM FFT discrete frequency element (a.k.a. subcarrier)
WiMAX™	worldwide interoperability for microwave access

The mobile WiMAX standards attempt to incorporate a number of innovative technologies to achieve the objectives of high performance, high capacity, and low cost.

multipath effects, physical obstructions, fading, Doppler effects, and various forms of interference. The mobile WiMAX standards attempt to incorporate a number of innovative technologies to achieve the objectives of high performance, high capacity, and low cost. Some of these technologies are inherent and mandatory; others are optional. Mobile WiMAX employs and manipulates the various technologies in an attempt to make best use of the radio channel and to allow the user to move from cell to cell without a break in communications.

The standards allow for either frequency division duplex (FDD) or time division duplex (TDD) transmission. While existing cellular systems are almost universally FDD, most implementations of mobile WiMAX will very likely be TDD. There are substantial advantages to TDD, especially when some forms of MAS technology are employed. The reasons for this are discussed later in this paper.

Mobile WiMAX is, of course, a digital transmission system. The basic modulation methods are quadrature amplitude modulation (QAM) for strong signal locations and different modes of quadrature phase-shift keying (QPSK) for weaker signal areas. QAM and QPSK are widely used protocols in both wired and wireless systems, as are other protocols used to accommodate varying RF environments. The mobile WiMAX protocols enable the continual monitoring of transmission path quality and the selection of the appropriate modulation method (sometimes referred to as modulation class or mod class). **Figure 1** illustrates the use of different mod classes (there are seven).

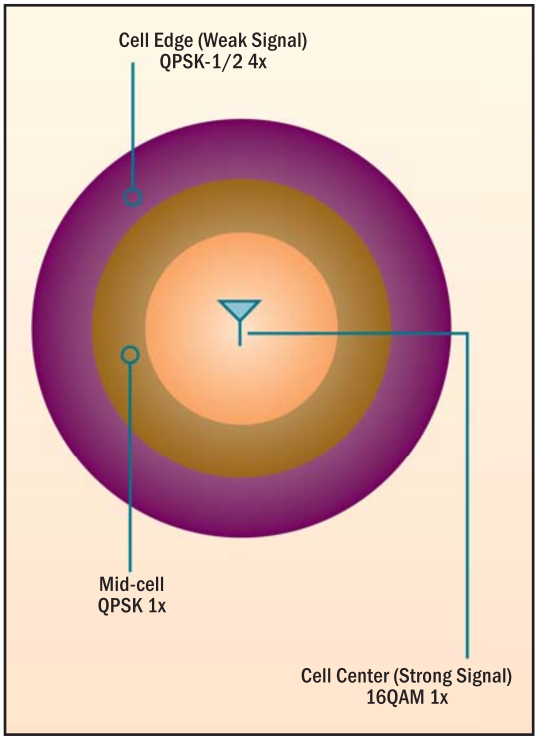

Figure 1. Illustration of the Use of Modulation Methods (Mod Classes)

The figure is overly simplified because it assumes that the signal is always stronger close to the antenna. In the real world, there are often weak signals in the cell center and strong signals at the cell edge.

OFDM

Transmission path variability such as multipath can be mitigated by using a knowledge of what is occurring in the channel at any given time to direct information to "clean" or desirable parts of the channel and away from less desirable parts. OFDM does this by dividing a frequency channel into as many as 2,048 subcarriers, also referred to as "tones," and then selecting groups of these subcarriers to carry data based on knowledge of which subcarriers are likely to be more desirable than others. The system then creates a communications channel using this group of subcarriers.

Channel knowledge is obtained by using many of these subcarriers to send special pilot symbols through the channel for later analysis. Because channel knowledge is imperfect, several algorithms have been written that attempt to optimize subcarrier assignment. Regarding the specific algorithms included in the WiMAX standards—partial usage subcarrier (PUSC), full usage subcarrier (FUSC), and adaptive modulation and coding (AMC)—it is sufficient to say that each assigns groups of subcarriers in ways that mitigate different forms of channel defects. The task of deciding which algorithms to use to improve system performance is fulfilled by the *scheduler*, a processing function distributed between the WiMAX base station and the client device.

The mobile WiMAX standards use an advanced form of OFDM called orthogonal frequency division multiple access (OFDMA) that improves system use efficiency by allowing subcarriers that are undesirable for one user's data channel to be used for another's.

Figure 2 is an example of a frequency plot showing data subcarriers, pilot subcarriers spaced at intervals of 11 data subcarriers, DC subcarriers, and unused "guard" subcarriers that keep adjacent frequency channels from interfering with each other. OFDMA is described in great detail in Reference [2].

Fast Fourier transform (FFT) is used to convert data from (discrete) time domain to (discrete) frequency domain. This is used to recover each OFDM tone's information from a composite time-domain symbol.

Inverse fast Fourier transform (IFFT) is used to convert data from (discrete) frequency domain to (discrete) time domain. This is used to construct a composite time-domain symbol from all OFDM tones.

OFDM mitigates multipath by dividing a frequency channel into as many as 2,048 subcarriers, also referred to as "tones," and then selecting groups of these subcarriers to carry data based upon knowledge of which subcarriers are likely to be more desirable than others.

MAS (SMART ANTENNAS AND MIMO)

The Interoperability Challenge

MAS incorporates a variety of techniques using multiple antennas for either reception or transmission (or both) at the base station or the client device. Under specific conditions, each technique offers value toward achieving the

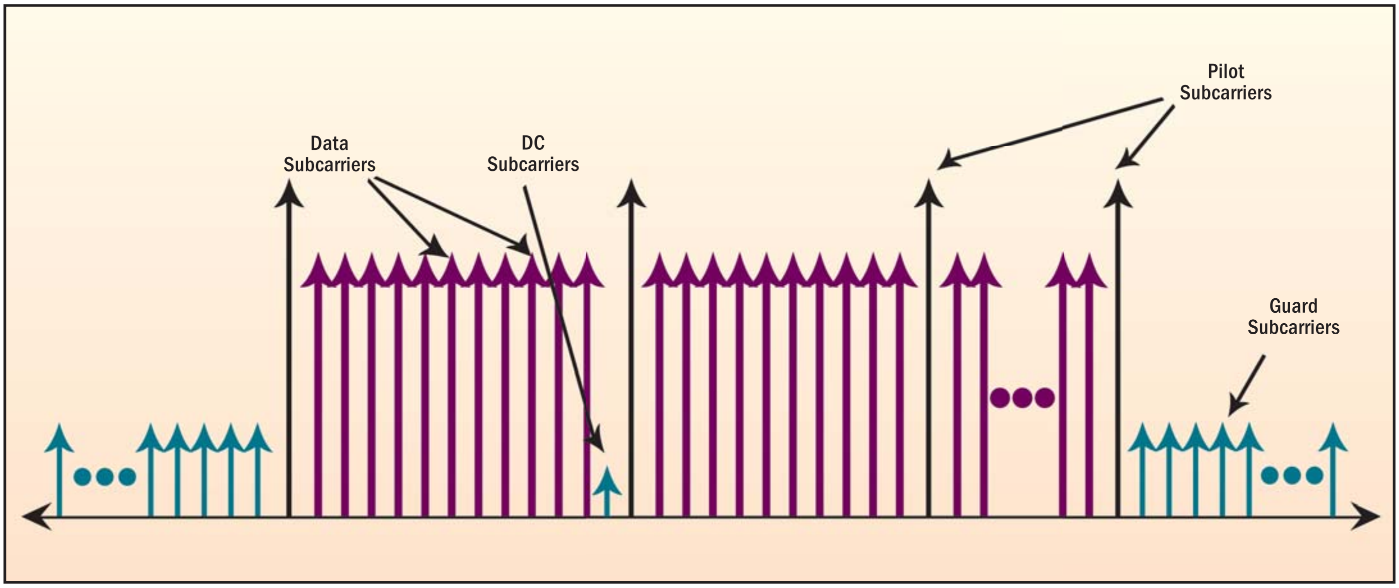

Figure 2. OFDM Subcarriers (Tones)

improved performance of mobile WiMAX. When properly implemented together, these techniques offer the opportunity for unprecedented performance. But the extraordinary flexibility of the WiMAX standards also presents a challenge to the industry with regard to interoperability. To address this challenge, the industry has taken the approach of adding MAS techniques incrementally. The WiMAX Forum has established "profiles" intended to facilitate interoperability and offers a process for obtaining interoperability certification. The first profile, called Wave 1, does not include MAS. Wave 2, which includes some mandatory and some optional MAS features, is expected to be implemented by some manufacturers by the end of 2007. But the process of refining and improving the mobile WiMAX standards, especially for MAS, will continue indefinitely. Just as operating system and application software continues to be improved as devices become more powerful and user needs are better understood, so the algorithms that are the basis of MAS and the processors that run the algorithms will continue to be improved over the lifetime of mobile WiMAX.

MAS uniquely exploits the dimension of space, making use of the fact that the multiple antenna elements at the receiver and transmitter occupy different positions in space.

Exploiting Time and Space

Techniques incorporated in MAS have been described using many terms, including smart antenna; multiple-input, multiple-output (MIMO); adaptive antenna system (AAS); space-time coding (STC); spatial multiplexing; and beam forming. Mobile WiMAX uses several error-correcting codes that operate solely in the time domain and are comparable to those used in wired and other wireless systems. But mobile WiMAX also uniquely combines at least one such code in both space and time (STC—transmission of different time permutations of a signal from multiple antennas to produce redundancy gains in the receiver's unpermutated signal—is discussed later in the paper).

MAS uniquely exploits the dimension of space, making use of the fact that the multiple antenna elements at the receiver and transmitter occupy different positions in space. Therefore, the data received and transmitted by each antenna element is affected differently by the transmission path variability mentioned earlier. And yet, over a short span of time, the only information that can be extracted from an antenna receiving element or delivered to an antenna radiating element is a signal having a particular amplitude and phase relative to other signals.

It would be correct to wonder how manipulating such a limited amount of variability can result in so many descriptions and algorithms, but, in fact, the signals from and to each antenna element can be manipulated in a myriad of ways. All that can be done with the outputs of the antenna elements in a receive array is to combine them while adjusting the phase and amplitude of each output to enhance the desired signal. And all that can be done to manipulate the radiation from an array of antenna elements is to adjust the phase and amplitude to enhance the signal received by a selected user or group of users. But, as will be seen, the nature of the phase and amplitude "adjustments" can have an extraordinary affect on the system.

Space-Time Coding

Transmitted data may be corrupted by combinations of scattering, reflection, refraction, man-made or thermal noise, etc. STC is a technique that addresses data corruption by transmitting multiple copies of bits or groups of bits in the data stream across a number of antennas at different times and then combining the received copies to improve transmission reliability. Because each copy takes a different path or appears at a different time, some are better than others. STC optimally combines the copies to extract as much information from each as possible.

The specific coding technique used in mobile WiMAX was introduced by Siavash Alamouti [3] and is unique in the simplicity of its receive implementation. It is used to enhance downlink performance, i.e., from base station to mobile. While it is necessary to have multiple transmit antennas, it is not necessary to have multiple receive antennas, although doing so improves performance.

STC is a form of error correction that uses the spatial dimension in addition to the time dimension most commonly used for this purpose. STC can make a communications channel more robust in the presence of certain corruption, but it does not increase the subscriber capacity of a system or the coverage of a base station. However, the MAS technique known as AAS does just that.

AAS—Spatial Division Multiple Access

When the outputs of the individual antennas in an array are combined, the array becomes a single antenna with gain and directional characteristics very different from those of the individual

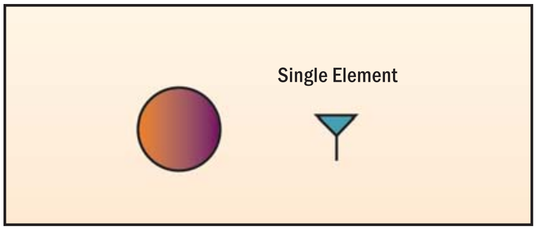

Figure 3. Single-Element Radiation Pattern

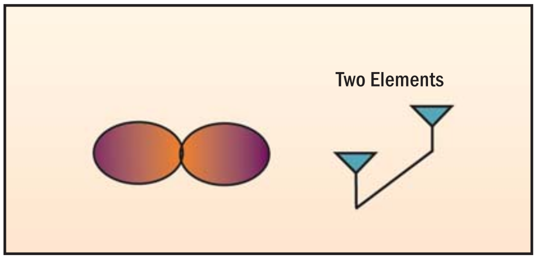

Figure 4. Two-Element Radiation Pattern

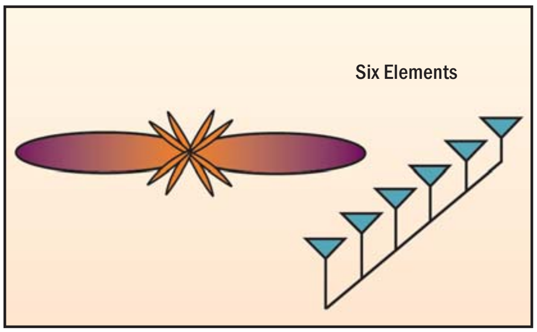

Figure 5. Six-Element Radiation Pattern

antennas that constitute the array. **Figure 3** shows the radiation pattern (or receive pattern) of a single antenna as viewed from above. If two antennas are spaced a half-wavelength apart and their outputs are simply added, a pattern is created similar to that in **Figure 4**. An array of six antennas at half-wavelength spacing produces a pattern as shown in **Figure 5**. If the radius of the pattern in Figure 3 is proportional to the strength of the signal radiated from the antenna, then the multi-antenna arrays exhibit greater signal strength, or *gains*, in certain directions and reduced signal strength, or *nulls*, in other directions. The gain is actually equal to the number of antennas. In the six-antenna example depicted in Figure 5, the radiated energy in the maximum direction is six times (or 7.5 db) greater than that of a single antenna.

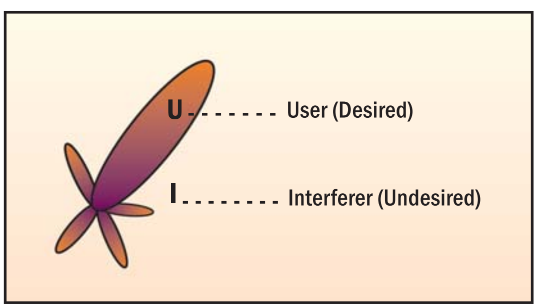

Figure 6. Illustration of a Beam-and-Null Pattern

AAS Evolution and Advances

As far back as World War II, multi-antenna arrays were deployed in configurations that could be mechanically aimed in desired directions.

The advent of powerful signal processors and extremely linear analog-to-digital converters made possible the ability to create patterns similar to that in Figure 5 but with complete control over the directions of the gain and the nulls. The arrays could now, at least theoretically, be adapted to the RF environment. **Figure 6** shows an *n*-antenna pattern that creates a beam in the direction of the user and a null in the direction of a potential interferer. It is from this concept that the term "beam forming" arose.

A major step forward occurred in the early 1990s when the opportunity presented by adaptive arrays was cultivated in a very different way. Rather than attempting to create beams, the objective of the array and its processor was stated as a mathematical problem: given (1) an array of antennas, (2) the ability to process its inputs and outputs, and (3) a number of users, create an algorithm that combines the array's inputs and outputs to optimize communication with each user while rejecting, to the greatest extent possible, the signals from other users. The results of this change in viewpoint are startling; these results are illustrated in **Figure 7**, which contrasts an AAS with a single-antenna system.

The RF environment is continually changing and the influences that corrupt radio signals are different at different times and in different places. No single algorithm works everywhere and all the time.

The RF environment is continually changing and, as mentioned earlier, the influences that corrupt radio signals are different at different times and in different places. No single algorithm works everywhere and all the time. Historically, as the power of digital signal processors increased and as the RF environment became better understood, it became possible to continuously analyze the RF environment and to better optimize avoidance of this corruption. The algorithms whose results are depicted in Figure 7 were created more than 10 years ago. Yet they sampled the RF environment hundreds of times per second and optimized signal reception and transmission by applying one of eight different algorithms to each sample. Since then, there have been remarkable advances in both algorithm development and device power.

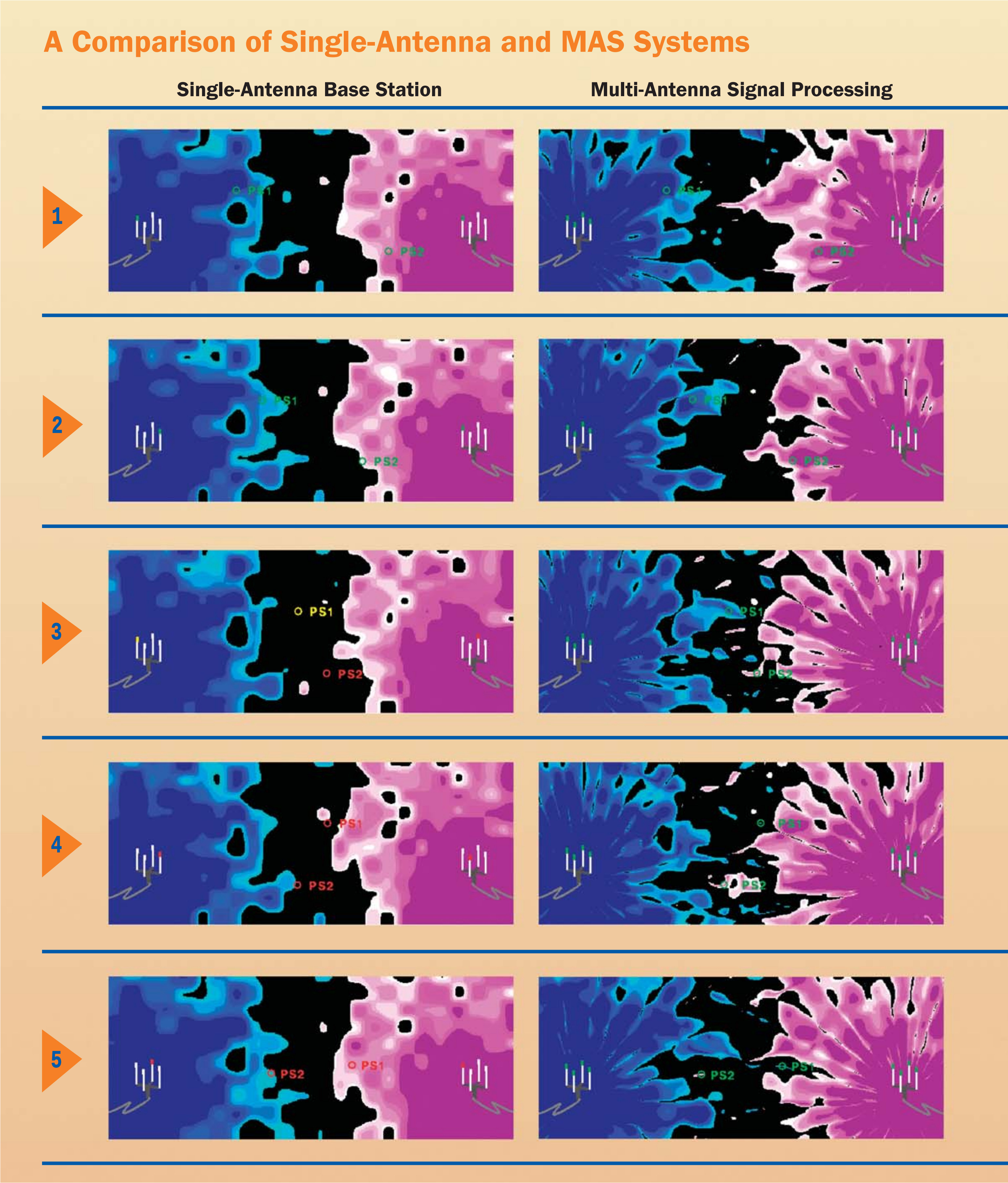

Figure 7. Illustrations of MAS Adaptive Arrays

Each user is close to its base station and communicating with that base station.

The users start moving away from their respective base station toward the other base station. Both users are communicating, but note that the users operating with single-antenna base stations have moved into weak signal areas. On the MAS side, the coverage pattern has changed (adapted) so that both users continue to be in strong signal areas.

The users continue to move away from their base stations. The single-antenna users are no longer in communication with their base stations. The MAS coverage pattern, however, has changed to keep both users in strong communication with their base stations.

Each user is now in the cell adjacent to its original cell. The single-antenna users do not communicate; the MAS users continue to experience strong signals. Note that each base station has created a null in the direction of the other base station's user. Each base station has also created a signal "island" around its user.

The users are now almost in line between the two base stations. Because this is a multipath radio environment, the MAS processor has adjusted the amplitude and phase of each antenna output to maximize the signal to its user and to avoid sending signal energy to the other user. Each user is receiving a strong signal even though the other user is almost directly between it and its base station. Clearly, there is no "beam."

The images shown in Figure 7 were extracted from a very accurate simulation of a TDD system using MAS technology to deliver voice and data at a rate up to 512 kbs. Each image shows two base stations in adjacent cells, each transmitting on the same radio frequency channel and in the same TDD time slot. The left column shows the system operating with single-antenna base stations. The right column shows base stations that are fully adaptive MAS-enabled with four-antenna-element arrays. The signal strength of each base station is indicated by the intensity of the color surrounding the base station. Black indicates a location where no signal can be detected, usually because the signals from the base stations interfere with each other.

The five panels shown in the figure progress in time from top to bottom. Two users, PS1 and PS2, are shown in each panel. Base stations and users are transmitting and receiving continuously throughout the sequence. In panel 1, the users are in communication with the base station closest to them. In successive panels, they attempt to continue communicating with that same base station as they move toward the other. When they are in successful communication, their label is green, like the antenna (or antennas) of their respective base station. If the connection is lost, the color changes to red.

Note that the radiation patterns of the single-antenna base stations are relatively static. Each MAS-enabled base station, on the other hand, continually adjusts its radiation pattern to optimize signal strength to its user while minimizing interference to the other user. By panel 3, the single-antenna users have lost communication. The MAS users, however, remain in communication even when the other user is between them and their base station. The coverage pattern for each MAS user has become an "island" surrounding the user. To create these islands of coverage, multipath signals have converged at each MAS user to maximize the signal from that user's base station while minimizing the signal from the other user's base station.

The simulations were confirmed to have a high degree of correlation with real-world results. There are about 300,000 base stations of the type described here serving tens of millions of subscribers in more than a half-dozen countries.

Understanding the Adaptive Process

Although the adaptive process is exceedingly complex, it can be described very simply with an example. The process begins when a user starts transmitting. The user's signal is received by each antenna element in the base station array, the antenna array outputs are digitized, and the adaptive algorithms are applied. This occurs simultaneously for all users of interest. An *n*-element array can separate out *n* users; in doing so, it creates virtual channels, called spatial channels. A spatial channel is created for each signal of interest by solving mathematical equations that calculate—for each user—the optimum combination of antenna element inputs and outputs, with the correct phase and amplitude adjustments to communicate with that user. The effect of these calculations is to create maximum gain for each user while nulling out other users. The signal to be received is enhanced, and the undesired signals are reduced. The base station has now received a much better version of the signal than would be the case with a single antenna, but this is just part of the process.

Because the cost of additional processing is minimal and continually dropping, it is expected that, in the long term, spatial multiplexing approaches in mobile WiMAX will evolve into fully adaptive AAS.

Since the base station has recorded a pattern, called a spatial signature, that is unique to each user, the base station can use that spatial signature to transmit information back to that user. If the outbound RF environment is the same as the inbound, all signal reception benefits described above accrue to the user in the sense that the transmitted energy is optimized toward that user and minimized toward undesired users (interferers). In fact, the inbound and outbound RF environments are very similar. This is especially true in TDD systems, where transmission and reception are on the same frequency. In these systems, the only difference between the receive and transmit patterns is any change in RF environment that may take place because the transmitted signal occurs a few milliseconds later. The result is excellent correlation and excellent reciprocity. In FDD systems, on the other hand, the correlation is not quite as good, since the return transmission occurs in a different frequency band. Although MAS systems can be very effective in FDD systems, the results are not as dramatic as in TDD systems.

The end result of the above process is that the AAS can create a number of two-way spatial channels on a single conventional channel, be it frequency, time, or code division multiplexed. Each spatial channel enjoys the full gain and interference rejection capabilities of the array. Theoretically, an array with *m* antenna elements can support *m* spatial channels per conventional channel; in practice, the number is somewhat less and depends upon environment.

AAS-enabled broadband wireless TDD systems are in operation today that achieve coverage in excess of 4 times greater and spectral efficiency 10 to 40 times greater than those of single-antenna systems. Achievement of such remarkable improvements requires as many as a dozen antenna elements in each array. With such an array, signal gain alone doubles the effective range of each cell. Further, with this many antenna elements, it is possible to serve at least three users on the same frequency and time slot in a given cell and to serve three additional users on the same frequency and time slot in each cell of the system (the virtual channels serving these users are often referred to as spatial channels). This compares strikingly with the cellular reuse pattern of a traditional idealized cell system, which provides for only one reuse in every seven cells. The AAS-enabled system described above achieves a reuse rate of over 20 times in the same seven cells.

Although simulations exist that show the promise of mobile WiMAX very clearly, the performance results described above are measured; no such results exist in actuality. **Figure 8** shows, under various conditions of mobility, the predicted signal-to-interference-and-noise ratios (SINRs) of a four-antenna, AAS-enabled, mobile WiMAX system compared with the SINRs of a single-antenna system. The SINR improvement for a pedestrian user translates to an increase in coverage of over four times. Even for a user traveling at 100 km/hr, a data rate improvement of more than two to one is predicted. The four-antenna spectral efficiency for the pedestrian case is 3.5 times greater than that of the single-antenna case.

An even less technical description of smart antenna technology than the one just presented appeared in *Scientific American* magazine in July 2003 [4].

Spatial Multiplexing

Spatial multiplexing is a subset of AAS technology. It is described here only because the WiMAX Forum profile descriptions identify spatial multiplexing as a possible element of the WiMAX Wave 2 profile. Consider the AAS scenario where a base station with at least two antenna elements creates two separate spatial channels to two different users. Each user

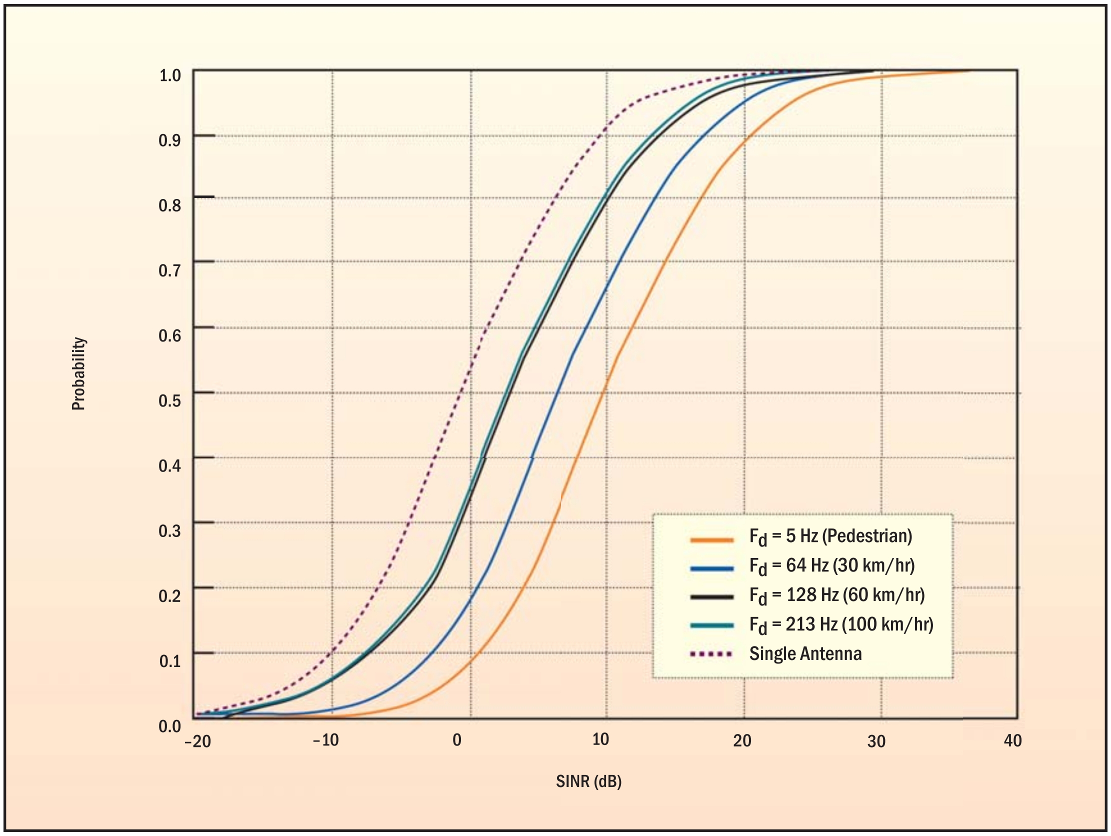

Figure 8. Four-Antenna Mobile WiMAX Simulation Results

has a single-antenna receiver. Now, imagine combining these two receivers into one package in such a way that the receiver outputs are additive. There is now a user who is receiving two separate data streams into a two-element array. The base station can now consolidate the two data streams to provide this user with twice the data rate compared with that of a single-antenna user. This description is idealized because it assumes no corruption on the radio channel. Under real-world conditions, the data rate is always better than that of a single antenna. On the other hand, adding more versatile AAS algorithms to this scenario that adapt to a changing environment will improve performance in the other ways discussed in the AAS section above. Because the cost of additional processing is minimal and continually dropping, it is expected that, in the long term, spatial multiplexing approaches in mobile WiMAX will evolve into a fully adaptive AAS.

OTHER FEATURES

Mobile WiMAX incorporates numerous other features that, while not unique, contribute to the effectiveness of the technology. For example:

- Rapid handoff is designed into mobile WiMAX in such a way that few data bits are lost during a handoff and yet handoffs are "hard"; that is, there is no provision for a mobile device to occupy channels in two cells at the same time, as is true in other wireless systems.
- Mobile WiMAX incorporates power-saving features intended to extend battery life in client devices.
- Several time-domain error-correcting codes are embedded in the mobile WiMAX protocol.
- Extensive provisions exist to provide control over quality of service (QoS) to different classes of subscribers.

The WiMAX Forum overview describes these features in more detail [1].

CONCLUSIONS

Mobile WiMAX offers an extremely flexible family of wireless broadband protocols that, collectively, have the potential to make mobile WiMAX a leading contender in the global race to meet consumer demand for low-cost, high-speed mobile access. This paper has attempted to describe the more distinctive features of mobile WiMAX that create this potential. Once these features are appropriately exploited, mobile WiMAX will be on its way to becoming a widely used and successful air interface. Successful deployment will be achieved when the following criteria are met:

Mobile WiMAX is an extremely flexible family of wireless broadband protocols that, collectively, have the potential to become a leading contender in the global race to keep up with consumer demand for low-cost high-speed mobile access.

- ***High spectral efficiency***—Exploitation of MAS techniques will provide for frequency reuse patterns of one or less in densely populated areas and extended range in less densely populated areas or during initial deployment.
- ***Low cost***—A direct result of high spectral efficiency will be an order of magnitude improvement in cost of deployment, operation, and maintenance, compared with that of competitive systems.
- ***High performance***—The data rate and QoS will match the requirements of the many new applications that will be engendered by the availability of low-cost service.
- ***Interoperability***—Economies of scale resulting from widespread use of interoperable mobile WiMAX applications and devices will result in a competitive environment in which costs will continue to decrease and devices and applications will continue to proliferate.

These criteria remain moving targets. Consumer demands for bandwidth and QoS will continue to increase indefinitely, and consumers will expect these improvements to come at no additional cost. Much work is yet to be done. ■

TRADEMARKS

WiMAX and **WiMax Forum** are trademarks of the WiMAX Forum.

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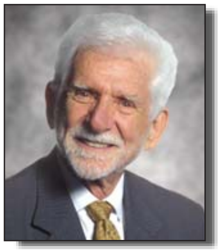
BIOGRAPHY



Martin Cooper is the Executive Chairman and co-founder of ArrayComm, LLC. A pioneer in the wireless communications industry, Martin conceived the first portable cellular phone in 1973 and led the 10-year process of bringing it to market.

During his 29 years with Motorola, Martin built and managed both its paging and cellular businesses and served as Corporate Director of Research and Development.

Upon leaving Motorola, Martin co-founded Cellular Business Systems, Inc. and led it to dominate the cellular billing industry with a 75 percent market share before selling it to Cincinnati Bell. He has been granted eight patents in the communications field and has been widely published.

Under Martin's leadership since its founding in 1992, ArrayComm has grown from a seed-funded startup in San Jose, CA, into the world leader in smart antenna technology with 400 patents issued or pending worldwide.

Martin received the American Computer Museum's George R. Stibitz Computer and Communications Pioneer Award in 2002, he was an inaugural member of *RCR's Wireless* Hall of Fame, *Red Herring* magazine named him one of the Top 10 Entrepreneurs of 2000, and *Wireless Systems Design* provided him with the 2002 Industry Leader award. He holds a BS and an MS in Electrical Engineering from Illinois Institute of Technology.