ADAPTIVE ANTENNA ARRAY focuses radio waves on a "personal cell" surrounding each mobile user. This smart-antenna technology can increase the range of wireless voice and data networks and allow several users in the same coverage area to communicate on the same frequency.

By Martin Cooper

ANTENNAS GET SMART

Adaptive antenna arrays can vastly improve wireless communications by connecting mobile users with virtual wires

Each of us is immersed in a sea of radio-frequency waves. The invisible electromagnetic energy comes from many sources: broadcast towers, cellular-phone networks and police radio transmissions, among others. Although this radiation may be harmless to our bodies, it can severely inhibit our ability to receive and transmit information. Excess radio energy is a kind of pollution, because it can disrupt useful communications. As the intensity of radio-frequency interference in our environment grows, we have to raise the volume of radio signals so that they can be heard over the electromagnetic background noise. And as our electronic communications become more intense, they simply add to the din of radio interference.

One solution to this problem lies in a new class of radio antennas that could dramatically reduce man-made interference. Instead of wastefully broadcasting personal communications—such as cell-phone calls—in all directions, these innovative antennas track the positions of mobile users and deliver radio signals directly to them. These antenna systems also maximize the reception of an individual cell-phone user's signal while minimizing the interference from other users. In effect, the antennas create a virtual wire extending to each mobile phone.

These systems are generically referred to as smart antennas, but the smartest members of the class are called adaptive antenna arrays. In 1992 I co-founded ArrayComm, a San Jose, Calif., company focused on developing adaptive arrays that can be incorporated into both new and existing wireless networks. Each of our arrays consists of up to a dozen antennas and a powerful digital processor that can combine and manipulate the incoming and outgoing signals. The technology, which is also being pursued by Lucent Technologies, Nortel Networks and other firms, promises to decrease the cost and improve the quality of wireless communications. Adaptive antenna arrays

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are already providing these benefits to millions of cell-phone users. Moreover, these smart antennas may become the linchpins of the wireless Internet because they are ideally suited to transmitting and receiving large amounts of data.

The Physics of Antennas

TO UNDERSTAND HOW smart antennas operate, it helps to know how ordinary, "dumb" antennas work. A radio antenna converts electric currents and voltages created by a transmitter into electromagnetic waves that radiate into space. Antennas also intercept such waves and convert them back into currents and voltages that can be processed by a receiver. The simplest and most common radio antennas, called dipoles, are merely rods of very specific lengths that radiate energy in all directions [*see top illustration on opposite page*]. Radio waves get weaker as they spread through space and are absorbed by obstacles such as air, trees and buildings.

Commercial radio and television stations need to reach geographically dispersed audiences, so it is logical for them to broadcast signals in all directions. A cell-phone call, though, is usually aimed at just one user. In a cellular network, users communicate with the nearest base station, a set of antennas that handle all the wireless service's signals in the surrounding area (called the cell). The base stations are located so that the entire coverage area can be divided into cells; when a user moves from one cell to another, the system automatically hands off the call to the appropriate base station. In this situation, it would be far preferable to focus the radio energy on each user, much as the reflector in a flashlight focuses light into a beam. A radio beam would extend much farther than a signal of equivalent power that is broadcast in all directions. And because the radio beams transmitted by the cellular base station to different users would be spatially separated, interference would be reduced.

Reflectors can focus radio waves into beams, but they are cumbersome and costly. So engineers have developed tricks to create radio beams without reflectors. If we stand two antennas side by side, with the distance between them equal to one half the wavelength of the radio signal, the radiated energy from this simple array assumes the pattern of a figure eight when viewed from above [*see middle illustration on opposite page*]. The radio waves travel farthest in the two directions perpendicular to the array (that is, perpendicular to the line connecting the antennas), because in these directions the user would receive both antenna signals at the exact same time (in other words, the two signals would be in phase). When two identical signals are in phase, they combine to form a signal that is twice as strong as either one alone. But in the directions parallel to the array, the user would receive the two antenna signals 180 degrees out of phase. The wave peaks from one antenna would arrive at the same time as the wave troughs from the other, so the two signals would cancel each other out. This phenomenon creates a null, an area where the signal cannot be detected.

The beam generated by the two-antenna array is a fairly broad one, and it extends in opposite directions. But engineers can progressively narrow the beam by adding more antennas. Such phased-array antennas have been used to focus radar beams since World War II. Although increasing the number of antennas makes the beam narrower, it also produces smaller beams, called lobes, on both sides of the main beam [*see bottom illustration on opposite page*]. Depending on the user's direction from the antenna array, the signal can be either stronger than the signal radiated by a single antenna ("gain") or weaker because of cancellation effects ("rejection").

Overview/*Smart Antennas*

- In wireless networks, it is often useful to employ an array of antennas at each cellular base station.
- Adaptive arrays include powerful processors that manipulate the antenna signals to enhance communication with one user while minimizing interference from all others.
- The companies involved in smart-antenna development include ArrayComm, Navini Networks, Lucent Technologies and Nortel Networks.

Aiming the Beam

RADIO BEAMS ARE OF LITTLE USE, however, if they cannot be pointed at their intended recipients. The most obvious solution is to physically turn the antenna array, but this method is very awkward and expensive. It is much easier to steer the radio beams electronically. Using one technique, called beam switching, antenna arrays create a group of overlapping radio beams that together cover the surrounding area [*see top illustration on page 52*]. When a cell-phone user makes a call, the radio receiver determines which beam is providing the strongest signal from the user. The array transmitter then "talks back" using the same beam from which the signal was received. If the user walks out of the original beam into an adjacent one, the radio's control system switches to the new beam, employing it for both reception and transmission.

Beam switching, though, does not work well in the real world of wireless communications. For a beam to be most effective, the mobile user has to stand in the center of the beam [*see bottom illustration on page 52*]. As the user moves off center, the signal fades, just as the light from a flashlight gets dimmer as you step away from the direction in which it is pointed. When the user approaches the far edge of the beam, the signal strength can degrade rapidly before the system switches to the adjacent beam. And what if there is another user who is trying to use the same radio channel but from a different direction? If the second user is standing in a null, there would be no interference, but if the interloper happens to be in the center of a lobe, the second signal may well block or distort the first.

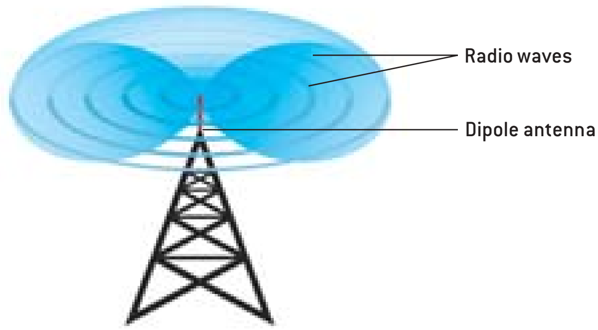
Another challenge for beam-switching systems is the fact that in most environments, radio signals rarely travel in direct paths. The signal you receive on your cell phone is usually a combination of reflections off natural and man-made objects—buildings, mountains, vehicles, trees and so on. And these re-

GENERATING A RADIO BEAM

SMART-ANTENNA TECHNOLOGY is based on the ability to shape the coverage patterns of radio waves. By focusing the waves on individual cell-phone users, smart antennas can extend the range of cellular systems and minimize interference.

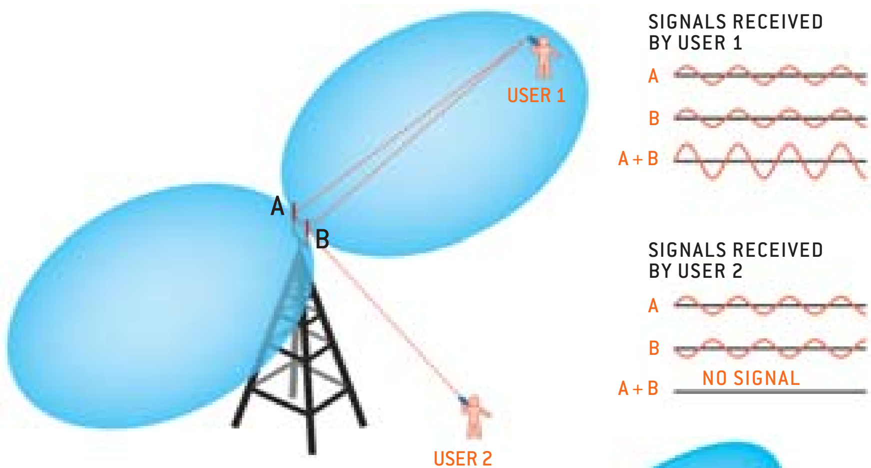
ORDINARY ANTENNA

The simplest antenna is a dipole, a metal rod that radiates energy in all directions. The radio waves get weaker as they propagate through space and are absorbed by obstacles. These antennas are suitable for radio and television broadcasts, which need to reach geographically dispersed audiences.



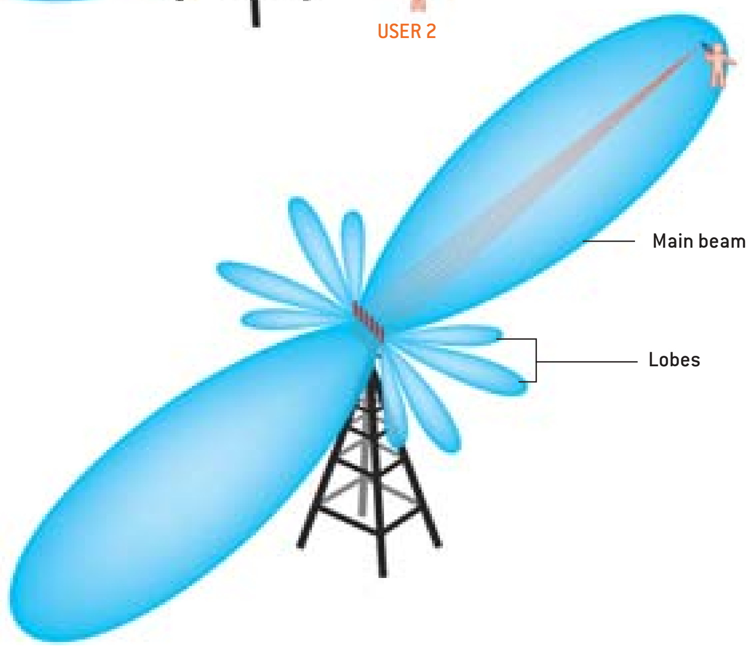
TWO-ANTENNA ARRAY

Now consider antennas A and B placed side by side, with the distance between them equal to half the wavelength of the radio signal that each is emitting. (For cellular systems, wavelengths range from 12 to 37 centimeters.) The cell-phone user standing perpendicular to the array (user 1) receives both signals at the same time, doubling their intensity. But the user aligned with the array (user 2) receives the signal from antenna B half a cycle before receiving the signal from antenna A. The two signals are 180 degrees out of phase, so they cancel each other out. Thus, the two-antenna array creates areas, called nulls, where the signal cannot be heard.



SIX-ANTENNA ARRAY

An array with six antennas generates a radio beam that is narrower and extends farther than the beam produced by the two-antenna array. The six-antenna array also creates smaller beams called lobes.



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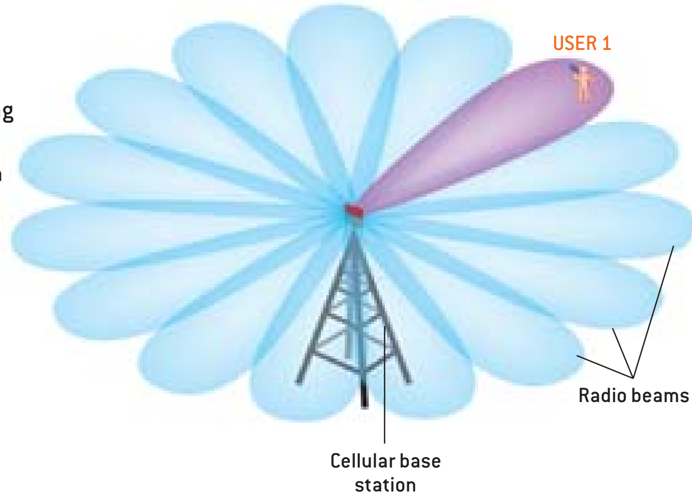
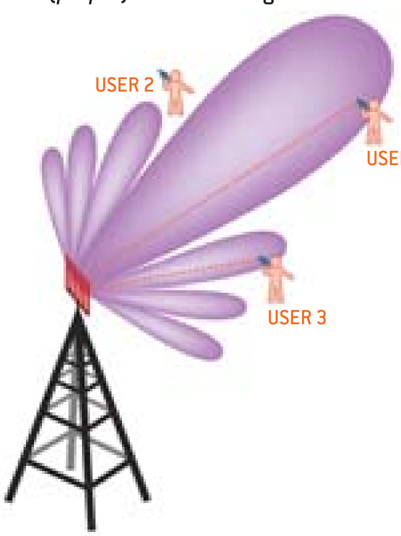
BEAM SWITCHING

A SMART ANTENNA must be able to point its radio beams at their intended recipients. One approach, called beam switching, can be easily incorporated into wireless networks, but the technique has some serious drawbacks.

SELECTING A BEAM

In a beam-switching system, an antenna array generates overlapping radio beams that together cover the surrounding area (*right*). When a cell-phone user makes a call, the radio receiver at the cellular base station determines which beam is best aligned with the user's signal. The array uses the same beam (*purple*) to transmit signals back to the user.





MIXED SIGNALS

The chief problem with beam switching is that the array does not always aim the beam directly at the user (*left*). As the intended recipient of a cell-phone call (user 1) approaches the edge of the beam, the signal strength can degrade rapidly. Other callers can communicate on the same frequency (but using a different beam) if they are in a null (user 2). But signals traveling to and from a cell-phone user in a lobe (user 3) may interfere with user 1's signals.

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flections are constantly changing, especially the ones caused by large vehicles such as buses. This phenomenon, known as multipath, also affects the signals sent from the cell phone to the base station. If a user in a beam-switching network is near the edge of a beam, the signal that he or she transmits may bounce into the adjacent beam before reaching the beam-switching array. In that case, the array would transmit to the wrong beam, and the user might miss the return signal entirely.

For practical applications, beam-switching systems are obviously inadequate. An antenna array that is truly smart would be able to aim a radio beam directly at a mobile user instead of choosing a beam that comes relatively close. The ideal array would also be able to adjust the beam pattern so that it minimized interference from other users who were communicating on the same frequency channel. And last, the array must be able to adapt quickly to changes in the user's position and shifting reflections. That is where adaptive antenna arrays come in.

The Cocktail Party Effect

WHAT MAKES THE ADAPTIVE ARRAY so smart? The key step is processing the information received by its antennas. A good analogy is the way the brain processes acoustic information from the ears. A person with normal hearing can usually locate the source of a sound even with his or her eyes closed. The convoluted folds of the outer ear produce differing resonances depending on the angle of the incoming sound. And unless the sound is coming from directly ahead or behind (or directly above or below), it reaches one ear before the other, so there is a time lag between the two signals. The brain receives this information and rapidly computes the location of the source.

What is more, people with normal hearing can pick up relatively quiet sounds—say, an interesting conversation—amid loud background noise. This phenomenon is commonly known as the cocktail party effect. Researchers have shown that the ability to focus on a specific sound partly depends on the ability to locate the sound's source. In an experiment that tested how well people can hear a signal while being blasted with background noise, subjects listening with both ears were able to detect much softer sounds than subjects listening with only one ear. Once the brain has determined the position of the acoustic source, it can focus on the sound and tune out unwanted noise coming from other directions.

Similarly, an adaptive antenna array can pinpoint the source of a radio signal and selectively amplify it while canceling out competing signals. The array's brain is a digital processor that can manipulate the signals coming down the wires from the antennas. A typical adaptive array contains four to 12 antennas, but for simplicity's sake let us consider an array of two antennas, separated by a distance equal to half the wavelength of the radio signal. In an ordinary array the signals from the two antennas are just added together, but in an adaptive array the signals are sent to the adjoining processor, which can perform any number of mathematical operations on them.

For example, suppose that the array is aligned north to south and a signal from a cell-phone user comes in from the east [*see top illustration on next page*]. The processor can quickly determine the direction of the signal: because the radio waves reach both antennas at the same time, they must be coming from a direction perpendicular to the array. To maximize reception, the processor adds the signals together, doubling their intensity. When transmitting back to the user, the array emits identical signals from both antennas.

But now suppose that another cell-phone user sends a signal from the south [*see middle illustration on next page*]. Because the radio waves hitting the north antenna are 180 degrees out of phase from the waves striking the south antenna, the processor can tell that the signal is coming from a direction parallel to the array. So the processor now *subtracts* one signal from the other—that is, it inverts the signal from the north (or south) antenna, turning wave peaks into wave troughs and vice versa, and adds this mirror image to the signal from the south (or north) antenna. Again, the signal's intensity is doubled. And when the array transmits back to the cell-phone user, the processor sends an out-of-phase signal to one of the antennas, generating a radio beam that runs from north to south.

Notice that in both these examples the radio beam generated for one cell-phone user does not reach the other. The two users could be communicating with the adaptive array at the same time and on the same frequency channel, but their signals would not interfere with each other. The array's processor can create radio beams pointing in other directions as well by performing more complex mathematical operations on the signals from the two antennas. The task of selective transmission and reception is thus reduced to solving a series of simultaneous equations. To direct beams at users who are moving around, the processor must repeatedly solve the equations with constantly updated information from the antenna array.

Adding more antennas to the adaptive array increases the locating precision and the gain of the signal [*see bottom illustration on next page*]. An array with 12 antennas can hear signals a dozen times as faint as those that can be heard by a single antenna. The array can also transmit 12 times as loudly and much more directly. And the processor can juggle the antenna signals to create beam patterns that ensure the greatest possible gain for a desired signal and the greatest possible rejection for other signals on the same frequency.

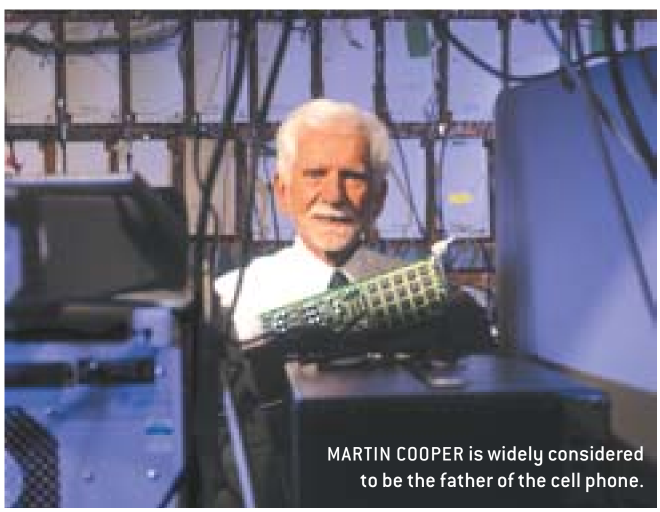
Because the processor is fast enough to perform this task many times a second, the array can continually readjust the radio beam as the cell-phone user walks or drives across the array's coverage area. The system is designed so that stray reflections of the user's signal against vehicles or buildings do not trigger abrupt changes in the direction of the beam. By tracking the user's route, the array can estimate the likelihood of future movements and discard erroneous information indicating sudden leaps in position.

Furthermore, the most advanced adaptive arrays can take advantage of the multipath phenomenon to focus radio signals still further. The processors in these arrays are so powerful that they can handle information from all the reflected signals that bounce along various routes between the cell phone and the adaptive array. By including the multipath reflections in the mathematical equations, the processor can extrapolate not only the direction of the signal but also the exact position of the user's cell phone. In an urban environment where there are nu-

An adaptive array can pinpoint the source of a radio signal and selectively amplify it.

THE AUTHOR

MARTIN COOPER is perhaps most famous for leading the development of the portable cellular phone. On April 3, 1973, Cooper—then a 44-year-old vice president and division manager at Motorola—used a prototype cellular system to call a rival at AT&T Bell Labs from a street corner in Manhattan. Ten years later Motorola introduced the first commercial cell phone, the DynaTAC 8000X, which weighed nearly two pounds and cost $3,995. During 29 years with Motorola, Cooper built and managed both its paging and cellular businesses and served as corporate director of research and development. After leaving Motorola in 1983, Cooper co-founded Cellular Business Systems, which became the dominant firm in the cellular billing industry before the company was sold to Cincinnati Bell. In 1992 he co-founded ArrayComm in San Jose, Calif., now the world leader in smart-antenna technology. Cooper holds bachelor's and master's degrees in electrical engineering from the Illinois Institute of Technology.



MARTIN COOPER is widely considered to be the father of the cell phone.

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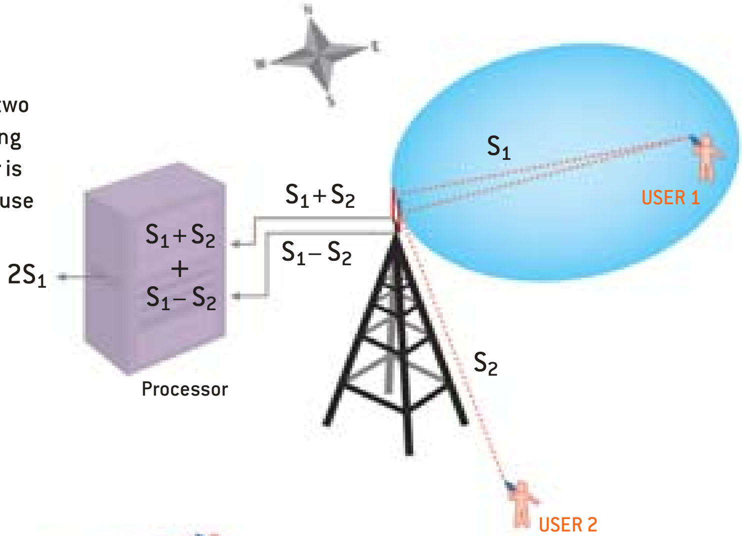
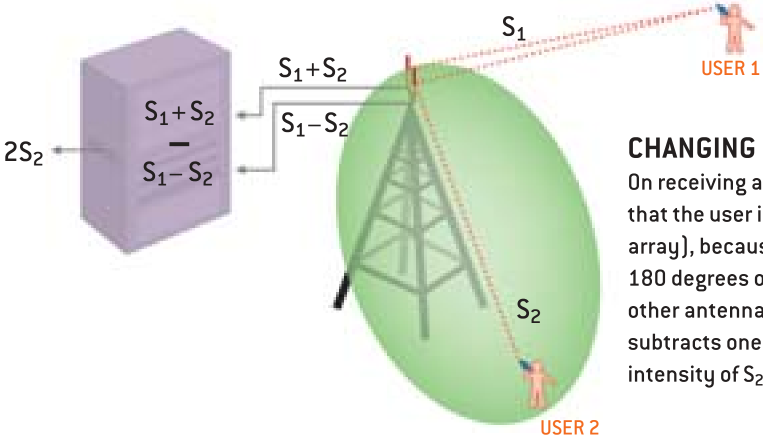
ADAPTIVE ANTENNA ARRAYS

THE SMARTEST ANTENNAS employ digital processors to manipulate incoming and outgoing signals. Called adaptive antenna arrays, these systems enhance reception from and transmission to one user while minimizing interference from others.

POINTING THE BEAM

The simplest example of an adaptive array contains two antennas spaced half a wavelength apart. On receiving a call from user 1, the array determines that the user is standing due east (perpendicular to the array), because the signal (S_1) arrives at both antennas at the same time. For user 1, the processor adds the signals from the two antennas to maximize the intensity of S_1 and to eliminate interference from user 2.



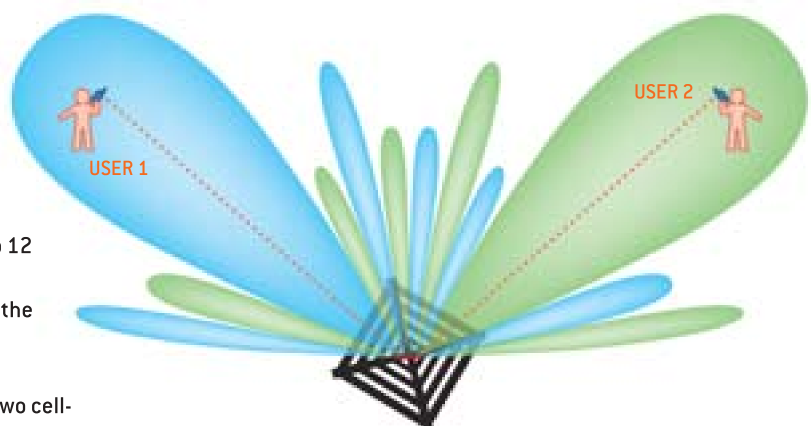


CHANGING DIRECTION

On receiving a call from user 2, the processor determines that the user is standing due south (aligned with the array), because the signal arriving at one antenna (S_2) is 180 degrees out of phase from the signal arriving at the other antenna ($-S_2$). For user 2, the processor therefore subtracts one signal from the other, maximizing the intensity of S_2 and eliminating the signal from user 1.

TWO CALLERS AT ONCE

In practice, an adaptive array contains four to 12 antennas. The processor performs complex mathematical operations on the signals from the antennas to ensure that the beam and lobes generated for user 1 (*blue*) do not overlap the pattern created for user 2 (*green*). Thus, the two cell-phone users do not interfere with each other even if they communicate on the same frequency.



Aerial view

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merous reflections, the adaptive array can receive from and transmit to a small area surrounding the phone. Instead of generating a radio beam, the array creates a "personal cell" that can be only centimeters in radius. And because the array is constantly recalculating the phone's position, this personal cell can follow the user as he or she moves about.

Benefits and Applications

WIRELESS NETWORKS THAT EMPLOY adaptive antenna arrays have several advantages over conventional cellular networks. Because a base station equipped with an adaptive array has a far greater range than an ordinary station transmitting at the same power, fewer stations are needed to cover a given area. Although adaptive arrays may be more expensive than traditional antennas, reducing the number of base stations dramatically cuts the overall cost of deploying and operating a wireless network.

All told, adaptive arrays provide cellular-phone service to more than 15 million people.

Adaptive arrays also enable a cellular service company to make better use of a scarce resource: the spectrum of frequencies allotted to the company for its radio signals. Many cellular systems are becoming overloaded with customers—in certain congested sectors, the barrage of signals sometimes exceeds the amount that can be carried on the limited number of radio channels. Customers feel the crunch when their calls are dropped or they hear poor-quality signals. But because adaptive arrays allow several cell-phone users within a base station's coverage area to share the same radio channel, the technology increases the capacity of the spectrum. The improvement over ordinary antennas is significant: base stations outfitted with adaptive arrays can serve about six times as many people for voice communications and up to 40 times as many for data transmission. The result is better service and less interference, not to mention less wasted energy and radio pollution.

It is not surprising, then, that adaptive antenna arrays are already in commercial use. Arrays using technology created by ArrayComm have been mounted on more than 150,000 cellular base stations in Japan, China, Thailand and other countries in Asia and Africa. All told, the arrays provide phone service to more than 15 million people. Commercial adoption has been slower in the U.S. and Europe, partly because the telecommunications industry's economic slump has curtailed new investment in cellular networks. But one U.S. manufacturer, Airnet in Melbourne, Fla., is currently making cellular base stations that employ ArrayComm's technology. And Marconi, a British telecommunications company, is developing an advanced base station that will contain adaptive arrays.

Adaptive arrays are also a boon to wireless data networks. Because the arrays minimize interference, they can receive and transmit more data to users in a given chunk of frequency spectrum. A base station equipped with an adaptive array could deliver data to as many as 40 concurrent users at a rate of one megabit a second, which is about 20 times as fast as the typical data rate for existing long-range wireless networks. Because all the users in such a network do not usually require peak data rates at the same time, one station with an adaptive array could serve several thousand people. Users with laptops or other portable devices would be able to get uninterrupted high-speed access to the Internet while walking or driving across the coverage area.

Since the late 1990s the telecommunications industry has been heralding the advent of the wireless Internet [see "The Wireless Web: Special Report"; SCIENTIFIC AMERICAN, October 2000]. The new networks have been developing more slowly than originally predicted, but work is nonetheless progressing. As wireless carriers continue to pursue 3G networks—next-generation cellular systems that transmit data in packets—other companies are offering a variety of competing solutions for high-speed data transmission. Smart antennas have been incorporated into some of these solutions and can be put to use in existing networks as well. A data network based on ArrayComm's technology is now operating in Sydney, Australia, and similar networks may soon be built in the U.S. and South Korea. Adaptive arrays developed by Navini Networks in Richardson, Tex., are also being tested by wireless carriers. Several major manufacturers of telecommunications equipment plan to incorporate smart-antenna technology into their next generation of products.

For almost 100 years after Alexander Graham Bell invented the telephone, voice communications relied on a physical connection—a copper wire or a coaxial cable—between the caller and the network. Over the past 30 years, though, cellular phones have given us a taste of the freedom to communicate without wires. With the help of adaptive-array technology, wireless carriers will be able to offer far better performance, at a much lower cost, than wired networks do. Only then will we rid ourselves of the copper cage. SA

MORE TO EXPLORE

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More information about smart antennas can be found at **www.arraycomm.com/Company/white_papers.html**