more than 100 years ago. Like a megaphone, it directs electromagnetic energy in a concentrated beam, thereby increasing gain without requiring more transmitting or receiving power. By mounting our antennas on rotatable robotic platforms, we could point the beams in any direction.

Such beam steering will be a key component of future millimeter-wave mobile systems, on both the base station and handset ends of the network. In the real world, as opposed to our experimental setup, mobile equipment such as smartphones and tablets will require electrically steerable antenna arrays that are much smaller and a lot more sophisticated than the ones we used for our tests. More on that later.

Packing in Patches: Samsung engineers are working to fit arrays of 28-gigahertz patch antennas into phones like the Galaxy Note II, pictured above. PHOTO: SAMSUNG

In total, we sampled over 700 different combinations of transmitter-receiver positions using frequencies around 38 GHz. This spectrum band is a good candidate for cellular systems because it has already been designated for commercial use in many parts of the world but so far is only lightly occupied.

To the great surprise of our mobile-industry colleagues, we found that this millimeter-wave spectrum can provide remarkably good coverage. Our millimeter-wave spectrum can provide remarkably good coverage. Our measurements showed, for instance, that a handset doesn't need a line-of-sight path to link with a base station. The highly reflective nature of these waves turns out to be an advantage rather than a weakness. As they bounce off solid materials such as buildings, signs, and people, the waves disperse throughout the environment, increasing the chance that a receiver will pick up a signal—provided it and the transmitter are pointed in the proper directions.

Of course, as with any wireless system, the likelihood of losing a connection increases as the receiver moves away from the transmitter. We have observed that for millimeter-wave signals transmitted at low power, outages start occurring at around 200 meters. This limited range may have been a problem for earlier generations of cellular systems, in which a typical cell radius extended up to several kilometers. But in the past decade or so, operators have had to significantly shrink cell sizes in order to expand capacity. In especially dense urban centers, such as downtown Seoul, South Korea, they have begun deploying small cells—compact base stations that fit on lampposts or bus-station kiosks—with ranges no larger than about 100 meters.

And there's another reason small cells may be ideal for millimeter-wave communications. It's well known that rain and air can attenuate millimeter waves over large distances, causing them to lose energy more quickly than the longer, ultrahigh frequencies used today. But previous research has shown that over relatively short ranges of a few hundred meters, these natural elements have little effect on most millimeter-wave frequencies, although there are a few exceptions.

To bolster our measurement data, we took our channel-sounding system to New York City, one of the most challenging radio environments in the world. There, in 2012 and 2013, we studied signal propagation at 28 and 73 GHz, two other commercially viable bands, and the results were nearly identical to our other commercially viable bands, and the results were nearly identical to our findings in Austin. Even on Manhattan's congested streets, our receivers could link with a transmitter 200 meters away about 85 percent of the time. By combining energy from multiple signal paths, more advanced antennas could extend the coverage range beyond 300 meters.

A New Spectrum Frontier

FUTURE 5G MOBILE NETWORKS COULD TAP VAST SPECTRUM RESERVES WITH MILLIMETER-WAVE DEVICES. HERE'S HOW THIS EMERGING TECHNOLOGY STACKS UP AGAINST TODAY'S CELLULAR SYSTEMS

We also tested how well these frequencies penetrate common building materials and found that although they pass through drywall and clear glass without losing much energy, they're almost completely blocked by brick, concrete, and heavily tinted glass. So while users might get some reception between rooms or through transparent windows, operators will typically need to install repeaters or wireless access points to bring signals indoors.

Encouraged by early measurements of millimeter-wave behavior in Austin, the other two of us (Roh and Cheun) and our colleagues at Samsung Electronics Co., in Suwon, South Korea, began building a prototype communication system for a commercial cellular network. In place of bulky, motorized horn antennas, we used arrays of rectangular metal plates called patch antennas. A big benefit of these antennas is their size, which as a rule of thumb must be at least half the wavelength of the signal frequency. Because we designed our prototype to work at 28 GHz (about 1 centimeter), each patch antenna could be very small—just 5 millimeters across, not quite the diameter of an aspirin tablet.

A single 28-GHz patch antenna wouldn't be of much use for cellular transmissions, because gain decreases as antenna size shrinks. But by arranging tens of these tiny panels in a grid pattern, we can magnify their collective energy without increasing transmission power. Such antenna arrays have long been used for radar and space communications, and many chipmakers, including Intel, Qualcomm, and Samsung, are now incorporating them into WiGig chip sets. Like a horn antenna or satellite dish, an array increases gain by focusing radio waves in a directional beam. But because the array creates this beam electronically, it can steer the beam quickly, allowing it to find and maintain a mobile connection.

An array that locks its beam on a moving target is called an adaptive, or smart, antenna array. It works like this: As each patch antenna in the array transmits (or receives) a signal, the waves interfere constructively to increase gain in one direction while canceling one another out in other directions. The larger the array, the narrower the beam. To steer this beam, the array varies the amplitude or phase (or both) of the signal at each patch antenna. In a mobile network, a transmitter and receiver would connect with each other by sweeping their beams rapidly, like a searchlight, until they found the path with the strongest signal. They would then sustain the link by evaluating the signal's characteristics, such as its direction of arrival, and redirecting their beams accordingly.

Photo: Marian Goldman/NYU **Big-Apple Bit Rate:** Students testing millimeter-wave transceivers in densely populated New York City found that high-frequency waves around the 28- and 73-gigahertz bands could be more useful for sending and receiving data than was once thought.

This beam forming and steering can be done in a couple of different ways. It can be done in the analog stage with electronic phase shifters or amplifiers, just before a signal is transmitted (or just after it's received). Or it can be done digitally, before the signal is converted into analog (or after it's digitized). There are pros and cons to both approaches. While digital beam forming offers better precision, it's also more complex—and hence more costly—because it requires separate computational modules and power-hungry digital-to-analog (or analog-to-digital) converters for each patch antenna. Analog beam forming, on the other hand, is simpler and cheaper, but because it uses fixed hardware, it is less flexible.

To get the best of both worlds, we've designed a hybrid architecture. We use phase shifters on the analog front end to form sharp, directional beams, which increase our antenna's communication range. And we use digital processing on increase our antenna's communication range. And we use digital processing on the back end to separately control different subsections of the array. The digital input lets us do more advanced tricks, such as aim separate beams at several handsets simultaneously or send multiple data streams to a single device, thereby increasing its download rate. Such spatial multiplexing techniques are known as multiple-input, multiple-output, or MIMO.

For example, in our 28-GHz prototype system, which Samsung announced in May 2013, we equipped each transmitter and receiver with a 64-antenna array about the size of a Post-it note. However, we divided this array digitally into two 32-antenna MIMO channels. Each channel used 500 MHz of spectrum and was capable of forming a 10-degree-wide beam. In a laboratory test, we used these independent beams to transmit nearly error-free data at more than 500 megabits per second to two mobile stations at once. In another test, we used both channels to connect with just one station, achieving a data rate of more than 1 Gb/s. For comparison, a typical data rate with a 4G LTE connection in New York City averages around 10 Mb/s and in theory can be as high as 50 Mb/s.

When we took our prototype outdoors in Suwon, a city near Seoul, we showed that it could maintain similar data rates even when we moved the mobile stations in random directions at up to 8 kilometers per hour—about the speed of a fast jog. We also tested the system's range using transmission power comparable to that of current 4G LTE networks. Even in non-line-of-sight conditions, we found that a mobile receiver could reliably connect with a transmitter up to almost 300 meters away, which supports the measurement results from Austin and New York City. When the stations were in sight of one another, their range was expanded to almost 2 km. We believe that even longer distances are possible, but our experimental license didn't allow us to test them.

Remember, too, that this prototype was just a proof-of-concept system. By using wider bandwidths, narrower beams, or more MIMO channels, real-world networks could achieve even higher data rates and larger coverage ranges. For instance, computer simulations of imagined small-cell networks using three-dimensional city models suggest that operators could reasonably provide data rates upwards of several gigabits per second.

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Photo: Marian Goldman/NYU **Incredible Shrinking Cell:** As small, short-range cells that cover distances of just a few hundred meters become more popular in urban areas, they could make millimeter-wave communications, like those being tested by New York University students here, more feasible.

One important limitation, though, will be the space available in handsets and base stations for these sophisticated antenna arrays. At Samsung, we've begun exploring arrangements of 28-GHz patch antennas in the Galaxy Note II. So far we've found that it's possible to fit as many as 32 of these little radiators around the smartphone's top and bottom edges while still providing 360 degrees of coverage. We expect future millimeter-wave base stations to be able to house 100 or more antennas.

These hardware experiments, and the measurement campaigns in Austin and New York City, have convinced us that millimeter-wave cellular communication will be not just feasible but revolutionary. The work of both our groups, however, is only the beginning. Engineering full-scale millimeter-wave networks will require robust statistical models of millimeter-wave channels, streamlined beam-forming algorithms, and new power-efficient air-interface standards, among many other design challenges. Government regulators will also have to take the initiative in making millimeter-wave spectrum available for cellular services.

Meanwhile, as industry groups worldwide begin considering candidates for 5G technologies, including schemes for better interference management and dense small-cell architectures, they're recognizing that millimeter-wave systems will be a key part of this mix. By 2020, when the first commercial 5G networks will likely start rolling out, millimeter-wave bands will no longer be regarded as the abandoned backwoods lots of radio real estate. They'll be the most fashionable destinations of all.

This article originally appeared in print as "Mobile's Millimeter-wave Makeover."

About the Authors

Theodore S. Rappaport is the founding director of New York University's wireless research center. With coauthors Wonil Roh and Kyungwhoon Cheun, vice presidents at Samsung Electronics, he is helping to realize future 5G networks. "I haven't been this excited about cellular technology since I got my Ph.D. in 1987, when the industry was just getting started," Rappaport says.