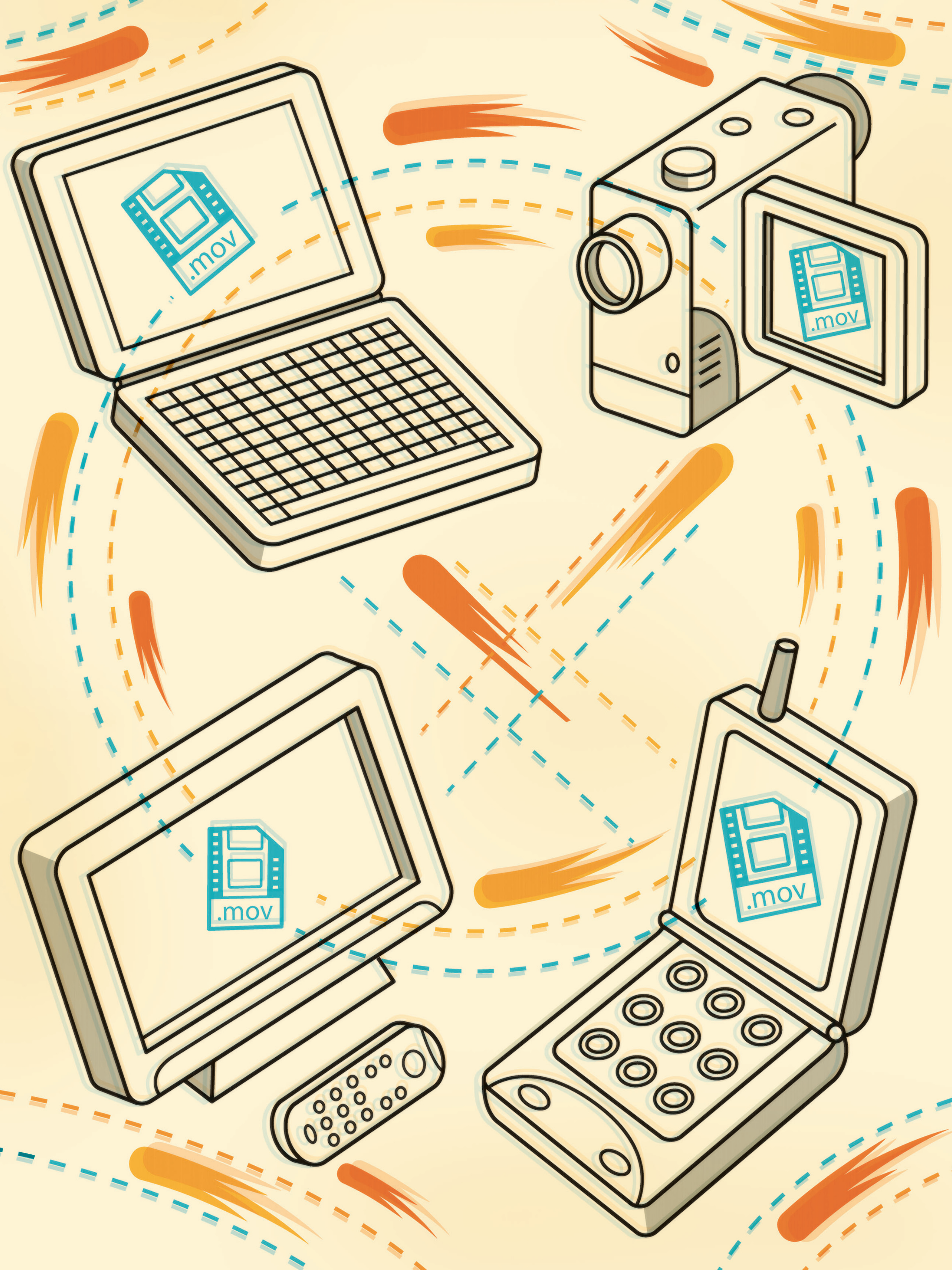
Gadgets Gab at 60 GHz

Cheap silicon transceivers broadcasting in this still-unlicensed band may usher in the hi-def wireless home

By Behzad Razavi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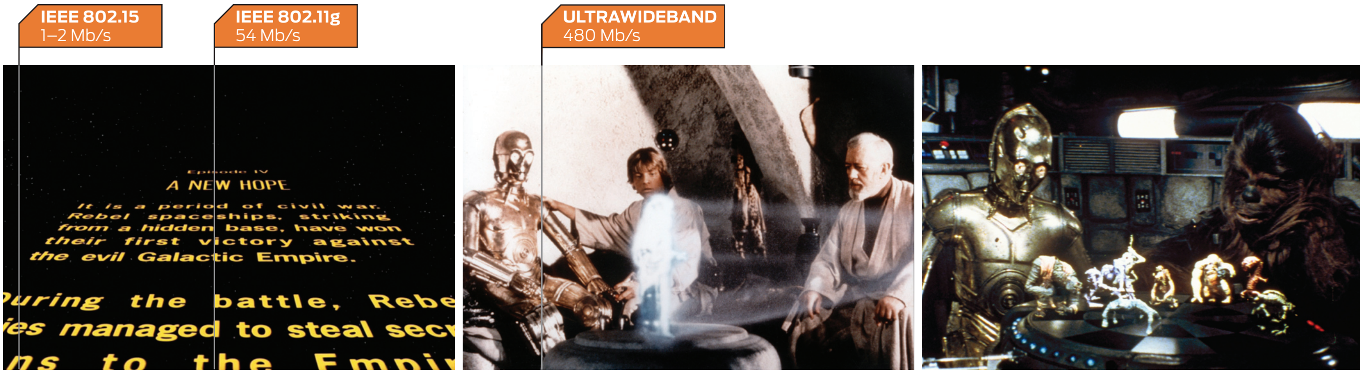


MAY THE POWER BE WITH YOU: A useful measuring stick for wireless transmission may be found in *Star Wars: Episode IV* (1977), the first in the *Star Wars* series. The six frames shown above are taken at equal time intervals from the movie's beginning to its end and are marked to show the portion that could be downloaded in the space of 2 minutes. Bluetooth (IEEE 802.15), at 2 megabits per second, would get a few seconds of the movie; the IEEE 802.11g standard would make it to the middle of the introductory narrative; and ultrawideband would get about a tenth of the way into the movie. Meanwhile, IEEE 802.15.3—the proposed standard for 60 GHz—would make it all the way to the final credit [far right]. PHOTOS: LUCASFILM/20TH CENTURY FOX/THE KOBAL COLLECTION

People not only talk on the airwaves, they increasingly expect their gadgets to do the same. The trend began in the late 1990s with Bluetooth, which provided 1 megabit of data per second. Then Wi-Fi and the IEEE 802.11 standard pushed the rate to 100 Mb/s. Now ultrawideband systems are going five times as fast as that.

In principle, such radio links, operating over short ranges, could replace the cables that now clutter our homes and offices, eliminate the speed penalty of going wireless, and even allow portable devices to off-load computing work to a nearby base station. The devices could thus shed hardware to become smaller, lighter, and cheaper.

But it won't happen until engineers lay their hands on more bandwidth. The various 2.4- and 5.8-gigahertz systems now in common use are rapidly running out of spectrum, and the inflexible 100-microwatt constraint on ultrawideband power will likely limit it to about 1 gigabit per second. Where do we go next?

Clearly, we must look upward, but just how far up isn't so obvious. One tempting thought is to use *really* high frequencies—infrared light. Although that tactic works fine if all you want to do is switch TV channels with your remote or operate a wireless mouse, it turns out that it's hard to modulate the output of infrared light-emitting diodes fast enough for more demanding applications. So for the moment anyway, RF makes more sense, and the best prospects to be found there reside in 7 GHz of unlicensed spectrum near 60 GHz. Those frequencies are 10 times as high as anything in common use today, and with the bandwidth they provide they can carry a lot more data. Until now, engineers designing products for the consumer market have shied away from 60 GHz because of various technical difficulties, but bandwidth hunger is finally awakening their interest.

Developments in chip design have also played a part. Today's 60-GHz technology depends on relatively expensive and power-hungry gallium-arsenide semiconductors, but various researchers—including engineers at IBM, the University of California, Berkeley, and those in my group at University of California, Los Angeles—have shown that silicon chips can do the job with much less power and at a fraction of the cost. The silicon option is what makes 60-GHz communications attractive.

The allure is so strong that a special task force is now working on an extension of the IEEE 802.15.3 standard for wireless personal area networks in

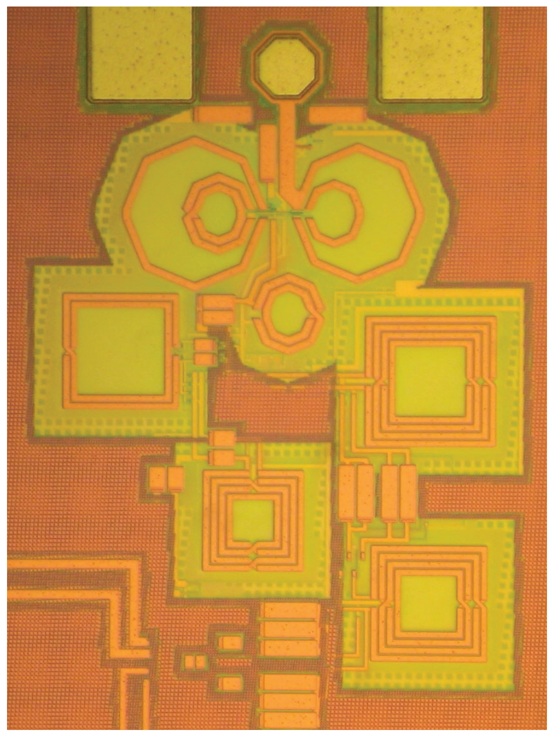
ILLUSTRATION ON PREVIOUS PAGE: HARRY CAMPBELL

IEEE 802.15.3
2–4 Gb/s

the 57- to 64-GHz band, and in 2006 a number of companies—including Matsushita, NEC, and Sony—came together to define a specification for transmitting high-definition video in this slice of the radio spectrum. Their group, called Wireless HD, of Sunnyvale, Calif., wants to link TV sets to disc players, video cameras, game consoles, laptops, and other devices at rates as high as 5 Gb/s—fast enough to transmit an HD feature movie in about a minute [see "May the Power Be With You"].

There are other advantages besides extra bandwidth and faster data rates. Because the wavelengths are so short, the antenna needn't be much bigger than the head of a pin, small enough to go on the transceiver chip. Indeed, it is feasible to integrate many antennas and transceivers into a single chip so that together they can, with proper phasing, form a beam to steer transmissions in a particular direction [see illustration, "Adaptive Antennas"]. Such phased-array antennas can also be used to boost reception. These operations can be conducted automatically so that the sender and the receiver can find each other without human intervention, constituting an adaptive-array (or "smart") antenna system.

The integration of the antenna avoids the need for wires to carry signals to and from the chip, reducing the cost of packaging by one to two orders of magnitude. Further, the absence of exposed inputs and outputs makes the transceiver less vulnerable to electrostatic discharge during fabrication and assembly. Manufacturers could thus dispense with antistatic devices, which add capacitance and degrade performance.



DESIGN TRICKS allow transceivers to accommodate bulky components—for instance, by nesting square and octagonal induction coils one inside the other.
PHOTO: BEHZAD RAZAVI/UCLA

THESE BENEFITS do not come for free, however. Communication at 60 GHz involves significant challenges at the system, circuit, and device levels—challenges that account for why this bandwidth has lain fallow for so long. Designers can, however, get around these obstacles by taking advantage of the capabilities available at one level to relax the requirements imposed at another.

The difficulties begin with the propagation of the 60-GHz wave itself. As with any electromagnetic signal, the number of watts passing through each square meter diminishes in proportion to the square of the distance from the transmitter. On top of that, the size of the antenna scales with the wavelength, so its effective area—and so the power it can capture—varies in direct proportion to the square of the wavelength (and therefore in inverse proportion to the square of the frequency). Hence a signal broadcast at 60 GHz will convey to the typical receiving antenna just 1 percent as much power as it would have done had it been broadcast at 6 GHz. Making matters worse, 60-GHz rays are blocked by solid objects.

Some possible solutions are to transmit at very high power and to use adaptive-array antennas to send signals to their target by indirect routes, through reflection and refraction. It's better, though, to rely on lots of transceivers. If enough were strewn through an office—and even worn by the people who work there—any two devices would always be able to talk to each other directly or through a third node.

For this strategy to work, a transceiver must be made cheap enough, small *Continued on p. 56*

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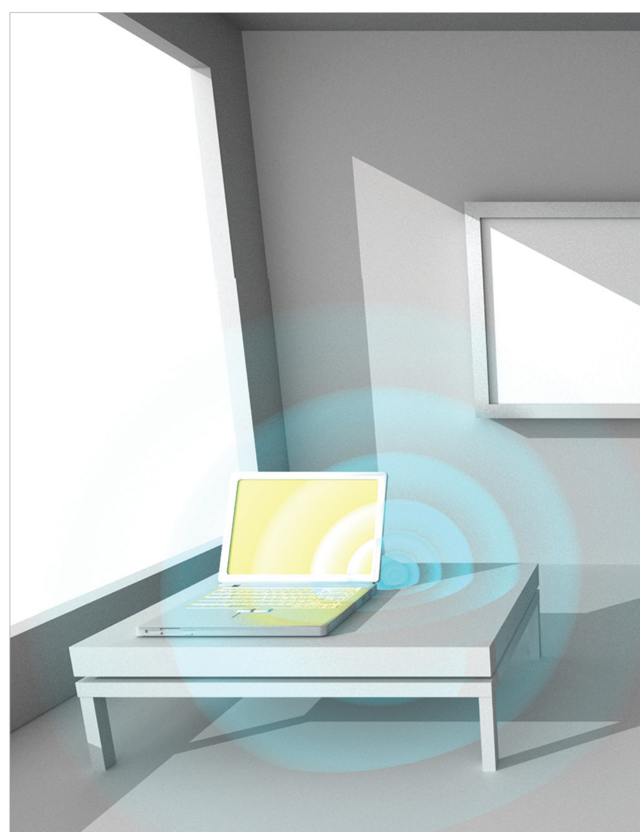
enough, and frugal enough to run a long time on a small battery. These requirements are complicated by the 10-fold speedup in operating frequency. (Transistors have gotten faster, but not that much faster.) A major design overhaul will thus be needed. What's more, the connections between transistors have resistance, capacitance, and inductance, which tend to sap performance at these frequencies. And the high-speed, high-resolution, analog-to-digital and digital-to-analog converters needed to process gigabit-per-second data rates are real energy hogs.

The seriousness of these issues depends on just which integrated-circuit technology is used. Bipolar transistors made of silicon-germanium offer high speeds, and this technology makes it possible to fabricate high-quality passive devices, such as inductors, right on the chip, simplifying design and boosting performance. IBM has reported making 60-GHz silicon-germanium transceivers that can shoot data at 1 Gb/s for as far as 8 meters. But with multiple transceivers, analog-to-digital and digital-to-analog converters, and ever more complex signal processing, the cost of silicon-germanium becomes prohibitive.

CMOS chips are much less expensive, but the lower speed of the transistors and poorer quality of the passive devices make designing the circuits exceedingly tough. Nonetheless, the history of the semiconductor industry is littered with examples of products that were first built with bipolar technologies but were soon replaced with CMOS counterparts, suggesting that 60-GHz CMOS chips will in the end win out.

DESIGNERS CLEARLY face high technical hurdles in fashioning CMOS circuits that can handle various RF-signal manipulations at 60 GHz. Many of these operations depend on heterodyning, in which the circuitry mixes two signals at different frequencies to produce an output that contains components at both the sum and the difference frequencies. A standard AM transmitter would, for example, multiply the relatively low-frequency audio signal to be broadcast (say, a 1-kilohertz tone) with the output of an oscillator running at a much higher



ADAPTIVE ANTENNAS can form a beam and direct it to a target, greatly reducing the attenuation of power, a serious problem in the 60-GHz band, which is strongly absorbed by air. In a conventional antenna [left], the received power declines with the square of the distance. Adaptive antennas [right] use an array of emitters with delayed phases that make the waves' peaks and troughs add constructively [insert]. This trick focuses the power into a beam, which can then be steered up (a) or down (b) electronically. Advances in 60-GHz transceiver design now make it possible to fit an adaptive array on a single chip.

ILLUSTRATION: BRYAN CHRISTIE DESIGN

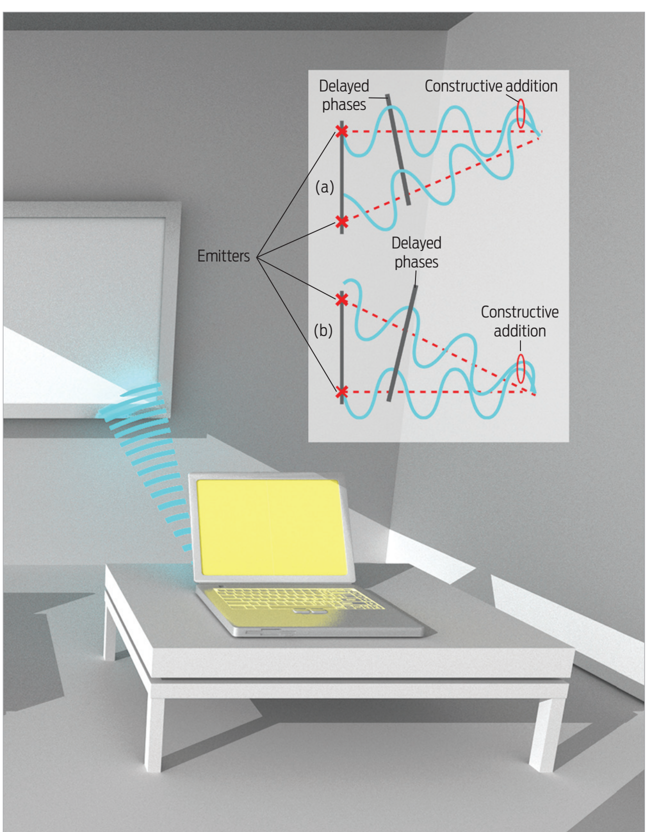
radio frequency (say, 1000 kHz). The sum and difference of these two frequencies (999 kHz and 1001 kHz) fall just slightly above and below that of the RF oscillator. That's why the original audio signal is said to be "up-converted" to RF. The receiver for such an AM broadcast would typically use a similar oscillator to "down-convert" the RF signal back to audio, using exactly the same heterodyning principle.

For high-speed data communications at 60 GHz, such operations can be a nightmare to implement. For one thing, the oscillator would have to produce two 60-GHz outputs that are exactly 90 degrees out of phase. This is because the final modulated signal is produced by combining a sine and cosine. The generation and routing of these two phases, while maintaining a 90-degree difference between them, is hard at 60 GHz.

Also, controlling the precise frequency of a 60-GHz oscillator is tricky because it's running too fast to measure directly, as crystal-controlled frequency standards are limited to about 100 megahertz. The 60-GHz signal must first be fed into a frequency-divider circuit that reduces the frequency by a large factor (say, 600). Only then can the output be compared with a frequency standard, which indicates whether the rate of oscillation is faster or slower than desired, so that it can be corrected accordingly. The tactic is simple enough, but the limits on transistor speed make it difficult to fashion such frequency-divider circuits that work at 60 GHz.

Fortunately, with a little cunning, you can make a receiver work using a 40-GHz oscillator instead. The first step is to mix the output of the 40-GHz oscillator with the 60-GHz received signal. That operation down-converts the signal to the difference frequency: 20 GHz. To down-convert the signal the rest of the way, the receiver circuitry need not incorporate a separate 20-GHz oscillator; it can simply use the output of a divide-by-two frequency divider attached to its 40-GHz oscillator. Because it operates on 40 GHz rather than 60 GHz, such a frequency divider is comparatively easy to implement. What's more, it is less vexing to route signals around a chip at 40 GHz than at 60 GHz. And happily enough for designers, the transmission path can follow the receiver operations in the reverse order to avoid 60-GHz oscillators and frequency dividers. That is, the data stream to be transmitted is first up-converted to 20 GHz and only then raised to 60 GHz.

Using 40 GHz for the oscillator frequency is just one way to dodge some of



the thorny problems posed by 60 GHz. The IBM transceiver takes a slightly different tack: it incorporates a 17-GHz oscillator followed by a frequency tripler to obtain 51 GHz, which is roughly 8.5 GHz below the target frequency. The 51 GHz thus can serve to down-convert the received signal to 8.5 GHz. And a divide-by-two frequency divider attached to the 17-GHz oscillator generates the 8.5 GHz needed for the second stage of down-conversion.

Although such designs avoid the need for a 60-GHz oscillator, they still require low-noise amplifiers and downconverters. These circuits typically use passive devices like inductors or transmission lines on the chip to overcome the speed limitations of the transistors. Alas, such passive components have large footprints, which normally forces them to be placed awkwardly far apart, their long interconnections creating lots of parasitic resistance, capacitance, and inductance. To alleviate this problem, designers can nest the inductor loops used to build these passive components so that the connections between them can be kept short [see illustration, "Design Tricks"].

THE ELECTRONIC DEVICES IN OUR HOMES AND OFFICES WILL BE CHATTERING FURIOUSLY AND WIRELESSLY IN ANOTHER FIVE TO 10 YEARS. CABLES WILL GO THE WAY OF THE BUGGY WHIP

A bigger concern is how to fabricate transmitter circuits that can deliver a lot of oomph to the antenna. For communication across a range of 10 meters at data rates of several gigabits per second, some tens of milliwatts are necessary. Performed by a power amplifier, the task requires large transistors, which are typically slow. The good news is that the upcoming generation of CMOS chips, which boast 45-nanometer gate lengths, may be up to the job of producing this much power at 60 GHz.

But that's not the whole story, because not all the power that goes into an on-chip antenna gets broadcast. The silicon substrate—just 10 micrometers below—absorbs (and hence wastes) some energy, so such antennas radiate only a fourth to a half of the power supplied to them.

Perhaps more research will lead to more energy-efficient antennas. Meanwhile, engineers can resort to off-chip antennas that operate at these tiny wavelengths. Another, cheaper, solution is to incorporate enough transmitters and on-chip antennas to compensate for the power lost to the silicon substrate. The future will tell whether we need to resort to this rather inefficient solution.

IT WILL take time for designers to master all this new technology, because the models that we use to simulate circuits can't easily handle 60 GHz. Today's transistor models are constructed as though all their capacitance and resistance came from small capacitors and resistors connected here and there. In reality, of course, the capacitance and resistance in these transistors are distributed over appreciable dimensions. So lumping things in this way fails to capture some important effects that manifest themselves most obviously at these high frequencies. Also, the electric and magnetic interactions between the passive devices and the silicon substrate are difficult to calculate from basic physical principles. For these reasons, modeling must rely on both the theoretical understanding of the behavior of the devices and on a large number of experimental measurements (which in turn can help refine the models).

The industry's vision is that we can solve these problems and that all the electronic devices in our homes and offices will be chattering furiously and wirelessly in another five to 10 years. Cables will go the way of the buggy whip. Now if the engineers at MIT can finally perfect their idea of using magnetically coupled resonators to charge batteries through the air, we'll eliminate those pesky power cords, too. Only then will we enter the *real* wireless age. ❑

TO PROBE FURTHER The IBM 60-GHz silicon-germanium transceiver is described in the Digest of Technical Papers *for the 2006 IEEE International Solid-State Circuits Conference (ISCC).*

Two CMOS transceivers for the 60-GHz band are described in the Digest of Technical Papers *for the 2007 ISCC.*

Detailed information concerning the IEEE 802.15.3 standard for the 60-GHz band is available at http://www.ieee802.org/15/pub/TG3c.html.