

## Tuning In to Graphene

*New ultra-fast wireless antennas may be on the way, but don't throw away your old wireless router just yet.*

**I**N MARCH OF this year, a team at the Georgia Institute of Technology made headlines when it revealed plans for a new microscopic antenna built out of graphene, a synthetic form of carbon with remarkable conductive properties.

Early press coverage focused on the promise of speedier wireless connections, and with good reason: such an antenna could, in principle, allow for terabit-per-second transfer speeds—fast enough to download a high-definition movie in a fraction of a second. At

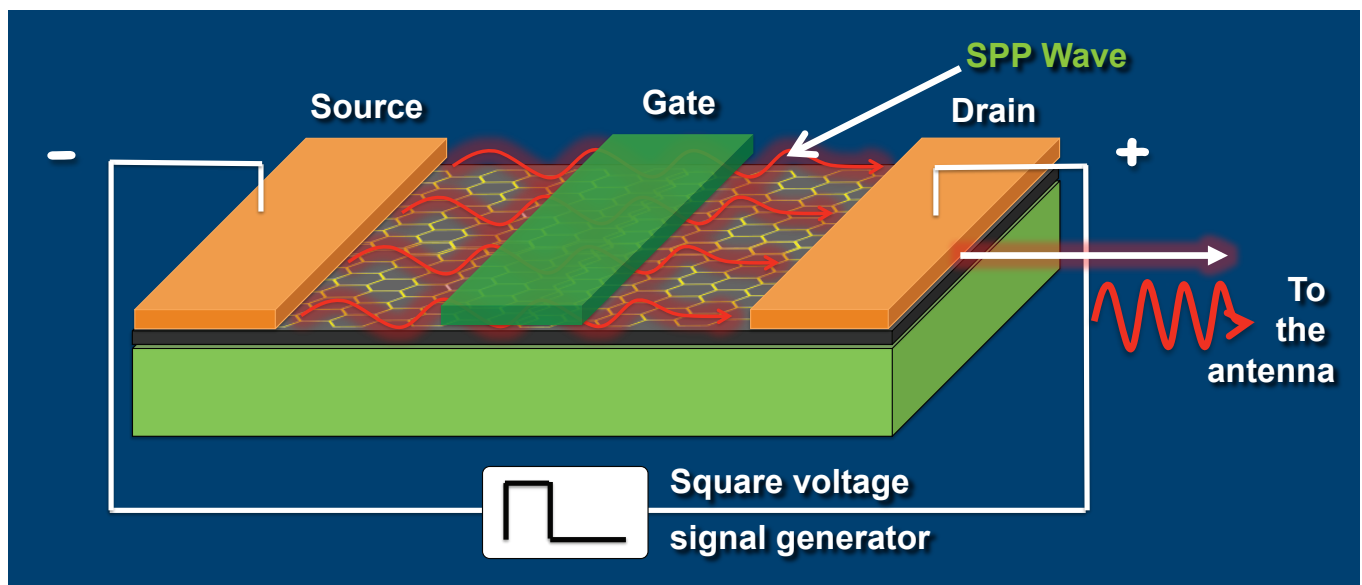
distances of a few centimeters, download speeds could approach an astonishing 100 terabits per second—the equivalent of three months' worth of HD footage.

While the prospect of faster downloads might come as welcome news to legions of everyday Web surfers, the technology's long-term potential extends well beyond the problem of easing Internet bottlenecks. Researchers are starting to explore a wide range of potential applications for graphene nano-antennas, such as linking the inter-

nal components of electronic devices or creating fine-tuned sensor networks capable of thwarting chemical or biological attacks.

Before any of those ideas can come to fruition, however, researchers will need to overcome a number of formidable hurdles—not least of which involves the prohibitive cost of making graphene in the first place.

In 2004, Andre Geim and Konstantin Novoselov of the University of Manchester invented graphene by taking strips of graphite (the same technology that pow-



The structure of a graphene-based plasmonic nano-transceiver for wireless communication in the terahertz band.

ers the humble Number 2 pencil) and attaching them to adhesive tape, then repeatedly separating the strips until they had isolated a one-atom thick layer of the substance they dubbed graphene.

Ever since that discovery—which earned Geim and Novoselov a Nobel Prize in 2011—graphene has generated a level of excitement in the materials engineering world not seen since the late-1990s boom in carbon nanotubes.

Some might argue that carbon nanotubes offer a cautionary tale: a much-hyped new material that failed to live up to its initial promise. Graphene's real-world prospects remain uncertain, given its current manufacturing cost of \$3,000 per square meter, but its promoters hold out hope that researchers will address that challenge in the years to come.

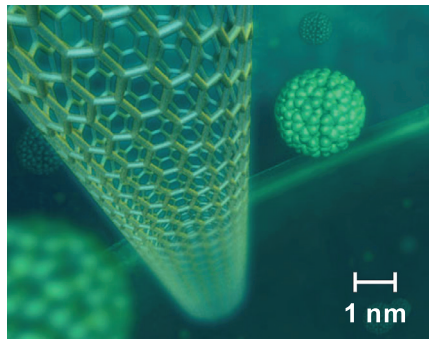
Several major university research initiatives are now under way to explore new techniques for working with graphene, some of them supported by a major research funding initiative from the European Union. Meanwhile, companies like IBM, Intel, and Samsung are moving quickly to perfect new techniques for synthesizing the material.

This flurry of activity stems from graphene's seemingly incredible promise. It is exactly one atom thick—as close to a two-dimensional material as possible. It is also nearly transparent, and flexible enough to take almost any form, yet it is also extremely dense—harder than steel or diamond.

That remarkable combination of lightness, flexibility, and strength has prompted scientists to envision any number of potential manufacturing uses, including ocean liners, airplanes, automobiles, washing machines, transparent touch screens, and new kinds of solar cells.

Beyond its remarkable structural properties, graphene also boasts a perfect honeycomb structure that allows electrons to move with almost no resistance, up to 500 times faster than in silicon. That level of conductivity makes it ideally suited for building transistors, processors, memory, cell-phones—or antennas.

Like carbon nanotubes, graphene features plasmons (electron oscillations) in one-dimensional structures that support the transmission of sur-



Nanomaterials enable new technologies.

face waves at frequencies in the terahertz band (0.1THz–10THz). Many other materials, like fibers and plastics, are transparent at these frequencies, but graphene's dense structure allows it to propagate these signals quite effectively.

The Georgia Tech team, led by Ian Akyildiz, has proposed making an antenna out of graphene by creating pieces of graphene that are between 2 and 100 nanometers wide and one micrometer long, each capable of detecting electromagnetic waves in the terahertz frequency band. By using ultra-thin graphene nanoribbons instead of relatively larger graphene sheets, the team has found they can enhance the propagation of surface plasmon polariton waves, thus improving performance. The team's results will appear in a forthcoming issue of *IEEE's Journal on Selected Areas in Communication*.

Such antennas would be small enough to fit inside any number of microelectronic components. By stitch-

**Graphene is just one atom thick, nearly transparent, and flexible enough to take almost any form, yet it is also extremely dense—harder than steel or diamond.**

ing together multiple components in this way, the nano-antennas could create an entirely new kind of nanonetwork in which devices communicate directly with each other.

In addition to providing a way to link all kinds of devices directly to each other and to the Internet, commercial graphene nano-antennas could also enable new kinds of access networks for 5G systems and small cell-enabled cellular network architectures for beyond 4G (B4G) networks.

Communicating over the terahertz band would also allow for higher bandwidth than conventional microwave or gigahertz bands. Those performance gains come at a price, however; graphene nano-antennas work best at ranges of less than one meter.

“The advantage of the terahertz band is the gigantic capacity,” says Akyildiz. “The disadvantage is that they are distance-limited, because it is so fine-grained that the water particles and gas molecules in the air affect the signal propagation. Gas molecules are the biggest enemy.”

Given these limitations, most research is currently focused on applications that involve communicating over short distances. That line of research has been evolving for several years, since well before the invention of graphene.

Peter J. Burke of the University of California, Irvine, conducted some of the foundational work on nanoantennas, developing the first RF circuit model for carbon nanotubes. Based on that early work, his team began to contemplate the possibility of nanoscale antennas, developing the first theoretical models of a carbon nanotube antenna, predicting—correctly—that they would work well at terahertz frequencies.

Burke's team has since moved on to working with graphene, in part because graphene holds a major advantage over carbon nanotubes: the ability to tune its conducting properties.

“Graphene is interesting mainly because it enables very efficient dynamic control of the antenna's parameter at terahertz frequencies,” says Julien Perruisseau-Carrier of the École Polytechnique Fédérale de Lausanne in Switzerland, whose team performed important early work on graphene an-

tennas, in particular analyzing the possibilities of dynamic reconfiguration across a wide range of frequencies.

Such reconfigurability could allow graphene antennas to save power and limit interference, as well as perform highly targeted sensing.

“We are very excited because we can tune the electrical antenna properties of graphene with a DC voltage,” says Burke. By changing the sheet resistance, his team has been able to lift the impedance of a graphene nanoantenna—something not possible with other kinds of nano-antennas.

In a recent paper, Burke’s team proved that graphene could function over a broad frequency range—at DC, 10GHz, 100GHz, and 100GHz–1.5THz in a single sweep. The team was able to measure the graphene sheet’s impedance with a novel spectrometer built by Elliott Brown at Wright State University in Ohio. Recently, the team has built on this work to tune the graphene antenna across the entire band from 100GHz to 1.5THz.

Given these physical limitations, researchers are focusing on scenarios that would benefit from placing nano-antennas and transmitters in close proximity to each other, to create what Akyildiz describes as “an Internet of nano-things.”

At the most pedestrian level, such a network could offer hope of speeding up the “last mile” bottleneck that bedevils so many everyday Internet connections: the humble wireless router. For all the much-heralded advances in network speeds over the past few years—FIOS, Terabit Internet, and IPv4, to name a few—many of us have yet to see the full promise of these advances, thanks to the speed limits inherent in the 802.11n standard that most wireless routers follow.

A full-fledged nanonetwork could go much further than replacing old Wi-Fi routers, however. It could also, in theory, harvest vibrational or electromagnetic energy from the environment to reduce power consumption.

Looking further ahead, researchers are also starting to imagine long-range applications of highly miniaturized antennas. “Imagine what you could do if you could build a radio that could fit inside of a single cell?” asks Burke, whose team is now exploring the pos-

sibility of graphene nanoantennas that could bind to DNA.

Burke’s team is working with Ned Seeman at New York University and Michael Norton at Marshall University, both of whom have done extensive work with DNA “origami,” to explore the possibilities of nanoscale networks for DNA sensing. If successful, this initiative could bring graphene nanoantennas closer to the world of biochemistry.

As intriguing as some of these ideas may seem, the practical challenges remain daunting. At the most fundamental level, nanoantennas cannot work by themselves without additional components such as nanotransmitters and nanoreceivers—neither of which exist yet. Akyildiz’s team is currently applying for patents for graphene-based nanotransmitters and nanoreceivers.

In the meantime, several other teams around the world are pursuing related ideas for graphene-based antennas and related devices. While the early results are promising, the real work is just getting under way.

“We have one idea about nano-antennas, but there are other people with other ideas about nano-antennas,” says Akyildiz. “It is a race.” **■**

#### Further Reading

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# ACM Member News

## LOVE OF SOLVING PROBLEMS SPURS YELICK ON PROGRAMMING



A love of using computational solutions to solve problems is what inspired Katherine Yelick,

professor of computer science at the University of California, Berkeley (UC Berkeley), to help develop the Unified Parallel C (UPC) and Titanium programming languages. “I love designing programming languages to make computers, particularly supercomputers with parallelism, less expensive and easier to use,” Yelick says. Yelick and UC Berkeley Electrical Engineering and Computers Sciences chair David Culler co-invented UPC in 1996; the Titanium language soon followed. Yelick has demonstrated the languages’ applicability across architectures using novel runtime and compilation methods. She also co-developed techniques for self-tuning numerical libraries, including the first self-tuned library for sparse matrix kernels, which automatically adapts code to properties of the matrix structure and machine.

Yelick’s proudest accomplishment is the recognition of her work on Partitioned Global Address Space Languages (PGAS), which lets users read/write data anywhere in the system and incorporates partitioning for accelerated communication.

“Twenty years from now, I hope programming languages better hide complexity in supercomputers, and that it will be easier to write good programs,” Yelick says.

Meanwhile, Yelick is collaborating with her husband and UC Berkeley colleague Jim Demmel on a paper called “Communication-Avoiding Algorithms.” Says Yelick, “Avoiding communication is not the right model for marriage, but it is great for parallelism, where communication slows you down.”

—Laura DiDio is principal at ITIC, a Boston IT consultancy.