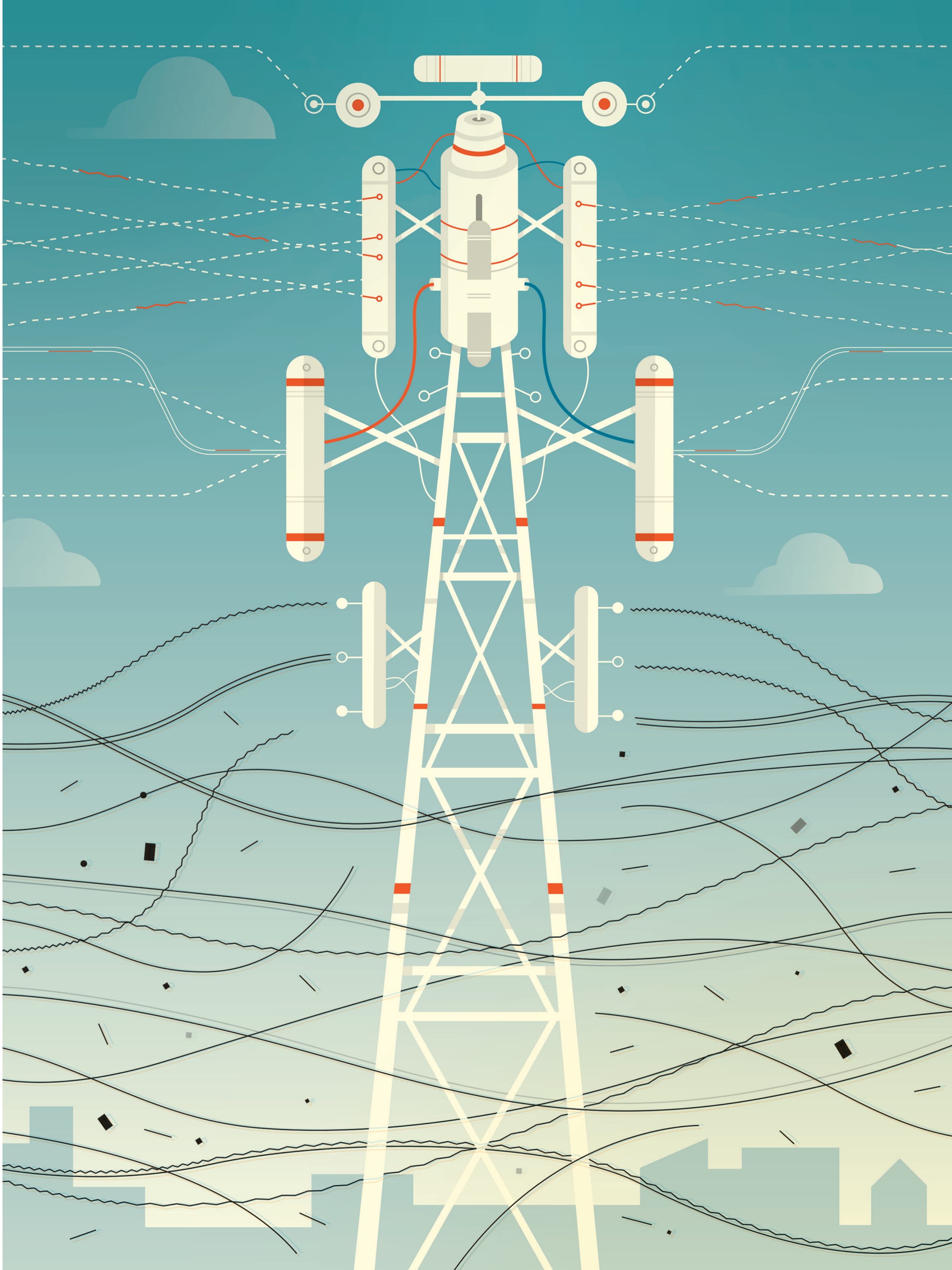
The Radio That Can Hear Over Itself

By **Joel Brand**

Self-interference cancellation allows radios to transmit and receive on the same frequency

ILLUSTRATION BY Harry Campbell



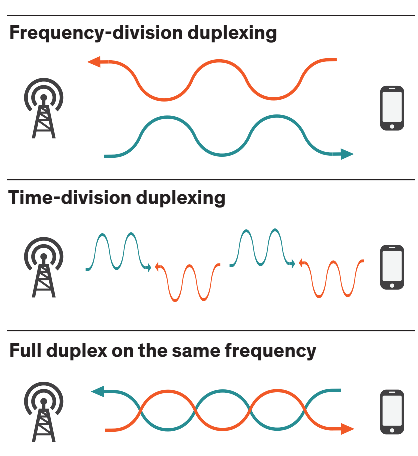
WIRELESS ISN'T ACTUALLY UBIQUITOUS. We've all seen the effects: Calls are dropped and Web pages sometimes take forever to load. One of the most fundamental reasons why such holes in our coverage occur is that wireless networks today are overwhelmingly configured as star networks. This means there's a centrally located piece of infrastructure, such as a cell tower or a router, that communicates with all of the mobile devices around it in a starburst pattern.

Ubiquitous wireless coverage will happen only when a different type of network, the mesh network, enhances these star networks. Unlike a star network, a mesh network consists of nodes that communicate with one another as well as end-user devices. With such a system, coverage holes in a wireless network can be filled by simply adding a node to carry the signal around the obstruction. A Wi-Fi signal, for example, can be strengthened in a portion of a building with poor reception by installing a node that communicates with the main router.

However, current wireless mesh-network designs have limitations. By far the biggest is that a node in a mesh network will interfere with itself as it relays data if it uses the same frequency to transmit and receive signals. So current designs send and receive on different frequency bands. But spectrum is a scarce resource, especially for the heavily trafficked frequencies used by cellular networks and Wi-Fi. It can be hard to justify devoting so much spectrum to filling in coverage holes when cell towers and Wi-Fi routers do a pretty good job of keeping people connected most of the time.

And yet, a breakthrough here could bring mesh networks into even the most demanding and spectrum-intensive networks, for example ones connecting assembly-floor robots, self-driving cars, or drone swarms. And indeed, such a breakthrough technology is now emerging: self-interference cancellation (SIC). As the name implies, SIC makes it possible for a mesh-network node to cancel out the interference it creates by transmitting and receiving on the same frequency. The technology literally doubles a node's spectral efficiency, by eliminating the need for separate transmit and receive frequencies.

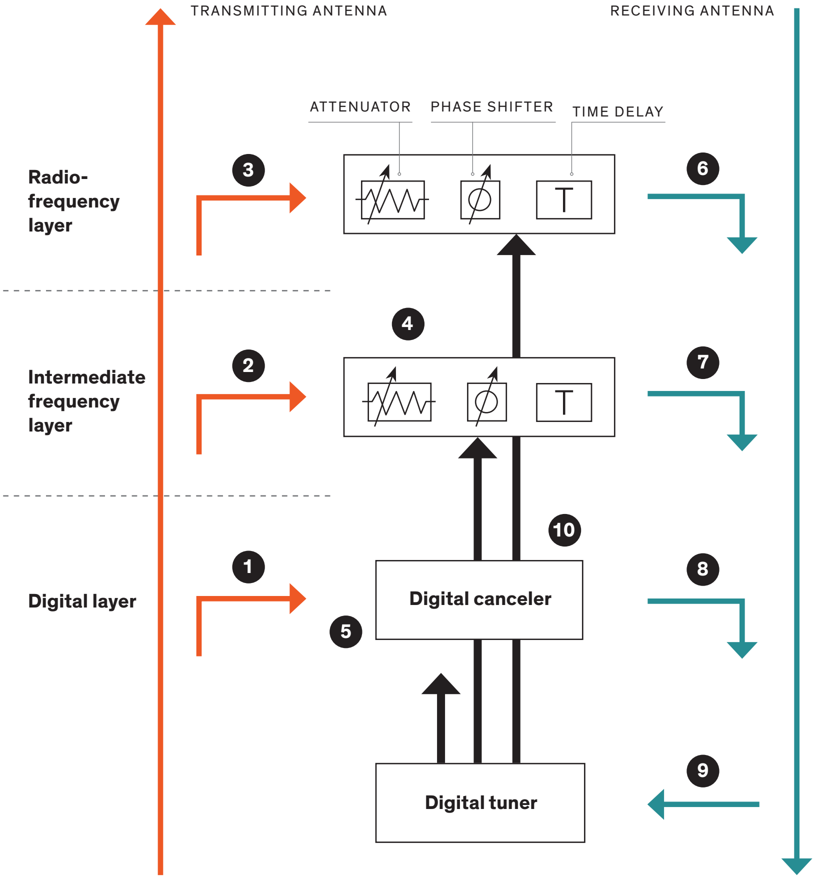
There are now tens of billions of wireless devices in the world. At least 5 billion of them are mobile phones, according to the GSM Association. The Wi-Fi Alliance reports more than 13 billion Wi-Fi equipped devices in use, and the Bluetooth Special Interest Group predicts that more than 7.5 billion Bluetooth devices will be shipped between 2020 and 2024. Now is the time to bring wireless mesh networks to the mainstream, as wireless capability is built in to more products–bathroom scales, tennis shoes, pressure cookers, and too many others to count. Consumers will expect them to work everywhere, and SIC will make that possible, by enabling robust mesh networks without coverage holes. Best of all, perhaps, they'll do so by using only a modest amount of spectrum.



Radios, like the one in your cellphone, typically communicate using different frequencies, or the same frequency at different times, to send and receive signals. These techniques are half as efficient at using spectrum as using the same frequency at the same time.

Cellphones, Wi-Fi routers, and other two-way radios are considered full-duplex radios. This means they are capable of both sending and receiving signals, oftentimes by using separate transmitters and receivers. Typically, radios will transmit and receive signals using either frequency-division duplexing, meaning transmit and receive signals use two different frequencies, or time-division duplexing, meaning transmit and receive signals use the same frequency but at different times. The downside of both duplexing techniques is that each frequency band is theoretically being used to only half of its potential at any given time–in other words, to either send or receive, not both.

It's been a long-standing goal among radio engineers to develop full duplex on the same frequency, which would be able to make maximal use of spectrum by transmitting and receiving on the same band at the same time. You could think of other full-duplex measures as being like a two-lane highway, with traffic traveling in different directions on different lanes. Full-duplexing on the same frequency would be like building just a single lane with cars driving in both directions at once. That's nonsensical for traffic, perhaps, but entirely possible for radio engineering.



An SIC component in a radio samples the transmit signal at the digital [1], IF [2], and RF [3] layers. At the IF and RF layers, the sampled signal is adjusted by several components [4] to create inverses of the samples. At the digital layer, algorithms cancel out alterations in the signal caused by environmental reflections [5]. When the signal is received, the SIC component cancels it at the RF [6], IF [7], and digital [8] layers. The transmit signal is also sampled [9] by a digital tuner that will adjust SIC components [10] to better cancel it next time.

To be clear, full duplex on the same frequency remains a goal that radio engineers are still working toward. Self-interference cancellation is bringing radios closer to that goal, by enabling a radio to cancel out its own transmissions and hear other signals on the same frequency at the same time, but it is not a perfected technology.

SIC is just now starting to emerge into mainstream use. In the United States, there are at least three startups bringing SIC to real-world applications: GenXComm, Lextrum, and Kumu Networks (where I am vice president of product management). There are also a handful of substantial programs developing self-cancellation techniques at universities, namely Columbia, Stanford (where Kumu Networks got its start), and the University of Texas at Austin.

Upon first consideration, SIC might seem simple. After all, the transmitting radio knows exactly what its transmit signal will be, before the signal is sent. Then, all the transmitting radio has to do is cancel out its own transmit signal from the mixture of signals its antenna is picking up in order to hear signals from other radios, right?

In reality, SIC is more complicated, because a radio signal must go through several steps before transmission that can affect the transmitted signal. A modern radio, such as the one in your smartphone, starts with a digital version of the signal to be transmitted in its software. However, in the process of turning the digital representation into a radio-frequency signal for transmission, the radio's analog circuitry generates noise that distorts the RF signal, making it impossible to use the signal as-is for self-cancellation. This noise cannot be easily predicted because it partly results from ambient temperatures and subtle manufacturing imperfections.

The difference in magnitude of an interfering transmitted signal's power in comparison with that of a desired received signal also confounds cancellation. The power transmitted by the radio's amplifier is many orders of magnitude stronger than the power of received signals. It's like trying to hear someone several feet away whispering to you while you're simultaneously shouting at them.

Furthermore, the signal that arrives at the receiving antenna is not quite the same as it was when the radio sent it. By the time it returns, the signal also includes reflections from nearby trees, walls, buildings, or anything else in the radio's vicinity. The reflections become even more complicated when the signal bounces off of moving objects, such as people, vehicles, or even heavy rain. This means that if the radio simply canceled out the transmit signal as it was when the radio sent it, the radio would fail to cancel out these reflections.

So to be done well, self-interference cancellation techniques depend on a mixture of algorithms and analog tricks to account for signal variations created by both the radio's components and its local environment. Recall that the goal is to create a signal that is the inverse of the transmit signal. This inverse signal, when combined with the original receive signal, should ideally cancel out the original transmit signal entirely—even with the added noise, distortions, and reflections—leaving only the received signal. In practice, though, the success of any cancellation technique is still measured by *how much* cancellation it provides.

Kumu's SIC technique attempts to cancel out the transmit signal at three different times while the radio receives a signal. With this three-tier approach, Kumu's technique reaches roughly 110 decibels of cancellation, compared with the 20 to 25 dB of cancellation achievable by a typical mesh Wi-Fi access point.

The first step, which is carried out in the analog realm, is at the radio-frequency level. Here, a specialized SIC component in the radio samples the transmit signal, just before it reaches the antenna. By this point, the radio has already modulated and amplified the signal. What this means is that any irregularities caused by the radio's own signal mixer, power amplifier, and other components are already present in the sample and can therefore be canceled out by simply inverting the sample taken and feeding it into the radio's receiver.

The next step, also carried out in the analog realm, cancels out more of the transmitting signal at the intermediate-frequency (IF) level. Intermediate frequencies, as the name suggests, are a middle step between a radio's creation of a digital signal and the actual transmitted signal. Intermediate frequencies are commonly used to reduce the cost and complexity of a radio. By using an intermediate frequency, a radio can reuse components like filters, rather than including separate filters for every frequency band and channel on which the radio may operate. Both Wi-Fi routers and cellphones, for example, first convert digital signals to intermediate frequencies in order to reuse components, and convert the signals to their final transmit frequency only later in the process.

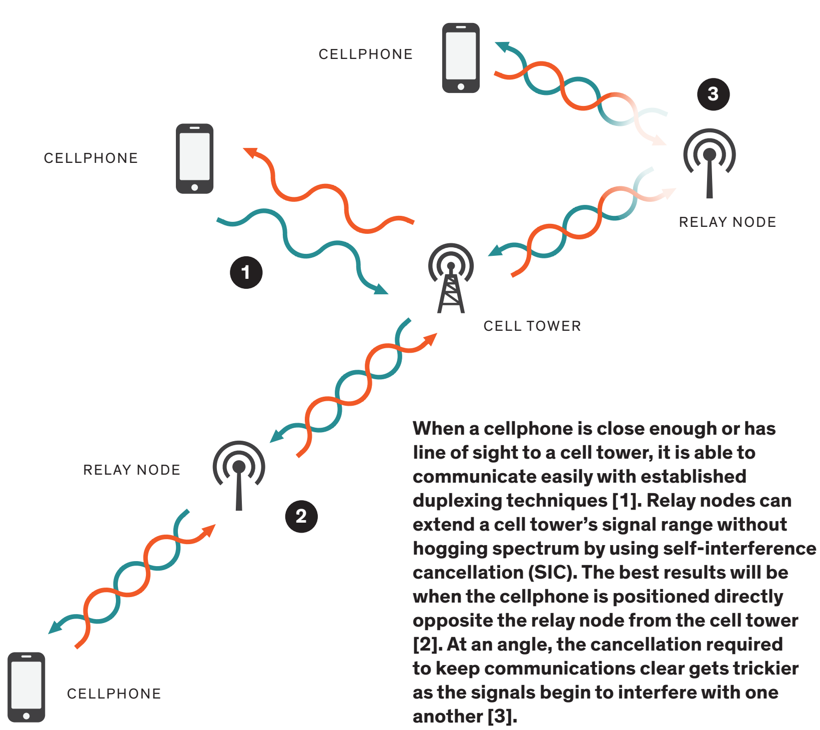
Kumu's SIC technique tackles IF cancellation in the same way it carries out the RF cancellation. The SIC component samples the IF signal in the transmitter before it's converted to the transmit frequency, modulated, and amplified. The IF signal is then inverted and applied to the receive signal after the receive signal has been converted to the intermediate frequency. An interesting aspect of Kumu's SIC technique to note here is that the sampling steps and cancellation steps happen as an inverse of one another. In other words, while the SIC component samples the IF signal before the RF signal in the transmitter, the component applies cancellation to the RF signal before the IF signal.

The third and final step in Kumu's cancellation process applies an algorithm to the received signal after it has been converted to a digital format. The algorithm compares the remaining received signal with the original transmit signal from before the IF and RF steps. The algorithm essentially combs through the received signal for any lingering effects that might possibly have been caused by the transmitter's components or the transmitted signal reflecting through the nearby environment, and cancels them.

None of these steps is 100 percent effective. But taken together, they can reach a level of cancellation sufficient to remove enough of the transmit signal to enable the reception of other reasonably strong signals on the same frequency. This cancellation is good enough for many key applications of interest, such as the Wi-Fi repeater described earlier.

As I mentioned before, engineers still haven't fully realized full-duplex-on-the-same-frequency radios. For now, SIC is being deployed in applications where the transmitter and receiver are close to one another, or even in the same physical chassis, but not sharing the same antenna. Let's take a look at a few important examples.

Kumu's technology is already commercially deployed in 4G Long Term Evolution (LTE) networks, where a device called a relay node can plug coverage holes, thanks to SIC. A relay node is essentially a pair of two-way radios connected back-to-back. The first radio of the pair, oriented toward a 4G cell tower, receives signals from the network. The second radio, oriented toward the cov-



When a cellphone is close enough or has line of sight to a cell tower, it is able to communicate easily with established duplexing techniques [1]. Relay nodes can extend a cell tower's signal range without hogging spectrum by using self-interference cancellation (SIC). The best results will be when the cellphone is positioned directly opposite the relay node from the cell tower [2]. At an angle, the cancellation required to keep communications clear gets trickier as the signals begin to interfere with one another [3].

erage hole, passes on the signals, on the same frequency, to users in the coverage hole. The node also receives signals from users in the coverage hole and relays them—again, on the same frequency—to the cell tower. Relay nodes perform similarly to traditional repeaters and extenders that expand a coverage area by repeating a broadcasted signal farther from its source. The difference is, relay nodes do so without amplifying noise because they decode and regenerate the original signal, rather than just boosting it.

Because a relay node fully retransmits a signal, in order for the node to work properly, the transmitter facing the 4G base station must not interfere with the receiver facing the coverage hole. Remember that a big problem in reusing spectrum is that transmit signals are orders of magnitude louder than receive signals. You don't want the node to drown out the signals it's trying to relay from users by its own attempts to retransmit them. Likewise, you don't want the transmitter facing the coverage hole to overwhelm signals coming in from the cell tower. SIC prevents each radio from drowning out the signals the other is listening for, by canceling out its own transmissions.

Ongoing 5G network deployments offer an even bigger opportunity for SIC. 5G differs from previous cellular generations with the inclusion of small cells, essentially miniature cell towers placed 100 to 200 meters apart. 5G networks require small cells because the cellular generation utilizes higher-frequency, millimeter-wave signals, which do not travel as far as other cellular frequencies. The Small Cell Forum predicts that by 2025, more than 13 million 5G small cells will be installed worldwide. Every single one of those small cells will require a dedicated link, called a backhaul link, that connects it to the rest of the network. The vast majority of those backhaul links will be wireless, because the alternative—fiber optic cable—is more expensive. Indeed, the 5G industry is developing a set of standards called Integrated Access and Backhaul (IAB) to develop more robust and efficient wireless backhaul links.

IAB, as the name suggests, has two components. The first is access, meaning the ability of local devices such as smartphones to communicate with the nearest small cell. The second is backhaul, meaning the ability of the small cell to communicate with the rest of the network. The first proposed schemes for 5G IAB were to either allow access and backhaul communications to take turns on the same high-speed channel, or to use separate channels for the two sets of communications. Both come with major drawbacks. The problem with sharing the same channel is that you've introduced time delays for latency-sensitive applications like virtual reality and multiplayer gaming. On the other hand, using separate channels also incurs a substantial cost: You've doubled the amount of often-expensive wireless spectrum you need to license for the network. In both cases, you're not making the most efficient use of the wireless capacity.

As in the LTE relay-node example, SIC can cancel the transmit signal from an access radio on a small cell at the backhaul radio's receiver, and similarly, cancel the transmit signal from a *backhaul* radio on the same small cell at the *access* radio's receiver. The end result is that the cell's backhaul radio can receive signals from the wider network even as the cell's access radio is talking to nearby devices.

Kumu's technology is not yet commercially deployed in 5G networks using IAB, because IAB is still relatively new. The 3rd Generation Partnership Project, which develops protocols for mobile telecommunications, froze the first round of IAB standards in June 2020, and since then, Kumu has been refining its technology through industry trials.

One last technology worth mentioning is Wi-Fi, which is starting to make greater use of mesh networks. A home Wi-Fi network, for example, now needs to reach PCs, TVs, webcams, smartphones, and any smart-home devices, regardless of their location. A single router may be enough to cover a small house, but bigger houses, or a small office building, may require a mesh network with two or three nodes to provide complete coverage.

Current popular Wi-Fi mesh techniques allocate some of the available wireless bands for dedicated internal communication between the mesh nodes. By doing so, they give up on some of the capacity that otherwise could have been offered to users. Once again, SIC can improve performance by making it possible for internal communications and signals from devices to use the same frequencies simultaneously. Unfortunately, this application is still a way off compared with 4G and 5G applications. As it stands, it's not currently cost effective to develop SIC technology for Wi-Fi mesh networks, because these networks typically handle much lower volumes of traffic than 4G and 5G base stations.

Mesh networks are being increasingly deployed in both cellular and Wi-Fi networks. The two technologies are becoming more and more similar in how they function and how they're used, and mesh networks can address the coverage and backhaul issues experienced by both. Mesh networks are also easy to deploy and "self-healing," meaning that data can be automatically routed around a failed node. Truly robust 4G LTE mesh networks are already being greatly improved by full duplex on the same frequency. I expect the same to happen in the near future with 5G and Wi-Fi networks.

And it will arrive just in time. The tech trend in wireless is to squeeze more and more performance out of the same amount of spectrum. SIC is quite literally doubling the amount of available spectrum, and by doing so it is helping to usher in entirely new categories of wireless applications. ■

POST YOUR COMMENTS AT spectrum.ieee.org/selfinterference-mar2021