Cognitive Radio

Smart radios and other new wireless devices will avoid transmission bottlenecks by switching instantly to nearby frequencies that they sense are clear

By Steven Ashley

Your favorite radio station transmits on a specific frequency. When you set your receiver to so many cycles per second, you tune the antenna circuit to pluck that station's frequency out of the ether. If other transmitters interfere with your reception, your only real option is to wait out the problem. In the best of all worlds, though, your receiver would respond by switching immediately to an open backup frequency that carries your station's broadcast. Such a solution is beyond today's radio technology, and perhaps that example makes the problem seem trivial. But now imagine that interference is interrupting an urgent, emergency cell-phone call. In that case, rapid transfer of the call to a clear cell channel would be more than merely convenient—it might save a life.

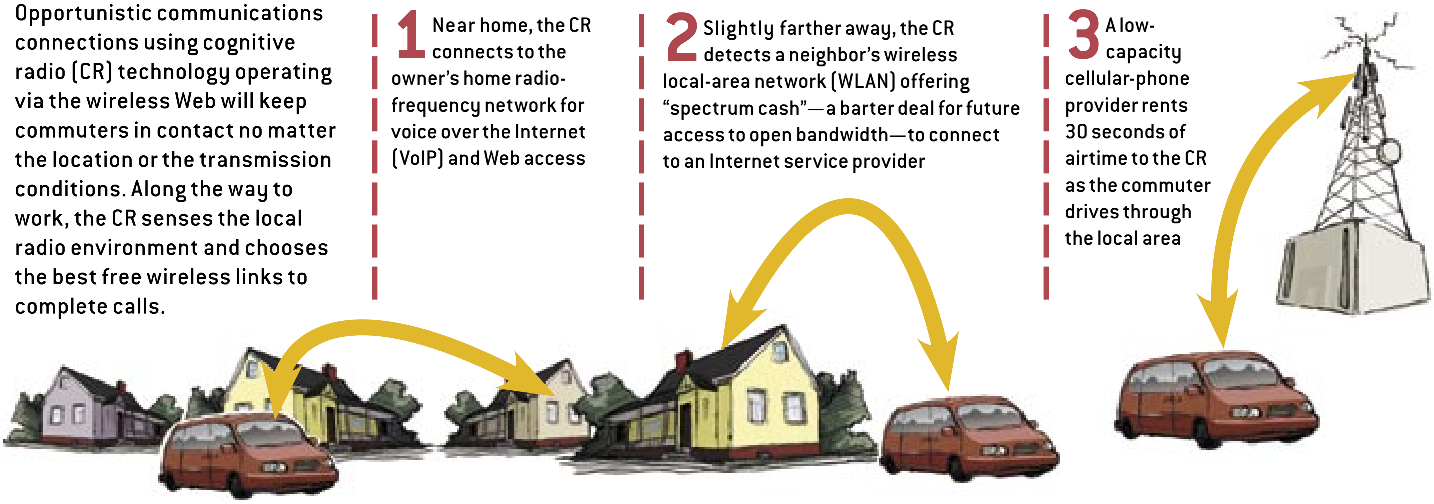
Engineers are now working to bring that kind of flexible operating intelligence to future radios, cell phones and other wireless communications devices. During the coming decade, cognitive radio technology should enable nearly any wireless system to locate and link to any locally available unused radio

WIRELESS SIGNALS jump automatically to an available, open frequency in cognitive radio. The result would be much more reliable transmissions—and maybe lower communications costs in the future.

MATT VINCENT

CAN YOU HEAR ME NOW?

Opportunistic communications connections using cognitive radio (CR) technology operating via the wireless Web will keep commuters in contact no matter the location or the transmission conditions. Along the way to work, the CR senses the local radio environment and chooses the best free wireless links to complete calls.



1 Near home, the CR connects to the owner's home radio-frequency network for voice over the Internet (VoIP) and Web access

2 Slightly farther away, the CR detects a neighbor's wireless local-area network (WLAN) offering "spectrum cash"—a barter deal for future access to open bandwidth—to connect to an Internet service provider

3 A low-capacity cellular-phone provider rents 30 seconds of airtime to the CR as the commuter drives through the local area

spectrum to best serve the consumer. Employing adaptive software, these smart devices could reconfigure their communications functions to meet the demands of the transmission network or the user.

Cognitive radio technology will know what to do based on prior experience. On the morning drive to work, for instance, it would measure the propagation characteristics, signal strength and transmission quality of the different bands as it rides along with you [*see box above*]. The cognitive radio unit would thus build an internal database that defines how it should best operate in different places and at specific times of day. In contrast, the frequency bands and transmission protocol parameters of current wireless systems have been mostly fixed.

As cognitive radios send and receive signals, they will nimbly bound in and out of free bands as required, avoiding those that are already in use. This lightning-fast channel jumping should permit cognitive radio systems to transmit voice and data streams at reasonable speeds. By making much more efficient use of existing radio-frequency (RF) resources to work around spectrum-availability traffic jams, wireless communications should become far more dependable and convenient and perhaps considerably cheaper than it is today. Indeed, if cognitive radio technology progresses as its developers hope, a glut of RF-spectrum options may actually arise in time. The airwaves will never be the same again.

Overview/*Intelligent Radios*

- Cognitive radio is an emerging smart wireless communications technology that will be able to find and connect with any nearby open radio frequency to best serve the user. Thus, a cognitive radio should be able to switch from a band of the radio spectrum that is blocked by interference to a free one to complete a transmission link, a capability that is particularly important in an emergency.
- Adaptive software will enable these intelligent devices to reconfigure their functions to meet the demands of communications networks or consumers as needed. These alterations will be based on the ability to sense and remember various factors such as the radio-frequency spectrum, user behavior, or network state in different transmission environments at any one place and time. As a result, wireless communications should become far more dependable and convenient.
- The new flexibility afforded by cognitive radio may also eventually enable consumers to take advantage of cheaper wireless network paths available locally to make calls, a feature that would do much to revolutionize the communications business.

No Room on the Air

UNFORTUNATELY, those airwaves are all too crowded nowadays. Some bands are so overloaded that long waits and interference are the norm. The availability of these transmission links depends on the wireless systems in use. The radio spectrum—the segment of the electromagnetic continuum containing waves in the radio-frequency range—accommodates countless communications devices today. In the U.S., the Federal Communications Commission assigns users to specific frequencies. These include the well-known AM, FM, shortwave and citizens bands and VHF and UHF television channels, as well as hundreds of less familiar bands that serve cellular and cordless telephones, GPS trackers, air traffic control radars, security alarms, radio-controlled toys and the like [*see box on page 71*].

The present shortage of radio spectrum results in large part from the cost and performance limits of legacy hardware established during the past century. By the late 1950s, for instance, the holdover designs of vacuum-tube TV sets forced new transistor-based models to receive only VHF signals until engineers could revamp the sets some years after-

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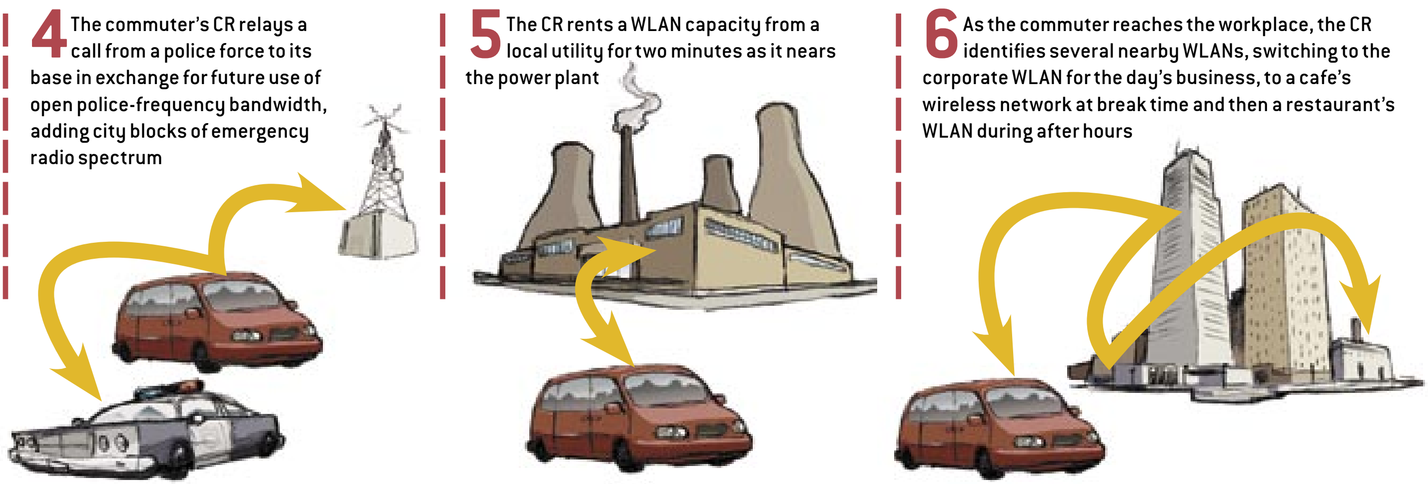
4 The commuter's CR relays a call from a police force to its base in exchange for future use of open police-frequency bandwidth, adding city blocks of emergency radio spectrum

5 The CR rents a WLAN capacity from a local utility for two minutes as it nears the power plant

6 As the commuter reaches the workplace, the CR identifies several nearby WLANs, switching to the corporate WLAN for the day's business, to a cafe's wireless network at break time and then a restaurant's WLAN during after hours



ward. Such hardware-related inflexibility is now being addressed by adaptive, software-based wireless designs.

This next-generation wireless technology, called software-defined radio (SDR), uses both embedded signal-processing algorithms to sift out weak radio signals and reconfigurable code structures to receive and transmit new radio protocols. Experts anticipate that in the relatively near term this software-driven advance will produce a seismic shift in radio design.

The change means, for example, that SDR code and other programmable radio-frequency front-end interface technologies running on a standard laptop computer (fitted with a small RF peripheral component interconnect card) could receive TV signals and display them. If the laptop were then equipped with an analog RF SDR card, it could upload software programming that would allow it to behave as a cellular handset or base station, a wireless personal organizer or even a military-frequency radio—whatever is required (and permitted) for the task at hand. Although few know it yet, the world has just entered the era of SDR wireless communications.

Cognitive radio is arriving on the heels of SDR technology and building on it. This new wireless paradigm involves SDR systems that can reconfigure their analog RF output and that incorporate "self-awareness" and knowledge of transmission protocols, etiquette and procedures. These developments will yield a cognitive radio able to sense its RF environment and location and then alter its power, frequency, modulation and other operating parameters so as to dynamically reuse whatever spectrum is available.

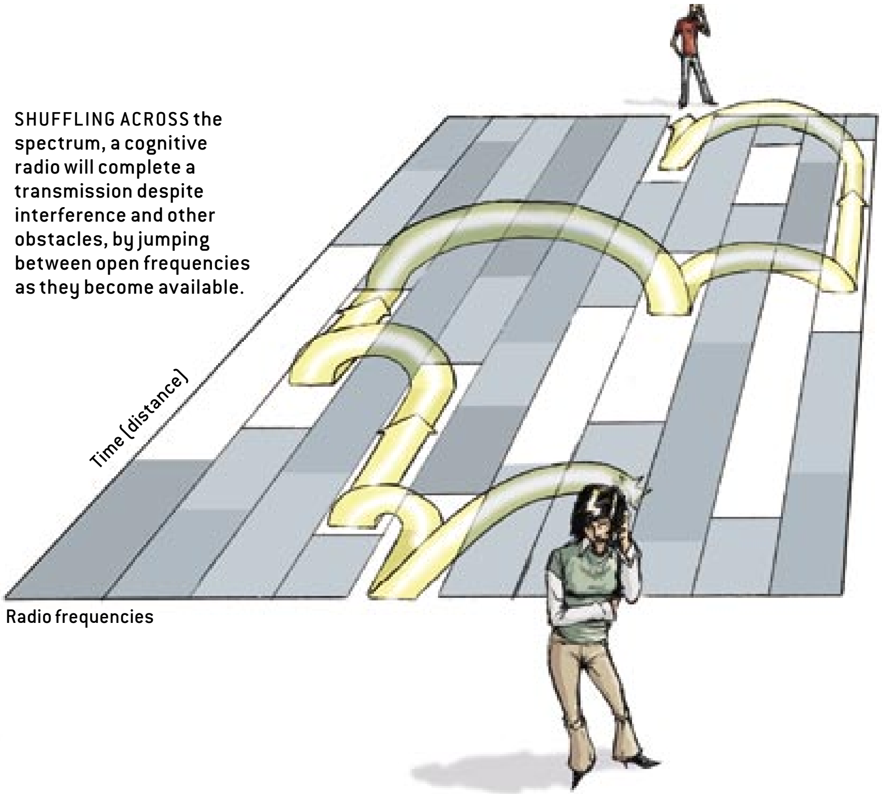
Self-awareness refers to the unit's ability to learn about itself and its relation to the radio networks it inhabits. Engineers can implement these functions through a computational model of the device and its environment that defines it as an individual entity ("Self") that operates as a "Radio"; the model also defines a "User" about whom the system can learn.

A cognitive radio will be able to autonomously sense how its RF environment varies with position and time in terms of the power that it and other transmitters in the vicinity radiate. These data structures and related software will enable a cognitive radio device to discover and use surrounding networks to the best advantage while avoiding interference from other radios. In the not too distant future, cognitive radio technology will share the available spectrum optimally without instructions from a controlling network, which could eventually liberate the user from user contracts and fees.

The potential for cognitive radio technology to redefine existing wireless services becomes clear when one considers their economics. A monthly cellphone service bill, for instance, contains charges for leasing radio spectrum, renting cell towers and purchasing the handset, as well as the amortization of the hardware at the cell base site, the cost of interconnections among cell sites, billing expenses and network operator profit. These fees pay for the investments that cellular service providers make to create and operate dedicated RF networks.

Such costs could drop dramatically, and service quality could improve greatly, when cognitive radio is finally unleashed in the marketplace. Think about the best advanced-technology cell phone now being sold. More than one gigahertz (GHz) of useful but underutilized radio spectrum is available to that handset. At any instant, however, the device employs at most 10 megahertz (MHz)—a hundredth of what there is—and even that is selected from only about 100 MHz of fixed spectrum allocations that the phone's circuits can access.

Furthermore, a typical cell phone incorporates several hundred million instructions per second of processing capacity that is largely dedicated to unique cellular standards. The service provider uploads these standards for its own purposes, such as fixing bugs in the software; they are not necessarily for the customer's immediate benefit. Case in point: that capacity could be used to securely upload third-party software



SHUFFLING ACROSS the spectrum, a cognitive radio will complete a transmission despite interference and other obstacles, by jumping between open frequencies as they become available.

that would permit the phone to link to a free wireless local-area network (WLAN). At a technical conference on mobile communications in 2004, a senior executive at Motorola stated that the WLAN-based telephone has been technically feasible for years but that cellular service providers do not want such a device. And it is little wonder: such a phone could automatically switch to corporate WLANs during the workday, depriving service providers of fees for hours every day.

But the cognitive radio genie is out of the bottle. SDR's entrée to little-used radio spectrum, together with the cognitive radio's autonomous control software (acting to the consumer's advantage), frames a business path toward the adoption of the technology.

Free Spectrum Abounds

EXCLUDING high-frequency and microwave bands greater than 6 GHz, about 2.8 GHz of currently allocated radio spectrum between 28 and 5,600 MHz is underutilized but accessible to cognitive radio. (That estimate derives from the nominal sensitivity of receivers and the gain levels of existing antennas.) Meanwhile the bands for cellular phones and wireless Internet services are often oversubscribed. Myriad electronic widgets, from keyless automobile entry fobs to garage-door openers to radio controls for toys, use those bands for short-range data communications; a gathering of users, such as a meeting of radio-controlled model-airplane enthusiasts, can swamp the allocated spectrum. Likewise, cellular bands that are typically almost empty at 3:30 in the morning are completely jammed at the peak calling time of 10 A.M. or during the evening homeward commute, particularly if road traffic is heavy.

Above 6 GHz, humidity and precipitation greedily absorb radio-frequency signals; even in dry air, absorption peaks near 20 and 60 GHz. Nevertheless, certain short-range data links (often categorized as "campus" or military "up the hill" links) now achieve megabit-per-second transmission rates at frequencies near 34 and 70 MHz. Rising computer power has recently enabled wireless devices operating in these upper bands to offer gigabits per second of instantaneous bandwidth within very small areas, or "picocells," of coverage. This technology could be helpful to mobile users communicating between vehicles on a highway, or among pedestrians, or in fixed wireless systems inside buildings.

Jens Zander, an authority on radio systems at the Royal Institute of Technology in Stockholm, argues that there is no shortage of radio spectrum, only a dearth of affordable communications infrastructure. Cellular-telephone towers, interconnections to the public switched-telephone network and billing systems, and so on make up the substantial and expensive underpinnings essential for leased spectrum. Since the 1990s, as cell phones shrank from the brick-size "bag phone" to the Motorola StarTac and on to today's multifunction clamshell device, building and maintaining a dedicated infrastructure was the only way to proceed. In early 2005, however, Vanu, Inc., demonstrated the first Global System for Mobile Communications (GSM) SDR base station with an RF converter that makes the radio signal processable by essentially a high-performance laptop without a keyboard or display. Only five years before, the GSM transcoder and rate adaptation unit alone needed its own server rack and kilowatts of operating power. During that period, semiconductor advances reduced the cost of a base station for an affordable small cell site, so that nowadays it could be a laptop or home computer.

Changes in the Air

THE ONGOING microelectronics and computer technology revolution has thus altered the fundamental limits of radio hardware during the past decade, cutting the costs of cellular infrastructure systems to less than 1 percent of what they were. The impact of these transformations on advanced wireless technology and their markets is just now being felt.

In earlier years analog TV (using specialized hardware and with 6 MHz bandwidth) was the largest practical consumer of the radio spectrum. At present, high-definition digital TV delivers the equivalent of nearly 100-megabit-per-second transmission rates in the same 6 MHz band. An Intel Pentium-powered laptop can now generate pictures and sounds using software and a digitized version of the analog TV signal from an RF converter unit. This converter changes the carrier frequency of a radio signal from RF at the antenna to some intermediate

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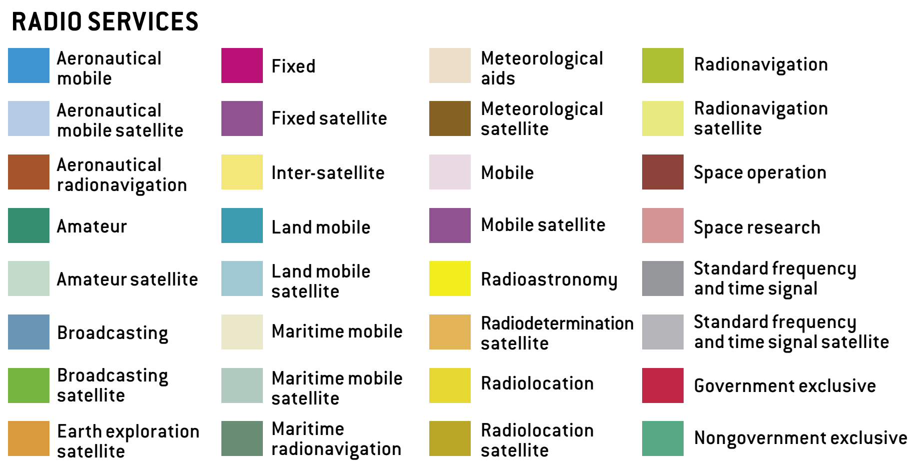
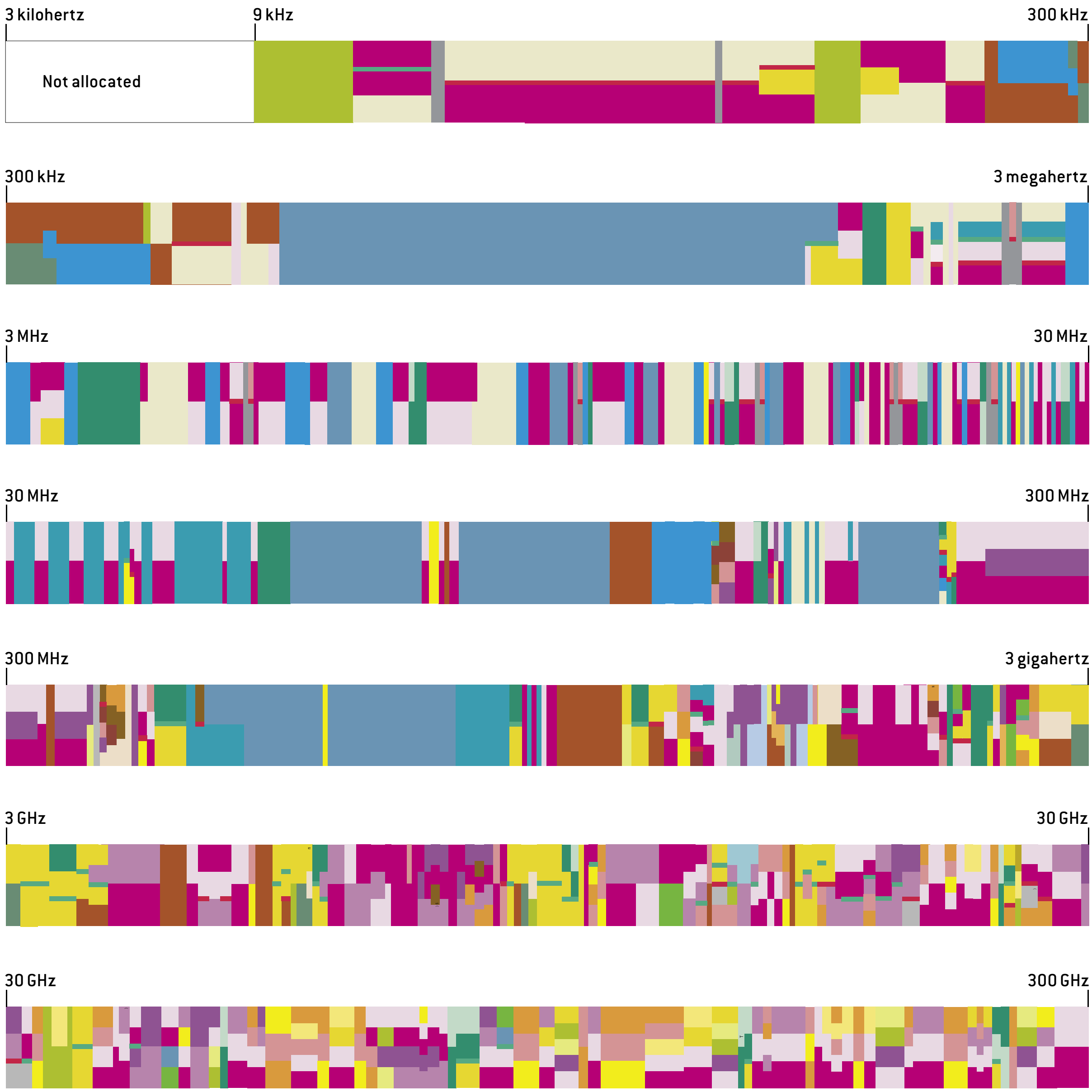
RADIO-FREQUENCY SPECTRUM

Radio spectrum in the U.S. is allocated by the Federal Communications Commission to a large variety of users and applications, with each assigned to a specific bandwidth located between frequencies of nine kilohertz—9,000 cycles per second—and 300 gigahertz. Here is a simplified representation of the radio-frequency spectrum and its allocations in the U.S.





SOURCE: U.S. DEPARTMENT OF COMMERCE

frequency that an analog-to-digital conversion chip can transform into a software-processable format. High-speed analog-to-digital conversion chips can thus exploit hundreds of megahertz of RF spectrum simultaneously. Some such chips are powered by microelectromechanical system (MEMS) circuits—semiconductors that incorporate micron-scale mechanical devices—such as a digitally reconfigurable analog RF capacitor. In production quantities, MEMS-based RF peripheral cards can access tens of megahertz of radio spectrum anywhere between 30 and 5,600 MHz for about the same price as a present-day cell phone.

MEMS-based RF devices have been slow to enter the market because they cost more than the less capable fixed-RF chip sets. A landmark ruling by the FCC in 2004 that favored the development of cognitive radio, however, offers new incentives for manufacturers to adopt RF MEMS products. The government agency recommended cognitive radio technology for use in low-power ad hoc networks in unused TV bands. This decision released more than 100 MHz for cognitive radio in typical urban markets. The emergence of RF MEMS and the FCC endorsement combine to push for greater spectrum sharing in days to come. Operating in the low and middle bands of the radio spectrum, one or two RF MEMS analog channels can create short-range ad hoc networks in any band where licensed users agree to rent, share or otherwise barter for radio spectrum.

An RF MEMS cognitive radio card can therefore turn a cell phone into a WLAN, a laptop into a cell phone or a cordless telephone into a picocell "tower." From such a picocell, a home computer fitted with a cognitive radio control system could rent airtime to passersby, billing for secure wireless voice or data through the associated Internet service provider.

Remaking the Wireless Web

IN TRADITIONAL cell-phone systems, most of the intelligence for efficient operation resides in the network. Although newer cell technologies feature greater processing capacity, they are really not that much smarter than their predecessors. Customers still need a contract with a service provider to obtain access to the network and then to the public switched-telephone network. Cognitive radio technology, in contrast, embeds the intelligence required to connect to wireless networks in the radio handset, laptop or wireless organizer. Because a cognitive control subsystem governs the SDR capabilities, a unit can detect RF-networking opportunities wherever it finds itself.

At present, 90 percent of new laptop computers contain WLAN capabilities. Home and business WLANs and related hot spots are multiplying exponentially. Cognitive radio will have the operational intelligence to rent or borrow WLAN and other RF spectrum quickly for seconds or minutes at a time in exchange for "spectrum cash," a verifiable promise to loan the cognitive radio's own picocell capabilities to another cognitive radio in the future. From these wireless Web access points, the Internet service provider would then transfer the user's data or call to anyone, anywhere in the world. One can see then that cognitive radio does not need a dedicated cellular network to connect a user via wireless and the Internet to other devices. In addition, as the cognitive radio interactions with the wireless Web expand, the need for a long-term contract with a cellular-service provider diminishes.

Spatial Radio Knowledge

WHEN A TYPICAL CONSUMER makes use of a wireless network employing current commercial electronics, the system does its best to consume as much

ALL COMMUNICATIONS LINKS, ALL THE TIME

Fast, reliable battlefield communications—a key to victory in modern warfare—could be guaranteed by cognitive radio technology. Whereas different forces and weapons systems today operate radio systems that can be incompatible, next-generation smart radio technology could help military commanders stay apprised of the latest situation in (and above) the combat zone with real-time voice, data and video links that reliably connect all friendly forces, despite interference caused by the fog of war. Future military radios could use cognitive radio technology to maintain these crucial communications lifelines.

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scarce spectrum as it can while simultaneously jamming other nearby radios. Cognitive radio will be smart enough to introduce etiquette—sensible transactional practices—into RF-spectrum operations. It will also intelligently detect and interact with nearby picocells to keep the cognitive radio user connected by the means that best serve his or her needs, which may differ among various times and situations.

To accomplish these tasks, a cognitive radio unit requires several things. First, it must "know" how radiated RF power at its location varies with distance along the ground, among obstructions and up in the air. Cell phones do not need this information because the fixed network employs dedicated radio spectrum that has been previously calibrated for existing radiated power patterns. Cognitive radios instead sense the entire local RF environment of low, medium and high bands, mapping its features as a function of space, time and frequency propagation. The development of spectrum-sensing cognitive radio will require the design of high-quality sensor devices and practical algorithms for exchanging spectrum-monitoring data between cooperating communications nodes. Systems that feature multiple-input/multiple-output capabilities will direct transmissions along complex multipath components—thereby accounting for reflections of signals from objects such as buildings and vehicles—and away from other potentially interfering radios.

A fully functional cognitive radio system will be smart enough to sense the local RF "scene," to choose the radio band, mode and service it needs as well as the SDR upload connections to the selected band and mode. It will then direct its transmission energy toward the intended receiver while minimizing interference with other radios, including cognitive ones. Thus, it will display a high level of spectrum etiquette and connect the user securely and privately.

The accuracy of such operations could be improved by the development of three-dimensional computer representations of the full local cityscape stored on gigabyte hard drives, which would be accessed wirelessly as needed. Predictions of received signal strength based on these models would allow cognitive radios to avoid most interference. Having standardized broadcast channels over which cognitive radios experiencing interference could "complain" without jamming others would complete the radio etiquette cycle.

The ideal of cognitive radio etiquette is complicated by the variation over time of the aggregate interference produced by the environment, which includes that created by natural electrical noise (from lightning), electrical power generators, electric motors, automobile ignition systems and radio transmitters. The effects of these RF sources change over time. At night, for example, few elevators are active, so their electric drive motors produce little noise, but during rush hour that noise grows. The total power radiated by all sources tends to be greatest in urban centers at about 10 A.M., with less activity occurring in rural settings and at night. Although the statistical complexity of such aggregate sources makes them difficult to predict, cognitive radio will learn the patterns at important locations (such as at the workplace and home) for known users.

The Future of Smart Radio

AFTER ASCERTAINING the varying energy patterns in each band, cognitive radio devices will be able to use Semantic Web technology [see "The Semantic Web," by Tim Berners-Lee, James Hendler and Ora Lassila; SCIENTIFIC AMERICAN, May 2001] to exchange this information freely with others. It will help to optimize each unit's search for underused and rentable spectrum. Cognitive radios can thereby avoid jamming other users yet transmit with sufficient power to overcome ambient interference and cooperate creatively.

The decisions concerning the future of cognitive radio technology are shaping up as a battle between two giant business sectors: the cell-phone and telecommunications industry versus "the Internet industry," which includes Microsoft, Intel, Google, Internet service providers and consumer computer firms. Although entrenched interests may resist it, progress toward cognitive radio seems likely because the relative chaos and inflexibility of unregulated radio bands (such as those now handling instrumentation, scientific and medical devices) could be avoided. Ultimately, smart operator etiquette based on cognitive radio technology will turn gigahertz of underused spectrum into wideband connectivity for many users.

If FCC regulators continue on the current path, they will make huge single-use swaths of spectrum hundreds of megahertz wide available for shared use. The long-touted scarcity of radio spectrum in the future may be replaced by a surfeit of available frequencies. Rather than a cell phone needing a minute to upload a compressed megapixel-size image, it might be able to handle 10 such images a second.

Just as the emergence of cell-phone technology has led to wide social and business consequences, cognitive radio's adoption will induce similar changes as advanced devices exploit the wireless Web to displace now traditional cell phones. The growth of cognitive radio will take some time to occur, but the effect on all our lives will be significant. SA

Steven Ashley is a staff editor.

MORE TO EXPLORE

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Cognitive Radio Architecture. Joseph Mitola III. John Wiley & Sons, April 2006.

European Community's End-to-End Reconfigurability (E2R) radio project: **phase2.e2r.motlabs.com**

Joseph Mitola's Web site is at the KTH (Royal Institute of Technology, Sweden): **www.it.kth.se/~jmitola**

Software Defined Radio Forum: **www.sdrforum.org**