Policy-Controlled Radio

Making Room in the

Cognitive radios, the next big thing in wireless, will get a jump-start with XG, the Pentagon's neXt-Generation communications research program. Will regulators climb on board?

By Charlotte Adams

Today new wireless technologies struggle for bandwidth. The spectrum is crowded with incumbents, some of whom have paid huge sums to operate in their bands. Communications companies reportedly have spent $20 billion on spectrum since federal auctions began in 1995. But more room is needed for cell phones, wireless e-mail, digital audio and other services, to say nothing of network centric warfare and its voracious appetite.

But the situation is not impossible if spectrum is viewed dynamically, as a function of time and space. The Defense Advanced Research Projects Agency (DARPA) claims only 2 percent of the spectrum is in use in the United States at any given moment, even though all spectrum is allocated. DARPA's XG (neXt-Generation) communications program is developing the technologies to allow spectrum sharing—in space and time—without interference. Regulators still would dictate what can and can't be done in the spectrum. But these policies would be expressed in machine-readable form. If you can't manufacture new spectrum, at least you can use the resource more efficiently, the thinking goes. Would a dynamic regulatory regime be safer for spectrum incumbents? Will the authorities buy in? All that remains to be seen.

XG Players

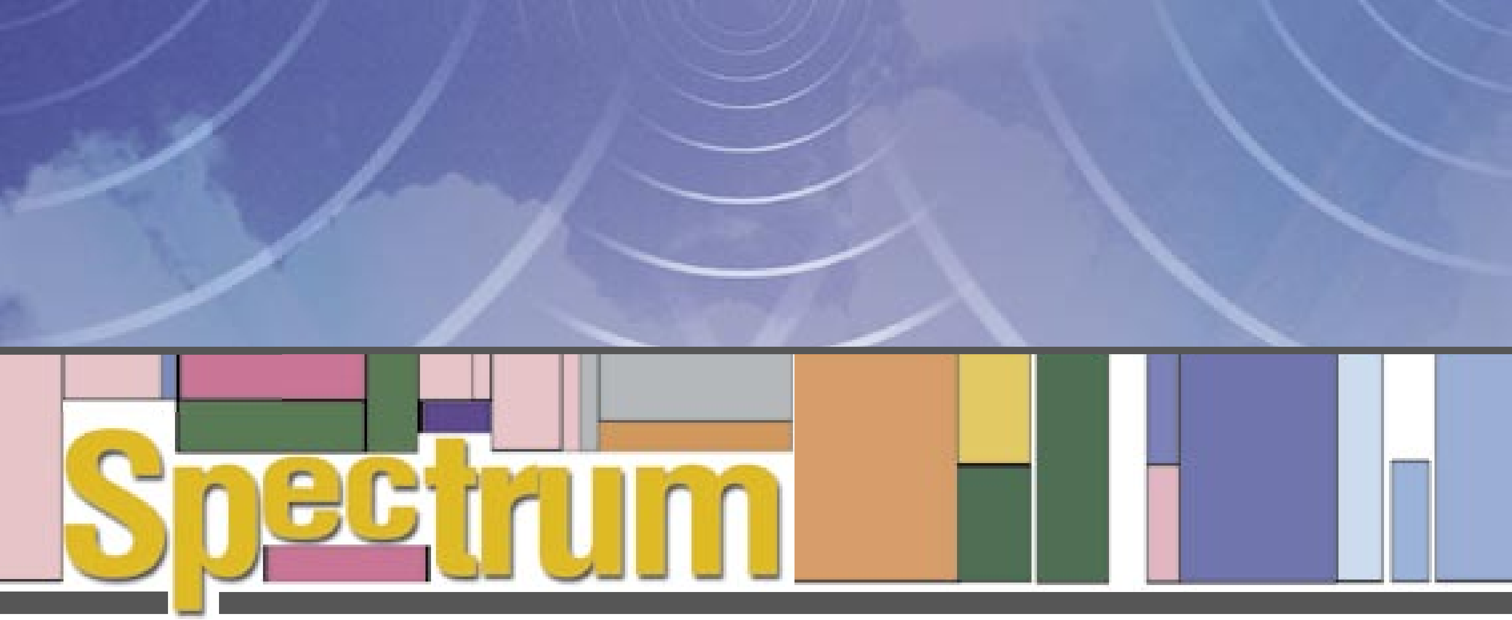
Launched in 2002, the XG program brought together Lockheed Martin, Raytheon and startup Shared Spectrum Co. (SSC) as primary radio designers, and BBN Technologies as a policy language and protocol developer, in the first two phases, now complete. Companies such as Rockwell Collins, General Dynamics and Vanu played associate or subordinate roles.

The third and final phase of XG was in source selection as this article went to press. DARPA hoped to award contracts in April. The agency will challenge one or two radio developers to pit actual XG radios against actual military and civilian receivers over the air in the real world—at military bases and in urban areas. DARPA will need to obtain temporary, experimental licenses to conduct such experiments. But since U.S. and foreign regulators are keen on the subject, DARPA expects support. The U.S. Federal Commmunications Commission (FCC), for example, has invited comments on allowing adaptive radio techniques to be used in unoccupied TV bands.

The XG radio—a computer with a wideband radio frequency (RF) front-end—is smart enough to sense its signal environment, understand the spectrum rules that apply at its location, and take action based on those rules. What if the radio could jump from channel to channel or from frequency to frequency, to take advantage of spectrum "holes" when and where they occur? If it works and the regulators buy in, it will be step one toward a "cognitive radio." While XG radios will emit based on policy, not on their past experience of the RF environment, they nevertheless will have to reason about their policy in order to apply it to specific conditions.

JTRS Upgrade?

DARPA sees XG as a future application for the $14-billion Joint Tactical Radio System (JTRS), a flexible radio that will draw from a large library of software waveforms. Still in development, JTRS equipment eventually will replace some 250,000 service-specific radios across the armed forces. XG radios use JTRS hardware assumptions and software conventions. But JTRS and other software radios will need the XG "overlay" to enable them to sense their environment and



collaborate on spectrum use.

XG's adaptability will be particularly useful for JTRS vehicle and dismounted radios, notes Bill Heisey, director of the embedded processing laboratory at Lockheed's Advanced Technology Labs. Ground radios have to deal with complex multipath issues and a small, rapidly changing RF footprint. These problems could be mitigated by sensing and collaboration. At the same time, soldier radio nets could reuse the same spectrum in a city if they are far enough apart. Lockheed envisions XG networks of from three to 15 nodes, and the company has simulated 1,000 radios, Heisey says.

XG also could improve spectrum access for unmanned air vehicles (UAVs). And policy-controlled radios could automatically select the appropriate frequencies when aircraft cross national borders, easing flight crew workload. In general aviation, the technology's ability to be aware of its position could enable it to select local FAA air traffic control frequencies or switch to satellite networks, if necessary, says Bruce Fette, chief scientist with General Dynamics' C4 Systems Division. In commercial aviation it could automatically select the best frequency for the RF environment and help maintain air/ground telephony and video links. Its position awareness could even be used to provide linkbacks to the ground Internet infrastructure for cabin applications by anticipating the ground points that provide the best connectivity.

But don't hold your breath until this comes to commercial aviation. Getting the concept through FAA and industry—to change the way aircraft communicate, especially for safety of life—"will be quite a monumental task," predicts Tom Hauer, director of business development on Collins' corporate staff. Maybe in 15 to 20 years, he says.

What XG Radios Do

- *Sense*—Monitor spectrum at low power in real time.
- *Characterize*—Rapidly determine waveforms.
- *React*—Determine best course of action.
- *Adapt*—Move network to a new emission plan.
- *Control*—Emit according to regulations expressed in a machine-readable format.

Source: DARPA

Measuring Spectrum

To verify XG's feasibility, contractors have measured spectrum use in different areas of the country. Shared Spectrum characterized the RF environment during the Republican convention in New York City last year. After scanning the 30-3000-MHz region during two days of this hectic event, the company found that, on average, 87 percent of the spectrum was free at any given moment. While cell phone and certain television bands were heavily used, there was clearly surplus spectrum. Lockheed Martin says it looked for contiguous 5-MHz and 10-MHz bands of usable spectrum in Philadelphia and found a large number of those bands.

For adaptive radios to be approved, regulators will have to accept the concept of opportunistic spectrum sharing. Since the authorities can't know exactly where a radio will jump to, regulators will have to trust the radio's processes vs. its effects, its policy language and protocols, and its ability to abide by its electronic rules. Today spectrum policy tells you what you can't do, rather than what you can do. If XG is successful and policy thinking changes, the technology could be safer than today's hardwired systems, which can turn into jammers when damaged.

Not surprisingly, the commercial sector sees the benefit of the idea. "The FCC and its Spectrum Policy Task Force talk about white space, underlays and interference temperatures, so clearly they're contemplating an XG-like regime," says Preston Marshall, DARPA's XG program manager. Spectrum agility would solve a lot of problems. Today it takes years, even decades, to negotiate with allies to identify a set of bands that can be used overseas for military purposes. And even then it can take weeks to set up the exact conditions for spectrum use. An adaptive radio could improvise. It could find unoccupied channels or frequencies automatically if time is of the essence. DARPA's broader goal is "zero infrastructure and zero setup time," Heisey says. The ultimate goal is to bring the radios into an area and have them automatically adapt to their environment without any prior knowledge.

Experiments

In phase 2 of the XG program contractors demonstrated through simulations that they could use spectrum 10 times more efficiently than legacy systems can. This means that the simulated XG radios were able to pass 10 times more information—data, video or voice—among themselves than legacy radios were able to do in the same amount of time.

These experiments showed how adaptive techniques would work in a synthetic environment. Signal parameters were varied to represent radios at different vertical and lateral distances along a 3D grid and to add the effects of terrain. Simulated XG units were inserted into recorded legacy radio traffic to see how well they could capture unoccupied spectrum as they moved around the scenario. Some teams also built hardware. Raytheon, for example, divided its campus into four sectors featuring different spectrum policies. Radios loaded with these policies were moved between the regions to prove that they could enforce the emission rules governing each area.

The phase 2 experiments demonstrated adaptability in a very limited manner. XG radios shifted a given waveform between different channels within a given frequency band, explains Richard Hinman, an engineer with the Air Force Research Lab's (AFRL's) Information Directorate. But things will get more complex in the program's final phase. Hinman expects to use policies that can control adaptability in frequencies, waveforms or both parameters.

"I would like to show how to use machine-readable policy to change the waveform set available, depending on where an aircraft is flying," says Hinman. Usage of the joint tactical information distribution system (JTIDS) command and control waveform, for example, is not permitted in certain countries. In those countries' airspace an XG radio would turn off JTIDS and select alternate bands and waveforms.

> "How can you regulate a radio when you can't know what frequency it will be on, what mode it will be operating in, and how it will morph itself in frequency, bandwidth, power or waveform?"

Real-World Problem

Shared Spectrum is applying XG concepts to UAV streaming video data link issues for the Office of Naval Research (ONR). Data links for small UAVs typically have a range of only a few kilometers if there's any obstruction. But the Navy wants a range of up to 31 miles (50 km), according to Mark McHenry, company president. The 2.4-GHz 802.11 unlicensed band used by some small UAVs is limited to about 0.6 mile (1 km) in restrictive terrain, using the maximum power allowed in unlicensed devices. Thus, extending the range will mean finding frequency slots somewhere in the 225-400-MHz NATO UHF bands.

Today UAV operators have to negotiate for exclusive access to a large section of bandwidth, McHenry explains. IEEE 802.11 wireless communications, for example, require a 20-MHz slot. Bandwidth often needs to be allocated theater-wide, he adds. Thus, flying a single UAV in Iraq might require a sizable percentage of all available bandwidth throughout the country, McHenry asserts.

Shared Spectrum aims to show that XG-style frequency sensing and adapting can meet ONR's needs. A hypothetical policy might work something like this:

➤ Allow the data link radio to transmit its 20-MHz signal in the unlicensed 2.4-GHz or 5-GHz bands, as long as that rather localized connection can be maintained;
➤ When that link can no longer be maintained, locate four unused TV channels, split the 20-MHz signal into four 5-MHz blocks, and transmit, using these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channels; and

➤ When it's necessary to vacate the channels, transmit in the 225-400-MHz NATO UHF bands, but only as long as necessary to reestablish the link, using methods one or two.

XG involves four core activities: sensing, characterizing, adapting and reacting. Sensing means detecting spectrum holes. Rockwell Collins developed an extremely fast sensor in phase 2. It can scan a sub-band 25 to 50 MHz wide in tens of microseconds, Marshall says. Its surveillance function can be interleaved with the operation of the radio—not slow it down.

Characterizing the environment means knowing who's there. If the incumbent is a television station, for example, and policy dictates absolutely no interference in that band, then it is important not to generate a signal that will interfere with anyone's reception. But a TV signal may be so strong that an XG radio could put a little power into that band locally without affecting TV reception in that area. Shared Spectrum has built a sensor that can listen for signals that policy makers might invoke, Marshall says. The signal-specific receiver operates in the time domain, looking for specific waveforms.

SSC also has designed a sub-band amplifier under the XG program. The technology would be helpful when one

Fancy Waveforms

Under the military's neXt-Generation (XG) communications research program, Raytheon developed a framework for a heteromorphic waveform, capable of changing its shape many times a second. It can be tuned to match its environmental conditions and notch out parts of the spectrum where interference is not permitted, says Scott Seidel, the company's principal investigator for XG. The waveform can morph to match available spectrum holes.

"Today radios are hard-wired to operate in a specific frequency band," he says. Even the military's Joint Tactical Radio System (JTRS) equipment will operate within fixed frequency bands. And JTRS radios will not be able to sense their environment, plan their emissions and automatically jump from band to band. The heteromorphic technology allows you to operate in discontiguous spectrum, Raytheon says, so a signal can occupy multiple holes close together.

Power management is key—the ability to adjust the amount of power in the radio frequency (RF) bandwidth. Power can be reduced nominally to zero, or a small amount of power may be put in portions of the bandwidth where the primary user is detected but coexistence is possible.

The heteromorphic waveform also improves performance, based on link conditions—the quality of the propagation between two nodes. Waveforms today are customized to specific applications—terrestrial or airborne environments, for example. Signals are designed to provide different amounts of Doppler spread and multipath resistance. The heteromorphic waveform, however, is designed to adapt. It can adjust the way data is coded and send as much data as possible under different link conditions. An unmanned air vehicle, for example, flying close to the waves and trying to transmit back to a ship at a low angle relative to the sea surface, will encounter severe multipath problems as the waves reflect or absorb the energy of its transmissions. The heteromorphic waveform might change itself to increase multipath resistance. It is adaptable in data rate, time, modulation level and spatial techniques, as well as in band, frequency, power and coding.


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Policy Puzzles

The long pole in the tent for the military's neXt-Generation (XG) communications program is policy. How can you regulate a radio when you can't know what frequency it will be on, what mode it will be operating in, and how it will morph itself in frequency, bandwidth, power or waveform? "You've got to trust the processes in the radio—you can't really measure the output," says Preston Marshall, XG program manager at the Defense Advanced Research Projects Agency (DARPA). "We're trying to build a technology that will work pretty much anywhere in the spectrum—anywhere you can measure locally," he says.

The answer to the regulatory conundrum is that XG radios will be policy-controlled. Because the policies are developed as software, regulators also will be able to change them far more readily than is possible with today's radios, which implement policy in hardware. In the program's final phase, contractors will demonstrate the ability to dynamically change policy while operating.

There's even the possibility down the road of spectrum "subleasing," where the incumbent in a band could write policies prescribing the rules for accessing its band and perhaps charge for use of excess capacity on an hourly basis. Although no one knows how sublicensing would be managed, Verizon—to name one company—is invited to almost all of the XG meetings. The communications giant views subleasing as a potential way to share spectrum, yet ensure that the primary user's spectrum is not interfered with, Marshall says. "That's a win/win if we prove we can do it."

DARPA expects that policies will differ not only according to spectrum but also according to the signal type, Marshall says. Some signals—especially military ones—tolerate a certain amount of interference in their bands. And some types of incumbent signals can be detected by XG "many milliseconds before we would cause interference to them," he says.

But writing XG policies will be no trivial matter. These regulations are numerous, voluminous and complex. Dozens and dozens of regulations would have to be encoded for frequency-adaptive radios to know what they are allowed to do. For a narrow band, rules would be less complex to put into machine logic, but may involve several strands of reasoning, such as: it's OK to use this frequency but not near an airport. XG policy language and protocol contractor, BBN Technologies, has so far encoded hypothetical policies applicable to narrow bands.

For starters an XG radio will have a policy conformance manager, explains Craig Partridge, BBN's chief scientist for internetworking. Before a radio transmits, it checks with the policy manager, which tells it yes or no, based on the spectrum rules encoded in the radio. BBN has created experimental policies using a declarative language that enables multiple policies to be merged together. This language—known as the ontology Web language (OWL)—enables the policy conformance manager to say, this is legal and that is not.

If an XG radio wants to transmit in a television band at a certain time and place, the policy engine may say, OK, but only at a specific power level and for a set duration.

Challenges

In phase 2 BBN simulated a policy engine dealing with around 100 policies, Partridge says. Simulations also tested the policy engine's responsiveness to radio queries in real time. The radio should be able to get an answer in less than 100 milliseconds, he says. "The point is to answer almost as fast as the radio can figure out it needs to send something."

But what do you do when the radio's transmission plan leaves out key parameters? For example, it knows which band it wants to jump to, and it understands the noise level and specific signals present on that band, but it does not tell the policy engine what power level it plans to put out. Does the policy engine fill in the blanks or just say no? Filling in the blanks involves a much more complicated policy reasoning and search problem than saying, yes or no, based on a simple rule. BBN has demonstrated the feasibility of filling in blanks, but only if a couple of parameters are left unset, Partridge says.

Then come the security issues. How do you know you're getting the right set of policies from the right person, not from an imposter? BBN expects that phase 3 of the XG program will tackle issues such as the security architecture, software robustness, execution speed, policy complexity, and search and reasoning logic.

Adaptability

The assumption is that policies will change rapidly, Partridge says, perhaps on an hourly basis, reflecting supply and demand, as in the case of spectrum subleasing. Or policies could change during a flight, as security or other conditions change along the fight path. New electronic policies would arrive, digitally signed, over the airwaves. Researchers also will begin investigating the translation of policy logic into a hardware chip, which will improve performance and ultimately lower cost. The policies, however, will continue to be expressed in the most flexible medium—software.

needs to amplify a very wide signal without creating "shoulders," or sidelobes, that "slop over" beyond the signal's available bandwidth. Instead of amplifying the whole signal, the sub-band amplifier divides it into pieces, which can be reassembled with less aggregate spillover.

"You can get the same amount of amplification, but your shoulders are reduced by more than one-half," asserts Michael Wellman, SSC's engineering manager. "Almost all the energy you're putting into amplification is going into the band of interest, not off to the side." This requires faster, more detailed frequency sampling than is done today, but the radio never notices that its signal was changed, Wellman contends.

The sub-band amplifier aids adaptability, too. If an 8-MHz-wide signal is chopped into eight 1-MHz chunks, it doesn't necessarily have to be reassembled into one contiguous piece, Wellman says. The eight chunks can be put into eight different holes and still maintain the link. This is useful, as smaller holes are easier to find. The prototype uses software, as well as hardware, but the final product will be all hardware.

Adapting and Reacting

XG radios also have to collaboratively adapt and react to their RF environment. They interact to form and execute an emission plan. Different nodes—and this is especially true for ground-based networks—search for and communicate about spectrum availability in a network "under" the main network. The more nodes, the better, Marshall claims, as this adds to the network's store of spectrum knowledge.

A network is organized around how fast it has to jump out of a band, Marshall says. If the radios have to jump out in 5 milliseconds, then they must never transmit more than 5 milliseconds before they turn their receivers back on to listen. Right now technology is in the 100-millisecond range, but DARPA has asked contractors to go down to 10 milliseconds. Below 5 milliseconds may not be worth worrying about at this time, Marshall says.

"False alarming" is also an issue that must be solved. Says Hinman: "If every pop or tick in the power in the spectrum causes the XG to shut down, it's going to limit [adaptability]." Phase 3 probably will include experiments to help identify parameters for thresholds on how to decide whether or not to transmit if the radio feels there's another user on the channel. ■