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Public Safety Radios Must Pool Spectrum

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ABSTRACT

The dynamic-spectrum-access research and development community is maturing technologies that will enable radios to share RF spectrum much more intensively. The adoption of DSA technologies by the public-safety community can better align systems with the future of wireless services, in general, and can contribute to making next-generation public-safety radio systems more robust, capable, and flexible.

A critical first step toward a DSA-enabled future is to reform spectrum management to create spectrum pools that DSA-enabled devices, such as cognitive radios, can use — under the control of more dynamically flexible and adaptive prioritization policies than is possible with legacy technology. Appropriate reform will enable spectrum portability, facilitating the decoupling of spectrum rights from the provision of infrastructure.

This article examines the economic, policy, and market challenges of enabling spectrum pooling and portability for public-safety radios.

INTRODUCTION

Dynamic spectrum access (DSA) technologies, including cognitive radio (CR) technologies, are in development for the next generation of commercial, military, industrial, *and* public-safety networks. These technologies hold the promise of delivering more flexible and adaptive radio architectures, capable of sharing the RF spectrum much more intensively than is feasible with currently deployed technologies. The current landscape of wireless networking reflects the legacy of a world premised on static network architectures and spectrum allocations. In this world, public-safety networks traditionally were designed to meet capacity and reliability "standards" that are based on user requirements at the worst-case level — that is, the capacity and reliability required during an emergency or a catastrophe. It is not assumed that the network will *always require* these levels of capacity and reliability during day-to-day operations. However, it is assumed that the network must *always have* these levels of capacity and reliability available when required. Worst-case planning implies that significant spectrum and equipment resources must be stockpiled and remain unused most of the time. This creates significant *artificial* spectrum scarcity, especially in the public-safety bands, which are small allocations fragmented across multiple bands and many system owners.

The wireless world is changing. The need for wireless systems of all types, and for public-safety systems in particular, has expanded greatly. This increases the costs and collective infeasibility of continuing worst-case planning and the wasteful allocation of resources that it implies. The future of radio, of necessity, will require shifting to more DSA-friendly modes of spectrum usage. Besides being inevitable, the transition to DSA offers many significant benefits for the public-safety community and for wireless users in general. These benefits include better mission responsiveness, expanded capabilities, and ultimately, lower costs. However, reaching this future also entails overcoming important challenges. A number of complementary innovations are required. These include further technical developments, public-policy reform, and changing industry and end-user attitudes. Although further technical research and product development is certainly required, our focus here is on the policy and business-practice challenges of developing DSA technologies for use by public-safety systems. See [1] for a more detailed discussion.

THE CHANGING ENVIRONMENT FOR PUBLIC-SAFETY RADIOS

Although the precise shape of the future of radio may be difficult to discern, certain key aspects appear certain. The future radio environment will include more wireless entities of all kinds, greater demand for mobility and portability, and more heterogeneous wireless networks. These future developments have concrete implications for the design of radio networks, including a requirement for more broadband capacity, which would enable more dynamic and flexible services, and a requirement for spectrum sharing.

	Past	Present	Future
Key characteristics of public safety radios	Proprietary, single user, single channel, single locale	Multichannel, trunked, narrowband (voice only) Regional Proprietary	Multichannel, multimedia (voice, data, integrated) National Open Interoperable Broadband (data) Mesh/ad hoc
Shared infrastructure?	No. All dedicated to single user/department.	Yes. Shared access infrastructure and base stations via trunking. Channels shared within trunk group but not otherwise.	Yes. Shared access infrastructure and radios. Pooling of spectrum for sharing among multiple trunked groups.
Shared spectrum?	No.	Channel sharing within trunk calling group only.	Yes. Sharing of spectrum across bands. Pooled spectrum.
Infrastructure/ spectrum tied?	Yes. Closely coupled, closed systems. Limited interoperability via gateways, tying up additional spectrum.	Yes. Spectrum still tied to infrastructure. Gateways used to link systems.	No. DSA facilitates unbundling of infrastructure and spectrum. Infrastructure shared across multiple bands.
CPE	Single-channel radios	Multichannel radios	Multiband radios and flexible CPE

Table 1. *Past, present, and future of public safety radios.*

POLICY-BASED RADIO

CR captures the flavor of these advances; a CR is capable of sensing its local radio environment and negotiating modifications to its waveform (modulation scheme, power-level, or frequency/channel access behavior) in real time with other CRs, subject to policy constraints (e.g., limitations to the range of waveforms allowed). The policy constraints are enforced by the radio policy engine. Policies can include authorization to transmit in specific locations and frequencies at specific times or access protocol constraints (e.g., listen-before-talk). These policies can be static and hard-coded into the radio, downloaded from a database, or can be dynamic and subject to updating in real time in communication with a network operator or other CRs. DSA/CR devices typically require location awareness capability to support the policy engine and because interference is a local phenomenon occurring at the location of a receiver. Finally, CRs are inherently multiband radios, enabling the radio to transmit or receive in a wider range of frequencies than might be used in a specific communication environment. This enables CRs to utilize unused spectrum opportunistically and facilitates their interoperability with legacy radio systems.

Although significant technical work still must be performed in academic research and commercial product development laboratories to field a commercially viable CR, prototypes already exist, and many aspects of the technology already are embedded and working at scale in commercial systems. In this article, we do not focus on the technical developments that still must be made, but rather on the policy innovations that are required to make commercialization viable.

NEXT-GENERATION PUBLIC-SAFETY RADIOS MUST EMBRACE DSA

The same forces that are shaping the future for commercial wireless apply even more strongly to public-safety wireless systems. First, public-safety first responders are more likely than most other users of information and communications technology (ICT) to require mobile, wireless access. In many first-responder scenarios, the only option is wireless. Second, first responders, who are dealing with life-and-death situations, generally are perceived as deserving higher priority in the event of competition for resources. Third, first responders are more likely to deal with adverse environments. This increases their need for flexible, adaptive systems (e.g., systems that are capable of supporting ad hoc or mesh networking in the absence of other supporting infrastructure). First responders are likely to suffer from localized congestion; disasters typically happen in specific places and at specific times. The demand for all wireless services by all first responders is likely to be concentrated in time and place, increasing the peak-provisioning problem. Finally, public-safety system capabilities still are woefully inadequate, even compared to the services available to commercial users (e.g., 3G mobile telephony vs. legacy land mobile radio [LMR] systems). The public-safety community shares this conclusion.[1]

Public safety cannot rely on the improvement of LMR designs. There is a requirement and an opportunity to replace outmoded legacy infrastructure with leapfrogging technology to enable the wireless future required by public safety. Rather than continue the development of static, private, and expensive narrowband digital LMR network infrastructures, public safety requires a network architecture where privacy, reliability,

[1] *See http://www.psst.org/publicsafetynetwork.jsp, last accessed July 14, 2008.*

capability, adaptability and flexibility are built in, no matter whose infrastructure the radios traverse, or even when infrastructure is damaged or non-existent. The future of public-safety radio must be much more adaptive and responsive to its environment (spatially, temporally, and situationally) to account for the greater demands placed on first responders. A public-safety responder must be able to take a radio, authentication and security, spectrum rights, and priority status with him or her to any incident in the country and power up the radio, be recognized, and be admitted to whatever incident command network he or she is authorized to support.

Table 1 summarizes our vision of the past, present, and future for public-safety radio.

FACILITATING DSA IN PUBLIC SAFETY

Currently, public-safety radio systems are fragmented, overly expensive, under-capacitated, and limited. In part, this is due to the legacy regime of dedicated, narrowband, and overly restrictive spectrum policy. However, regulatory reforms such as the consolidation of licensing eligibility, approving the certification of software radios, and allowing secondary trading for some licensed spectrum demonstrate that progress is being made. In contrast to the case for commercial wireless services that depend more directly on market-based processes, reform of public-safety spectrum management depends on non-market institutions to coordinate cooperative evolution. Over time, a number of policy reforms helped to make spectrum pooling and DSA more feasible in public-safety applications.

COOPERATIVE ROLE- AND POLICY-BASED INSTITUTIONS ARE DEVELOPING

The national system of frequency coordinators, the regional planning committees (RPCs), and the introduction of the National Incident Management System (NIMS) within the National Response Framework (NRF) provide the institutional foundation required to enable the transition to DSA and spectrum pooling.[2] These relatively new institutions are positioned to enable public-safety managers to define global and local priorities and static and dynamic rules and policies that can assist in self-regulation of spectrum use. The development of appropriate user-based prioritization and policies that reflect accepted practices in emergency management and incident response are essential to support developing CR and DSA technologies.

REGIONAL PLANNING FOR PUBLIC-SAFETY BAND MANAGEMENT

Since its creation, the Federal Communications Commission (FCC) has licensed public-safety spectrum by segregating uses/users into eligible and non-eligible categories to control radio interference. Eligible users compete for very small slivers of available spectrum. "The results are: (a) a set of narrow slots spread throughout the spectrum that users of different eligible classes cannot traverse; (b) a body of super-expensive technologies designed to serve specific channel assignments; and (c) a patchwork of non-interconnected transmission facilities serving single-use licensees. Each user/licensee is compelled to build its own infrastructure, and jealously guard its spectrum allocation and existing licenses [2]." This fragmentation of the public-safety spectrum results in artificial spectrum scarcity. As we discuss below, the spectrum pooling concept can help correct this problem.

In 1982, Congress provided the FCC with the statutory authority to use frequency coordinators to assist in developing and managing the LMR spectrum. Frequency coordinators are private organizations that have been certified by the Commission to recommend the most appropriate frequencies for applicants in the designated Part 90 radio services. In general, applications for new frequency assignments, changes to existing facilities, or operation at temporary locations must include a showing of frequency coordination. Although the FCC issues the actual license, frequency coordinators perform essentially all of the spectrum acquisition activities on behalf of licensees. Each community of users in the LMR bands has at least one frequency coordinator entity that is owned and operated by its trade association, or in the case of the Federal Government, by the Department of Defense (DOD).

In the newer 700- and 800-MHz bands designated for public safety, the FCC has required that RPCs be formed to create policy and to prioritize uses for the band on a regional basis. The RPCs must submit detailed regional plans to the FCC that are developed by consensus in each region and that serve to pre-coordinate access to the band for all eligible public-safety entities in a region.

The essential role of both the frequency coordinators and the RPCs is to organize the access to spectrum so that interference is avoided, and communications requirements (both present and future) are planned for and accommodated. Frequency coordinators and RPCs also perform the valuable function of communicating with existing licensees about plans for new facility construction, and they provide a valuable consensus and peer-review function. Additionally, RPCs can establish prioritization for the band through a consensus-based process.

The RPCs and frequency coordinators are federally sanctioned and empowered, trusted, local, user-owned, and controlled agents who implement group (pool) policies to manage spectrum and avoid interference. If the RPCs were authorized and empowered to implement more extensive and flexible policies that could be enforced by better technologies, public-safety spectrum management could move out of a spectrum-scarcity paradigm and into a world where communication was always available and portable across both geography and spectral bands.

THE DYNAMIC COOPERATIVE-POLICY FRAMEWORK

The recent adoption of the NIMS and the Incident Command System (ICS) within the NRF provide an excellent working basis for the new

[2] The NRF describes the national framework for responding to all hazardous events, including describing who is responsible for what. The NIMS is the system/framework under the NRF for managing the reporting and tracking of domestic hazardous incidents across all federal, state, and local agencies. See National Response Framework (NRF), U.S. Department of Homeland Security, January 2008 (available at: http://www.fema.gov/emergency/nrf/) and National Incident Management System (NIMS), U.S., Department of Homeland Security, March 1, 2004 (available at: http://www.nimsonline.com/docs/NIMS-90-web.pdf). The incident command system (ICS) is a management tool, originally conceptualized in the 1970s, intended to assist in emergency response. It identifies best practices and is an important element of NIMS (see http://www.training.fema.gov/EMIWeb/IS/ICSResource/index.htm or Incident Command System Review Materials, 2005; http://www.training.fema.gov/EMIWeb/IS/ICSResource/assets/reviewMaterials.pdf).

To fully realize the benefits of sharing on a large, national scale, standardized approaches toward sharing must be developed to simplify negotiating multilateral sharing agreements and to facilitate the design and production of equipment that can take advantage of pooled bands.

paradigm for dynamic policy-based spectrum management. The NIMS is a set of generic protocols for incident preparedness, management, response, and recovery that all U.S. first responders must conform to. The NIMS includes the ICS, which defines the specific way incidents will be managed, from very small and local to major nationwide disasters. The ICS and NIMS include planning and response and recovery protocols for day-to-day, tactical, and emergency activities.

With national frequency coordinators managing the knowledge of license rights granted in all bands across the nation, with RPCs empowered to create static regional prioritization rules and access protocols, and with the NIMS and ICS to ensure hierarchical consistency and to guide local-layer dynamic prioritization and localized, tactical network formation on the ground; the federal, state, and local public-safety communities have a significant part of an institutional framework in place to enable public-safety spectrum pooling.

Transferring Incident Management Values to Spectrum Management

DSA/CR and associated radio technologies will provide the technical solutions to enable spectrum rights and authentication to be transferred dynamically and to enable radios to follow the policies associated with more complex spectrum transfers and authorizations. Facilitating the commercialization of these advanced radio technologies, however, *requires* the creation of spectrum pools. This is a classic chicken/egg problem. Without spectrum to share dynamically, the value of deploying DSA/CR technology is reduced. Without commercially available DSA/CR equipment, incentives to invest in the business relationships and policies required to share spectrum are reduced. Pooling of public-safety spectrum can address this conundrum.

Spectrum Pooling Extends Radio Resources for Incident Response

In the most general sense, spectrum pooling is the situation wherein multiple users share access rights to a common pool of spectrum. We envision a context in which holders of exclusive-use licenses for public-safety spectrum would voluntarily agree to contribute their spectrum to a common pool. Access to the pool would be closed, relative to an unlicensed regime of open-access, to all/any complying devices. In essence, the license rights would transfer to the pool from the individual. The use of the spectrum would be in compliance with pool policies.

Enforceable restrictions on who is permitted to use pooled spectrum and strong limits on what constitutes acceptable secondary use likely will be important. At the radio-system level, technologies and access policies/protocols must ensure that the radio will learn and confirm that spectrum is accessible, that access is allowed (including the terms that govern such access), and that its use is appropriate (i.e., a better alternative is not available). Additionally, the radio systems must include the capability to signal and learn when conditions change (e.g., when the primary user must preempt or reclaim pool spectrum) and allow the radio to release the spectrum when it is no longer required or the radio is no longer allowed to use the spectrum.[3] This makes it feasible to allow the intended use to dictate the best choice of spectrum usage, based on factors including the radio environment and location (e.g., "I am underground."), the application (e.g., "I must stream video."), the incident (e.g., fire, hurricane, interstate pile-up, chemical spill), the role (e.g., "I am a paramedic."), and the permissions (i.e., "I have authority.").

Pooling can enable DSA/CR radios to combine narrowband channels opportunistically to support broadband access. Pooling provides not only a way to access spectrum without individual licenses, it creates the mechanism for spectrum policies to be authored, adopted, and transmitted to DSA/CR radios. Pooling is the first step in dynamic spectrum management.

To fully realize the benefits of sharing on a large, national scale, standardized approaches toward sharing must be developed to simplify negotiating multilateral sharing agreements and to facilitate the design and production of equipment that can take advantage of pooled bands. Standardized approaches are also important to enable users to roam more widely, even nationally.

Standardized Elements for Pooling

A number of core systems/elements are required to appropriately manage spectrum pool access and usage policies.

Structured Pooling Policies — Spectrum-access policies are required both for placing frequencies into a pool and for accessing them from a pool. Some policies may be static, some may be universal, and some may be dynamic or regional. Some policies may be invoked only in certain circumstances and at certain locations. Some static policies can be hard-coded into the CRs when they are manufactured, whereas others can be downloaded periodically from a database. We envision a hierarchy of spectrum pool policies that guide the radio to the best choice for channel selection, based on its ability to resolve available options within a structure of rules.

Figure 1 represents a possible policy hierarchy for pooling and accessing spectrum. After the radio learns the static policies that apply in any location, it can resolve dynamic user requests for spectrum, based on more situational policies, depending on such factors as the application, the user's role in the incident, or the developing ICS as an incident grows and wanes.

Policy Servers — Policy servers are the primary infrastructure element of a DSA/CR radio network. Replacing radio system controllers, which control channel trunking and channel assignments in an LMR network today, policy

[3] *See [3] for a discussion of how time-limited leases can be used to implement this functionality.*

servers will sit at multiple locations in a network, including the incident area to enable local incident command to issue specific policies to responder radios (e.g., to set up a tactical network). As the radio powers up and authenticates, it asks the server for its policy update, role, and tactical assignment information as shown in Fig. 2.

Embedded CR Technology — CRs must include appropriate technology to enable them to know and obey DSA policies. For some policies, especially the most dynamic and location/context-dependent, the CRs must know their location and specific characteristics of the spectral environment in that location. Other policies can be hard-coded.

Policy Authoring Tools — Standardized policy authoring tools are required that enable flexible policies to be designed and communicated to the radio infrastructure and managers. CR policies must be rendered into appropriate machine-readable formats and distributed to the radios and the band managers. Moreover, conflicts among policies must be detected and resolved.

Policy Enforcement — To ensure that policies are followed, and that all policies co-exist without conflict or interference, a policy enforcement system is required.

Spectrum Portability — A user must have the ability to roam with his radio across applications, locations, and networks. The ability to serve the radio the best available channel for the user (based on role and authentication), the use (i.e., applications, e.g., broadband, video, or sensor data), and the location ("I am providing mutual aid to a community that is not my home base.") is what we call spectrum portability. Our concept has important differences from current trunking practices. Today, radio systems that can trunk channels, serve the next and best-available channel to the user requesting a talk channel. However, that only works in the user's home radio system, where the radio is hard-coded with access to a limited number of talk groups, and the base stations are hard-coded to specific frequencies. Because a DSA/CR radio will not rely on hard-coded base stations, but instead will sense "white spaces" in a broad range of frequencies, it will, in theory, have the capability to transmit on any unused channel at any given time. Its decision about which channel to use will be determined, not by hard-coded information (having the "system key" installed in current trunked system architectures), but by knowing and following the policy rules of the pools for each band. A public-safety DSA/CR radio could be "told" to access only the public-safety spectrum pools. But the policy servers and policy enforcers must recognize and authenticate this radio as a public-safety radio before it receives its policy download. This recognition and authentication should be portable across the nation much like recognition and authentication of cellular phones currently is portable across national networks. Such portability involves the development of roaming agreements between infrastructure owners, allowing access to infrastructure resources such as policy servers, backbone networks, switches, and frequencies.

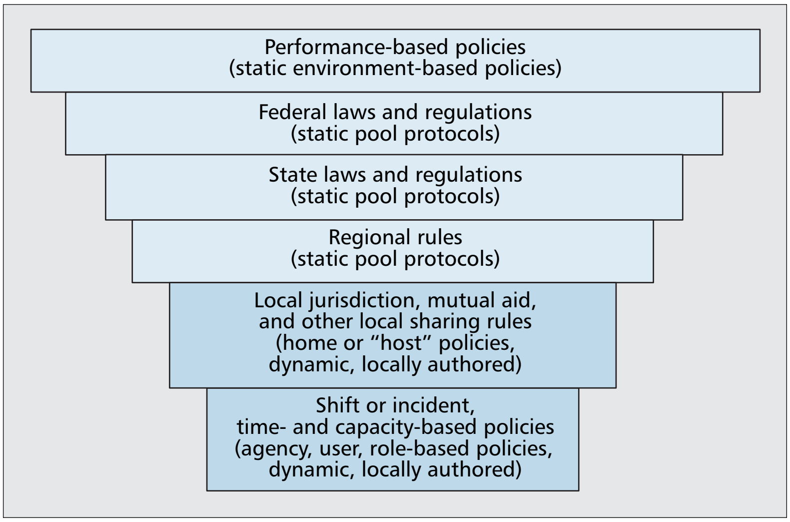

Figure 1. *Hierarchy of pooling policies.*

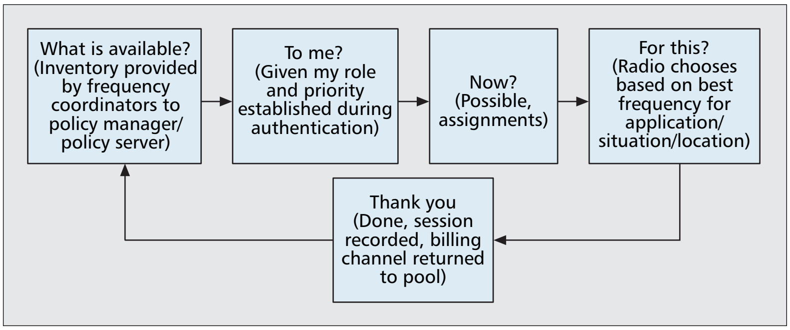

Figure 2. *How policies resolve.*

The pool managers must be vested with the ability to represent pool members and commit pooled resources to binding mutual agreements between pool members and suppliers of network resources (such as infrastructure, additional secondary rights to other pooled frequencies, and application services). This is required to economize on transaction costs. It is impractical to expect individual licensees to negotiate individual agreements with each other. We believe that frequency coordinators are well positioned to manage this top level of DSA pool relationships and transactions.

Overcoming Challenges to Spectrum Pooling

Spectrum pooling and DSA represent elements of a cooperative spectrum management regime. This paradigm is very different from the current prevailing command-and-control approach that underpins spectrum allocations and rights. Because it is so different, the public-safety community and wireless stakeholders generally are not expected to embrace the concept until it is challenged and proves effective. Table 2 summarizes what we see as both real and perceptual challenges to spectrum pooling in public safety.

Real Challenges
Technology will not work as expected • Legacy services will work less well than with traditional technology • Prioritization will not work, Secondary uses not preemptible • Shared spectrum will have more congestion, less assured peak access than traditional model • Systems will fail to perform as predicted/promised
Government regulations will not permit • Necessary changes in regulatory framework will not occur • Political failure, Resistance of *status quo* vested interests
Early-adopter challenge • Pioneers face higher costs, lower benefits (network externalities) • Getting the adoption bandwagon started
Cost of NextGen Public Safety wireless systems • Learning, scale & scope economies accumulate over time, lowering costs • Managing cost recovery of shared systems • Incremental deployment and managing overlays
Perceptual Challenges
Risk of losing spectrum assets • Spectrum shared will not be reclaimable • Loss of ability to obtain additional spectrum allocations • Loss of control over radio networks
Systems will not be adequately reliable • Systems cannot be made robust (or as robust as legacy systems) • Cost of making systems adequately robust prohibitive for public safety radios • Systems will fail to meet standard of "worst case" planning which is necessary
Expanding pooling to wider communities • Sharing beyond narrow first-responder/public safety community infeasible, too risky

Table 2. *Challenges for spectrum pooling in public safety.*

Conclusions and Future Research Directions

The radio frequency spectrum must be shared much more intensively than has been possible with legacy technologies, business models, and regulatory policies. A paradigm shift is required to enable a wireless future of greatly expanded wireless usage and advanced capabilities required by our information-based economy and society.

The need for this paradigm shift is especially acute in the public-safety community. The legacy regime severely limits interoperability among first responders and with those with whom they must communicate. The fragmentation of infrastructure into incompatible silo-based networks increases costs, reduces available capabilities and capacity, and ultimately, harms the ability of public-safety professionals to perform their jobs.

The traditional approach of over-provisioning static network infrastructure to meet worst-case scenario requirements is neither feasible nor desirable. Luckily, it also is no longer necessary. DSA technologies like software/ CR are making it feasible to share spectrum much more intensively. Transitioning to a future of DSA/CR for radio will enable radio systems to be much more flexible and adaptable to local conditions. This will increase system capacity and capabilities, enhance interoperability and reliability, and reduce costs.

Although the wireless future is bright, reaching it will not be easy. Coordinating the design, investment, and deployment of new technologies without disrupting existing operations will be challenging. Even if all of the requisite technology existed and were commercially available at scale — which is far from the current reality — we would be required to reform business models and spectrum-management policies to enable use of the technologies.

One important and mandatory first step toward building the wireless future is to transition to spectrum management based on spectrum pooling. With pooling, public-safety users would expand their effective access rights and facilitate the adoption of DSA/CR wireless technologies.

Significant progress already was accomplished toward establishing the institutional and policy framework to successfully implement the spectrum pooling concept. The NRF, the NIMS, the ICS, frequency coordinators, and the RPCs provide some of the glue and apparatus required to coordinate and manage pooled spectrum. Essential components (e.g., agreement on prioritization policies to manage shared access) still must be developed and challenges overcome (e.g., mobilizing coordinated adoption of DSA/CR technologies) to progress along the path to next-generation public-safety communication systems.

To maximize the likelihood of a successful transition, it is important to move incrementally. If public-safety professionals are to be convinced that spectrum pooling is indeed a concept whose time has come, they will require assurance that they will not experience any degradation in current capabilities or loss of resources. Future progress will build on early experience and learning. Over time, however, we expect the spectrum sharing concept to be accepted. All future wireless systems should be more dynamic and capable of interacting with expanded notions of priority in spectrum access rights. Public safety provides an important first-test case for commercialization of these sharing ideas, and success here will deliver positive externality benefits for the wider adoption of DSA/CR more generally.

REFERENCES

[1] W. Lehr and N. Jesuale, "Spectrum Pooling for Next Generation Public Radio Systems," *Int'l. Symp. New Frontiers at DySPAN 2008*, Oct. 2007.

[2] N. Jesuale and B. Eydt, "A Policy Proposal to Enable Cognitive Radio for Public Safety and Industry in the Land Mobile Bands," *Int'l. Symp. New Frontiers at DySPAN 2008*, Apr. 2007.

[3] J. Chapin and W. Lehr, "Time-Limited Leases for Innovative Radios," *IEEE Commun. Mag.*, June 2007.

BIOGRAPHIES

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