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Spectrum Pooling for Next Generation Public Safety Radio Systems

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ABSTRACT

The Dynamic Spectrum Access (DSA) research and development community is maturing technologies that will enable radios to share RF spectrum much more intensively. Adoption of DSA technologies by the public safety community can better align systems with the future of wireless services more generally 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 in order to create spectrum pools that DSA-enabled devices such as Cognitive Radios (CRs) may make use of 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 paper examines the economic, policy, and market challenges of enabling spectrum pooling and portability for public safety radios.

1. 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 more flexible and adaptive radio architectures, capable of sharing the RF spectrum much more intensively than is feasible with today's currently deployed technologies, regulatory frameworks, and business models. Such increased sharing is critical for the continued growth of wireless services in order to help alleviate growing spectrum scarcity. The commercialization of DSA technologies represents an important next step in the evolution of the wireless services ecosystem. The need for and the opportunities offered by DSA are especially relevant to the public safety community, which provides an important test case for the commercialization of DSA techniques.

The current landscape of wireless networking reflects the legacy of a world premised on a more limited set of user/system capabilities and needs, reflecting some fundamental assumptions about static network architectures and spectrum allocations. In this world, public safety networks have traditionally been designed to meet channel capacity and reliability "standards" that are based on user requirements at the "worst case" level – that is the capacity and reliability necessary during an emergency or catastrophe. It is not assumed that the network will *always need* these levels of capacity and reliability during "day to day" operations. But it is assumed that the network must *always have* these levels of capacity and reliability available when needed. Such worst-case planning implies that significant spectrum and equipment resources need to be "stockpiled" and remain unused most of the time. This creates significant *artificial* spectrum scarcity.

The wireless world is changing. The needs for wireless systems of all types, and for public safety systems in particular, have greatly expanded. This increases the costs and collective infeasibility of continuing worst-case planning and the wasteful allocation of resources it implies. As we explain, the radio future, of necessity, will require shifting to more DSA-friendly modes of spectrum usage. Besides being inevitable, the transition to DSA will offer many significant benefits for the public safety community and wireless users more generally. These benefits will include better mission responsiveness, expanded capabilities, and ultimately, lower costs. However, getting to this future will also entail 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.

In this paper, we explain why public safety spectrum pooling – the sharing of public safety spectrum among public safety users and possibly others – is an important and logical first step toward the transition to DSA. Even if one assumes that all of the requisite technology existed today, the DSA world would be hampered by a lack of appropriate policies and business models to enable DSA's safe use. While further technical research and product development is certainly needed, our focus here is on the policy and business practice challenges of developing DSA technologies for use by public safety systems.

To make our case, we first articulate a vision of the radio future in Section 2, including explaining more fully how DSA/CR relate to the requirements for next-generation public safety systems. In Section 3, we examine the role of government spectrum management policies in creating the legacy environment and the steps being taken that make it now reasonable to adopt the spectrum pooling concept as a logical next step. In Section 4, we examine more fully the concept of spectrum pooling and summarize the benefits for public safety from moving toward the DSA/CR future. In Section 5, we discuss some of the practical next steps that may be taken and core elements that are needed to implement spectrum pooling, before turning in Section 6 to address some of the key challenges impeding adoption of the concept. Section 7 concludes with a discussion of some of the broader issues and benefits expected from the success of public safety spectrum pooling and directions for future research.

2. CHANGING ENVIRONMENT FOR PUBLIC SAFETY RADIOS

As we explain, the future of radio systems of all types –- but especially those for public safety -- will require much greater reliance on Dynamic Spectrum Access (DSA) and related technologies. This is clear from examining trends in technology and research priorities, market growth, and the changing mission requirements for public safety professionals. DSA is necessary to enable new capabilities in the face of growing demand for spectrum access from all sources.

2.1. Vision of the Radio Future

While the precise shape of the radio future may be difficult to discern, certain key aspects appear certain. The radio future will include lots more wireless of all kinds, greater demand for mobility and portability and more heterogeneous wireless networks. These future developments will have concrete implications for radio network design, including the need for more broadband capacity, enabling more dynamic and flexible services and spectrum sharing.

In the following sub-sections, we discuss more fully each of these developments for the public safety radio future.

2.1.1. Lots more wireless of all kinds

There will be many more wireless users, uses, and devices and lots more wireless traffic than we have today. This means that demand to share RF spectrum will intensify. There will be more and richer interactive communication among users (multi-party) and with devices (computers talking to people and other computers). These communications will include exchanging mixed video, voice, and data for services such as video conferencing, video streaming, distributed collaboration and resource sharing (files, printers, storage), and cable-free interconnection. There will be increased use of both remote (passive) sensing (via satellite imaging) and active sensing (via RFID or active sensor networks). This means there will be a greater need for higher bandwidth wireless services (broadband) and more flexible/dynamic platforms to support changing user/application needs since the requirements of applications will differ and the range of applications used by different users will also vary (over time, by location, and by type of user).

The same will be true for next generation public safety systems, especially in light of the heightened awareness of the need to coordinate across multiple agencies in our post-9/11, post-Katrina world. First-responders will need lots more wireless of all kinds to allow them to communicate with the wider array of agencies and departments with which they will need to coordinate; to take advantage of the sensor technology being built into today's smart buildings and embedded in transportation grids; to make use of high-resolution satellite imaging; and to enable their personal smart appliances (e.g., biometric monitors embedded in safety gear and clothing) to communicate with on-site management and possibly hospital personnel.

2.1.2. Greater demand for mobility/portability

A key feature of wireless is that it enables mobility. This includes the fast mobility required to sustain a conversation in an automobile going 100km/hour while passing across the coverage areas of several base stations as well as the slower mobility of pedestrians moving around the coverage area of a single base station. It includes the mobility associated with nomadic uses (WiFi hotspot roaming) and to support equipment/user moves within an office, across town or state, or to another country. It includes the flexibility of cable-free deployment.[1] Moreover, increased mobility often also implies a need for greater portability with its attendant limitations on form factor, weight, and power (batteries). While not all wireless devices need to be portable or have the same mobility requirements, demand for such portability and mobility (in all its attendant flavors) will surely increase. And, of course, for public safety users, mobility and portability are essential features. First-responders in remote areas or areas where infrastructure has been destroyed or is otherwise over-burdened may have no alternative but to bring their communication capabilities with them.

2.1.3. More heterogeneous wireless environment(s)

There will be many types of networks and networking environments to support all of these wireless uses and users. This will include Personal Area Networks (PANs), Local Area Networks (LANs), and Wide Area Networks (WANs).[2] In the public safety context, these concepts are expressed with slightly different emphasis. Public safety requires PANs, Incident Area Networks (IANs), Jurisdictional Networks (JANs) and WANs.[3] These wireless networks will be implemented over a wide-range of technologies and architectures (high and low power, broadband and narrowband, fixed and mobile, hierarchical and peer-to-peer,

[1] For example, Bluetooth or UWB to connect stereo components or personal biometric monitoring sensors mounted on a patient or first-responders hazmat suit.

[2] Wireless technologies for different ranges (from a few inches to thousands of miles) and use environments have very different requirements that give rise to specialized and different technologies. While technologies designed for one purpose may often be used for another (e.g., VoIP over WiFi), there is no single technology/architecture that is best in all situations.

[3] See Section 8, SAFECOM, "Public Safety Statement of Requirements for Communications & Interoperability," U.S. Department of Homeland Security, Volume I, Version 1.2 (October 2006) ("SAFECOM SoR") (available at: http://www.safecomprogram.gov/NR/rdonlyres/8930E37C-C672-48BA-8C1B-83784D855C1E/0/SoR1_v12_10182006.pdf).

centralized and distributed, planned and ad hoc) under a variety of business models (customer-owned and operator-provided, for-profit and subsidized, single and multi-provider).

The heterogeneity in infrastructure and service models will be mirrored by (and driven in part by) the heterogeneity in end-user traffic profiles. We expect user traffic distributions to become more fat-tailed as new applications/uses become available and the range of user types expands. For example, sensors may expand demand for narrowband, delay-tolerant wireless networking while high-resolution video imaging (medical imaging) may expand the demand for high-bandwidth, real-time services. Individual traffic is likely to become more bursty (i.e., peak-to-average traffic rates will increase for most users and the range of user types will expand) as new higher data rate services become available.[4]

2.1.4. Greater demand for modularity, openness, and integrated services

Demand will grow for all types of electronic communication services, both wired and wireless. The growth in wired services will be synergistic and complementary to the growth in wireless.[5] An obvious implication of this will be to increase demand to support seamless integration and interoperability across wired and wireless services and networks.

Modularity, componentization, standardization, and open interfaces have helped drive the exponential cost reductions and productivity improvements that have characterized information technology for many years. These trends in hardware and software system design have helped enable mix-and-match bundling (expanding the product space to augment aggregate demand), facilitated the realization of global scale and scope economies, and helped promote competition, with its attendant benefits in terms of encouraging still greater efficiency improvements.

These benefits will continue to be felt across the entire Information and Communications Technology (ICT) value chain, but increasingly across wireless services and devices, which traditionally, have been more likely to be single purpose, closed/proprietary, integrated systems. For public safety to benefit from these economies of scale, it must adopt the same advanced technologies as the larger community of commercial users. The concern with commercial off-the-shelf technology (COTs) in the public safety environment has always been, and will continue to be reliability. Commercial equipment spans the range from consumer-grade solutions where cost is often more important than reliability to industrial grade solutions, where communications infrastructure are regarded as mission-critical, essential services. Although public safety users may have somewhat atypical reliability requirements (e.g., public safety radios may encounter more averse environments than in the typical business office), this does not mean that their reliability needs are best addressed by building wholly separate, customized solutions. We address this further below when we discuss the challenges facing public safety users.

2.1.5. Broadband needed

While many of the future wireless services – including traditional voice and low-bit-rate data services do not require high-bandwidth channels – many of the newer services *will*. This will include bandwidth hungry applications such as high-resolution video streaming or video conferencing. Even narrower-band services such as voice-over-IP (VoIP) or other overlay services may need access to a broadband channel. This represents a new challenge for mobile networks and for the current spectrum management regime.

Traditional spectrum management has sliced spectrum into narrow frequency bands, especially for the beachfront lower-frequency spectrum below 3GHz. While advances in modulation techniques continue, the biggest benefits in accelerating data rates are likely to come from spreading signals over wider-frequency bands (spread spectrum). This is especially true for legacy public safety radio systems in which narrow banding and dedicated channel assignments have left the public safety spectrum overly fragmented. DSA technologies may enable the bonding of multiple narrowband channels and facilitate dynamic service relocation to meet broadband "on demand" needs.

2.1.6. More dynamic, flexible, and interoperable radios needed

The increased heterogeneity of uses, users, and environments means that radio systems will need to become more flexible and dynamic as well as more reliable. This flexibility and reliability is needed to support the heterogeneous usage models. Users do not want to carry separate radios for each of their diverse application tasks. Flexibility and dynamic adaptability are also needed to help support end-to-end interoperability and reliability in the heterogeneous networking environment expected in the future. Additionally, increased flexibility and dynamic capabilities are needed to support end-user customizability and are in keeping with the trends toward modularity, competition, and open systems discussed above.

One key direction for expanding the capabilities of wireless systems is to better enable federated, ad hoc, mesh networking to support end-to-end interoperability across diverse users/applications/networks, to support roaming, and to

[4] All users will be heavy users some of the time (when they use resource-intensive applications), and there will be more users who are heavy users more of the time (and those who are light users more of the time). Examples of all such profiles/users are easy to suggest.

[5] Although in some cases, wired services may be viewed as substitutes for wireless, overall, we expect the impact of growing wireless and wired services to be complementary. For example, consider how WiFi routers helped increase aggregate demand for DSL/cable modem services by making such services more valuable. And, consider how the expansion of fiber toward the edges of wired networks expand the capabilities of high-bandwidth, shorter-range wireless services.

expand coverage.[6] These capabilities, which are of special importance to public safety radios, are largely missing today. They can also provide so-called "infrastructure-less" or "carrier-free" networking. For example, public safety users in a community may find themselves in a location where there is no public safety or operator infrastructure (e.g., they are in a remote locale or the infrastructure has been destroyed). Ad-hoc networking will be a key innovation on the reliability front. If devices can rely on the ability to self-form networks, without power or transmission infrastructure, a key concern about today's network reliability and resiliency (that the tower will go down) is moot.

Finally, the rapid pace of innovation and the need to communicate between legacy and new systems further accentuates the need for flexibility and interoperability.

2.1.7. Spectrum sharing needs to increase

The overall growth in wireless of all flavors and the need to support broadband and heterogeneous usage implies that spectrum will be increasingly scarce. Dedicating spectrum to a specific use or radio technology and "worst case" provisioning typical in public safety architectures will be harder to sustain. Users and uses will need to share spectrum more intensively. There will be many drivers for increasing spectrum sharing.

First, there are demand-side drivers propelling wireless services toward greater spectrum sharing. For example, increased demand for broadband services and more dynamic services make it less feasible to dedicate spectrum to a single use/user in advance of an actual need.

Second, users seeking seamless interoperability are going to expect their services to roam across diverse devices, wireless platforms, and from wireless to wired networks. From a commercial perspective, operators are going to want to offer services that support a customer experience that is independent of the physical layer (as much as possible). In the public safety realm, responders will need to access applications that are familiar whether they are in their home area or not, and whether they are mobile, or in the stationhouse. This drive toward increased interoperability and independence between infrastructure, services, and applications/uses will be accentuated by industry restructuring (through mergers and acquisitions) in the carrier community that will change the spectrum resources available to the operator and the networks that need to be integrated and supported.

As the carrier marketplace changes, the public safety landscape will change with it. Public safety users will expect (justifiably!) to have available enhanced applications which are (at least) as capable, simple to use, and offer the same sort of ubiquitous, plug-and-play, 24/7 availability across multiple vendor platforms as will be available to mass market consumers.

Third, on the supply-side, spectrum sharing will contribute to efforts to minimize network provisioning costs in the face of increasing traffic burstiness, fat-tailed usage patterns, and the need to support multimedia traffic. These forces will encourage commercial and public safety network operators to adopt technologies for sharing spectrum resources more intensively.

Fourth and finally, regulatory policies for spectrum management are being reformed. Restrictions that precluded more intensive spectrum sharing are being removed. For example, new allocations of unlicensed spectrum and more flexible licensing frameworks (e.g., technology neutral, tradable licenses) are being adopted in a number of countries. The unprecedented award of a national license for public safety broadband spectrum to a non-profit trust in the US is another example of policy reform that enhances prospects for sharing.[7]

2.2. DSA, Cognitive Radio technologies help make wireless future feasible

At the same time that user requirements for wireless services are increasing and the policy environment is becoming more favorable to spectrum sharing, the capabilities of wireless technology have expanded significantly. Advances in antenna design, signal processing, software/cognitive radio, and new networking technologies (e.g., mesh and ad hoc networking) are making it increasingly feasible to support the diverse array of wireless services and usage scenarios suggested by the future described above.

These technologies significantly expand the capabilities of wireless systems to support more rigorous application requirements such as higher data rates and better signal resolution in more adverse environments (e.g., with lower power, lower signal-to-noise ratios, and more congestion) and at lower cost.[8] These technologies also make it increasingly viable to implement systems that are more dynamic and responsive to their local environments, including allowing those devices to be frequency agile.

Collectively we refer to these as Dynamic Spectrum Access (DSA) technologies. These allow radios to traverse one or more frequency bands across time, geography, and users/uses. While such sharing may be enabled by a single network operator over spectrum resources under a single party's control (e.g., when public safety networks trunk frequencies and share them among multiple entities), more generally, such

[6] Federated networking refers to the ability to traverse heterogeneous network architectures owned by others. Ad-hoc networking refers to the ability for devices to communicate without network infrastructure. Mesh networking is a specific type of ad-hoc networking wherein devices form networks by routing traffic from and to other devices nearby.

[7] We refer to the recent award of the 700 MHz public safety broadband spectrum license to the Public Safety Spectrum Trust (PSST). This policy is discussed more fully in subsequent sections of this paper.

[8] At this early stage of development, DSA/CR technology solutions are likely to be more expensive than legacy solutions when used for legacy applications, at least in the near term.

technology may enable spectrum sharing across multiple providers' infrastructure and users. This includes infrastructure-less mesh or ad hoc networking. Such sharing could utilize unlicensed spectrum or share exclusively licensed spectrum resources (i.e., spectrum pooling – as we shall discuss further below). While the unlicensed management model provides only limited interference protection, the spectrum pooling model is explicitly designed to provide robust interference protection.[9]

Cognitive 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., that may limit the range of waveforms allowed). The policy constraints are enforced by the radio's policy engine. Policies may include authorization to transmit in specific locations and frequencies at specific times, or may include access protocol constraints (e.g., listen-before-talk). These policies may be static and hard-coded into the radio, downloaded from a database, or may 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 in order to support the policy engine and because interference is a local phenomenon occurring at a receiver's location. This may be implemented via some sort of GPS technology (e.g., terrestrial or satellite). Finally, CRs are inherently multi-band radios, allowing the radio to transmit or receive in a wider range of frequencies than might be used in any specific communication environment. This allows CRs to opportunistically make use of unused spectrum and facilitates their interoperability with legacy radio systems.

While significant technical work remains to be done in academic research and commercial product development laboratories to field a commercially viable CR, prototypes already exist and many aspects of the technology are already embedded and working at scale in commercial systems. In this paper, 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. In the following table, we summarize how DSA/CR technology will aid in realizing the DSA future:

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[9] A key difference between unlicensed spectrum access and spectrum pooling is that the former does not prioritize or limit user access. With unlicensed spectrum, any device that complies with the technical access requirements may use the spectrum, and users are not protected from interference due to congestion or from other compliant uses. With spectrum pooling, the range of users may be restricted and priorities granted to enable interference protection. Assurances of such protection are likely to be essential in gaining public safety user trust and acceptance of the pooling concept, as we discuss further below.

Table 1: DSA & Cognitive Radio (CR) are key enablers of wireless future	
Need for:	How DSA/Cognitive radio helps:
More spectrum sharing	Focus of DSA is to enable more dynamic spectrum sharing, in all dimensions of spectrum space (geography, time, frequency, modulation scheme, etc.)
Flexible, adaptive, dynamic radios	CR may use local information to adjust their behavior in real-time, subject to policy constraints. This allows CR's to respond to changing needs and the user/usage environments.
Interoperability	CR concept supports ability to modify waveform to allow two radios to negotiate communication protocol, or to allow CR to communicate with legacy radios.
Broadband	DSA/CR can support sensing of RF "white space" and bonding of multiple narrowband frequency channels to support wider-band channels for broadband.
Ad hoc, mesh networking	CRs can negotiate with each other and other radios to support infrastructure-less or multihop mesh networks, which are especially valuable when traditional infrastructure is overloaded or unavailable (e.g., destroyed).

2.3. *Next Generation Public Safety radios need to enable the wireless future*

As already noted, the same forces that are shaping the future for commercial wireless apply with even stronger force to public safety wireless systems.

First, public safety first-responders are more likely than most other users of ICT to require mobile, wireless access. For many folks, a wired alternative may be less convenient, but may still be feasible. In many first-responder scenarios, the only option is wireless.

Second, first-responders who are dealing with life-and-death situations are perceived generally as having a higher social welfare value than commercial or leisure uses, and thus meriting higher priority in the event of competition for resources.

Third, first-responders may be more likely to deal with adverse environments. For example, in the event of a natural disaster or forest fire, first-responders may need to operate where there is little physical infrastructure (remote areas) or the infrastructure has been destroyed (Katrina, inside a burning tunnel underground). This increases their need for flexible, adaptive systems (e.g., 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 are likely to be concentrated in time and place, increasing the peak-provisioning problem.[10] While demand is likely to be positively correlated, pooling will enable users to take advantage of such multiplexing opportunities as exist and offer greater flexibility in prioritizing whatever rationing needs to occur.

Fourth, first-responder systems have traditionally been locally provisioned and subject to the vagaries of public funding. As such, these are often the users whose budget constraints and whose ability to fund dynamic capacity adjustments are most challenged.[11] As we discuss further below, this helps explain why public safety network operators are especially cost-sensitive and risk-adverse. Spectrum pooling will facilitate cost sharing and more dynamic capacity planning.

Fifth, while the general need for rich interactive multimedia entertainment services remains suspect (e.g., mobile television), there are many compelling first-responder applications promised by the wireless future. This includes much better capabilities for situation awareness (e.g., on-site medical video, remote/local sensing data sharing), interactive communications (e.g., video conferencing, robust telephony for adverse environments[12]), and interoperability support (e.g., to support inter-agency/department communications, roaming for mutual aid support). Specific demand scenarios are discussed further below.

Sixth, in the post-9/11, post-Katrina world, there is a heightened awareness of the challenges that first-responders and other public safety providers need to be prepared for, and the role for advanced wireless services such as those discussed above.

Finally, and in spite of the fact that the public safety needs have been understood for a long time, public safety system

[10] This is another reason why traditional worst-case provisioning is cost prohibitive in the public safety future.

[11] Oversight of public funding and non-profit status impose bureaucratic constraints on expenditures and budgets that make it difficult for public safety network operators to rapidly scale or adjust their capacity, and typically also impose tight constraints on overall spending.

[12] This includes voice conferencing in infrastructureless environments (underground, remote areas, where traditional infrastructure has been destroyed) and noisy environments (high interference).

capabilities are still woefully inadequate, even compared to the services available to commercial users (e.g., 3G mobile telephony v. legacy LMR systems). The public safety community shares this conclusion. According to the PSST:

> "Emergency responders have been demanding better tools to meet increased responsibilities and pressures. Public safety has long required more efficient and effective interoperable data communications systems and tools to meet its growing needs. For example, automatic vehicle location functionality, streaming video with high resolution images and computer-aided dispatch all support emergency responders and are capabilities needed to protect them and the communities they serve."[13]

Public safety radio systems need to continue to evolve to be consistent with the DSA future of radio system designs. They cannot rely on LMR designs "getting better." There is both the need and opportunity to replace outmoded legacy infrastructure with leapfrogging technology to enable the wireless future needed by public safety. Rather than continue development of static, private, and expensive narrowband digital LMR network infrastructures, public safety is in need of a network architecture where privacy, reliability, capability, adaptability and flexibility are built in, no matter whose infrastructure their radios traverse, or even when infrastructure is damaged or non-existent. The future of public safety radios needs to be much more adaptive and responsive to its environment (spatially,[14] temporally,[15] and situationally[16]) to account for the greater demands placed on first responders. A public safety responder should be able to take his radio, his authentication and security, his spectrum rights, and his priority with him to any incident in the country, power-up the radio, and be recognized and admitted to whatever incident command network he is authorized to support.

Table 2 summarizes our vision of the past, present, and future for public safety radio.

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[13] http://www.psst.org/publicsafetynetwork.jsp, last accessed 7-14-08

[14] Radios will need to be dynamically reconfigurable spatially to work within buildings, on-site, and in conjunction with wider-area coverage systems. Radios will need to support out-of-home area roaming.

[15] Radios will need to be dynamically flexible over varying time-scales, including being able to address congestion issues in real-time during an event and at longer time scales covering equipment reconfiguration (setting up for an event) and investment (upgrading and expanding system capabilities).

[16] Radios will need to be capable of adapting to special circumstances such as destruction/failure of existing infrastructure and special needs for interoperability (e.g., using commercial facilities). Longer-term, this implies graceful scaling of infrastructure.

Table 2: Past, Present and Future for Public Safety Radios			
	Past	Present	Future
What are 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/dept.	Yes. Shared access infrastructure and base station radios via trunking. Can share channels within trunk group but not otherwise.	Yes. Shared access infrastructure and radios. Pooling of spectrum for multiple trunked groups to share
Shared spectrum?	No.	Channel sharing within trunk calling group. No spectrum sharing.	Yes. Sharing of spectrum across bands. Pooled spectrum.
Infrastructure/ Spectrum tied?	Yes. Closely coupled, closed systems. Limited interoperability via gateways which ties up additional spectrum	Yes. Spectrum still tied to infrastructure so limited sharing. Gateways used to link systems.	No. Key to DSA is beginning of unbundling of infrastructure and spectrum. Infrastructure shared across multiple bands.
CPE	Single channel radios	Multichannel radios	Multiband radios and flexible CPE

2.4. Public safety user requirements that must be met

The above vision is fully consistent with emerging standards and requirements for public safety radios. Table 3 summarizes the statements of public safety radio requirements that may be gleaned from an analysis of important documents prepared by the community. These include the SAFECOM Statement of Requirements for Next Generation Public Safety Communications Systems,[17] Project MESA Statement of Requirements,[18] the NTIA Spectrum Policy for the 21st Century Report,[19] and the Public Safety Spectrum Trust Information to Bidders.[20] A system designed to meet all or even most of these capabilities will be, by definition a DSA system – as we explain below -- capable of efficient, flexible spectrum access, under strict and enforceable policies.

[17] SAFECOM is program of Department of Homeland Security focused on interoperability issues among state, local, and Federal public safety users. See *Statement of Requirements for Next Generation Public Safety Wireless Communications & Interoperability*, the SAFECOM Program, Department of Homeland Security, Version 1.0, March 10, 2004 (available from: http://www.safecomprogram.gov/NR/rdonlyres/3FFFBFBA-DC53-440E-B2EF-ABD391F13075/0/SAFECOM_Statement_of_Requirements_v1.pdf).

[18] Project MESA (Mobility for Emergency and Safety Applications) is an international collaborative effort to coordinate the development of next-generation mobile wireless data systems (see http://www.projectmesa.org/MESA_SoR/mesa_sor_executive_summary.pdf).

[19] See *Spectrum Management for the 21st Century: The President's Spectrum Policy Initiative*, National Telecommunications Information Agency (NTIA), March 2008 (available at: http://www.ntia.doc.gov/reports/2008/FederalStrategicSpectrumPlan2008.pdf) ("NTIA 21st Century Report").

[20] These are the rules advanced by the Public Safety Trust for potential D-block bidders (see http://www.psst.org/documents/BID2_0.pdf).

Table 3: Requirements for Public Safety Radio Systems		
Type	Capability	Source
Administration	Flexible and dynamic system administration (includes admin of wireless data networks, adding users, giving permissions, etc.).	SAFECOM
Authentication	Ability to initiate wireless data communications by requiring the user to enter (on his terminal/radio) a user identification that authenticates and validates the user and loads the user's profile. This profile defines data resource capabilities for the user and completes all radio network administration for the user's data communications with other members of the user's agency/jurisdiction and with other agencies/jurisdictions, as previously authorized	SAFECOM
	Capability to implement network preemption.	MESA
Bandwidth	Capability of high-speed data transfer with ability to sustain performance at network interconnections.	SAFECOM
Network	Support self-controlled prioritized use to dynamically address user needs.	WARN
	Ability to quickly and transparently establish and maintain on scene wireless data networks (e.g., in a building).	SAFECOM
	Ability of on-scene personnel to transparently exchange data.	SAFECOM
	Ability to sustain resilient operations, including tolerance to individual system failures, redundant coverage from adjacent sites, resistance to impact of catastrophic events, etc.	SAFECOM
	Two-way communication.	MESA
	Over-The-Air Rekeying (OTAR).	MESA
Security	Blocking of unauthorized access.	MESA
Spectrum	Share Spectrum vertically (federal, state, local) and horizontally (police, fire).	NTIA
	Access to additional spectrum during emergencies creates the ability to scale capacity for public safety upon demand	PSST
	Sufficient capacity to meet the needs of public safety, particularly during emergency and disaster situations.	PSST
	Improvements in spectrum efficiencies.	MESA
	Frequency neutral technology.	MESA
	Adequate interference protection.	MESA
	Regulatory compliance.	MESA
	Incorporation of frequency neutrality and/or agility.	MESA

2.5. *DSA Technology offers important benefits for Public Safety Radio Future*

The above requirements imply that the future of public safety radios will need to rely on DSA/CR. This is both necessary and desirable, because DSA/CR technologies offer important benefits for the public safety radio future. These benefits may be grouped into four key areas, as follows:

Table 4: Benefits of DSA/CR Future for Public Safety Radio
Increased spectrum access and system capacity • Enable secondary use, access "white space" • Reduce spectrum needed for guard bands, backhaul, interoperability channels • Take advantage of multiplexing of uncorrelated peak usage demands • Enable dynamic prioritization for optimal resource allocation during peaks
New services and capabilities • Flexibility and adaptability allow resources to be deployed where/when they are needed • Greater support for interoperability • Broadband from bonding of white space channels
Robustness, Reliability & enhanced Interoperability • Mesh, ad hoc networking enhance responsiveness to new failure modes • Dynamic frequency selection enables routing around faults/capacity limits • Open interfaces support mix-and-match interoperability
Cost-savings • Shared instead of dedicated infrastructure/spectrum lowers aggregate system costs • Economies of scale/scope over time and over systems lower costs • Enhanced competition from expanded market based on open interfaces • Deployment costs reduced because DSA/CR may be deployed incrementally, as overlay to legacy systems • Learning economies over time as experience accumulates with DSA/CR • Lower regulatory costs as management divulged to market and adoption of common future enhances opportunities for best-practices sharing

3. Public policy is on course to facilitate DSA in Public Safety

Today's public safety radio systems are fragmented, overly expensive, under-capacitated (with respect to desired services and capabilities), and support too limited interoperability. This is due, in part, to the legacy regime of dedicated, narrowband, and overly restrictive spectrum licensing. However, regulatory policy reforms such as the consolidation of licensing eligibility pools (discussed further below), 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 will depend on non-market institutions to coordinate cooperative evolution.

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) assist in providing the necessary evolution in the institutional framework for public safety spectrum reform.[21] These relatively new institutions are positioned to enable public safety managers to define global and local priorities, and both static and dynamic rules and policies that can assist in self-regulation[22] of spectrum use. The development of appropriate user-based prioritization and policies that reflect accepted practices in emergency management and incident response are required to support developing CR and DSA technologies. Such policies are needed to ensure reliable and safe spectrum and network resource sharing, and to garner the support of the public safety community.

In the following sub-sections, we examine the changing role of regulatory policy in shaping the spectrum management regime for public safety radios, and discuss the emergent institutions that we expect to play important roles in managing spectrum pooling in the DSA/CR future.

[21] The NRF and NIMS are discussed further below.

[22] Since RPC's are composed of "all" public safety users in a region, and must reach agreement by consensus, they can and do adopt policies which regulate the priority of uses for spectrum. These policies are generally followed by mutual agreement.

3.1. *Legacy of fragmented and non-interoperable spectrum licensing*

The traditional spectrum licensing framework has helped promote today's legacy of "silo" systems based on parochial, closed, proprietary networks and architectures. In the absence of adequate technologies to provide interference protection, government regulations perpetuated a legacy of specifically-licensed infrastructure that segmented users/uses on separate frequency bands and radio networks. These systems are not interoperable with each other (across agencies, across regions, and across responder communities from different locations) and are not adequately scalable or sufficiently flexible to meet today's greater wireless demands. Moreover, this legacy of silo/non-interoperable systems is expensive to support and unnecessarily wasteful of spectrum resources.

Since its creation, the FCC has licensed spectrum to users on the basis of the type of use or user, controlling interference among stations by segregating uses/users into eligible and non-eligible categories for 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;[23] 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."[24] As Jesuale and Eydt point out, "the Land Mobile Radio (LMR) services are particularly impacted. These bands spread from 25 MHz to 4.9 GHz, with interleaved slices of bands divided among the military, public safety and nearly 50 other classes of service squeezed between television broadcasting, mobile telephone, mobile data and other spectrum users." This fragmentation of the public safety spectrum into narrow bands limits opportunities for spectrum sharing (trunking and spectrum portability[25]), resulting in *artificial* spectrum scarcity.[26] As we discuss below, the spectrum pooling concept is intended to help correct this problem.

Over time, there have been a number of policy reforms that help make spectrum pooling more feasible. For example, in February 1997, the FCC consolidated land-mobile license classes into two general pools: a business/industrial pool for commercial, industrial and other government users and a public safety pool.[27] These pools combined a diverse array of geographic, frequency band-delineated spectrum allocations into common license pools. Eligible licensees in each pool are equally eligible to apply for frequency licenses within their respective pool; however, with today's technologies, a licensee cannot readily mix-and-match from multiple bands. Thus, each licensee is still limited to finding a single band with enough available channel assignments to meet their "worst case" capacity requirements.

3.2. *Frequency Coordinators and Regional Planning Committees*

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 (See CFR 47, Section 90.175). The frequency coordinator organizations manage the frequency blocks in the sense that they maintain databases on current owners and transmitters, contour coverage and interference studies, and can identify when a frequency can and cannot be licensed. Although the FCC issues the actual license, frequency coordinators essentially perform all of the spectrum acquisition activities on behalf of all licensees short of granting the license. 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). Non-federal users have several frequency coordinators that have been homegrown in an entrepreneurial marketplace of user/consultants/trade associations.

In the newer 700 and 800 MHz bands designated for public safety, the FCC has required that RPCs be formed to create

[23] The hyper-fragmentation of the LMR market produces small levels of buyer demand for very specialized equipment. A 20-channel digital trunked radio system in any band with three transmit towers and three repeater towers (typical mid-size city configuration) will cost around $20 Million. Portable radios will cost $3,000 to $6,000 each, depending on features -- or 1000 times more than an i-Phone!

[24] Quoted from Jesuale, Nancy and Bernie Eydt (2007), "A Policy Proposal to Enable Cognitive Radio for Public Safety and Industry in the Land Mobile Bands," in *IEEE International Symposium on New Frontiers Dynamic Spectrum Access Networks 2007 (DySPAN2007)*, April 2007.

[25] Essentially, spectrum portability is very similar to "roaming" and involves the ability to use spectrum access rights of the user on infrastructure owned and operated by another party. Under the current architectures and regimes, this is impossible. I cannot go to another state or another network, and have my public safety radio negotiate access to a channel in spectrum I am licensed to use for use on another licensee's network. Under a DSA paradigm, spectrum portability will be common, acceptable and necessary. The concept of Spectrum portability (the ability to be served the best frequency available by virtue of one's role at any place and time) is discussed further in the following sections.

[26] We refer to this as "artificial scarcity" because it results from regulatory constraints as opposed to technical or market constraints. More spectrum would be available for all users if regulatory policies allowed the cumulatively available spectrum to be shared more efficiently.

[27] The business/industrial pool now includes Power, Petroleum, Forest Products, Film & Video Production, Relay Press, Special Industrial, Business, Manufacturers, and Telephone Maintenance Radio Services and the Land Transportation Radio Services (Motor Carrier, Railroad, Taxicab, and Automobile Emergency Radio Services).

policy and prioritize uses for the band on a regional basis. The RPCs must submit detailed regional plans to the FCC which are developed by consensus in each region, and which serve to pre-coordinate access to the band for all eligible public safety entities in a region. However, once the RPC work is completed, each individual license applicant is still responsible to conduct a frequency coordination study, and submit its application through a frequency coordinator before the license is granted.

The essential role of both frequency coordinators and RPCs is to organize the access to spectrum so that interference is avoided and communications needs (both present and future) are planned for and accommodated. Frequency coordinators and RPCs also perform the valuable function of communicating with existing public safety licensees about new licensees preparing to construct facilities in nearby geographies, and they provide a valuable consensus and peer review function to insure that public safety entities in a region know about others with facilities and channel assignments in the same and adjacent bands. Additionally, RPCs can establish prioritization for the band in consultation with all users via a consensus-based process.

The RPC's have the administrative tools and ability to manage spectrum more efficiently than current rules and conventions allow. Essentially, these 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 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 RPCs and frequency coordinators can play an important role in collective management of pooled public safety spectrum.

3.3. *NIMS and ICS Supply the Dynamic Cooperative Policy Framework*

The recent adoption of the National Incident Management System (NIMS) and the Incident Command System (ICS) within the National Response Framework (NRF) provide an excellent working basis for the new paradigm for dynamic policy-based spectrum management.[28] The NRF is an overarching blueprint recently adopted by the Federal government for Federal aid and involvement in local incidents. The NRF includes and relies upon the NIMS, which is a set of generic protocols for incident preparedness, management, response and recovery which all US first responders must conform to. NIMS includes the ICS, which defines the specific way incidents will be managed, from very small and local to major nationwide terrorist or natural disasters. For example, when a major catastrophe or emergency occurs, multiple agencies are involved in responding, and are coordinated via the NRF and NIMS, which directs all responders, across vertical (Federal, State and local) and horizontal (multiple local jurisdictions and states) to use the national ICS. The ICS and NIMS include planning, response and recovery protocols, for day-to-day, tactical and emergency activities. ICS includes the management of communications resources for tactical, operations, support and air-to-air and air-to-ground networks.

NIMS and ICS are response systems that are replicated from the smallest local jurisdiction to the largest national event. The system is flexible, but internally consistent. The NIMS framework can be known in advance, and is generalizable to all situations, in all communities, at all times. It is a hierarchy of federal state and local policies, with the most static policies specified at the top level (federal), and the most flexible policies and delegation to local control at the site and during the emergency incident. As such, these response systems provide an appropriate policy framework for defining the operational policies needed to enable DSA/CR-based spectrum management.

With national frequency coordinators who maintain knowledge of all license rights granted in all bands across the nation, with RPCs to create static regional prioritization levels and rules and access protocols for users and uses, and with the NIMS and ICS systems 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 amount of the policy-based spectrum management puzzle solved. They basic policies and protocols are in place to enable public safety spectrum pooling.

However, although important progress has been made in establishing core elements to support shared policy and operational practices, technologies to code these policies into spectrum policies that DSA/CR radios can "follow" are not yet in place. Spectrum policy, and spectrum use by networks still has to be controlled statically. Spectrum portability (the ability to be served the best frequency available by virtue of one's role at any place and time) is not here yet. A first responder responding to an incident in another community today is unable to bring along a radio that can be used on the local radio system.

[28] The NRF describes the national framework for responding to all hazard 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 hazard 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, U.S., Department of Homeland Security, March 1, 2004 (available at: http://www.nimsonline.com/docs/NIMS-90-web.pdf). The 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), available at: http://www.training.fema.gov/EMIWeb/IS/ICSResource/assets/reviewMaterials.pdf).

DSA/CR and associated radio technologies will provide the technical solutions to allow spectrum rights and authentication to be transferred dynamically, and to allow 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 needed to share spectrum are reduced. Pooling of public safety spectrum can address this conundrum.

4. SPECTRUM POOLING IS AN IDEA WHOSE TIME HAS COME

We have explained our vision of the radio future and how this coincides with the requirements for next generation public safety systems. As we have explained, transitioning to a future that embraces DSA/CR technologies is necessary and consistent with core trends in wireless markets, technology, and policy. We have also highlighted the important roadblock to progress posed by the fragmentation of spectrum licensing. Spectrum pooling is a key concept that is intended to help alleviate this fragmentation and offer important benefits for all. In the following sub-sections, we explain what spectrum pooling is and how it might work, then highlight what we expect the important benefits to be derived from embracing the concept.

4.1. What is spectrum pooling?

In the most general sense, spectrum pooling is the situation wherein multiple users share access rights to a common "pool" of spectrum. This is the case with unlicensed spectrum in the ISM bands,[29] wherein multiple users share access to spectrum subject to complying with certain access protocols. While this provides one regulatory framework for how spectrum might be shared, it is not the one we have in mind here. Rather, 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. Any use of the spectrum would be in compliance with pool policies.

Implementation of this concept requires addressing two critical elements: first, what are the terms under which those contributing spectrum to the pool contribute their spectrum rights; and second, what are the terms governing usage of the spectrum. As we explain further below, we believe that generating user acceptance to this concept of spectrum pooling requires us continuing to regard those contributing spectrum as *primary* users with respect to the spectrum rights they contribute, and those who make use of the pool spectrum as *secondary* users. Primary users are presumed to have an enforceable (both technically and as a matter of policy) right to pre-empt secondary use. Whether the class of secondary users is limited to the set of licensees contributing spectrum, or some larger class of users is something that can evolve over time. The larger class of users might include non-public safety government agencies or non-government users such as hospitals or aid agencies, or even unrelated commercial users who may use the spectrum when it is not needed by the public safety/first-responder users. As we explain further below, we anticipate that generating support for this concept among managers of public safety spectrum will be easier if the distance from the current framework of exclusive rights is incremental. Stronger restrictions on who gets to use pooled spectrum and strong limits on what constitutes acceptable secondary use are likely to be important, at least initially. Over time, as experience accumulates, we believe more generalized sharing models will become more acceptable.

Additionally, it is reasonable to imagine that the "pool" of available spectrum might include rights that are shared in common (among all eligible pool participants as co-primary users[30]). For example, the FCC might elect to designate additional spectrum for use in the "pool" of available frequencies, to be shared among all qualified users (perhaps restricted to public safety uses). An example might be the FCC's allocation of the national license for the public safety 700 MHz block to the Public Safety Spectrum Trust (PSST). Local public safety agencies were presumed to be primary rights holders, even though the license was held "in trust" by the PSST.[31] An incremental designation of common pool spectrum (perhaps from the D-block or perhaps from other spectrum that may become available in the near future) to seed the "spectrum pool" could prove an important carrot to induce other public safety providers to contribute their rights to the pool. For example, access to the common spectrum might be made conditional on a public safety operator contributing its 800 MHz rights to the pool. Moreover, an initial allocation would help jumpstart the pool and help alleviate first-mover/chicken-egg problems by assuring that those contributing to the pool would gain access to at least some additional spectrum. Once again, experience gained with

[29] The Industrial, Scientific, and Medical (ISM) bands include frequencies at 900MHz used by cordless phones and 2.4GHz and 5GHz used by wireless LAN technologies like Wi-Fi. Use of these bands is unlicensed, subject to the requirements of complying with the FCC's Part 15 rules for unlicensed devices.

[30] Access among co-primary users may be prioritized according to whatever policies the pool managers deem appropriate, with guidance provided by he NIMS/NRF framework.

[31] The public safety 700 MHz license and the D-block are discussed further below. Under the current proposal, the FCC's plans call for a commercial licensee to construct a common national infrastructure that would be tied to both the D-block frequency band and the PSST's band. This overlay network would sell "wholesale" services to public safety users across the nation. An alternative perspective might call for this spectrum to be assigned to a common pool that could be shared by public safety infrastructure across the nation, which need not be integrated into a single network.

sharing a smaller, more restrictive spectrum pool ought to facilitate sharing of a larger pool over-time.

To provide a more concrete (albeit abstract) notion of how the above might work, consider two communities with fire and police departments (Pa, Pb, Fa, Fb), each of which have licenses to non-contiguous frequency bands (Spa, Spb, Sfa, Sfb). If these four agencies pool their spectrum rights, then in principal, each would gain access to a much larger band of spectrum rights (Spa+Spb+Sfa+Sfb). For example, Pa would retain primary access rights to Spa and would gain secondary access rights to (Spb+Sfa+Sfb). This would expand options for enabling interoperability among the agencies, support wider-band services for use by Pa, and would make resources available for mutual aid public safety support from out-of-town responders (Pb, Fb).

At the radio system level, for the pooling concept to be valid, there need to be technologies and access policies/protocols that support the requisite DSA/CR functionality anticipated by the sharing concept. This requires DSA technologies and processes to serve spectrum to the user's radio that will allow the radio to learn and confirm that spectrum is (1) accessible, (2) that access is allowed (and the terms governing such access), and (3) that its use is appropriate (i.e., there isn't a better alternative available). Additionally, the radio systems must include the capability to signal/learn when conditions change (e.g., when the primary user needs to pre-empt/reclaim pool spectrum) and allow the radio to release the spectrum when it is no longer needed or the radio is no longer allowed to use the spectrum.

4.2. Benefits from spectrum pooling

Spectrum pooling is necessary to transition to the DSA/CR future implied by the statements of public safety radio system requirements in Table 3, and to realize the benefits of expanded capacity, enhanced capabilities, improved interoperability, and reduced costs summarized in Table 4. Spectrum pooling will provide the reservoir of spectrum rights that may be accessed by DSA/CR enabled radios on a dynamic basis. CRs may access a larger number of frequencies across multiple bands than traditional radios. 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 (I am underground), the application (I need to stream video), the incident (fire, hurricane, interstate pile-up, chemical spill), the role (I am a paramedic), and the permissions (I have authority).

Without pooling, spectrum is managed with static band assignments and rules. Pooling allows DSA/CR radios to know the local, regional, state, and federal policies for using pooled spectrum, even if the radio user has brought the radio from a distant jurisdiction on a potentially ad hoc basis (unplanned mutual aid effort). Pooling can create the spectrum rights that DSA/CR radios need across multiple bands, with local dynamic and static policies that can be followed to ensure appropriate prioritization of access. For example, pooling will enable DSA/CR radios to opportunistically combine narrowband channels 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 creates the dynamic spectrum management needed for the advanced technologies to work.[32]

5. MAKING SPECTRUM POOLING WORK

The full potential of spectrum pooling will be realized when enabled among multiple classes of spectrum holders (public safety, commercial, federal and business/industrial licensees) using multiple spectrum bands. While political, economic, regulatory and organizational barriers may preclude the emergence of such generalized sharing for a long time, there are still significant benefits to be had from pooling spectrum more narrowly, among subsets of licenses and licensees. The public safety community and its dedicated spectrum present just such an opportunity.

In fact, the necessity for spectrum sharing has already been identified between federal, state and local spectrum holders to accomplish broadband networking, as a result of the WARN experimental network in the DC area[33] and the Alaska Land Mobile Radio (ALMR) system.[34] Spectrum sharing is also a key underpinning of the proposed national shared broadband wireless network (SBWN) contemplated for the D-Block 700 MHz spectrum combined with the public safety 700 MHz block.[35]

While the public safety community has recognized the need for more spectrum sharing, the mechanism for sharing has not been adequately addressed. To fully realize the benefits of sharing on a large, national scale, standardized approaches toward sharing need to be developed. Such standardized approaches will simplify negotiating multilateral sharing

[32] According to Jesuale and Eydt (2007): "Rather than just considering how to prevent interference in isolation, the new paradigm needs to organize spectrum access on the basis of co-existence, adopting, from the field of artificial intelligence, policy-based rules. These rules would govern priority use when contention for access exists, but otherwise maximize access to any available channel across a wide swath of frequencies."

[33] See "DC public safety network selected to monitor effectiveness in sharing radio spectrum with federal, state, and local governments," Government Technology, May 1, 2006 (available at: http://www.govtech.com/gt/articles/993555).

[34] See Alaska Land Mobile Radio: "Our commitment is to provide a wireless, cost effective public safety interoperable communication system for all of Alaska" (http://www.ak-prepared.com/almr/); or, Clifton, Kristine (2007), "Alaska Land Mobile Radio (ALMR) Update," powerpoint presentation, November 28, 2007 (available from: http://www.fea.gov/Documents/Spec%20Briefings/ALMR%20Update%20to%20FEA%2028%20Nov%2007.ppt)

[35] See, for example, Public Safety Spectrum Trust (PSST), "Public Safety Spectrum Trust Public/Private Partnership Bidder Information Document," November 2007, available from: http://www.psst.org/documents/BID2_0.pdf).

agreements and will 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.

In the following sections, we discuss the spectrum that may contribute to forming the pools and certain core elements needed to manage access to the pools once created.

5.1. Spectrum for Public Safety Pooling

The public safety community has long held that reliability and accessibility of its networks is primarily based on a reserved, licensed and private allocation of spectrum for its exclusive use. Most voice land mobile radio systems constructed by public safety entities in the United States use narrowband frequencies (12.5 KHz) in the very narrow (less than 4 MHz) VHF and UHF bands. Larger cities and States have developed narrowband trunked radio systems in the 800 MHz frequency bands. These bands are crowded, fully licensed, and narrowband-only. Today, there are two "Greenfield" bands reserved for public safety broadband applications: the 700 MHz public safety band (24 MHz) and the 4.9 GHz band (50 MHz). Both of these bands are essentially vacant today, and both are reserved for broadband applications.[36] There are very limited options for both network equipment and user devices because of the small, emerging market and the lack of certainty with regard to licensing in both bands. As such, these "empty" bands are possibly good candidates for the establishment of spectrum pools.

5.1.1. The 700MHz Broadband Public Safety and D-block bands

The broadband 700 MHz public safety band was recently removed from the general pool of available public safety frequencies, and licensed to a Public Safety Spectrum Trust (PSST), a national non-profit corporation composed of representatives of state and local government who are charged with managing the band in the best interests of all first responders in the nation. The PSST is also obligated to "share" the band with the D-Block licensee (10 MHz of broadband 700 MHz commercial spectrum nationally). In fact, the 700 MHz public safety band has already been pooled by the FCC and awarded to the PSST as band manager. However, the current vision of usage by public safety is that the trust will lease the public safety block in total to the D-Block operator, who will then sell subscription service to individual public safety entities as a carrier. There can be no usage of the spectrum at all by any other user, until the D-Block operator constructs its 700 MHz cellular system and provides coverage in the area in which the user is located. Since no D-Block operator license has been awarded, the spectrum remains fallow.

The D-Block licensee is to construct a national commercial network, but allow the PSST to define terms for public safety priority access to the network, and the ability to both preempt commercial traffic from the network and to flexibly expand usage into the commercial band spectrum in an emergency. First, it is worth noting that the current plan calling for a national public safety infrastructure implies over-building the patchwork of local, legacy systems with a national cellular network. Second, much of what would be involved in designing the network, managing the sharing among public safety users, and sharing with commercial users has not been specified yet. For example, there are no rules or standardized practices among the disparate public safety users themselves to determine priority use of the national network, within and among their broad classification of "public safety users and uses." Federal users may be excluded, as they are not generally eligible for public safety frequencies provided by the FCC rules, and instead are allocated spectrum by the NTIA. The federal pool of spectrum, which is separate, does not have broadband channels identified for use in homeland security in any band.

The FCC's attempt to auction the D-block spectrum in January 2008 did not succeed in attracting any bids that met the reserve price,[37] and so the future allocation of this band and the licensing rules that will govern its management are once again open for debate.[38] Whether DSA/CR radios are deployed by the D-Block operator or not, the mechanism for managing the pooled PSST spectrum does not yet exist, and must be decided upon. It could be a static frequency re-use mechanism, or it could be a dynamic policy-based mechanism. In light of the overall trajectory of wireless systems, it seems advisable that the dynamic framework should be seriously considered.

[36] The 700 MHz public safety band is actually composed of two sets of spectrum; half is reserved for narrowband licenses, and the other half is reserved for broadband uses. The broadband allocation has been licensed to the PSST, and is intended to be shared by the D-Block licensee, should one be awarded. Currently, its status remains in limbo as the FCC reconsiders.

[37] In comments to the FCC, Coleman Bazelon identified a number of problems with the D-Block auction rules which contributed to its failure. For example, he estimated that the restrictive rules imposed on D-Block bidders, constraining them to share spectrum with public safety providers and be subject to public safety pre-emption substantially reduced the value of the license. See *Comments of Coleman Bazelon*, In the Matter of Service Rules for the 698-746, 747-762 and 777-792 MHz Band (WT Docket No. 06-150), Implementing a Nationwide, Broadband, Interoperable Public Safety Network in the 700 MHz Band (PS Docket No. 06-229), Development of Operational, Technical and Spectrum Requirements Permitting Federal, State and Local Public Safety Communications Requirements through Year 2010 (WT Docket No. 96-86), Federal Communications Commission, June 20, 2008 (see http://fjallfoss.fcc.gov/prod/ecfs/retrieve.cgi?native_or_pdf=pdf&id_document=6520030998).

[38] See FCC, *Second Further Notice of Proposed Rulemaking In the Matter of Service Rules for the 698-746, 747-762 and 777-792 MHz Bands* (WT Docket No. 06-150), Implementing a Nationwide, Broadband, Interoperable Public Safety Network in the 700MHz Band (PS Docket No. 06-150), Adopted May 14, 2008 (see http://hraunfoss.fcc.gov/edocs_public/attachmatch/FCC-08-128A1.pdf)

5.1.2. The 4.9GHz band

The 4.9 GHz band has lain essentially fallow in most communities for three reasons: (1) there has not been much networking equipment and no end-user devices available to implement broadband networks in this band; (2) there are no funding sources to pay the high costs of network construction, as these frequencies require an access node network topology that supports mobile hand-off and includes repeaters inside almost all buildings and on multiple floors of the buildings;[39] and (3) most communities using broadband data applications that would be suitable for a network of this type are actually using more commercially accessible Wi-Fi equipment and networks in spite of the fact that they are unlicensed and subject to interference.[40]

This band has very small-area propagation characteristics, making it unsuitable for the typical public safety network architecture of high-powered, high-height antenna sites, and low-powered user devices. As such, this band may be well-suited for personal area and incident area broadband uses, especially by an ad hoc network architecture that can also make use of 700 MHz broadband channels (or other bands) as well as wired facilities for out-of-incident traffic. This large band of broadband, reserved-use frequencies is an important resource that cannot be efficiently tapped with current public safety network management approaches, because it demands an infrastructure of local policies and DSA/CR radios, or an infrastructure of access points too numerous to be affordable. Once again, this band is ripe for spectrum pooling to help facilitate the transition to DSA/CR.

5.2. Necessary Elements for Pooling

Assuming the public safety community may be induced to adopt the pooling concept, a number of core systems/elements will be needed to appropriately manage spectrum pool access and usage policies. These core elements are discussed in the following sub-sections.

5.2.1. Structured Pooling Policies

Spectrum access policies are needed 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.[41] Some policies may only be invoked in certain circumstances, and at certain locations. Some static policies may be hard-coded into the CRs when they are manufactured, while others may be downloaded periodically from a database. More dynamic policies may be updated based on control channel signaling or on-board programming intelligence. When temporary policies expire, the radio needs to know that they are no longer in force, and revert to a default or “home” set of policies. We envision a hierarchy of spectrum pool policies, which will guide the radio to the best choice for channel selection based on its ability to resolve available options within a structure of rules.[42]

Figure A below, represents a possible policy hierarchy for pooling and accessing spectrum. The policy hierarchy starts with the most generic and universal rules for each band, and progresses down to the most specific and conditional policies to resolve policy options and allow access. Federal laws and FCC rules are at the top of the hierarchy, followed by state laws and regulations, then local agreements, and finally to situational/context-dependent local policies. At the uppermost layers of federal, state and regional policies, agreements can be planned and once implemented remain relatively static. Once the radio learns the static policies that apply in any location, it can resolve dynamic user requests for spectrum based on more situational policies, dependent on such factors as the application, the user’s role in the incident, or the developing incident command system as an incident grows and wanes.

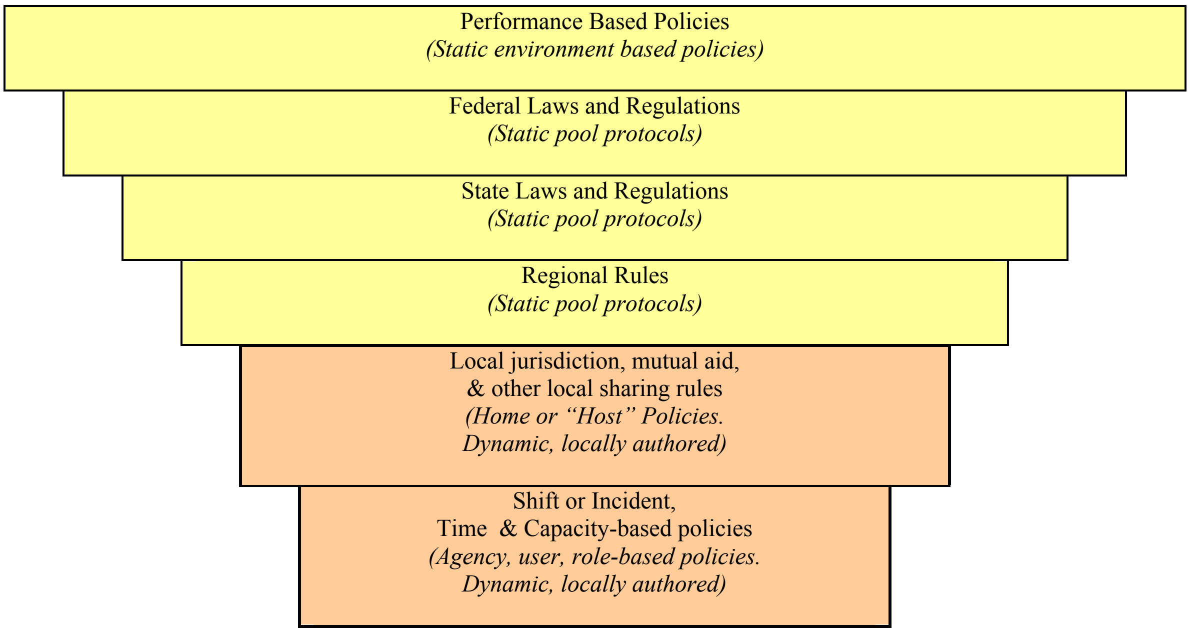
[39] Repeaters are needed for operation at 4.9GHz because operation at these higher frequencies requires line-of-sight and has poor penetration properties through building materials. The density of repeaters needed substantially increases the up-front infrastructure investment cost required to enable wireless broadband services in this band.

[40] This suggests the importance of cost/ease of deployment in public safety provisioning decisions, and the willingness to trade-off strong reliability requirements to save money or enable advanced capabilities.

[41] For example, a static policy might include notching out frequencies that are never to be included in the pool. A regional policy might specify different sets of pooling frequencies for different locales, which could be identified/enforced by the GPS capability of the radio system. A more dynamic policy might be a pre-emption notification indicating that certain frequencies are no longer available in a specific locale at a specific time.

[42] For a discussion of how time-limited certificates might be used in a CR architecture to enforce dynamic policies, see Chapin, John and William Lehr (2007), "Time-limited Leases for Innovative Radios," *IEEE Communications Magazine*, June 2007.

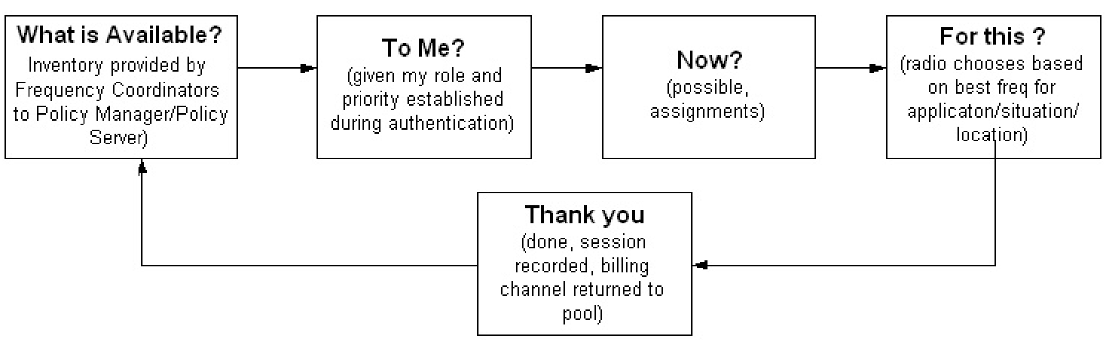
Figure A: Hierarchy of Pooling Policies



5.2.2. Policy Servers

Policy servers will be 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 servers will sit at multiple locations in a network, including the incident area to allow local incident command to issue specific policies to responder radios, such as policies to set up a tactical network. The radio servers may rely on an IP network to replicate and resolve policies where needed. However, static, high-level policies can be known, and resolution of dynamic policies at the more granular level will presume that higher-level policies cannot be violated in order to implement incident and local level policies. As the radio powers up and authenticates, it asks the server for its policy update, role, and tactical assignment information as shown in Figure B below.

Figure B: How policies resolve



5.2.3. Embedded CR Technology

CR's must include appropriate technology to allow them to "know" and "obey" DSA policies. For some policies, especially the most dynamic and location/context dependent, the CRs will need to know their location and specific characteristics of the spectral environment in that location. Other policies may be hard-coded. They must have a policy "engine" to update spectrum policies based on their location, and other factors. The ability to technically implement potentially abstract policies in appropriate radio behaviors (wave forms) is necessary to ensure the non-interfering coexistence of multiple CRs and non-CR spectrum users.

5.2.4. Rights

The permission to use spectrum must be based on a system of spectrum access rights that may be more detailed than the rights defined in current licenses. For instance, the radio user may acquire rights from a licensee to use a channel for a short time, based on the situation in a specific place, and the user's role in the incident command structure. Other secondary use rights may be associated with pool membership or defined by the dynamic policies and prioritization schema developed collectively by the user community.

5.2.5. Band Managers.

For spectrum pooling to work, it is likely that there will be a need for a common interface with the pool, and a system for managing the pooled frequencies. It may be that some frequencies are available in the pool at a specific location and at a specific time, but in a different location or at a different time, the frequencies are not available. Availability may be conditional based on role, application, time-of-day, or other policies. Pools must be managed and coordinated. An adequate supply of available frequencies must be developed and managed according to usage histories and forecasts of network requirements. Frequency coordinators, who already manage interference protection, eligibility, and compliance may play an important role as spectrum pool managers.

Regional Planning Committees (RPCs) currently develop band policies and priorities. They are responsible for developing FCC-approved band plans on a regional basis for the 700 and 800 MHz public safety bands. RPC's are composed of all public safety users in their defined region, and plans must be reached by consensus. RPCs are an excellent policy body to develop both the static and dynamic policies necessary to allow flexible spectrum access in compliance with NIMS/ICS protocols.

5.2.6. Policy Authoring Tools.

Standardized policy authoring tools are needed that will allow flexible policies to be designed and communicated to the radio infrastructure and managers. For example, suppose two neighboring fire departments agree to a special policy for sharing spectrum. This policy has to be rendered into appropriate machine readable formats and distributed to the radios that will implement those policies and to those radios that will interoperate with them, as well as to the band managers. Moreover, any conflicts among policies need to be detected/contemplated and resolved.

5.2.7. Policy Enforcement.

To ensure that policies are followed, and that all policies co-exist without conflict or interference, a policy enforcement system will be required. The policy enforcer will check all policies before they are acted upon, to ensure that they do not cause conflict with other policies, and that they do not cause interference.

5.2.8. Spectrum Portability

Given a DSA/CR radio with access to a pool of frequencies, and operating according to policies developed and managed in a hierarchy as suggested above, a user should expect the ability to roam with his radio across applications, locations, and networks. The ability for the radio to be served the best available channel for the user (based on role and authentication), use (applications, such as broadband video, or sensor data), and 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 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. Since a DSA/CR radio will not rely on hard coded base stations, but will instead 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 today's 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 is portable across national networks today. Such portability will involve the development of roaming agreements between infrastructure owners, allowing access to infrastructure resources, such as policy servers, backbone networks, switches, and frequencies.

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 necessary 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.

6. OVERCOMING CHALLENGES TO SPECTRUM POOLING

In the earlier sections we have explained why we believe the transition to a radio future of more intensive spectrum sharing that enables DSA/CR technologies is inevitable and desirable for wireless services in general, and for public safety in particular. Without this future, public safety systems will fail to meet the requirements that have already been articulated. They will be both less functional *and* more expensive.

We have also explained why spectrum pooling is a necessary first step for realizing this future, and why pooling in public safety spectrum offers a key opportunity for moving wireless systems more generally toward the DSA/CR space. Nevertheless, moving the public safety community and wireless stakeholders more generally to embrace the concept confronts many challenges. Some of these are real risks that must be overcome, while others are more perceptual, requiring education. In the following sub-sections we address a number of these important real and perceptual challenges (see Table 5):

Table 5: Challenges for 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 pre-emptible • 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

6.1. Technology will not work as expected

Although we believe DSA/CR represents the future, there are still many technologies that need to be developed, and among those that exist as prototypes, need to be commercialized. For example, there already exist commercial software radio and experimental/demonstration cognitive radio platforms, modularized radio hardware, open interfaces, and significant work toward defining/building/testing radio policy-frameworks; however, putting all of these elements together represents a challenge for the entire wireless value chain. The movement to DSA/CR radio systems represents a fundamental paradigm shift that will require lots of innovation in technology, spectrum management regulatory policy, and business practices.

The fact that evolving technologies do not work precisely as expected is hardly new. While we recognize these risks, we assume here that the technical problems will be resolved and focus instead on the spectrum management policies and practice innovations that are also needed. Nevertheless, there are several points about the technical uncertainties/risks that need to be clarified.

First, the need for new capabilities and the fact of increasing congestion of the RF bands means that moving to new technologies that will share the spectrum more intensively is absolutely necessary. There is not enough available RF to dedicate exclusive spectrum for all users and uses. Moreover, given the pace of innovation in information technology of all sorts (including wireless) and the trend toward open interfaces, modularization, and interoperability, the pace at which new technologies need to be adopted has increased (i.e., product life-cycles are shorter in a world of on-line software updates and continuous innovation). While we may debate the timing of when the new technologies should be adopted, the eventual move to a DSA/CR future appears unavoidable.

Second, advanced wireless systems offering expanded capabilities are inherently more complex. Increased complexity means it is not possible to fully anticipate all fault modes in advance. This is a problem for certification of the performance/reliability of all complex systems and is not special or limited to DSA/CR systems.[43] Appropriate design for such systems necessitates building in flexibility and capabilities to adjust systems when they behave in unanticipated ways. For example, this may include having systems default to basic operating modes, consistent with legacy system operations.[44]

Finally, it is precisely because the challenges of transitioning to a new spectrum management paradigm are significant that we recommend moving carefully toward the DSA/CR future. While we believe that spectrum pooling is a concept that can be generalized to include not just public safety users, but also other government and commercial users, attempting too much too soon may harm overall progress. For a number of reasons, we believe pooling in the public safety spectrum offers a prime opportunity for early implementation of this concept. This will provide valuable learning experience for the more ambitious pooling/sharing models we expect to follow in the future.

6.1.1. Legacy services will work less well than with traditional technology

A general concern is that next generation public safety radio networks will work less well than legacy technologies. When considering this proposition, it is important to distinguish between legacy services and new services. The legacy systems do not support many of the new capabilities such as broadband and more flexible roaming that are key features of the DSA/CR radio future. Just as with mobile telephone service in the early years, we believe public safety users will understand the value of accepting less than 99.999% availability as worthwhile to take advantage of the new capabilities. Of course, the value of new capabilities will depend on their quality, reliability (and cost).

A more appropriate concern is that enabling the new services will reduce the quality or resources available to legacy services such as two-way and broadcast telephony services. With appropriate prioritization of spectrum access and the ability to default to legacy operating modes, this concern should be readily addressable. It should be up to the public safety users whether the performance of legacy services are degradable to make room for new capabilities when resources have to be rationed. More generally, the new capabilities should actually improve the performance of legacy services such as voice (better encoding, ability to sustain voice communications in situations where legacy systems cannot such as ad hoc or mesh networking, etc.).

6.1.2. Prioritization will not work, Secondary uses not preemptible

A key feature of emerging DSA/CR system architectures are the ability to express, implement, and enforce much richer prioritization policies. This is essential to support preemptible secondary use. That is, if radio B is using resources that radio A needs and radio A has priority, there has to be a technically robust way to ensure A can assert its priority. This will require a mixture of appropriate sensing technology and system design/management to enforce these capabilities.[45] This is an important and active area of research and development, but there is growing evidence that "white space" access is feasible without causing interference to primary spectrum users.[46]

6.2. Government regulations will not permit

Change in regulatory policies at the federal, state and local level are needed to enable the spectrum pooling concept. We believe that key reforms have already occurred and the progress made toward implementing the NRF/NIMS/ICS framework demonstrate significant movement toward enabling the DSA/CR future. Thus, while we recognize the risk that good policies which should be approved may not be, we do not discuss these in detail in this paper.

In addition to the challenge of educating policy-makers, there is the challenge of overcoming vested interests. Some of the manufacturers and providers of public safety radio systems and services have benefited from the legacy of fragmented, silo-based architectures. Some of those entities may be less well-placed to succeed in the DSA/CR future than other manufacturers or providers. Additionally, some spectrum managers and public safety system operators may fear a loss of control or the challenge of having to learn new wireless technologies and operating modes. Many among those who have a vested interest in the *status quo* have significant engineering and operational experience that they may use to try to derail efforts to progress toward the DSA/CR future.

Overcoming the resistance of vested interests and educating those who do not fully understand the benefits/necessity of the DSA/CR future will be important challenges. Focusing on the primacy of the public safety mission and need for enhanced capabilities, greater interoperability, and greater opportunities to take advantage of modular systems and competition across the wireless value chain should help overcome such resistance.

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[43] See Chapin, John and William Lehr (2007a), "The path to market success for dynamic spectrum access technology," *IEEE Communications Magazine*, Special Feature on Cognitive Radios for Dynamic Spectrum Access, May 2007.

[44] See Chapin, John and William Lehr (2007b), "Time Limited Leases for Innovative Radios," *IEEE Communications Magazine*, June 2007.

[45] Among the technologies being discussed to manage preemption are listen-before-talk, reliance on a control channel, and time-limited certificate leases.

[46] See, for example, Petty, V., R. Rajbanshi, D. Datla,, F. Weidling, D. DePardo, P. Kolodzy, M. Marcus, A. Wyglinski, J. Evans, G. Minden, and J. Roberts (2007), "Feasibility of Dynamic Spectrum Access in Underutilized Television Bands, 2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN2007), 17-20 April 2007, pages 331-339.

6.3. Early-adopter challenge

One of the biggest challenges is getting the community of public safety network operators to adopt spectrum pooling. Even assuming that the technology works and that the legal/policy hurdles to implementation have been overcome, there is likely to be resistance among public safety users to participate in a spectrum pool unless they can be assured that others also will participate. The real benefits from spectrum pooling are realized when the community of participating public safety networks is large. However, this does not mean that unilateral adoption offers no benefits. For example, consider two networks, A and B, such that network A agrees to contribute its spectrum to a pool but network B does not. Network B benefits from the opportunity to access A's spectrum on a secondary use basis. While network A does not receive a similar benefit from the opportunity to access B's spectrum, network A does benefit from having the option to allow B users to roam on A's network. Such roaming could be important to support a mutual aid agreement or interoperability. While the benefits are less if B does not also pool, there are still benefits for network A.

Although there are benefits even to unilateral pooling, the benefits will be greater and the costs of the enabling technologies will be lower as pool grows. More pooling means more spectrum to share and more opportunities to benefit from a wider community of interoperable networks to support roaming, cost sharing, and market economies. Learning, scale, and scope economies will expand as the market for public safety DSA/CR expands, which will cause system capital and operating costs to fall over time. These are the positive externality effects that are realized as a network grows. In light of the uncertainties confronted by early adopters and expectations of declining costs and increasing positive network externalities, waiting to adopt may be perceived by many networks as an optimal strategy.[47]

Even if one ignores the benefit/cost timing issues associated with early adoption, adoption of a new paradigm or technology depends on what adopters think others will do. In the presence of network externalities such as are likely in this case, the more likely you think others will adopt, the more likely you will be to adopt. Because everyone thinks this way, the expectations are mutually interdependent. Events that cause users to change expectations can result in earlier or later adoption. Economists have referred to such situations as bandwagon equilibria: bandwagons are notoriously difficult to start and hard to stop once started.[48]

While this poses a challenge, it highlights the importance of early/first steps. The bandwagon that needs to be started is less pooling itself, but rather the movement toward DSA/CR technologies. A key point of the pooling concept is that it is a relatively small and risk-free first step that can play an important role in initiating the bandwagon toward next generation wireless systems. Pooling by itself (without any deployment of advanced radio technology) does not produce much value, but it also does not incur much risk.

A reason this concept is so ripe for a first step by public safety operators is precisely because of the fact that legacy systems are so inadequate to today's challenges, the costs of continuing the silo-based architectures and "worst case" provisioning are so astronomical, and there are so many public safety providers that are in the same situation. There is a window of opportunity. Following Farrell & Saloner (1986), the penguins are on the edge of the ice flow and this is a great time for them to jump in.[49]

The FCC can help get the bandwagon started by making the 700MHz and 4.9GHz spectrum designated for public safety use available for spectrum pooling.

6.4. Cost of NextGen Public Safety wireless systems

We have already discussed the fact that the costs of adopting next generation wireless systems are likely to be more expensive (relative to legacy systems) initially, but that costs should fall over time as the market gets bigger. The focus on modular, interoperable, and shared infrastructure will help drive these trends faster. Hardware and software systems providers will respond to a larger market. Enhancing opportunities for competition across the value chain by encouraging the adoption of more open and less silo-based technologies will help drive down costs and prices. Obviously, the potential cost savings (and interoperability benefits) will be even greater to the extent public safety users are able to meet their needs with COTS components.

[47] Even in the absence of uncertainty, there is a dynamic programming problem that individual networks must solve: the optimal time to adopt will be when the net present value of the future stream of benefits is larger than the net present value of the costs of adoption, after accounting for the foregone benefits/costs you would have incurred if you had adopted earlier. The relative rates of change in benefits and costs (and heterogeneity across potential adopters due to local circumstances) will result in a distribution of optimal adoption times. When you introduce uncertainty, there is a real option effect which might cause you to wait to adopt (i.e., learn which is the best technology before committing investment to a technology which you might have learned is inferior). This uncertainty is likely to make early adoption even more expensive.

[48] See David, P. and Greenstein, S., "The Economics of Compatibility Standards: an Introduction to Recent Research", *Economics of Innovation and New Technology*, vol 1 (1990) p3-41.

[49] See Farrell, Joseph and Garth Saloner (1986), "Competition, Compatibility and Standards: The Economics of Horses, Penguins and Lemmings", Technological Innovation Project/Political Economy of Technological Standards Seminar, Stanford University, October 1986. Farrell and Saloner describe how pioneers used to tie their horses together on the plains to keep them from wandering off. The horses could not agree on a direction to go so they stayed put. They also mention how penguins accumulate on the edge of the ice before jumping in, eventually getting so crowded that a few are pushed in. The penguins do this because they want to see if there is a predator waiting. If the first penguin in is not eaten, then the rest can jump in safely. Finally, the example of lemmings provides an image of the difficulties of stopping a bandwagon once started.

Spectrum pooling will also lower costs because it will facilitate opportunities to share the costs of network infrastructure, in addition to spectrum assets. Such cost sharing may occur over space and time. For example, multiband radio base stations may be mounted on common/shared antenna towers to share cell site costs across multiple public safety providers (sharing across space). Similarly, software-updatable radios extend the life of hardware components, allowing these to be amortized over a longer-period (sharing across time). Furthermore, the added flexibility and adaptability of DSA/CR should lower direct and indirect operating costs over time by relaxing capacity constraints and reducing congestion (e.g., by moving users/users to another frequency dynamically).

6.4.1. Managing cost recovery of shared systems

With the opportunity to share comes the challenge of figuring out how to manage the costs of shared systems. In an age of tight budgets for everyone, the incentives to free ride on the investments of others are strong. There may also be attempts to introduce usage-based fees for secondary access as a way to help incentivize network operators to participate in the pooling concept. We would argue against such strategies in the near term. For publicly-funded public safety users who are subject to fixed budgets, usage-fees for secondary access would likely significantly reduce incentives to share the spectrum. There is little benefit to encouraging supply if you do so at the expense of discouraging demand. Spectrum sharing should not be viewed as a revenue source with which to defray the costs of constructing next generation systems, at least initially and at least as applies to other public safety users.[50] A cautionary lesson should be taken from the experience of municipal wireless systems that were sold to cities on the promise that these would provide universal broadband access *and* be revenue positive at the same time. The fall-out from such over-selling of the municipal wireless concept has made it more difficult for those with valid plans to move forward. Over-hyping with respect to the revenue potential from spectrum pooling is a significant risk here also. We expect that the principal financial benefits from spectrum pooling will be lower costs, *not* new revenue streams.

Nevertheless, while the aggregate costs due to sharing should be less, figuring out how to share the costs of common infrastructure will present a contentious challenge. Fortunately, this is hardly a new problem and there are many business/regulatory models for managing this challenge. Traditional cost sharing/allocation frameworks from telecommunications and other network industries provide one class of options.

6.4.2. Incremental deployment and managing overlays

Introducing a new technology on top of existing technologies does increase the complexity of system management. Public safety users need to keep track of which users/parts of the system have only legacy capabilities and which have new, enhanced capabilities. While managing an overlay technology may add some challenges, on balance, the opportunity to deploy in this way is likely to deliver significant advantages.

One of the biggest challenges confronting public safety radio operators in the past is the need to maintain coverage and interoperability. With closed, silo-based architectures, this often meant either system-wide replacements (which are expensive) or slower-paced upgrades (which implies lagging enhancements to capabilities). The flexibility/adaptability/scalability of DSA/CR architectures means that these systems can be deployed incrementally to allow investment to be managed more smoothly over time. This also makes it easier to train users and overcome resistance to the new technologies by allowing experience to accumulate over time.

Furthermore, it suggests that the choice of services which first make use of the pooling concept might be managed to minimize the costs and risks of interacting with legacy systems. Thus, focusing spectrum pooling first on the delivery of new capabilities such as high-speed broadband data services (rather than voice) is likely to lower deployment costs and ease the challenge of overcoming opposition.

6.5. Risk of losing spectrum assets

The challenges discussed previously, pose real risks to the realization of the DSA/CR future. The following challenges we view as more perceptual than real: they reflect real concerns in the public safety community but concerns which should be overcome with education.

The first of these concerns that will fuel resistance to spectrum pooling is the fear that a network who contributes spectrum to the pool will lose spectrum assets. This might be articulated in a number of ways, including the following:

- "If we agree to share our spectrum, it will signal we have excess spectrum that we might lose"
- "If we commit to the pooling concept, we will weaken our ability to apply for additional allocations of dedicated spectrum"
- "If we allow others to share our spectrum, this is the slippery slope to losing our priority access to it. We will not be able to reclaim our spectrum when we need it"[51]
- "If we commit to the pooling concept, we will lose control over our spectrum future. Our ability to address our needs will be contingent on the actions of others outside of our community and not part of our mission"

The above concerns are reasonable but all rest on some fundamental misconceptions. First, spectrum pooling with appropriate prioritization will mean more spectrum for

[50] The case for imposing usage fees on commercial users who might share public safety spectrum in the future is more ambiguous.

[51] The question of whether it is technically feasible to pre-empt secondary users has already been addressed.

everyone by allowing unused (and with today's legacy technologies, unusable) spectrum to be tapped. Appropriate prioritization should ensure that no one is worse off than they are in the world in which they elect not to pool.[52]

Second, the reality of the spectrum future is that additional allocations of dedicated spectrum for public safety are unlikely to be made available. The most likely prospect is that if additional spectrum is made available, it will be for shared spectrum.

Third, the movement toward increased interoperability, regional/inter-agency coordination of public safety entails a certain loss of local autonomy and control (e.g., need to comply with the NRF) but that is unavoidable. The benefits of cost sharing and lower costs because of bigger common equipment markets offer strong compensation. Moreover, the increased flexibility, adaptability and capabilities enhance local autonomy and control in a number of important senses. For example, control over management and system design is traded for control over ability to access a larger range of better services. You can get the information you need where you need it, instead of being the victim of limited, static technologies.

Fourth, the fear that the added aggregate capacity delivered by sharing will be offset by reductions in aggregate spectrum allocations to public safety seems unlikely given the heightened awareness of enabling enhanced capabilities for public safety providers. The risk is less that public safety will lose spectrum, but rather that it will fail to get additional spectrum.

Fifth, the fear that secondary spectrum users will be squatters who will be hard to displace is really a question of how to manage prioritization over time. In reality, the legacy of provisioning public safety systems on a local basis is outmoded in today's more integrated world. The spectrum pooling concept is intended to move the world toward a future in which narrow frequency assignments to dedicated users/uses are replaced by more active sharing. What will matter is that access to spectrum is assured, not access to a particular channel or frequency. The pooling concept is intended to strength the assurance that priority access will be realized (even when the dedicated channel or frequency is not available or is congested).

6.6. Systems will not be adequately reliable

As noted earlier, given the importance society places on public safety services, reliability is a key consideration. While we may say it is acceptable to allow market competition to determine the quality of mobile telephone service (e.g., what is an acceptable level of dropped calls?), we do not believe that it is acceptable for a policeman speaking to his dispatcher to experience a dropped call because of network congestion. Or, while we accept that our cable television or telephone service may occasionally become unavailable, we expect our first responders to be able to communicate 24/7, wherever a problem arises. While the notion of a higher priority for reliability for public safety relative to mass market consumer services seems intuitively reasonable, this does not mean that strong reliability requirements are either unique or absolute. Moreover, what we aspire to and what we realize are often too different things. Today, in many environments, commercial mobile services offer higher service availability and quality (including enhanced capabilities) at lower cost than are available to public safety providers using legacy systems.

In assessing the reliability requirements of public safety systems, it is important to go beyond the hype. It is necessary to distinguish between the reliability requirements of legacy and advanced services (not supported by legacy systems). For legacy services, it is reasonable to require that service availability and quality should not be degraded relative to the performance of legacy systems. Thus, switching to VoIP over a wireless broadband Wi-Fi channel is not likely to be perceived as a viable option for supporting 2-way voice telephony. On the other hand, for advanced services, it is unreasonable to expect that the same reliability requirements are appropriate or feasible. Getting high-definition video some of the time but perhaps not 99.999% of the time is better than no video at all.[53] Furthermore, it is important to recognize that the way to ensure reliability with the new technologies and in a spectrum pooling environment are different than in the traditional silo-based world. Shared capacity provides redundancy protection only if access to this is appropriately enabled (including prioritized). Defining the right reliability standards for legacy and advanced services will be important, and will require additional work and development, made more difficult by the expanded wealth of options available.[54]

6.6.1. Systems cannot be made robust (or as robust as legacy systems)

It is worth noting that the reliability requirements of public safety radio are not unique. Many businesses with far deeper pockets regard communications services as essential infrastructure and have developed commercial technologies to manage these systems for very high reliability and availability. These include financial services companies, electric power and transportation system operators, and commercial telecommunications service operators.

Furthermore, DSA/CR enable robustness to new failure modes. For example, modularity/flexibility that increases interoperability and substitutability provides an alternative to

[52] Operators may elect to adopt prioritization that gives higher priority to secondary users (e.g., mutual aid, first responders who are roaming) over primary users. Such a policy is elective and so does not represent an involuntary loss of spectrum access.

[53] Similarly, ad hoc/mesh networking that enables telephony in places not served by traditional infrastructure (on a mountain fighting a forest fire or in a collapsed subway tunnel) provides enhanced reliability with respect to the challenge of getting communication services where they are needed.

[54] With limited service choices, making decisions is easier.

hardening and over-provisioning.[55] VoIP over Wi-Fi over DSL proved to be a valuable service in post-Katrina New Orleans when traditional infrastructure was unavailable. As the complexity of the environment to be planned for increases, it becomes infeasible to provision for every possible disaster state and so heightened reliability depends on flexibility.

6.6.2. Cost prohibitive for public safety radios

To the extent public safety reliability requirements are able to make use of COTS components, it will be easier to realize cost economies and the benefits of wider interoperability across both the public safety and commercial wireless realms. If the requirements are too different, then public safety systems will face higher costs and there will be reduced choice and supply competition.

In some cases, special requirements seem unavoidable. For example, the radio needed by a fire-jumper has to be a lot more rugged than the cell phone needed by a corporate executive. Similarly, the requirements for hardening antenna sites and other infrastructure in remote sites might exceed what commercial customers would demand.[56]

In the near term certainly, and possibly in the long term as well, it is likely that public safety and commercial systems will not be fully substitutable which will impose a cost penalty on public safety systems. We may choose to recognize this as a necessary expenditure, or we may sacrifice real world capabilities and reliability by spreading the available funds more narrowly. In making these decisions, it is important to realize the benefits of using COTS where possible and the trade-offs between cost economies and specialized reliability requirements offered by alternative radio system designs.

7. Conclusions and Future Research Directions

Under the traditional spectrum management framework, interference protection was provided via separation: wireless users were segmented into minimal allocations of spectrum frequencies, exclusively dedicated to non-interoperable, single-purpose wireless technologies. This approach is no longer viable in light of growing demand for spectrum access rights from an ever larger number and diversity of wireless devices. The radio frequency spectrum will have to be shared much more intensively than has been possible with legacy technologies, business models, and regulatory policies. A paradigm shift is necessary 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 they need to communicate with. The fragmentation of infrastructure into incompatible silo-based networks drives up costs, reduces available capabilities and capacity, and ultimately, harms the ability of public safety professionals to do their jobs. In the post-9/11, post-Katrina world, it is clear that we need much greater coordination and real-time advanced communication capabilities available to our public safety professionals. Professionals from different departments and jurisdictions need to be able to talk and interactively share data (including video) quickly, reliably, *and* wirelessly. We want our public safety professionals to be able to respond wherever, whenever the need arises with the appropriate tools to complete their mission of saving lives and property.

Meeting the expanded mission requirements will require significant investment in new infrastructure to expand system capabilities and capacity. The traditional approach of over-provisioning static network infrastructure to meet worst-case scenario needs is neither feasible nor desirable. Luckily, it is also no longer necessary. Dynamic Spectrum Access (DSA) technologies like software/cognitive radio (CR) are making it feasible to share spectrum much more intensively. Transitioning to a radio future of DSA/CR will allow radio systems to be much more flexible and adaptable to local conditions. This will increase system capacity and capabilities, enhance interoperability and reliability, and will lower costs.

While the wireless future is bright, getting there will not be easy. A new ecosystem of wireless devices, usage and business models, and spectrum policies are needed to supplant the legacy ecosystem. While limited in capabilities, legacy systems have become essential to meeting current requirements. 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 reality today – we would need to reform business models and spectrum management policies to enable use of the technologies.

One important and necessary first step toward building the wireless future is to transition to spectrum pooling. Public safety users should pool their spectrum to expand their effective access rights and facilitate the adoption of DSA/CR wireless technologies. As we explain in this paper, this will offer important benefits for public safety systems and is consistent with the trajectory of wireless innovation and growth more generally.

Significant progress has already been accomplished toward establishing the institutional and policy-framework to successfully implement the spectrum pooling concept. The National Response Framework (NRF), the National Incident Management System (NIMS), the Incident Command System (ICS), frequency coordinators and the Regional Planning Councils (RPCs) provide some of the glue and apparatus

[55] If every gadget carried could be a phone or if they all use the same batteries then reliability of phone service no longer depends on the likelihood of failure of any single device.

[56] Unlike commercial customers who can choose where to locate their operations to minimize costs, public safety providers need to be where the need is.

needed to coordinate and manage pooled spectrum. We identify other essential components (e.g., agreement on prioritization policies to manage shared access) that must be developed and challenges overcome (e.g., mobilizing coordinated adoption of DSA/CR technologies) along the path to next generation public safety communication systems.

To maximize the likelihood of a successful transition, we believe it will be 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 need 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 generalized. All future wireless systems should be more dynamic and capable of interacting with expanded notions of priority in spectrum access rights. Public safety users may start out by reciprocally enabling secondary use of their dedicated spectrum bands by other public safety first-responders, then expanding to other government agencies and non-government affiliates, and ultimately, to commercial users/uses. The increased sharing of infrastructure and resources will benefit all if implemented appropriately. Public safety provides an important first test case for commercialization of these sharing ideas as we have explained herein, and success here will deliver positive externality benefits for the wider adoption of DSA/CR more generally.

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