Considerations and Recommendations for Software Defined Radio Technologies for the 700 MHz Public/Private Partnership

Approved 5 December 2007

TABLE OF CONTENTS

1. Summary

This report describes how software defined radio (SDR) technologies can help achieve the public/private partnership goals of the upcoming US FCC 700 MHz frequency band spectrum auction. This report also covers cognitive radio (CR) and dynamic spectrum access (DSA) technologies as well. The context for this report is the Second Report and Order (FCC 07-132, released 10 August 2007) which establishes rules governing wireless licenses in the 700 MHz band.

The SDR Forum is uniquely positioned to consider the role of these new technologies in the 700 MHz band since its membership includes commercial mobile radio service providers, public safety representatives, technology developers, systems integrators and equipment manufacturers. The information and recommendations in this report focus on technology and related policy considerations to (a) prospective bidders and service providers, (b) potential grantees of the Public Safety Broadband License, (c) equipment manufacturers, and (d) regulators[1].

[1] It is not the intent of this report to suggest any changes to FCC rules, regulations, or orders.

2. Introduction

The upcoming auction and licensing of 700 MHz spectrum represents a significant opportunity to fulfill the growing demand for spectrum resources for commercial and Public Safety broadband applications. The FCC has defined open platform requirements for one of the licenses, adopted the strictest build-out rules ever implemented for wireless services, and established rules to govern the partnership between commercial carriers and public safety to share spectrum and network resources.

This additional supply of spectrum and the associated regulations present new opportunities and accompanying challenges for spectrum access and deployment of wireless networks. The SDR Forum believes that software defined radio, cognitive radio, and dynamic spectrum access technology are vital components of a system design to deliver the robustness, flexibility and efficiencies necessary to meet the FCC's expectations and the communications needs of a wide range of users.

In this report the SDR Forum provides specific examples of how these technologies can be used to address critical implementation challenges of systems that meet the FCC's defined service rules. An approach incorporating software defined radio, cognitive radio, and dynamic spectrum access technologies, in both the system infrastructure and subscriber units, provides a highly flexible network solution that can meet diverse requirements and develop in concert with technology and operational evolution.

The challenges in implementing the proposed network can be generally described as developing a network that can meet the inherently diverse needs of a Public/Private Partnership. The specific challenges described in this report were derived from requirements defined by the FCC.

3. Definitions and Key Concepts

There are a number of terms used extensively in this report. To ensure clear understanding of the concepts and approaches described in this section, definitions for key terms are listed in this section. The definitions are quoted from the SDR Forum's set of definitions for software defined radio and cognitive radio.[2]

Software Defined Radio (SDR): Radio in which some or all of the *physical layer* functions are *Software Defined*.

Physical Layer: The layer within the wireless protocol in which processing of RF, IF, or baseband signals including channel coding occurs. It is the lowest layer of the ISO 7-layer model as adapted for wireless transmission and reception.

Software Defined: Software defined refers to the use of software processing within the radio system or device to implement operating (but not control) functions.

Cognitive Radio: (CR) a.) Radio in which communication systems are aware of their environment and internal state and can make decisions about their radio operating behavior based on that information and predefined objectives. The environmental information may or may not include location information related to communication systems.

b.) Cognitive Radio (as defined in a.) that utilizes *Software Defined Radio*, Adaptive Radio, and other technologies to automatically adjust its behavior or operations to achieve desired objectives.

Waveform: A waveform, also known as a communications standard, is the set of transformations and protocols applied to information that is transmitted over a radio channel.

[2] *SDRF Cognitive Radio Definitions*. SDR Forum Report SDRF-06-R-0011.

4. The Inherently Diverse Needs of a Public/Private Partnership

In reviewing the rules for licensing and use of the 700 MHz spectrum, the SDR Forum identified several challenges that can be more effectively met using SDR/cognitive radio technology. The public safety spectrum and D-block spectrum are intended to be used in a network which meets both public safety and commercial requirements. While there is significant commonality among such requirements, there are also key inherent difference in the goals and requirements that present a challenge to creating and sustaining an economically viable network that meets public safety needs.

4.1 Challenge 1: To build a commercially viable network that meets public safety needs.

The proposed public/private partnership envisions a network that meets the needs of the public safety community while also earning sufficient return from commercial operation to support the buildout and operation of the network. It will be very challenging to achieve this goal. The requirements and business models for public safety networks are significantly different from the requirements and business models for commercial networks.

One approach to overcome this challenge would be to seek commercial users whose mission critical communications requirements are similar to those of public safety users and would be willing to pay a premium for reliable service. However, it is not clear that this commercial community is large enough to make the proposed nationwide network economically viable. Moreover, even if a network limited to these users could be viable, all stakeholders will benefit if the user base of the network is expanded to additional commercial users. Higher revenues from an extended commercial user base will both improve returns for the network operator and provide funds for higher levels of service and faster buildout for public safety users. Therefore it is a requirement that the network must effectively support multiple user communities with different requirements and business models.

A network designed to meet the coverage and reliability requirements of public safety, the most demanding users, will also in most cases accommodate the requirements of the less demanding user communities. However it will not be able to offer service to them at a competitive price. Providing service economically to these users, which is essential for success of the public/private partnership, requires optimizing for progressively higher levels of efficiency and capacity as user requirements are progressively relaxed. This relationship is highlighted in Figure 1. The critical tensions highlighted in the figure include the following.

- The high reliability requirement for public safety is directly opposed to the economic requirement for high resource utilization in a commercial network. High reliability against service unavailability due to failures is achieved by provisioning redundant equipment, overlapping cells, excess link budget, and similar features. High reliability against service unavailability due to overload is achieved by provisioning greater capacity than is needed in normal operation. Both forms of over-provisioning increase investment in the network, reducing the return on that capital expense.

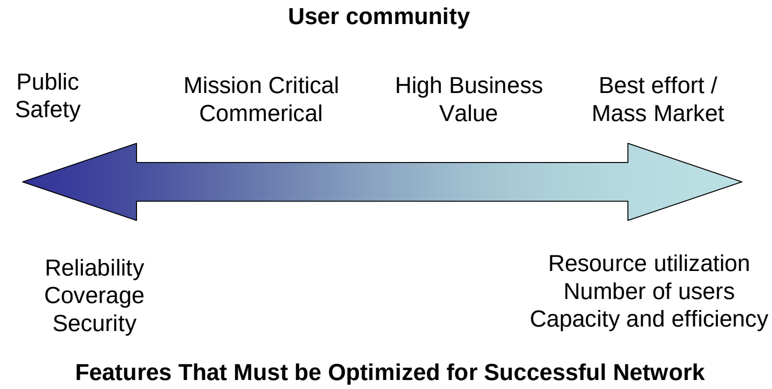

Figure 1. Divergent requirements on a public/private shared network

- The universal coverage requirement for public safety is opposed to the commercial mandate to maximize usage levels, and hence revenues, given a particular amount of investment. Providing coverage in rural areas with low population density reduces the commercial return on investment. Similarly, ensuring coverage in tunnels, elevators, underground garages, and similar hard-to-reach places diverts investment and capacity from locations where larger numbers of users are located.
- The security requirement for public safety is opposed to the commercial mandate to maximize capacity and spectral efficiency. Measures for high security, particularly those that defend against denial of service attacks, add spectral occupancy and time occupancy overheads that reduce capacity and efficiency. These effects reduce the number of users that can be supported and thus the network’s return on investment.

These divergent requirements create significant challenges for network design and implementation.

Software Defined Radio/Cognitive Radio Capabilities

Flexibility Is the Key

The key to solving problems created by divergent requirements is flexibility. There is unlikely to be a single network operating mode that meets all user requirements of these diverse user communities. However, if the network can offer multiple operating modes, and can reallocate its resources as the mix of users and applications changes, it is possible to satisfy a wide range of user needs.

Software defined radio techniques provide a cost-effective way to support multiple operating modes and flexible resource allocation. Cognitive radio techniques assure that the network allocates its resources appropriately. These technologies are therefore critical parts of a network design that meets public safety requirements and that is also commercially successful.

In particular, software defined radio technology enables three key types of flexibility.

1. Waveform. Software defined radio technology enables the use of multiple different waveforms on a single hardware device.[3] It may be appropriate for different user categories on the public/private shared network to use different waveforms, or to select different options within a single waveform standard. For example, one waveform can prioritize reliability and coverage by encoding data bits in a way that is highly noise-tolerant, while a different waveform prioritizes capacity by using encoding that allocates less time and energy per bit. One waveform may have packet headers with sufficient redundancy and authentication information to defend against spoofing and denial-of-service attacks, while another may omit these features to achieve more compact headers that enable higher efficiency. Software defined radio provides flexibility to offer different waveforms or options to different users without duplicating hardware.
2. Resource allocation. Software defined radio technology enables a device to flexibly reallocate resources such as computational capacity among different tasks. In a traditional radio the allocation is fixed: there is a certain amount of hardware circuitry devoted to each task. In a software defined radio the resources are fungible. For example, if a high priority user encounters difficult channel conditions, such as when a public safety officer enters a tunnel, the nearby infrastructure base station can activate more sophisticated receive processing and higher transmit energy for that user to compensate for the link loss. The resources required to do this can be recovered by making small adjustments that reduce processing requirements and transmit power for a number of lower-priority users, any one of whom will notice only a small reduction in performance. Another view of this capability is that the base station only needs to allocate resources to provide coverage in the tunnel at times when there are public safety officers actually located there and using the system. Those resources are free at other times to improve commercial capacity at other locations. Software defined radio used in this way can enable the network to significantly increase commercial capacity without reducing its support for public safety requirements, at the same level of investment.
3. Software modification. A software defined radio's capabilities can be flexibly modified and upgraded over time, without hardware modification and without physically accessing the device. The network can be configured to offer different behaviors and different services in different geographic areas, by using different software versions in different devices. These benefits of software defined radio aid the public/private network to cost-effectively meet user requirements that vary by location or that evolve over time.

The flexibility of software defined radio technologies provides an opportunity to achieve interoperability goals and network economic viability without imposing

[3] A waveform, also known as a communications standard, is the set of transformations and protocols applied to information that is transmitted over a radio channel. Sometimes the term "waveform application" is used to differentiate between the set of parameters describing the radiated RF energy from the rest of processing involved in a protocol.

specific a priori requirements such as a common air interface for all users. The next sections describe in more detail how software defined radio flexibility coupled with the automatic control features of cognitive radio can be used to address some specific challenges of a public/private shared network.

Coverage

Of all requirements that a public safety system must meet, coverage is one of the most important to the public safety user, and one of the most difficult challenges for the public safety communications system design. Coverage to a public safety user means being able to communicate with high quality throughout a large percentage (usually in excess of 95%) of a specified service area, which often includes tunnels as well as buildings with signal penetration losses 30 dB or higher. Geographic coverage for public safety is required for areas where they need to monitor or respond to incidents. While that includes populated areas, it also includes unpopulated areas as well (consider the needs of a law enforcement officer making a traffic stop on a rural road, or a firefighter fighting a wildfire). Coverage for commercial networks, however, is far less ubiquitous, and for economic reasons is generally concentrated in areas sufficiently populated to generate adequate usage revenue.

The current rules specify a buildout timeline based on population coverage. While the approach is logical based on achieving the greatest impact most quickly and supporting the economic viability of the buildout, it defers attainment of public safety's greater geographic and in-building coverage requirements. Without changing the requirements set forth in the rules, software defined radio and cognitive radio capabilities can provide economic means to more effectively support public safety coverage requirements minimizing the impact of the support to commercial users.

A coverage solution that enhances coverage for public safety and yet is scalable would be an enabling factor for accommodating these divergent requirements. If this scalability is dynamic (i.e., changeable in "real time"), it may avoid the need to design the coverage of a system for worst case conditions. One example is the use of vehicular repeaters to provide portable coverage inside a building without requiring that the entire infrastructure achieve such in-building coverage.

Coverage is limited by insufficient link budget or excessive interference. Both limitations can be substantially mitigated, and flexible and scalable coverage solutions achieved through the capabilities offered by software defined radio and cognitive radio in both the radio and the network. Table 1 summarizes the capabilities afforded by SDR and CR for coverage enhancement and flexible, scalable coverage solutions.

Table 1 Examples SDR and CR Benefits for Coverage Enhancement and Flexibility

	Interference Mitigation	Link Budget Improvement
Software Defined Radio	Flexible Mode-dependent Receiver Filtering Dynamically adaptable Modulation and frequency selection	Flexible Mode-dependent Receiver Filtering Dynamically adaptable Modulation CR-based mesh networks for coverage extension [4]
Cognitive Radio	Smart network-wide frequency selection to: - find unoccupied spectrum - avoid use of adjacent channels for users in close geolocation proximity[5] Intelligent transmit power control	CR-based mesh networks for coverage extension[6] Intelligent transmit power control

Adaptable Modulation and Frequencies

The modulation (i.e., waveform) influences the link budget and thus the coverage; higher data rate modulations in a given bandwidth have less coverage range than lower data rates. Similarly, the higher rate modulations tend to have less tolerance to interference than those with lower rate and often have higher transmit spectral sidelobes that tends to cause more interference to others. Hence, radios that can rapidly change waveforms, such as radios employed in many commercial data systems, can dynamically modify the balance of coverage versus data rate. Even though software defined radio is not necessarily required to enable these waveform changes, it does offer enhanced flexibility over a hardware radio, enabling a wider range of waveform parameters to be changed with more precision. For example, software defined radio can better balance coverage versus data rate, accommodating both commercial and public safety users. Cognitive radio algorithms can adjust waveform bandwidths and frequency selections based on the geolocation and relative positions of the users.

Flexible, Mode-Dependent Receiver Filtering

The filters used in a receiver influence both the sensitivity (which affects the link budget) and the tolerance of the receiver to interference. The filter choice must seek to achieve the best balance between these factors to meet system-level requirements, and will be generally different for every modulation type that is used. Furthermore,

[4] SDR enables radio reconfiguration to mesh
[5] including avoidance of "near-far" interference situations
[6] CR enables optimal setup/control of the mesh

due to different system level requirements for public safety and commercial, the filter may be different between the two types of systems even if the modulation is the same. Software defined radio affords the potential for dynamically reconfiguring filters in real time to enhance filter optimizations for disparate services.

Coverage Extension

Extension of coverage through means external to the infrastructure is another method to affect scalable coverage. One method employed by public safety systems is to use vehicular repeaters to retransmit signals received from the infrastructure to a portable within a building. Software defined radio and cognitive radio are key enablers of flexibility for configuring operating frequencies of the repeaters, base stations, and portables to mitigate interference in these types of systems.

Another concept for coverage extension that has been receiving considerable attention is to use the radio flexibility afforded by software defined radio and intelligence afforded by cognitive radio at the network level to adaptively configure ad hoc mesh networks using a group of radio terminals to extend coverage beyond that of the infrastructure. Examples include terminals in tunnels and in outdoor areas where there is a coverage "hole" in the infrastructure.

Intelligent Transmit Power Control

Transmit power control, which is employed today in many commercial cellular systems, can improve the efficiency of the system. Currently implemented techniques are focused primarily on maximizing battery life by controlling transmit power as a function of distance from the cell site. This is generally performed by an individual handset as a function its location. A more sophisticated cognitive radio approach could be implement that incorporates the locations and activities of multiple users to improve performance of multiple users and multiple links. For example, frequency selection for one link could be selected minimize adjacent channel interference to another user, allowing that user to maintain a lower transmit power which in turn maximizes battery life. Cognitive capabilities in such scenarios are likely to be distributed among subscribers and the network; subscriber devices may provide information about the RF environment while decision logic relating to multiple links and subscribers would likely be performed at the network.

4.2 Challenge 2: The network must facilitate operational control of the network by the Public Safety Broadband Licensee to the extent necessary to ensure public safety requirements are met.

Local public safety radio managers typically own and operate the infrastructure transport elements of the system. This provides them complete control over redundancy, maintenance, expansion, coverage, and other network operations and management functions. Many public safety networks, for instance, do not lease commercial towers, or commercial circuits to interconnect towers, where they can build microwave links that they own and control. In situations in which public safety agencies do lease components of the network, they are often dedicated to public safety use. The reason for this preference to own the infrastructure is to control capacity, reliability and coverage including the hardening of the network infrastructure against vandalism, power loss, wind and ice, to ensure build-outs in sparsely populated areas, and avoid over-subscription from shared usage.

The D-Block licensee's infrastructure will be, by definition, shared with non-public safety uses and applications. Moreover, in any given area (city, county or region) many different "public safety" entities will be operating on the same network, which will be the D-Block licensee's facility. This common use requires the development of mechanisms that can be trusted, at least as well as current methods and mechanisms typical in existing public safety-only networks, to provide the public safety broadband licensee (PSBL) and its constituent agencies with controls. These controls must be more robust than simply enforceable contractual requirements, because these users will have no option to take their broadband business elsewhere—all broadband public safety spectrum will be subsumed under the D-Block license and cannot be disaggregated.

To adequately support the first responders, the FCC has recognized that the PSBL must be able to exercise operational controls in real time. This control must include the built-in agility and network management capabilities to allow the PSBL to determine that the network is always configured to meet the needs of many types of first responders simultaneously responding to different events, of different duration, in different geographic areas, and constituting different levels of “emergency.” The concept of operational controls could include the ability to actually control certain network infrastructure behaviors as well as exercising operational and network management policy control in real time to assist the D-Block licensee to meet the standard of "ensuring public safety requirements are met."

In addition to the shared operation control issue between the lessee and the PSBL, there is also a control issue with respect to ensuring that communications support the National Incident Management System (NIMS) while allowing local variations and implementations of NIMS requirements. NIMS defines a framework for incident response; the communications capabilities deployed for incident response, including the public/private broadband network, must support that response. However, NIMS is intended to be flexible to accommodate local and regional differences in public safety agency structure and functions, and incident variations. Thus while NIMS provides overall direction and commonality in incident response command and control, communications policies and procedures will vary. Furthermore, responders may desire particular features of their “home” system that can be executed in the network while preserving interoperability.

Software Defined Radio/Cognitive Radio Capabilities

The application of emerging SDR and CR technologies in the PSBL's and D-Block spectrum is the best way to ensure that the broadband network for public safety can be managed efficiently, meet commercial requirements for profitability, accommodate local and regional variations in policies and procedures, and allow the Trust to confidently manage its responsibilities to ensure public safety requirements are met today and into the future. Employing policy based radio architecture is potentially the best way to provide operational controls to meet disparate needs and requirements. Perhaps the most important contribution a policy-based architecture can make is its ability to dynamically adjust the use and configuration of network assets to ensure both spectral efficiency and network performance, especially in disaster and emergency conditions. The concept of a policy-based network is shown in Figure 2. By disseminating new policies, wireless systems automatically adjust their operation based on new rules and constraints in terms of frequency bands, bandwidths, power levels, sensing configuration, and network topology. This enables a rapid automated network establishment and interoperability with other wireless systems without an extensive planning while providing transparency to stakeholders.[7]

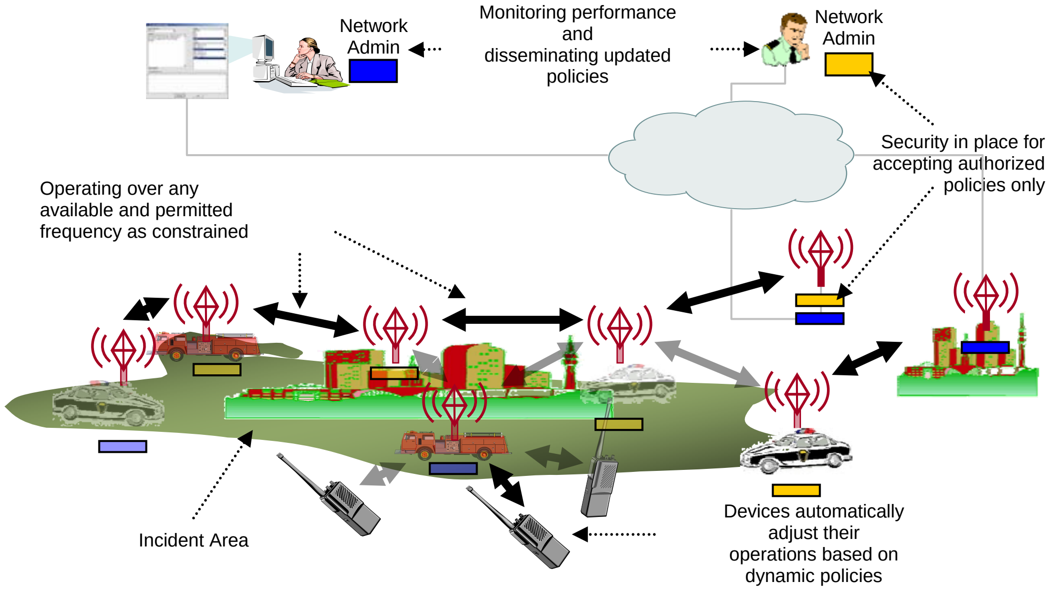

Figure 2 Policy-Based Network Concept of Operations (Shared Spectrum Company)

Policy-Based Network Infrastructure

A cognitive radio can manage operational control of discrete network assets and infrastructure at any time. Even where infrastructure is damaged, or hasn't been built, some communications capabilities can be established without reliance on communications infrastructure such as towers, base stations and back-haul networks. For an ad-hoc policy-based radio system, policies are the infrastructure architecture. Policy Infrastructure is used to create the "stack" of operational protocols that the radios follow in any geographic, frequency, or time dimension. Cognitive radios can reconfigure themselves dynamically in order to optimize their spectral efficiency and performance, in conditions where no radio infrastructure exists, and to avoid harmful interference under conditions where many non-cognitive radio signals are detected. They have not only autonomy to create, join and maintain networks, but also follow enforceable parameters that oversee the correctness of the cognitive network operation as well as the operation of every cognitive networked device.

[7] Perich, F., and McHenry, M., "Policy-based Spectrum Access Control for Dynamic Spectrum Access Network Radios," to appear the Journal of Web Semantics.

These might include:

1. Frequency bands, standards-based waveforms, and power output
2. System identifier and system key for any existing first responder system in any geographic region.
3. Tactical Interoperability requirements. For example, elements of a region's Tactical Interoperable Communications Plan could be incorporated into policy definitions.
4. Mutual Aid agreements
5. Existing radio system talk groups and licensed channels
6. Prioritization of use
7. Quality of service (QoS) as a function of user

Dynamic policies: Dynamic policies can be loaded onto radios at any time, including during the management of an incident. These might include:

1. Incident command structure ("virtual talk groups")
2. Incident awareness information
3. Routing policies for specific types of information (e.g. data and images)
4. Revisions to pre-determined policies (such as user prioritization)
5. Updated talk group information
6. Updated frequency use information
7. Updated geographic data

The benefits of cognitive radio technologies for operational management are:

- Flexibility - High-level specification policies apply to multiple heterogeneous devices simultaneously.
- Autonomy - Cognitive devices autonomously balance their resources and optimize networks as permitted by policies. Different models can be implemented to allow various approaches to human intervention; for example, cognitive radios could be eventually be developed that execute general direction from the network manager or Communications Unit Leader based on policies and in reaction to their environment,.
- Assurance - Policies from multiple stakeholders are enforced locally on every device at runtime guaranteeing proper operation without violating any requirements.
- Transparency - High-level specifications can be verified by theorem-proving systems for correctness at any time.
- Ease of policy authoring - A declarative language creates a policy abstracting low-level requirements.

- Secure policy management and distribution - The management framework allows control of the policies a device is using as well as monitor a device. Using a distribution model, policy commands and queries can be securely transmitted. The framework can be further secured for limiting who can control devices.
- More sophisticated traffic management and control that can more efficiently utilize network resources as needed across public safety and commercial uses. For example, SDR/CR technology can allow rapid scaling to meet evolving incident response needs. CR can perform “smart” dynamic channel allocation, depending on user locations and the amount of traffic measured per geographic area. CR can perform load balancing at the network level, limiting lower-priority traffic in bandwidth and/or message times.

4.3 Challenge 3: Public safety network must work under all types of disastrous and emergency conditions, including loss of power.

The network is required to have backup power generation capabilities and “hardened” sites. But even well-designed networks can be subject to failure, especially in unanticipated events (natural or man-made). Economically viable approaches are needed to supplement the traditional approaches for providing redundancy and reliability to achieve and surpass public safety requirements.

Software Defined Radio/Cognitive Radio Capabilities

SDR/CR can augment the traditional techniques of physical hardening and replication/redundancy of equipment by providing new and innovative ways to fill gaps in capability during disasters and/or emergencies.

One effect of a localized disaster or emergency in a public safety system’s service area is increased traffic load for the base station sites that provide coverage to that location. If the sites don’t have sufficient number of talkpaths to accommodate the additional traffic load, the Grade of Service (GOS) can be degraded to the point of precluding rapid channel access required by life critical situations. SDR/CR can recognize when such a situation occurs (via traffic monitoring and geolocation capability) and perform dynamic reallocation of frequency channels throughout the network to bring more frequency channels to bear in the disaster area. Such reallocation may require a priori frequency coordination or analysis, whereby the system recognizes sites with low traffic volume from which to “borrow” the additional frequencies until the disaster response is completed. Another method to add talk paths to an area is to change waveforms to ones with additional FDMA subchannels, possibly at the expense of decreased coverage or reduced voice quality due to lower rate vocoding.

Even with physical hardening of sites and equipment, a severe disaster (e.g., a category 5 hurricane disabling a site designed for category 3 hardening) can cause gaps in radio coverage if sites or equipment are severely damaged or lose power backup. For these instances, the flexibility and adaptibility of SDR/CR are applicable for coverage re-optimization and extension into the coverage gap from other sites near sites that are disabled, so that users in their coverage areas are provided connectivity. Further, the waveforms from the nearby sites' base stations and the terminals within the disaster area could be changed to ones that provide enhanced coverage to improve the coverage overlap in the affected area.

Another potential benefit of CR used in conjunction with SDR radios that have multi-service capabilities (e.g., radios that have both public safety LMR for their primary service and a cellular commercial service) is to affect a combined network and radio change to the alternate service in the area where the primary service is down. This has the same effect as the requirement in the Report and Order for portables to have satellite capability, but may be more cost effective.

4.4 Challenge 4: The public/private partnership is new, and there are aspects that will likely need to be changed and adapted as operators and public safety gain experience and feedback is obtained from real-world experience.

The proposed network is an ambitious undertaking that will involve spectrum sharing and associated issues of governance, operational control, and technology to support divergent requirements on an unprecedented scale, so adjustments will be required as operational experience is gained in using the system. The challenge is to ensure sufficient flexibility in the network to allow changes to be rapidly implemented.

To be useful in diverse conditions and varied scenarios and to exploit evolving technologies over a long term, the Public Safety radios and networks must be flexible and robust enough to accommodate changing protocols, multiple frequencies, and a variety of topologies.

Technology refresh cycles of public safety networks and commercial networks historically have been vastly different. However, the proposed network is to service both business models with the same network and technology.

Expensive public safety equipment will need to be upgradeable, as capabilities are introduced in shorter cycles than the past public safety equipment "life-span."

Software Defined Radio/Cognitive Radio Capabilities

In any new system provision must be made for error correction, upgrades, changes in requirements, new operations policy, and introduction of new technology as operational experience is gained in its use. SDR supports sufficient flexibility in the network to allow rapid implementation and deployment of necessary changes.

If SDR is used in mobile devices, they can be reprogrammed over-the-air as needed. SDR in mobile devices is not cost-effective yet for many commercial users. However, these users have higher tolerance for communications problems than public safety users, so rapid upgrades are less critical.

With SDR in the infrastructure, it becomes cost-effective to experiment with new behaviors on a small scale to validate their performance in actual operation. A new radio device with a waveform modification can be deployed to a single agency (or even a single fire engine). The software necessary to support that waveform can be remotely loaded onto all the infrastructure base stations in the operating area of that agency. However no resources need be dedicated in any cell to supporting that waveform, except when a user with the new device is actually present in a given cell and using the feature. The feature can be used for a time, its correctness and interaction with other aspects of the system checked, and the operational concepts (CONOPS) to employ it developed—all without visiting a single infrastructure site or taking significant resources away from the primary operational system. Once the new feature or waveform has been approved for wider use, it can be rapidly and cheaply deployed, especially if SDR is used in the mobile devices in addition to the infrastructure.

The ability to "improve as you go," enabled by the flexibility of software defined radio, will be highly valuable given the complexity of the new network and the many challenges facing its designers.

4.5 Challenge 5: The network design must be balanced to maximize the potential for commercial success, while planning conservatively in order to assure public safety requirements are met.

This challenge arises because the network must be designed to meet strict requirements. It is difficult to predict a priori how different design choices will affect key goals such as capacity, efficiency, robustness and coverage. In order to guarantee that public safety user's strict requirements are met, network designers must make conservative choices in any area where modeling or small-scale experiments provide uncertain predictions.

However, given the significant challenge of delivering competitively-priced commercial services over a public/private shared network, a more balanced design that also prioritizes efficiency and capacity may be required. Network designers face a significant challenge to balance these varying requirements due to the uncertainties in predictions during the design phase.

Software Defined Radio/Cognitive Radio Capabilities

The solution is to follow the same "improve as you go" strategy described in the previous section. Initially the network can be built out with a highly conservative design, for example allocating significant processing and radio resources to all public safety users at all times. As operational experience is gained, the network can be gradually evolved through software downloads towards an operating mode that frees more resources for commercial operation, while still meeting all public safety requirements. New changes in this direction can be evaluated in small-scale use, then deployed more widely once all stakeholders have developed trust that the changes are safe.

The flexibility of software defined radio to evolve over time enables the network operator to achieve much higher efficiencies and commercial returns over time than would be possible if all design decisions had to be made before the network is built or deployed.

4.6 Challenge 6: Public safety radio systems have a long-life span, over which requirements and the operational context will evolve, so the users gradually become less well supported by the features of the radio system.

Communications requirements for public safety agencies evolve over time. For example, demographic changes cause changes in coverage requirements; building construction and vegetation growth change RF performance; organizational changes cause policy and procedure changes; availability of new data changes capacity requirements; operational lessons learned cause reviews and changes to policies and procedures and possibly radio features. Given the historical life-span of public safety networks and the expected life-span of the 700 MHz broadband network, one can anticipate a variety of desirable changes over the lifetime of the network to ensure that users' requirements continue to be met.

Software Defined Radio/Cognitive Radio Capabilities

The flexibility of software defined radio enables upgrades over time to shift the network behavior to meet changing requirements and operational context. Without software defined radio, the radio system can become a barrier to effective public safety performance.

4.7 Challenge 7: Public safety radio networks have historically evolved much more slowly than commercial radio networks, so the shared network must continue to provide effective service to public safety users on one waveform even if commercial users have adopted a new waveform.

Historically the technology in public safety radio networks has had longer life cycles than commercial radio networks. It is possible that there will be economic incentive for the introduction of new waveforms for commercial users more frequently than public safety users will be willing to invest in new equipment or adopt new technology.

Software Defined Radio/Cognitive Radio Capabilities

Software defined radio directly solves this problem, since an infrastructure base station can host software for supporting multiple waveforms. If there are users with an older waveform in the local cell at the current time, resources such as spectrum and processing capacity can be allocated as appropriate to support them. If all users are on the latest waveform, the capacity of the basestation can be focused on that waveform. The ability to support multiple waveforms enhances interoperability while simultaneously enabling introduction of new technology, and allows network resources to be allocated as needed regardless of the technology in use by the users on the system.

Therefore, software defined radio makes it cost effective for a network to support multiple user communities with radically different technology refresh cycles.

4.8 Challenge 8: With the D-Block licensee's aggressive, population-based build-out schedule, there will be many areas of the country not served for several years, and other areas, with sparse population, that are unlikely to be built at all by the D-Block licensee. This could leave vast geographic areas, especially in the central and western states, mountainous regions and tribal lands without broadband services for either commercial or public safety use.

Recognizing this challenge in connection with public safety use, the FCC will allow local public safety entities to build out and operate separate systems, at their own expense, in the 700 MHz public safety broadband spectrum at any time, subject to several regulatory conditions and restrictions. The Public Safety Broadband Licensee must approve any such separate, independent network and enter into a spectrum leasing arrangement with the public safety entity. (FCC 2nd R&O at Paragraphs 470-484; 47 C.F.R Sec. 27.1330.) The rules also require these independent networks to (1) provide broadband operations; (2) be fully interoperable with the shared national broadband network; (3) be available for use by any public safety agency in the area; and (4) satisfy any other terms or conditions required by the PBSL. The Public Safety Broadband Licensee must also retain control of the entire spectrum associated with such local leases and exercise actual oversight of the spectrum lessee's activities. In areas subject to a build-out commitment, the public safety entity may not commence operations on the network until ownership of the network has been transferred to the D Block licensee.

Constructing systems in remote areas with local funding (or limited federal grant money) in a way that meets these requirements may be difficult. Moreover, these sparsely populated areas may not be attractive to the commercial D-block licensee, who is also prohibited from partitioning its nationwide license to other commercial or public safety entities seeking to cover unserved areas. (47 C.F.R. Sec. 27.1333) The PSBL is similarly restricted. (47 C.F.R. Sec. 90.528(e)). Finally, the FCC rules require that the D Block licensee make available to public safety users only one handset that includes a seamlessly integrated satellite solution, do not set forth a time table for the handset's availability and do not require that the D Block licensee incorporate support for satellite communications into the infrastructure of the shared terrestrial network

Software Defined Radio/Cognitive Radio Capabilities

For those low density communities that fear being left behind in the broadband era (as when railroads and highways may have bypassed them in the past), cost-effective SDR/CR technologies could allow the development of compatible local public safety and commercial broadband systems which meet the robustness and reliability requirements of the nationwide broadband network in the event they are eventually integrated. While a single hybrid terrestrial/satellite device is required, the timing and cost of this solution is uncertain.

SDR/CR technologies facilitate the use of commercial off-the-shelf (COTS) end-user devices that work on the shared national broadband network, local independent public safety networks and ad-hoc “gap-filler” networks, which would allow seamless interoperability and the rapid formation of terrestrial networks where a fixed network infrastructure is damaged or unavailable. Similarly, SDR/CR devices subscribed to the nationwide broadband network could, with proper authentication pursuant to the lease terms, “roam” onto the local independent network. When they become available, SDR/CR-based satellite solutions can be integrated accordingly. Just as existing private computer networks interoperate seamlessly with the Internet, locally financed, constructed and operated public safety IP-based 700 MHz networks using SDR/CR technology could accelerate the provision of broadband public safety service in areas where coverage from the D-Block operator is not available.

The local public safety build-out and operation provisions in the rules also could facilitate the integration of legacy data or narrowband 700 MHz networks with the new public safety broadband services using CR/SDR capabilities. However, the notion of such reconfigurable, hybrid, multimode networks and devices may require more flexible and dynamic spectrum leasing arrangements. Dynamic leases would be particularly useful where spectrum access is needed only to fill coverage holes with temporary ad-hoc networking or where additional capacity is required for bandwidth intensive applications. Thus, such leasing arrangements would accommodate the ability of funds-limited local public safety entities in rural communities to use CR technology to access 700 MHz broadband spectrum opportunistically only when needed and without having to build new infrastructure. Alternatively, in order to get broadband service for both public safety and its citizens, such communities may have to resort to leasing or buying spectrum from 700 MHz licensees in other blocks that are not subject to the restrictions imposed on the D-block and the public safety broadband spectrum.

5. Relevant Activities of the SDR Forum

The SDR Forum is engaged in a number of activities to further the development and deployment of the SDR and cognitive radio capabilities identified in the preceding section. The SDR Forum is an open, non-profit corporation dedicated to supporting the development, deployment, and use of open architectures for advanced wireless systems, with a mission to accelerate the proliferation of SDR/CR technologies in wireless networks to support the needs of civil, commercial, and military market sectors. Activities focus on:

- Developing requirements and/or standards for SDR and CR technologies, including working in liaison with other organizations to ensure that Forum recommendations are easily adapted to existing and evolving wireless systems;
- Cooperatively addressing the global regulatory environment;
- Providing a common ground to codify global developments;
- Serving as an industry meeting place.

With the SDR Forum, key issues relating to the development and deployment of SDR and cognitive radio technology in public safety are addressed in the Public Safety Special Interest Group (SIG). The Public Safety SIG is one of several special interest groups within the Forum that bring together developers, users, regulators, and educators to address issues specific to the application of SDR technology to a particular domain or market area. Goals of the Public Safety SIG are to interface with the public safety community (including both users and vendors), to raise awareness of SDR, to publicize the activities of the Forum in addressing those issues, and to increase participation of the public safety community in the SDR Forum. The Public Safety SIG also interacts with other committees and working groups within the Forum to provide the public safety community's inputs into the publications and initiatives undertaken by the Forum.

The Public Safety SIG is a unique venue, because participation in the SIG has historically included public safety organizations, land mobile radio vendors, advanced technology developers, service providers, manufacturers of SDR for military applications, software developers, researchers, and regulators.

Technical work with the SDR Forum is performed by the Technical Committee, which includes a number of Working Groups. Working Groups addressing specific issues relevant to the topics described in this paper include the following:

- Cognitive Radio Working Group—developing definitions, nomenclature, and conceptual models of cognitive radio to help categorize and clarify the relationships of cognitive and SDR functions.
- Metalanguage for Mobility Working Group—developing a metalanguage standard for cognitive radio applications that will enable automated SDR software installation, compataibility, and maintenance; the metalanguage standard will lead to languages for specification of policies for cognitive radios across various applications domains (e.g., commercial and public safety).

- o Research and Development Working Group—identifying and describing technologies and development topics, significant for SDR/cognitive radio in terms of need, technological challenge and maturity by creating white papers, recommendations, and summary reports, and advancing those technologies in the industry.
- o Security Working Group—producing a security framework that can be applied to various uses of SDR to address security issues that arise from the introduction of SDR technology.
- o Smart Antenna Working Group—developing a specification for a Smart Antenna Application Program Interface.

(Other Working Groups include a Design Process & Tools Working Group, Software Communications Architecture (SCA) Working Group, System Interface Working Group, Space Working Group, and Education Working Group.)

Key technical issues associated with the deployment of SDR and cognitive radio technology outlined in Section 3 can be addressed within this Working Group structure.

The SDR Forum also has a Regulatory Committee which provides an industry perspective on regulatory issues relating to SDR and cognitive radios.

Finally, the SDR Forum has initiated a Smart Radio Challenge, in which challenge problems are defined, and university teams compete to develop demonstrated solutions to the problems.

6. Conclusions

The public/private partnership to utilize new 700 MHz spectrum is an innovative attempt to provide public safety with a needed nationwide broadband network funded by sharing resources with a commercial system. This is clearly uncharted territory for public safety and presents a number of challenges. Emerging software defined radio and cognitive radio technology provide near-term and longer-term solutions to these challenges. Thus it is paramount that the stakeholders in the system account for the benefits that can be gained by this technology in the system design and implementation, negotiation of agreements among the PSBL and the D-block awardee, and the governance structures that are developed for the network. Otherwise the options for providing an economically viable network that meets public safety requirements are unnecessarily, and significantly, curtailed.