A Policy Proposal to Enable Cognitive Radio for Public Safety and Industry in the Land Mobile Radio Bands

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Abstract—**The frequency bands that have been licensed to the land mobile radio (LMR) services for decades are a tremendously fertile field for the deployment of cognitive radio technology. This paper outlines several reasons why policy-based cognitive radios would be particularly useful for modern public safety, federal non-military and business/industrial applications, especially in the VHF and UHF bands, where 80% of the public safety, federal and business/industrial licenses are currently held. This paper argues that many interoperability deficiencies are directly related to the original approach to spectrum policy and radio frequency regulation developed in the early 1920's, which segmented uses of LMR spectrum into several use classes. It provides a historic perspective to explain why the current status of LMR infrastructure, operations and licensee behavior is a direct result of antiquated policies and technologies still applied and deployed in these bands.**

The paper discusses the reasons that cognitive radio could be a successful solution for the apparent congestion in the bands. It suggests that policy-based cognitive radio systems operated on a cooperative, shared basis could lower costs of use and aid coordination for emergency responders across both public and private sectors of the traditional LMR user community. We discuss policy reforms and innovations such as spectrum pooling and spectrum portability that could spur new shared infrastructure development and spectrum efficiencies. We suggest several key policy reforms for consideration, including immediate cessation of ongoing narrowbanding initiatives, de-coupling of spectrum licenses from spectrum access, and national spectrum management by frequency coordinators.[1]

Index Terms—**cognitive radio, land mobile radio, public safety, spectrum policy, emergency communications**

I. Introduction

One of the most significant deficiencies in the public safety and emergency response community in the United States has been identified as a lack of "interoperability" between first responder radio systems. Nearly all of these radio systems operate in the Land Mobile Radio (LMR) radio bands authorized by either the US Federal Communications Commission (FCC) or the National Telecommunications and Information Administration (NTIA), the arm of the US Commerce Department responsible for managing federal users of the spectrum. Frequencies set aside for public safety use are interleaved with or adjacent to frequencies designated for business/industrial/transportation users and non-military federal users. The business/industrial/transportation users and federal users' radios and networks are not interoperable, either with each other or with the public safety radio systems. Though all sectors will likely be called to respond to a natural disaster or terrorist event, and though each has spectrum and radio facilities side by side with the other, when the time comes to mutually respond, their radios today will not talk to each other.

Discussions to date on resolving interoperability issues have focused on either urban agencies not being able to communicate with each other (such as those experienced between the New York City police and fire departments during 9/11), or problems between federal, state and local level responders (such as those highlighted during the Katrina response). Efforts to address interoperability problems through regulatory means tend to focus on "new" spectrum bands for public safety users, such as the 24 megahertz in the 700 MHz band designated by the US Congress for public safety use. This, of course, requires the construction of new systems and the acquisition of new radios. To fund these, billions of taxpayer dollars will be expended through NTIA and Department of Homeland Security (DHS) grant programs, and local bond issues and property taxes.

Recent regulatory efforts aimed at promoting spectrum efficiency and spectrum availability for a variety of narrowband, wideband and broadband public safety applications are focusing on secondary markets and secondary use, attempting to lump together interests of first responders with those of commercial service providers. This is notwithstanding the real inherent conflicts of objectives and capabilities of cellular and public safety radio networks.

Left out of the discussion of spectrum policy reform so far has been any serious look at innovation in the UHF and VHF bands, across the user pools of rural public safety, federal users and especially the critical infrastructure, business, industrial and land transportation sectors of the economy. Once the outdated walls of separation between federal, public safety and business/industrial use are set aside, we believe these bands can be rescued from antiquated policy and management, and revitalized into a robust dynamic service.

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II. MANAGING INTERFERENCE: THE HISTORIC BASIS FOR LICENSEE ASSIGNMENTS

A. Early History

As early as 1922 it was clear that the primary problem of an unregulated radio broadcasting marketplace was interference[1]. From 1922 through 1925, the US Department of Commerce sponsored a series of four annual National Radio Conferences. These conferences brought together representatives from the government and the radio industry, plus private citizens, in order to provide guidance to Commerce Secretary Herbert Hoover on the future of radio. The 1922 report stated:

"Resolved, That the types of radio apparatus most effective in reducing interference should be made freely available to the public without restrictions.
I. Allocation of wave bands for radio telephony.
A. It is recommended that waves for radio telephony be assigned in bands, according to the class of service"

As a result of the conferences, the Department of Commerce established 21 classes of radio service and one "reserved" class. These classes included military uses, industrial uses (especially by railroads and shipping), public broadcasting, educational broadcasting, local government broadcasting, fixed and mobile radio telephony, amateur radio and "city and state public safety broadcasting." Exclusive and non-exclusive classes were established, creating primary and secondary users on various spectrum assignments.

The Radio Act of 1927 and the Communications Act of 1934, which established the US Federal Communications Commission, essentially retained this station classification system and the FCC for decades continued to license 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, and defining power output and antenna height within the classes of use. The FCC has continued to license spectrum to users on the basis of use, controlling interference by segregating uses into eligible and non-eligible categories, and defining power output and antenna height within the classes of use.

While this approach to managing interference would suggest that sharing spectrum resources among like uses/users would be fostered and encouraged, silos were erected and exclusivity (*i.e.*, the right to exclude others) was granted to certain licensees. In doing so, the FCC introduced spectrum scarcity as a bi-product of purported interference reduction policies. 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 technologies designed to serve specific channel assignments; and (c) a patchwork of non-interconnected transmission facilities serving single-user licensees. Each user (a broadcast station, public safety agency or business/industrial/transportation entity) is compelled to build its own infrastructure, and jealously guard its spectrum allocation and existing licenses.

Now, however, after ninety years of segregating LMR users into minute groups with their own separate infrastructures isolated from other LMR user infrastructures, they are expected to interoperate.

B. LMR Bands Today: Chaotic and Arcane

The policy approach of the 1920's remains intact today. The solution to resolving interference is still to continue to segregate spectrum users into discreet channel assignments, and limit their tower height and power output. The result is a divisive patchwork of inefficient spectrum assignments limited by type of use, type of user, and location. The 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.

C. Local vs. Wide Area Radio Communications

When the rules were established in 1927, they anticipated local uses of a single channel on a single tower, not multi-channel wide area LMR networks needed today. To establish a radio service, for public safety or business/industrial/transportation uses, an applicant today must complete an interference study, and a complicated frequency coordination process for every transmit location, and every frequency to be used. Any change to the transmitter location, height, power output or number of channels requires a new interference study and frequency coordination process. Even a municipal police or fire network in a medium sized city is likely to have ten to fifteen transmitter or repeater sites, and up to twenty or more channels at many of these sites. A statewide public safety network may have over 300 transmitters.

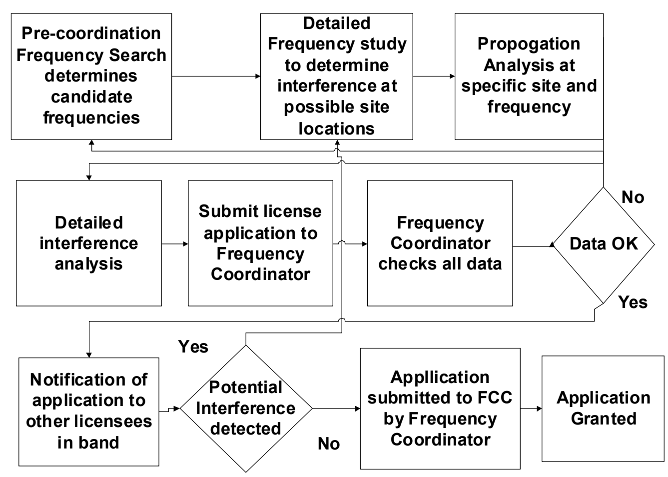

Fig.1. Frequency Coordination Process. The frequency coordination process is complex and lengthy.

In 1982, Congress provided the Commission 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

TABLE I
FREQUENCY COORDINATOR DESIGNATIONS IN THE PART 90 RULES

Pool	Type	Designation
Business/Industrial	IP	Petroleum Coordinator
	IW	Power Coordinator
	LR	Railroad Coordinator
Public Safety	PF	Fire Coordinator
	PH	Highway Maintenance Coordinator
	PO	Emergency Medical Coordinator
	PP	Forestry Conservation Coordinator
	PS	Special Emergency Coordinator
	PX	Any Public Safety Coordinator, except the Special Emergency Coordinator

[a] Note: Frequencies without any coordinator specified may be coordinated by any coordinator in its respective pool.

TABLE II
US PUBLIC SAFETY FREQUENCY BANDS

Band (MHz)	Bandwidth (MHz)	Status
25-50 (VHF Low Band)	6.3*	Narrowbanding required
150-174 (VHF High Band)	3.6*	Narrowbanding required
220-222 (220 MHz band)	0.1*	Narrowbanding required
450-470 (UHF band)	3.7*	Narrowbanding required
764-776/794-806 (700 MHz band)	24	Not currently available due to DTV transition
806-821/851-866 (800 MHz band)	3.5	Rebanding
821-824/866-86 (NPSPAC11[a] band)	6	Rebanding
4940-4990 (4.9 GHz band)	50	Equipment not currently available

[a] NPSPAC = National Public Safety Planning Advisory Committee
* denotes approximation
Note: Several of these bands are technically in UHF spectrum, but the 440-470 band was the first to claim this title so the 700 and 800 MHz bands are referenced as different bands.

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). Public safety, forestry, transportation and other groupings of eligibles formed frequency coordinator organizations for each designation to provide licensing information and frequency coordination. Frequency coordinators were designated for each service.

In February 1997, the FCC consolidated licensees into two general pools. 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). The FCC also combined all of the separate blocks of public safety frequencies into one single public safety pool where any and all eligible public safety agencies were equally eligible for any frequency in the new combined pool. Frequency coordination was also pooled, and today frequency coordinators authorized in any pool can coordinate for any eligible in that pool.

Because the bands allocated for both the public safety and business/industrial pools are fragmented and narrow, it can often be the case that the first licensee in a pool (class of user) takes nearly all the available channels in a band. The next user in the same area, must look to another frequency band to find available frequencies for licensing. The result is public safety agencies in the same city or town layered into different frequency bands, using equipment that can only tune to the specific band they are licensed in, and none other. To guard their ability for expansion of units on their radio system, the user/licensee in the UHF band, (for instance the police department of a city) may deny or discourage access to another user (say the fire department), who must then not only find available spectrum in another, likely higher band, but build a completely new radio infrastructure to create adequate coverage.

In the VHF, UHF and 800 MHz Business/Industrial pool, there are thousands of 1 or 2-channel users (schools, small businesses, building owners, etc.) as well as larger users like transportation and transit organizations, railroads, forestry product manufacturers, energy companies and utilities who are likely to exist in an entirely analogous environment to public safety (multi-channel trunked wide-area systems). Even more complex, is how this licensing structure works for national entities in the pool, for instance railroads, who must extend their communications systems across the continent. US Federal agencies, like the FBI, Customs and Border Patrol, and others also experience similar issues, but obtain their frequencies from the NTIA [2].

D. Spectrum Efficiency and LMR Reality: The "Analog Divide"

Conventional analog public safety LMR systems, most over fifteen years old dominate our national landscape. The Association of Public Safety Officials (APCO) estimates that 80% of all licenses currently issued to public safety radio users are VHF or UHF licenses for conventional (non-trunked) networks. These systems are most likely to be more than fifteen years old, which means they are analog, non-trunked systems. The other 20% are licensed in the 800 MHz band, and are likely to be digital trunked radio systems constructed after 1996, and are likely to be located almost exclusively in densely populated urban areas.

In fact, trunking was not introduced to the public safety community until after 1990. The first Motorola analog public safety SmartZone 800 MHz trunked radio system was turned on in Portland, OR, about 1991 and the second soon after in San Diego, CA. Portland estimates a needed investment of over $30 Million [3] and San Diego estimates needing over $300 Million [4] to refresh their systems and upgrade to APCO Project 25 (P-25) digital trunking in the next five to ten years. Many of the communities and statewide agencies using VHF and UHF frequencies are unable to afford trunking. They also cannot afford the infrastructure necessary to move to the higher bands because of the additional tower requirements. To create comparable coverage using these higher frequencies, licensees must place three to four times as many towers. Equipment associated with trunked radio systems is more complex to operate, and is likely to cost more than double the amount per radio site than conventional technology. Thus, most public safety radio systems in operation today (with the exception of those located in major metropolitan areas) are conventional VHF or UHF analog systems constructed in suburban, rural and wilderness areas, serving smaller communities and or agencies. These are also the areas that are likely to be sparsely populated, and therefore underserved or in many cases, totally un-served by market-based commercial wireless providers and other voice and broadband providers (like DSL and cable television modem service). These areas, however, are not immune to the types of events and natural disasters that require the presence of first responders from multiple federal, state and local agencies and officials from private companies (*e.g.*, an oil refinery or power generation plant explosion).

Trunked systems using the 700-800 MHz bands and the UHF bands are more prevalent in large metropolitan areas. These population centers produce a tax base which can support well-equipped public safety communications systems. These are densely populated urban centers with sophisticated public safety organizations serving urban communities. Though these urban centers have the most modern communications systems, and so, arguably are the best off, policy discussions around interoperability and spectrum policy for public safety have focused almost entirely on their urban requirements and urban profiles. An example is the suggestion that cellular services can be a replacement or augmentation to public safety LMR. Cities are the centers where commercial telecommunications facilities are located, including wire line and cellular. In communities outside of major and medium sized cities, cellular service is extremely spotty, and in rural and wilderness areas it can be non-existent for miles, even along interstate freeways, rivers, and railroads providing critical transport corridors. In these communities, LMR in the 50-450 MHz bands is essential for communications, because one tower can deliver signal for many miles, over rugged terrain.

E. Frequency Coordinators and Regional Planning Committees

As discussed above, FCC-designated frequency coordinators are private organizations that assist the Commission in managing the LMR frequencies. Unlike the services in which licensed spectrum blocks are auctioned by the FCC and are freely transferable in the secondary market, LMR users typically do not pay directly for the right to access and use their licensed frequencies. Rather, they must license them site-by-site and channel-by-channel, on a first-come, first-served basis. 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 be licensed and when it can't. Also, they have regular contact with other frequency coordinators in their pool, and can file license applications electronically with the FCC, charging, of course, fees for these services. 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. In the 700 and 800 MHz bands for public safety, the FCC has required that Regional Planning Committees (RPCs) be formed to manage the public safety 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 the assignments among the available channels 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 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 finally, they provide the 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. However, today, this coordinating function and information sharing is, with few exceptions, limited to clients within a pool of eligibles. The isolation of the pools is enforced by current spectrum policy, which encourages both the frequency coordination community and eligibles to view their pool as a dwindling resource. However, if regulatory policies and economic incentives advance along with technology, more efficient spectrum management is possible.

F. Narrowbanding in the LMR Bands: More Chaos

In a 1995 Report by NTIA on Land Mobile spectrum needs[5] and a 1994 "Requirements Study" by NTIA[6], it stated that of the 319 MHz of spectrum between 25 MHz and 2 GHz allocated for land mobile use, 42 MHz (13 percent) is allocated for Federal use, while 277 MHz (87 percent) is for non-Federal use. That Study also found that "a total of 204 MHz will be needed for land mobile operations within the next 10 years" and, of this amount, 50 MHz of this spectrum was identified specifically for public safety/industrial uses

Currently, although more than ninety-seven megahertz of spectrum are allocated in support of public safety communications [7], 74 MHz of this spectrum is in bands (700 MHz and 4.9 GHz) which are still largely unavailable for licensing or use by public safety due to incumbents and equipment availability. Of the remaining bands, both UHF and VHF bands are subject to narrowbanding requirements [8], and the 800 MHz band is currently being "rebanded."

The narrowbanding process requires the use of 12.5 kHz (and potentially 6.25 kHz) channels for voice communications and would phase out use of 25 kHz channels by January 1,

2013. For data applications, licensees must deploy technology that achieves a spectral efficient data rate of 4800 bits per second per 6.25 kHz (768 bps/Hz) if the bandwidth for transmissions is greater than 12.5 kHz. These mandates will force many licensees to re-invest in base stations, mobiles and portables for land mobile systems prior to the FCC's January 1, 2013 deadline for narrowbanding completion. In many cases, licensees have equipment already that can be re-tuned to the narrower bandwidth, but there are expenses associated with this as well, as the process cannot be done remotely through a software download. Federal government, public safety and industrial systems are all impacted. Many analog and conventional systems in the bands subject to narrowbanding in the 150-512 MHz bands may be replaced with trunking systems. Many larger communities and states that can afford to do so, are planning to migrate to a 700 or 800 MHz system rather than narrowbanding in the UHF or VHF frequency bands because of the congestion in these bands. In addition, the growing interoperability problems as more urban users adopt 800 MHz are a factor in deciding to re-license in the higher bands. However, this migration is difficult due to the expense of tripling the tower requirements necessary to obtain adequate coverage from transmission facilities in the higher frequencies. The expense is often crippling for state agencies with large terrain to cover. The state of Oregon is currently contemplating a new $700 Million statewide public safety radio system to replace its four VHF systems currently in need of narrowbanding (Forestry, Corrections, State Police and Transportation Departments each operate a separate system). The State of New York is currently spending over $2 Billion to construct its statewide wireless network.

In theory, the freed-up spectrum from narrowbanding in the VHF and UHF bands would be returned to the licensing pool as available narrowband (12.5 KHz spacing) frequencies. However, rebanding is not required to be completed until 2013 (that is, if the deadline is not extended). This means that in the interim, these frequencies, even if returned to the pool, may not be available for reassignment in the same geographic area because geographically contiguous systems that are not yet narrowbanded would not be able to use the narrowband channels on their existing equipment or could experience interference if the channels were assigned. Thus the narrowbanding mandate is unlikely to produce the channel efficiency anticipated until the changeover process is uniformly completed in every community.

The availability of spectrum and infrastructure for radio communications for both public safety and industrial use is very much in flux, and pressure on system owners and system managers is extreme. Reinvestment and planning costs are high, and the rules, trade-offs and benefits of investing in one strategy versus another are confusing. In an ironic twist of lagging policy, at the same time that users are trying to explain their need for wideband and broadband channels to the FCC, the most heavily used bands in operation are subjected to narrowbanding. It is therefore important to move away from static, command-and-control frequency allocations, narrrowbanding mandates and individual assignments to hundreds of thousands of individual entities. We must move toward a policy approach that eschews individual licensing and replaces them with *access*. Cognitive radios provide the tool to efficiently access spectrum resources for use over interoperable networks designed to serve public safety, business, industry, transportation and the federal government with only incremental investment and preservation of useful legacy systems.

III. Envisioning Dynamic Spectrum Access in the LMR Bands

A. Introduction to the Proposal

Several policy proposals have been floated in the aftermath of Hurricane Katrina and the Report of the 911 Commission concerning ways to make public safety communications more interoperable and more flexible. Two of these; the FCC's recent NPRM proposal to establish a national network in the 700 MHz band [9], and the CyrenCall proposal [10] suggest a national public safety network in the 700 MHz band, shared on a secondary basis with commercial uses. In both proposals, public safety users would have priority access to available channels (which are already allocated to them exclusively), and commercial providers could access fallow or unused channel resources on an interruptible basis. This paper proposes another approach, which continues to reserve all of the LMR bands for public safety, business, industry and critical infrastructure, and non-military federal use, but relies on the inherent promise of cognitive radio technology to allow these broad classes of users to establish access arrangements within their pooled spectrum, and benefit from shared interconnected network architectures.

Our proposal relies on the promise of cognitive radio to sense and detect radio signals, finding available channels on which to "roam" from band to band and network to network while adhering to local, regional and national policies across all three eligibility pools: public safety, business/industrial and federal/non-military. Users would dynamically access spectrum and shared infrastructure, whether commercial, industrial or government owned. Cognitive radio attributes including spectrum sensing, policy-based operation and ability to rapidly change frequencies, power, bandwidth, and waveform would ultimately empower a much more robust communications paradigm for public safety, critical infrastructure and industrial users than the proposals on the table have envisioned to date.

Business/industrial users and federal users could "flex" into public safety spectrum for transmissions as necessary, but only on a secondary basis. In return, public safety could flex into the business/industrial and federal pools, under a "lights and sirens" type access agreement, where their temporary occupancy of these channels would be a priority use, overriding non-emergency transmissions in order to route all emergency calls on a non-contention, first priority basis.

Cooperative users could reorganize network infrastructure assets. Today federal, business/industrial and public safety users in any region occupy not only the same or contiguous bands, their transmission facilities sit on the same hilltops, are often accessed by the same private roads, and in many cases, are trussed to the same towers. The ability of local agencies to configure these shared mountaintop arrangements is evidence that, with proper operational policies and financial incentives, these organizations could merge facilities further at the transport and network access layers (i.e., by using TCP/IP protocols), and manage shared base stations, antennas and radio controllers. Ultimately collaborative or outsourced management of databases, routing, switching, authentication, provisioning and credentialing would negate the need for billions of dollars of duplicated facilities across the nation.

B. New Paradigm: Dynamic Access, Not Channel Licenses

Licensing spectrum slots to users is inefficient, primarily for all eligibles that do not succeed in receiving a license, either because they cannot build infrastructure, or because the licenses are already granted to others. It would be much more efficient to grant eligibles access to the pooled spectrum and infrastructure on a dynamic basis. If policy reform could be pushed to this degree, the spectrum coordinators and RPCs could build on their existing tools, knowledge and roles to manage a dynamically accessible spectrum pool.

Because of their overview of the licensed and licensable pool, their electronic data analysis tools which can identify available frequencies, their existing systems of negotiation and arbitrage with other coordinators, and their close relationship to trade associations, the frequency coordination community and RPCs could be a key building block to introducing policy-based cognitive radio, spectrum sharing, spectrum leasing and band management in the LMR public safety and business industrial pools. Essentially, they have already developed "policy" databases which tell them when a frequency is available and to what type of user, for what purpose and at what location (coverage contour).

It is not inconceivable that their current role could be expanded to provide trusted management of pooled spectrum on behalf of the eligible users. The frequency coordinator would act as the eligible's agent to assign spectrum dynamically, according to the policies of the pool, including user priority access, per-use compensation between pools, time of day pricing and policing of the spectrum, allowing shared use of a portion or all of the region's spectrum, depending on the ability of the region's eligibles to reach agreement on what amounts of spectrum could be pooled.

C. Combining the LMR Eligible Pools

Today, eligibles (whether they are Federal, business or public safety) have a great deal of difficulty finding enough available spectrum in any of their individual bands to deploy a multi-channel, multi-site wide area (city-wide, regional or statewide) network. Negotiations to share, trade, or acquire licenses from license holders are very problematic because the community of license holders within a specific pool (for instance, the public safety pool) are dozens of separate organizations or jurisdictions, with many historic institutional barriers to cooperation or commerce between them. To look beyond their pool, (for instance for public safety to look to the business/industrial pool) complicates this "soup" even further. More layers of historic hands-off separation come into play. While they have formed umbrella organizations like the Land Mobile Communications Council (LMCC), even the spectrum coordinators from different pools do not routinely communicate on issues of day-to-day spectrum use or access.

However, if the right motivations could be found to encourage spectrum pooling, shared infrastructure and trunking across the public safety and business/industrial pools, in all bands, it is likely that the efficiencies gained in spectrum use and infrastructure deployment costs would be enormous. If both the public safety and business/industrial spectrum assignments were available on a combined basis, it would essentially double the spectrum potentially available in each band, in every region for every eligible user. Policy-based cognitive radios and networks that recognize the priority of the user or a given transmission will be very useful in defeating the concerns that a non-essential use would block an essential use. Shared infrastructures on cognitive radio architectures could be deployed on each band, in every region, and without the need to entirely displace legacy radios and facilities until a more natural transition dictates an upgrade.

Motivation to consider regional pooled LMR systems across federal, public safety and the business/industrial pools requires a huge paradigm shift in thinking about how to better manage interference and spectrum access through automated, policy-based approaches and joint communications needs of all of these sectors. 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.

This paradigm shift may be very near for several reasons:

1) In the LMR bands, where users have already been pooled, and coordination entities already exist to identify resource availability on a regional, local and national basis, frequency by frequency, tower by tower and user by user, it isn't such a large leap to imagine that these mechanisms could adapt and automate their existing systems and processes to dynamic spectrum coordinating roles.
2) Narrowbanding affects all users in the most used spectrum bands at the same time. Narrowbanding mandates put pressure on all users with older, conventional analog radio systems to upgrade their radio infrastructure between now and 2013, but such significant investments (with no foreseeable return) can be deferred while new technologies are naturally transitioned.
3) The propagation characteristics in the bands to be narrowbanded are ideal for smaller cities and rural areas, in other words, for most of the country. The coverage contours of towers can be 20 times larger than similar towers in the 800 MHz band. For users in the VHF or UHF bands to move to the 700 or 800 MHz band in order

to acquire more frequencies would involve at least tripling the number of transmit sites (at an average cost of over $300,000 per site or more). This means that existing federal, business/industrial and public safety users have to stay in the same bands, or come up with millions of dollars to migrate to a new band.

4) Narrowbanding requires immediate action, to either move or modernize all systems in these bands right away. This creates a window of opportunity for joint planning and implementation that has never existed before for both the business/industrial and the public safety community.
5) As a result of Homeland Security Presidential Directive 7 [11], infrastructure, such as roads, bridges, health care facilities, factories, monuments, dams, agriculture and other business sectors are recognized as part of the "critical infrastructure" of the nation, and efforts to secure them from natural and man-made disasters are a priority of DHS. Railroads, transit agencies, water, power, manufacturing and agriculture are petitioning to be recognized as an integral part of the disaster planning, mitigation and recovery community. As such, their requirements for redundant, interoperable and reliable communications systems are approaching the same levels as public safety and their need for interoperability with federal agencies, police, fire and 911 communications is becoming more obvious. Their needs for surveillance, intruder identification, background checks, GIS data, hazmat data and other advanced radio applications are similar to those of the police and fire community. However, the business and industry sector has efficiencies in purchasing, planning and technology deployment cycles that are enviable compared to government.
6) The business/industrial pool users already own towers, base stations, buildings, battery systems and other radio infrastructure in the same communities, and most often on the same hilltops as the public safety and federal user community. Their investments can be leveraged along with public safety to expand into a dynamically shared architecture rather than always overbuilding two or more separate single purpose LMR infrastructures in the same geography.

D. Transmission Utilities: Network Services Providers

In the LMR bands, site-based licenses require timely construction and use of facilities or they will be automatically terminated by the FCC. If spectrum resources were pooled and licenses replaced by a regime of managed subscriber/user access based on service level agreements (SLA) among the parties, cognitive radio facilities and network components will still need to connect to transmission facilities and gain access to rights-of-way. Moving to a radio service utility model (where network access is sold to user/subscribers as opposed to user-owned facilities) requires either the existence of a strong market for utility based services, or a subsidized or regulated "highway" system of transmission facilities. Another option is for pool members, to organize like an electric cooperative to build a single shared infrastructure for transmission of their frequencies. Currently enough transmission towers and backhaul facilities exist in any medium sized to major city to put all LMR frequencies on the air, but no one licensee has access to all of the facilities, frequencies or rights-of-way. Radio systems are silos. However, the precedent conditions are developing for shared infrastructure and subscriber-based usage of radio systems in both the business and public safety pools.

For example, regional and statewide public safety systems already exist in several areas. Some of these sell "subscriber access" to utility, transportation, transit, security and other public safety user organizations. Today these are still very limited efforts, but they are definitely a trend. A major reason for this trend is the expense of infrastructure to cover wide areas, especially at the higher frequency bands. The economics of the network architectures are driving user agencies to cooperate, and the added benefits of interoperability are further encouraging shared networks. However, users cannot "roam" to another system in another area, or another band, nor in most cases, can they switch transmission service providers. Still the principles of aggregating users onto a shared architecture are taking hold in both the public safety and business pools to some degree. For instance, the City of Portland's 800 MHz trunked radio system serves more than 100 public safety and public service agencies and jurisdictions in a county-wide region, and interconnects to other similar "utility" model systems in a four-county region, which extends across state boundaries to encompass Clark County, WA. In the utility model, a public or private entity owns and operates an LMR system to provide radio service to multiple user organizations on a use-for-fee, or subscription basis. In Portland, the operator (the City) charges approximately $35 per month to subscribe either a mobile data terminal, portable or mobile radio, and includes all service and maintenance. Several dispatch centers are interconnected, serving multiple separate response agencies, including the region's mass transit entity, area hospitals, school busses and security, water, power and federal, state and local first responders.

An immediate opportunity exists to accelerate this trend by having regulators facilitate and encourage pooled frequency access and shared network architectures to relieve serious congestion and reinvestment pressure. The FCC has begun this by adopting a broader definition of "public safety" eligibles, relaxing other LMR eligibility limits, facilitating secondary markets in spectrum licenses (including public safety to public safety spectrum leasing), giving public safety licensees the discretion to employ interruptible spectrum leasing, and encouraging tower co-location and infrastructure sharing (especially in rural areas). However, LMR user groups need to be the real champions of change by looking beyond regulatory relief as their last and only hope and by seriously examining new technology solutions.

Rethinking the narrowbanding requirements in the VHF and UHF LMR bands is important. Narrowbanding is not going to achieve the goals of spectrum efficiency. Narrowbanding, as it is currently being undertaken is simply going to continue dividing users onto separate infrastructures. Narrowbanding all channels in the VHF and UHF bands simply forces users with broadband needs to abandon these frequencies for higher bands, leaving those without resources to be left behind by broadband technologies. An alternative to the current approach would be to retain a deadline for returning spectrum to the pool, but provide planning grants for current licensees to design a shared, trunked, cognitive radio architecture to serve eligibles across pools.

Frequency coordinators could play a pivotal role by retaining frequencies that have been returned to a pool for dynamic access by eligibles. Frequency coordinators could provide “license access” and “spectrum portability” to users on a fee for use basis. Using cognitive radios, VoIP and IP routing and switching strategies, it would be possible to bind frequencies into broadband channels on a time basis, or to use narrowband voice transmissions on smaller “slices” of channel capacity.

Frequency coordinators or LMR operators operating as a “utility” could develop the ability to acquire and operate the facilities and spectrum of existing licensees, and lease them back on a subscription basis. Negotiated SLAs could guarantee to the former owner that they will have at least as much, if not more capacity as they had before, without the limitations and burdens of accessing and maintaining their own capacity constrained system. By agglomerating facilities and licenses in a region, the frequency coordinator can develop much more efficient allotments of both spectrum and network facilities to the communities they serve, and at a much more efficient cost. If frequencies were no longer licensed to specific users exclusively, or to specific facilities, facility owners would have incentive to divest, or merge their facilities so that they could maximize both availability of potential subscribers, and system revenues. There would no longer be the need to build an LMR system for the Power Company next to the LMR system for the police, and next to yet another five LMR systems for a variety of users. Instead there would be a limited number of high capacity shared-use network facilities competing for the user community's business. Because frequency coordinators are often organizations owned by the national association serving a community of users, these networks could be organized to allow nationwide roaming for end-user devices.

CyrenCall's proposal to the FCC approaches some of these concepts with a couple of important differences. CyrenCall proposal would not address spectrum efficiency problems in existing public safety bands. Instead it will create a whole new swath of spectrum dedicated to public safety, on a primary basis, and to commercial uses on a secondary basis. Presumably, because the shared network would operate in a new spectrum “greenfield” it avoids all the mess of incumbent interests. The new spectrum allocation would be managed by a public safety “trust” rather than the existing frequency coordination organizations (though one presumes that since the public safety community owns and operates the public safety frequency coordination organizations that significant overlap is possible). The CyrenCall proposal also does not address the interests of other non-public safety LMR users, especially those that comprise the wider definition of first responders, such as federal agencies, utilities, transportation, medical and construction users who presumably would continue with no relief under the current LMR regime.

IV. Cognitive Radio in LMR Bands

A. The Value Proposition of Cognitive Radio

While a number of regulatory and cultural changes must occur to achieve our proposed vision for LMR, cognitive radio is the technical component that makes the vision possible and its promise is becoming clearer. Advanced cognitive radio systems are aware of their spectral environment and can make decisions about radio operating behavior based on that awareness and the software policy controls embedded in the radio. In the case of the LMR bands, a network of cognitive radios can sense which channels are available across the available and authorized LMR spectrum and then determine which band is most suitable for a given objective. If spectrum pools are combined, and access to them authorized, this provides even more options from which the system can choose. Moreover, in the absence of narrowband restrictions, cognitive radio systems can combine channels to support wideband or broadband voice or data applications. Spectrum need not be contiguous, as cognitive radio systems could adapt to support a variety of configurations. For example, two communicating radios might support a wideband data service by selecting several channels that flank both ends of spectrum supporting a single priority narrowband voice session. The less regulatory restrictions on the uses and users of the spectrum, the greater potential benefit of cognitive radio, because more options means more opportunities for efficiency gains and less chance that unused spectrum will remain fallow.

B. Technical Developments Related to Cognitive Radio

For cognitive radio to become a reality in the LMR bands, several developments must happen. First, protocol specifications must be written to support predictable spectrum sensing and sharing. Standards such as CDMA, 802.11 and 802.16 have rudimentary forms of cognition that enable radios to select frequencies based on recent spectrum access experience, but the current state of radio technology does not support the functionality this paper envisions for the LMR bands. Further advancement of techniques used in existing protocols along with expected innovations from ongoing academic, government and industry research will likely produce the necessary results in time, particularly if regulatory reform continues to facilitate the creation of a market for the technology. So, while advanced cognitive radio functionality may not be available today, it feasibly could be commercially realized prior to the current 2013 deadline for narrowbanding.

For cognitive radio systems to achieve the promised benefits, radios must also be frequency agile – i.e., have the ability to operate over a wide range of frequencies and switch between them in near-real time. Today, most LMR radios are designed only to support frequencies in a single band because providing frequency agility increases the cost of the radio without any immediate benefit in the current LMR environment. Furthermore, power amplifiers in radios are typically efficient over a relatively narrow range of frequencies. Consequently, frequency agile radios may be less power efficient than current models, which may be a significant concern for radio applications that depend on batteries. Antenna technology also has similar limitations, as traditional antennas are only efficient within a certain range of frequencies.

Manufactures would likely develop the requisite technical capabilities if communications policy would facilitate the growth of markets for frequency agile and cognitive technology. For example, several firms are currently competing to create frequency agile transceiver chips, in one case promising support for frequencies from 400 MHz to 6 GHz. This range is outside of the VHF public safety frequencies because the chip manufacturer is targeting commercial applications, but new designs could support lower frequency ranges if the demand existed. Developments in smart antenna technology tell a similar story. Finally, even if greater frequency agility is not fully realized within appropriate time frames, multi-band, multi-mode radios can be built using arrays of today's front end components with an interface to a common software platform for baseband signal processing.

C. Policy-based Radio

In the future, frequency-agile cognitive radios may have capabilities far beyond what their users need to support a particular radio application at a particular point in time. For a variety of radio system stakeholders (e.g., operators, frequency coordinators, users), this extra capability is a risk, because it means the radio may be capable of causing harmful interference, connecting to unauthorized networks, or initiating undesired services. Policy-based radio enables one or more of these stakeholders to temporarily limit a radio system's capabilities for a particular application or set of applications. The general idea of policy-based radio is to enforce a set of machine-interpretable rules that govern the behavior of the radio system. The machine-interpretable policies are reconfigurable, so they can be modified over time as stakeholder requirements change.

In terms of innovation, the LMR industry typically is viewed as a technology laggard relative to commercial wireless, defense and intelligence markets, but it currently is a leader in the area of policy-based radio. For instance, many if not most of the recent digital LMR models are programmable, often supporting this feature over-the-air. Programmable radio is, in effect, a rudimentary form of policy-based radio. Today, this programmability typically is limited to the radio's "personality" – i.e., subscriber IDs, available frequencies, talk groups, traffic encryption keys, etc. In the future, this programmability could be extended to incorporate knowledge of the various pools in which the radio can operate and to what extent the pools have been integrated. The programmability might also include rules for communicating with frequency coordinators that might one day automate their assignment processes. Radio platforms could be designed to adapt to a changing regulatory and frequency coordinating environment because their policies would be reconfigurable at any time.

C. Securing Cognitive Radio

Neither regulators nor public safety communications officials will embrace cognitive radio unless it is coupled with strong assurance mechanisms that both ensure the availability of emergency radio communications and minimize the likelihood of harmful interference. Frequency-agile cognitive radios represent a threat as well as an opportunity to the user community. One method for countering the threat is for the radios to be policy-based and enforce machine-interpretable polices that codify the requirements of various radio system stakeholders, including both operators and users. However, more is needed. The radio platform needs to have mechanisms for preventing the user and others from circumventing the policy enforcement mechanism. To accomplish this, some form of process separation must exist (i.e., isolating the policy enforcement software, from the radio software and user applications, etc.). Another desirable control is attestation, which enables one radio to provide cryptographically trusted configuration information to another radio. For example, a base station in the radio infrastructure may require that subscriber units attest to compliance with a particular policy regarding spectrum access before they are permitted on the network. Policy enforcement, process separation and attestation as well as other controls are necessary to provide reasonable assurance that the proposed regulatory reforms will lead to the intended outcomes.

Authentication is also a complex and significant issue. Radios and their users will need to be authenticated, but other objects will also require authentication services. For example, radio systems will need to authenticate policies before enforcing them; otherwise, the systems adversaries could write bogus policies to achieve a number of malicious objectives. Similarly, any network messages related to spectrum availability would require authentication to avoid interference. The radio software supporting new protocols and cognitive functionality also requires authentication.

Public safety has two authentication challenges not typically encountered by most other wireless systems users. First, emergency responders need mechanisms for authenticating users, radios, and other objects when radio infrastructure has been destroyed or is otherwise unavailable due as the result of a disaster. Second, emergency responders need the ability to authenticate systems with which they have had no prior operational relationship, which could be necessary in the case of a multi-jurisdictional response to a major incident. Cognitive radio introduces more complexity and greater authentication challenges than is present in today's LMR systems. To address all of these requirements, the public safety community likely will need to develop a public key infrastructure (PKI) to support both day-to-day operational activities as well as new spectrum access policies. PKI technology is currently absent in LMR technology, but is used very successfully for Internet e-commerce and numerous other information technology systems, in which ordinary consumers routinely perform a variety of transactions with other entities with which they have no prior relationship.

V. SUMMARY OF THE PROPOSAL

Policymakers should review the potential of all of the LMR bands with their acquired knowledge of the state of the industry, and consider the following possibilities:

A. Cessation of the Narrowbanding Mandate

To achieve a policy environment where cognitive radios can provide the most benefit to both public safety and business industrial users, spectrum policy for cognitive radios should be as important in the VHF and UHF bands as it is in the "greenfield bands" at 800 MHz, 700 MHz and 4.9 GHz. Excluding the VHF and UHF bands from cognitive radio policy consideration, and narrowbanding them for voice communications, relegates them to a "graveyard" where no enhanced services can be implemented, in spite of their propagation (coverage) benefits.

B. De-Coupling Spectrum Access from Infrastructure Ownership

De-coupling of access to spectrum from licensing of transmission facilities allows spectrum use privileges to remain with the user, not the radio infrastructure providing transmission. Much like the way power generation has been separated from power transmission, spectrum access privileges would be separated from transmitter ownership.

C. Pooling of LMR Spectrum and Licensing the Pool Manager

Individually licensing LMR users, and requiring them to build infrastructure is a primary deterrent to efficient spectrum use and interoperability among users. Instead we need to set aside spectrum in blocks which are pooled for eligibles (one "group license" per pool). Blocks of spectrum available across classes of users could be managed to provide the greatest level of access for all eligibles.

D. Band management by Frequency Coordinators

Frequency coordinators could manage the LMR spectrum pools to allow secondary use, spectrum sharing between pools, network provider relationships and contracting, user billing and payments to network providers as well as other management functions that can migrate from a strictly local (system by system) basis to a national level. RPCs could retain the role of setting local and regional policies for use of the band pool and network infrastructure, including prioritization of usage for various eligibles, talk group management, and other regional operational policies that cognitive radios would follow.

E. Spectrum Portability

Once network provider contracts, eligible users and pooled spectrum are managed or coordinated within a national system, users should be authorized to "roam" and take their spectrum usage privileges with them. "Spectrum Portability" or "access portability" would use an authentication "look-up", (analogous to the telephone ANI/ALI database[2]) so that all network providers recognize each first response unit, on all bands, even if it is affiliating on a network that is not its "home" network. With this portability, cognitive radios could be authorized to roam geographically, and between bands, and have the capability to conform to regional policies for radios.

F. Competition in Provision of Networks

Network providers should be authorized to compete for the transmission business of spectrum users, without holding the licenses themselves. The authority of the user to transmit should transfer to the transmission facility while the user affiliates with the transmission facilities, and then follow the user. Like number portability, "spectrum portability" would insure that the right to use spectrum stays with the eligible, and is not permanently held by the network infrastructure provider.

For example a user who prefers a cellular network for data transmissions that must be received on the opposite coast would affiliate with a national cellular provider for that transmission, while local public safety data or push-to-talk traffic could be routed to open LMR facilities in the local area. Competition for transmission business would allow spectrum coordinators to contract in bulk on behalf of their eligible user community for transmission over network provider facilities; negotiating roaming agreements, competitively negotiating price per minute of use by the pool, and in a variety of other ways, apply market power to the acquisition of network infrastructure. RPCs and frequency coordinators would have the information necessary to implement bill-back policies, time of day pricing, bandwidth pricing, roaming agreements and other requirements, which could be downloaded to cognitive radios as radio policies.

G. Policy Based Radios

Among the current community of LMR (including public safety, federal users and the business/industrial users), the basic sets of relationships and transactions necessary for the operation of cognitive radio have not yet developed. Our current system of licensing channels to individual users who must then build infrastructure, has so far, obviated the need for usage-based policies, negotiations among eligibles, and a method of transacting, recording transactions and settling transactions between users in the LMR bands. The outcry for interoperability has produced rudimentary efforts to cooperate, but these are likely to continue to be fractious and awkward, due to the basic underlying disorganizing characteristics of current spectrum policy and current methods of LMR system deployment. The compelling organizing principle of these bands currently is to protect (close off) spectrum and radio systems once they are licensed.

[2] The ANI/ALI Tagging System appends all telephone call records with location and number identifying information.

Policy based radios will require a different principle, where spectrum use and network access is open. To organize usage in an open system of access, cognitive radios will be used to implement the organizing and transactional policies of the eligibles and their frequency pools. To do so, they will need access to an "intelligence center" or database of negotiated operating policies, which can be updated every time the radio affiliates with a network. The policy repository should include both regional and national pooling policies that assign the user device its priority on the network and manage spectrum allocation dynamically based on both user priority and message priority. Users with the highest priority, or messages with the most urgent content must traverse through the network ahead of non-critical traffic. Priority rules should allow management of the spectrum to produce the greatest level of user access, while protecting emergency communications. The system should be smart enough to queue non-emergency traffic, even from radios used by first responders. Open access policies will require a system of guaranteed "ruthless preemption," which moves non-critical spectrum uses to the back of the queue behind critical uses.

We believe that the critical policy areas which will facilitate dynamic spectrum use within the community of LMR users include the following:

1) Regional and Local User Preferences

Regional mutual aid agreements, existing incident command policies, pricing and other local and regional issues could be coded as policies accessible to cognitive radios. RPCs and frequency coordinators are ideal entities to ensure that regional policies are available to cognitive radios. These same radios could recognize the local and regional policies of other areas during the time that they are roaming over a network other than their "home" network, such as when they involved in incidents away from their home geography.

2) Ability of Radios to Choose Preferred Infrastructure and Band

Cognitive radios should be provided policies for choosing the "best available" network infrastructure based on preference. Preferences might be established by type of transmission, message content, geographic location, load, cost, time of day, availability, reliability, or other factors, which the radio would understand as part of its policy download.

3) Network Access Billing

All access across networks associated with a user should be recorded as billable events, and settlement of access charges could become as automated as the telephone industry's carrier access billing, roaming and long distance settlements are today.

4) Standards and Protocols

Cognitive radios should be capable of a variety of protocols and standards based operations depending on the transmission. Thus a single cognitive radio should be able to invoke P-25 standard air interfaces when required by the message, or use IP over IEEE 802.11, or any other standard protocol, depending on the policies loaded into the radio for various circumstances.

VI. Conclusion

Tactical group voice communication is the essential "mission critical" communications tool of public safety. Push to talk radio is a tool that cannot be replaced by speed dialing a telephone number. However, the augmentation of push to talk radio by mobile data, image files, text and video, often using commercial networks, is strong evidence that public safety users are poised to integrate enhanced information tools into the tactical operation. The technology they have deployed today, which is a direct result of spectrum policy, is not going to serve their future needs. Cellular services, designed for the consumer market are also ill-conceived for emergency and first response communications.

LMR with cognitive functionality can provide both critical push-to-talk, data and video services and enhanced service quality, without sacrificing coverage, capacity or reliability. Critical infrastructure, police, fire agencies and federal agencies need coverage in the most remote and hard to serve areas that is as reliable and robust as in the more densely populated areas. They need to talk through dispatchers from one to many receivers. Their communications include sensitive, private information, especially in emergencies. Their need to communicate reliably will spike during a regional emergency, exactly when the public wireless networks capacity will also be overburdened. However, LMR users' current frequency allocations, radio system design, equipment choices and business models are so antiquated, that they work against gaining efficiencies and advanced capabilities.

Recent proposals, such as the FCC's recent NPRM on forming a national public safety radio system in the 700 MHz band, and the CyrenCall proposal each continue to isolate public safety from the interests of critical infrastructure and each proposes that their obvious partnership is with the cellular industry rather than the business/industrial radio user community. Both proposals do not address the majority of users who rely on the propagation characteristics of the lower VHF and UHF bands to provide coverage in the remote and wilderness areas of the country, and each assumes that a single national entity can and will uniformly serve rural and urban areas while also achieving a market for commercial services from the same infrastructure.

We have proposed another alternative for consideration. Rather than migrate the public safety community to a new "reservation," and assume that a single national network could optimally serve all users, we suggest that the reserved spectrum assignments be pooled and portable, for use over both commercial and enhanced cognitive private networks designed to serve public safety, business and industry and the federal government.

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