Cover Sheet

PUBLIC SAFETY COVERAGE ENHANCEMENTS USING SIMPLE COGNITIVE RADIO CONCEPTS

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ABSTRACT

The ultimate RF coverage solution for a Public Safety (PS) radio system would provide communications at 100% of the locations where a first responder may be needed for 100% of the time, with perfectly understandable voice quality. This would include 100% coverage within areas such as basements, stairwells, tunnels, and buildings that often have well over 30 dB signal penetration loss. This goal for ubiquitous radio coverage is certainly understandable, since the ability for a first responder to reliably communicate can often determine the difference between life and death. Unfortunately, cost-benefit tradeoffs in designing a public safety radio system, not to mention laws of physics, have traditionally constrained public safety systems coverage from reaching this holy grail of ubiquity.

There has been considerable academic research into Cognitive Radio (CR) algorithms which can improve coverage. However, the pragmatic, skeptical public safety user community will not embrace these techniques until they reach the extremely high degree of maturity that is demanded for life-critical communications systems. Therefore, the incorporation of CR into the public safety community needs to be in small increments that are very low risk rather than in quantum leaps. This paper explores some simple techniques that could be useful in introducing CR into the PS community in this manner, rather than more esoteric, complicated, and likely higher risk concepts/algorithms which are presented in other literature.

1. INTRODUCTION

1.1. Background

Part of the SDR Forum's definition of a cognitive radio is 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" [1]. Over the past few years, CR has been receiving increasing attention due to its potential benefits for addressing today's and future communications requirements. The public safety community shares this interest in CR, as exemplified by ongoing work within the Public Safety Special Interest Group (PSSIG) of the SDR Forum. For example, in 2008, the PSSIG published a report [2] on benefits of CR for the 700 MHz public/private partnership, which included how cognitive radios/networks could mitigate the degradation of the system's radio coverage caused by interference. More recently, the PSSIG has been developing use cases describing how CR could benefit first responders for a hypothetical chemical plant explosion scenario. One of these use cases discusses how CR radios and systems could enhance radio coverage for both "noise limited" (received interference level is negligible compared to receiver noise) and "interference limited" (received interference level is much greater than receiver noise) conditions.

Also, work has been performed outside the public safety community on programs such as "Wireless Network after Next" (WNaN) [3] to investigate/demonstrate how CR can potentially enable lowering the radios' cost by utilizing a cognitive radio network to enable relaxation of RF requirements on the radios while achieving the required coverage. Also, universities such as Virginia Tech [4] and small business startups such as Cognitive Radio Technologies [5] have been performing substantial research into how radio/network performance, including coverage, can be managed via CR techniques such as game theory, Markov theory, neural networks, genetic algorithms, etc.

1.2. Challenge for Incorporating CR into PS Systems

The public safety user community is very risk-adverse and pragmatic; this is rightfully so, since lives can be lost if "bugs" happen to arise in new-technology communications systems deployments. These users will not likely adopt new concepts or technologies unless they have been thoroughly proven and show favorable benefits versus cost. Therefore, the incorporation of CR concepts, algorithms, and technologies into the public safety community needs to be performed in small incremental steps rather than quantum leaps. Rather than the more esoteric concepts/algorithms that have evolved in the literature, this paper deals more with fundamental coverage concepts that hopefully can be easier understood by those not versed in higher mathematics and provides a roadmap for introducing CR into the PS community through simple, understandable, and low risk incremental advancements.

Some might argue that some of the simple concepts discussed herein are not truly "cognitive radio", which is to be expected since there seems to be many different opinions of what a cognitive radio actually is. Arguably, they can be called "cognitive" because they meet the definition at the beginning of this section. It is merely a semantics issue as to whether all of these concepts are CR or not, which doesn't really impact the recommendations to be discussed.

2. COVERAGE REQUIREMENTS

A complete understanding of the coverage requirements for a public safety communications system is needed before coverage improvements afforded by CR can be assessed.

2.1. Coverage Topologies

A representative coverage topology for a typical public safety system is shown in Figure 1, involving a site with base stations communicating with vehicle-mounted radios (mobile terminals) and handheld radios (portable terminals) often within buildings and basement areas. Communications between terminals are usually through the tower site's repeater, but sometimes local communications is a small area (e.g., a fire scene) is conducted directly between the radios in simplex "talkaround" mode. Even though only one tower site is shown in Figure 1, typically there will be several, depending on many factors including the size of the area to be covered, the coverage reliability requirements, and the degree of in-building coverage required.

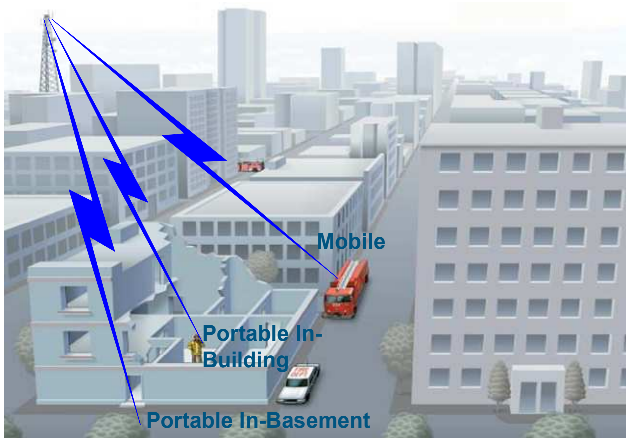

Figure 1. Representative Public Safety Coverage Topology

One driver of coverage topologies is the fact that traditional public safety systems predominantly use group ("one to many") calls instead of individual ("one to one") calls which cellular systems usually employ. With group calls, all sites that have users logged in on a given group (which could be several occupied sites in densely populated areas) will use a frequency channel. This tends to drive the coverage topology to maximize the area covered by individual channels (high towers with high power), with the limiting topology being simulcast (all sites transmit on the same frequency at the same time) in urban areas.

2.2. Typical Coverage Quality

A public safety system must meet stringent requirements for coverage reliability in a prescribed service area (e.g., city, county, statewide jurisdictional boundary), which is usually 95% or greater. In all but the most rural systems, requirements often including portable coverage within any general building that has up to 30 dB (or sometimes even higher) loss. Furthermore, urban and/or suburban public safety system will usually require coverage in several specified buildings (e.g., shopping malls, government office buildings, jails, hospitals, etc.), often including stairwells and basement areas, regardless of the signal penetration loss.

Coverage of 95% in a service area means that an officer must be able to communicate, with a minimum prescribed voice quality and/or data throughput (typical criterion for data communications) for at least 95% of the attempted communications throughout that area. Voice quality is usually described in terms of "Delivered Audio Quality" (DAQ); Table 1 defines the various DAQ ratings [6] and the Bit Error Rate (BER) required to achieve each for a P25 Phase 1 system with Rayleigh fading. For voice communications, greater than DAQ-3.4 (BER less than 2%) is a typical requirement. BER is considered "raw", before any error correction processing.

Table 1. P25 Phase 1 Public Safety Voice Quality Definitions with Required BER and E_b/N_o

Delivered Audio Quality	**Description**	**Required Bit Error Rate**	**Required E_b/N_o (dB) in 10 Hz Doppler Rayleigh Fading**
DAQ-4.0	Speech easily understood. Occasional Noise/Distortion	< 1.0%	19.0
DAQ-3.4	Speech understandable with repetition only rarely required. Some Noise/Distortion	< 2.0%	15.6
DAQ-3.0	Speech understandable with slight effort. Occasional repetition required due to Noise/Distortion	< 2.6%	14.2

For any particular type of modulation, the BER is relatable to a fundamental variable called E_b/N_o, which is defined as the received signal's "energy per bit divided by noise spectral density". For example, Figure 2 shows BER versus E_b/N_o for a P25 Phase 1 C4FM signal with Rayleigh fading with 10 Hz doppler. The required E_b/N_o values to achieve the BERs for each of the DAQ values are also shown in Table 1. As one would expect, voice quality improves as E_b/N_o (signal level) increases.

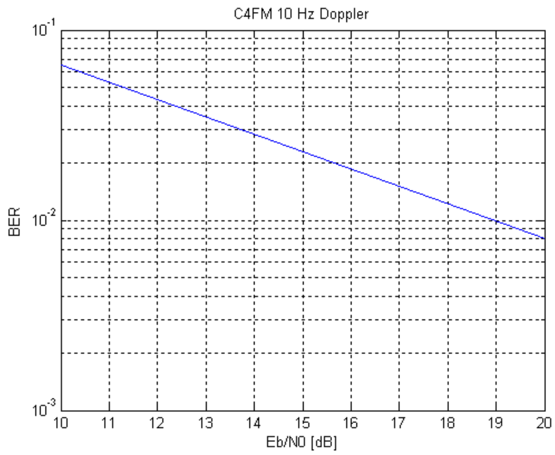

Figure 2. BER versus E_b/N_o for P25 Phase 1 C4FM Modulation

Data communications throughput is also dependent on BER and hence E_b/N_o. The focus for this discussion is voice communications, but the results to be presented are applicable to data communications as well.

3. COVERAGE VARIABLES

For this discussion, coverage will be specified in terms of coverage distance d, with larger values of d denoting better coverage. Without loss of generality and to simplify this discussion, line of sight coverage will be assumed rather than more complicated models in the literature (e.g., Longley-Rice, Okumura, etc.).

For a communications system with interference sources, the line of sight coverage distance d can be written as

$$d = K/(Mf)\sqrt{\frac{G_{ts}G_{rs}P_{ts}}{(E_b/N_0)(R/B)[N_0B + \sum_{j=1}^{N}(ACR_j\frac{G_{tij}G_{rij}K^2P_{ij}}{f^2 d_{ij}^{\ 2}})]}} \quad (1)$$

where

d = distance between desired transmit radio and receive radio

$K = (3.X10^8)/(4\pi)$

E_b/N_o = Energy per bit to Noise Ratio (related to the modulation being used and the desired BER)

M = margin factor (>>1) to account for blockage, foliage, buildings, etc

N = number of interference sources

P_{ts} = transmit power for the desired signal

G_{ts} = transmit antenna gain for the transmit radio

G_{rs} = receive antenna gain of the receive radio in direction of desired signal

G_{tij} = transmit antenna gain of interference j in the direction of the receive radio

G_{rij} = receive antenna gain of the receive radio in the direction of interference j

f = frequency of signal

R = data rate of the desired signal in bits per second

P_{ij} = transmit power for the undesired (interference) transmitter j

d_{ij} = distance of the receive radio from an undesired (interference) transmitter j

N_0 = receiver noise spectral density (fixed parameter, inversely proportional to receiver sensitivity)

B = receiver noise bandwidth

ACR_j = Receive radio bandlimiting filter's rejection[1] of interference source j

3.1. "Noise Limited" Coverage CR Control Variables

For cases where the receiver interference noise is much greater than the interference noise, i.e.

$$N_0B >> \sum_{j=1}^{N}(ACR_j\frac{G_{tij}G_{rij}K^2P_{ij}}{f^2 d_{ij}^{\ 2}}) \quad (2)$$

the coverage is said to be noise limited. For this situation, Equation 1 simplifies to the following:

$$d = (K/Mf)\sqrt{\frac{G_{ts}G_{rs}P_{ts}}{(E_bN_0)RN_0}} \quad (3)$$

Based on Equation 3, if a "simple" CR system could somehow sense that interference is not limiting coverage, it can adjust the following controls to improve the coverage:

1. Maximize antenna gains G_{ts} and/or G_{rs} in the direction of the desired communication path.
2. Change modulation (with reduced required E_b/N_o) and/or reduce data rate R to the minimum needed for the communication.
3. Assuming that the following is true, choose a lower frequency band:
   - The antenna gains don't decrease in proportion to frequency decreases (i.e., larger apertures are used in the lower frequency bands).

[1] For this discussion, ACR is defined as the attenuation of interference signals by the receiver's filtering relative to the filter's gain for the desired signal. Smaller ACR indicates better interference rejection. More selective receiver filters and greater frequency separation of the interference reduce ACR.

- The different frequency bands have overlapping coverage.

4. Have a switchable circuit in the radio receiver that could be selected to reduce the receiver's noise figure, which is proportional to N_o, at the expense of degraded receiver front-end linearity (front-end linearity is less important if there is no interference).
5. In cases where the required E_b/N_o is greater than what it optimally can be because of degradation caused by receive filter bandwidths being narrow (for attenuating interference), widen the receive filter bandwidth.
6. In cases where delay spread fading or simulcast overlap is causing coverage degradation (in essence raising the required E_b/N_o to achieve a requisite BER for a voice quality or data throughput criterion), utilize an adaptive time domain equalizer in the receive terminal.
7. Change sites or systems to one that has a better signal to noise ratio, if the radio link degrades below minimum criteria.
8. Change channel coding algorithms to enable a higher required BER (i.e., reduce required E_b/N_o) for a given voice quality or data throughput.

3.2. "Interference Limited" Coverage CR Control Variables

For cases where the interference noise is much greater than the receiver noise, i.e.

$$\sum_{j=1}^{N}(ACR_j \frac{G_{tij}G_{rij}K^2P_{ij}}{f^2{d_{ij}}^2}) >> N_0B \tag{4}$$

the coverage is said to be interference limited. For this situation Equation 1 simplifies to the following

$$d = (1/M)\sqrt{\frac{G_{ts}G_{rs}P_{ts}}{(E_bN_0)(R/B)[\sum_{j=1}^{N}(ACR_j \frac{G_{tij}G_{rij}P_{ij}}{f^2{d_{ij}}^2})]}} \tag{5}$$

Based on Equation 5, if a "simple" CR system could somehow sense that interference is the limiting factor for coverage, it can adjust the following controls:

1. To mitigate interference to others, balance P_{ts}/P_{ij} throughout the system, using only enough power to maintain communications at the minimum acceptable level. In fact, for low priority communications paths, the power could even be set for degraded voice quality relative to the paths with the highest priority to reduce interference.
2. Maximize G_{ts} and/or G_{rs} in the direction of the desired communication path.
3. Minimize G_{tij} of the interference in the direction of the receiver, if the CR system also has control of the interference source.
4. Minimize G_{rij} in the direction of the interference.
5. Reduce data rate R to the minimum needed for the communication.
6. Increase the rejection of the interference, i.e. reduce ACR_j, by
   a. Increasing frequency separation of the interference sources from the desired radio path to increase receive filter rejection of the interference.
   b. Changing the receiver filter to provide better rejection of the interference, usually by narrowing the receiver filter bandwidth. (However, if the bandwidth is narrowed too much, the required E_b/N_o may increase to the point of counteracting the ACR improvement.)
   c. If the interference is controlled by the CR system, change its transmit modulation and/or data rate to narrow its transmit spectrum so that its transmit sidelobes are diminished within the receiver's bandwidth.
7. In situations where "blockage" is detected whereby the receiver's RF front end is being forced into compression and/or limiting by a strong interference source, switch in signal attenuation to reduce the signal into the linear range at the expense of decreased receiver sensitivity and thus decreased noise limited performance.
8. Change sites or systems to one that has a better P_{ts}/P_{ij} ratio.
9. Change channel coding algorithms to enable a higher required BER (i.e., reduce required E_b/N_o) for a given voice quality or data throughput.

4. ROADMAP FOR INTRODUCING CR COVERAGE ENHANCEMENTS INTO PS SYSTEMS

A complicated CR system could be envisioned that incorporates all eight controls discussed in section 3.1 and all nine controls mentioned in section 3.2 in a multivariable optimization of system-wide coverage. Such a system would likely leverage academic studies such as those cited in Section 1.1. However, as Section 1.1 also discusses, this author has considerable skepticism as to whether such a system would be embraced much less even considered by the pragmatic public safety community until proven beyond a shadow of doubt.

Instead, it is recommended that CR be deployed in increments, with each increment being a "baby step" toward achieving the eventual full CR capability. The initial increments, which need to establish a solid foundation on which to build additional, more elaborate CR systems, must be low risk in regards to potential disruptions of

QOS/reliability, low cost, and not perceived as a radical departure from known system designs and operating procedures. Of course, the initial increments must also demonstrate sufficient improvement in coverage so that the PS community sees them as a favorable benefit versus cost tradeoff.

Considering the above constraints, and sorting the methods discussed in sections 3.1 and 3.2 with respect to factors such as risk, cost, and anticipated acceptance, Table 2 shows a coverage roadmap for introducing CR coverage enhancements into PS communications systems. It is noted that some of the initial increments are already implemented in today's operational systems.

With this approach, the intelligence and control for the first ten increments of the roadmap resides in the terminals and/or base stations, and the later increments assume that additional intelligence/control is added *at the network level*, along with terminal geolocation and dynamic user priority, which should enable substantial further improvements in coverage performance. Ultimately, the roadmap leads to more complex techniques such as those mentioned in Section 1.1, provided that the experience that will have been gained by the previous increments indicates that it makes sense to do so.

5. SUMMARY

This paper has explored some simple techniques that could be useful in introducing CR for coverage improvements into the PS community in a "baby steps" manner, which this author feels will be more amenable to the public safety community than more complex techniques. Some of the initial CR increments are even shown to be implemented in some of today's PS communications systems to reinforce the notion of low risk. No claim is made that the techniques discussed herein comprise a complete, exhaustive list; they are intended to be a possible first order solution and the techniques will likely change as PS CR coverage solutions evolve, coverage improvements using CR are quantitatively measured, and end-user reaction is assessed.

6. REFERENCES

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[2] "Utilization of Software Defined Radio Technology for the 700 MHz Public/Private Partnership", SDRF-08-P-0004-V0.8.0, 18 June 2008, http://www.sdrforum.org/pages/documentLibrary/documents/SDRF-08-P-0004-V1_0_0_Technology_for_700_MHz_Spectrum.pdf

[3] "Wireless Network after Next" project website, http://www.darpa.mil/sto/strategic/wireless.html

[4] http://www.cognitiveradio.wireless.vt.edu/

[5] http://www.crtwireless.com/

[6] "TIA Telecommunications Systems Bulletin, Wireless Communications Systems Performance in Noise and Interference Limited Situations, Part 3: Performance Verification", TSB-88.3-C, February 2008

Table 2. Roadmap for Introducing Public Safety CR Coverage Techniques

INCREMENT	CAPABILITY	CONTROLS THAT ARE IMPLEMENTED (Section-Control Number)	WHERE INTELLIGENCE AND CONTROL RESIDES	DESCRIPTION	REQUIRED NEW HW & SW
1	Change systems or sites if signal is degraded below minimum criteria	3.1-7 3.2-8	Terminals	Smart roaming algorithm changes sites/systems if RX signal quality is degraded below minimum criteria. *Note: This is already implemented in high-end radios*	None in high-end terminals
2	Receiver front-end gain control	3.1-4 3.2-7	Terminals and/or base stations	Given blockage interference and adequately strong desired signal, an attenuator is switched in to reduce signal level into the radio's front-end. *Note: This is already used in some radios*	Front end overload sensor, switch, attenuator, and control HW and/or SW
3	Power control in	3.2-1	Terminals or	Turn down transmit power	SW in terminals

INCREMENT	CAPABILITY	CONTROLS THAT ARE IMPLEMENTED (Section-Control Number)	WHERE INTELLIGENCE AND CONTROL RESIDES	DESCRIPTION	REQUIRED NEW HW & SW
	terminals (especially Mobiles) to reduce interference to others (e.g., mitigate "near-far" problem)		terminals + base station	to "just enough" to maintain the requisite quality to reduce potential for interference to others. *Note: Some radios are already capable of this.*	and/or base station to measure received RSSI, BER, and/or some other quality metric. Also, power control of terminals' PA. If sensed in base station, send message to terminal with required TX power.
4	Change frequencies in the same band if interference is excessive	3.2-6a	Base station or terminals + base station	Change frequencies in the same band and same site/system if excessive interference is detected on a frequency. *Note: Typical PS base stations already do this on the control channel for a trunked system*	Interference sensor. If sensed by the terminal, the base station must be made aware with new messaging to coordinate the change
5	Receive delay spread equalizer	3.1-6	Terminals and/or base stations	Adaptively sense and equalize delay spread in real time. *Note: Some radios have this already.*	SW within the radio's existing programmable processor. e.g., adaptive FIR filter
6	Smart RX antennas for the base stations	3.1-1 3.2-2, 3.2-4	Base stations	Steer RX mainlobe in desired direction and set a notch in the interference direction. *Note: Not recommended for base stations' TX antenna due to group calls*	Adaptive RX antenna with control algorithm implemented in SW and/or HW
7	Change frequency bands	3.1-3 3.2-6a	Base station or terminals + base station	Change frequency bands to improve noise limited performance or to avoid interference frequenc(ies). *Caveat: Requires overlapping coverage of the different frequency bands.*	Requires multi-band radio. Possibly implement by including systems in different frequency bands in present radios' roaming algorithm system list
8	Smart receiver bandlimiting filter	3.1-5 3.2-6b	Terminals and/or base stations	The balance between adjacent channel rejection and sensitivity is dynamically adjusted, depending on whether coverage is noise- or interference-limited, by changing bandwidth of the receiver band-limiting filter	Best implemented in a FPGA and/or DSP. Needs receive signal quality sensing software (RSSI, BER, or other quality metric), and several different selectable I, Q filters (perhaps FIR)
9	Smart terminals RX/ TX antenna	3.1.1 3.2-2, 3.2-3, 3.2.4	Terminals, especially mobiles	Steer mainlobe in desired direction and set a notch in the interference direction.	Adaptive antenna with control algorithm implemented in SW and/or HW
10	Smart modulation, data	3.1-2, 3.1-8 3.2-5, 3.2-6c, 3.2-9	Terminals and base stations	Balance amount of FEC vs. the modulation's	- Receive signal quality sensing

INCREMENT	CAPABILITY	CONTROLS THAT ARE IMPLEMENTED (Section-Control Number)	WHERE INTELLIGENCE AND CONTROL RESIDES	DESCRIPTION	REQUIRED NEW HW & SW
	rate, and/or coding control			*Eb/No* req'ts vs. data rate to maintain requisite data throughput and/or voice quality, yet reduce interference to others. *Note: Although this technique can offer some improvement by being terminal- or base station-centric, including network intelligence (increment 20) will substantially improve coverage performance*	software (RSSI, BER, or other quality metric) - Control software changes to both the terminals and base stations - Additional messaging between terminals to coordinate the changes
11-20	Same as 1-10, except augment the above capabilities with network intelligence that uses knowledge of the states of the above controls plus geolocation and dynamic priority of terminals for substantial further improvements in system-wide performance.				
21-?	Mature game theory, Markov theory, neural networks, or genetic algorithms, etc.				