SDR Market Study, Task 5:
The Cognitive Radio Market

Prepared for
The SDR Forum

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About the Author

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He is currently developing a series of Software Defined Radio (SDR) market and technology studies for the SDR Forum. The completed reports are listed below. He is author of market research reports entitled Wireless Infrastructure: Technology and Markets that have been published by Forward Concepts. He served as principle investigator on a DARPA SUO project to develop advanced software radio architectures for military and commercial waveforms. He is co-author of "Communication Mediums for Intelligent Transportation Systems" (TRB/National Academy Press), which is a multi-media/multi-medium communication system design guide.

Completed SDR Forum Market Study and Technical Reports:

1. SDR Market Study, Task 1: Market Segmentation and Sizing, 2005
2. SDR Market Study, Task 2: Cellular Terminals and Infrastructure, 2005
3. SDR Market Study, Task 3: WiFi, WiMAX and Beyond 3G / 4G, 2007
4. SDR Market Study, Task 4: The US Public Safety Market, 2007
5. SDR Technical Study, 2006
6. SDR Market Study, Task 5: Cognitive Radio Market, 2007 (This Report)

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1 Executive Summary

This report entitled "The Cognitive Radio (CR) Market" provides a comprehensive look at an emerging technology that many industry stakeholders are identifying as an essential enabling technology to achieve future goals in key wireless industry market segments. These include commercial, public safety, and military segments. The key near-term goals are spectrum efficiency and spectrum availability to support emerging requirements and market opportunities. The longer-term goal is cognitive capability not only for spectrum efficiency, enhanced regulatory effectiveness, licensing, and spectrum management purposes, but to adaptively anticipate and accomodate user needs and efficiency. Most standards organizations regard CR and Software Defined Radio (SDR) as distinct but complementary, and mutually enabling, technologies.

Regulatory authorities focus on spectrum efficiency, availability, and management. A key issue for them is to provide supporting CR regulatory initiatives without favoring or impeding any particular approach. They largely support the idea that the competitive marketplace is the most appropriate venue to evolve CR technologies and initiatives, unencumbered by excessive unnecessarily constraining regulations. CR visionaries appear to have broader goals for CR that including cognitive or intelligent support for market, regulatory, user application needs, as well as enabling the benefits of improved spectrum management and efficiencies.

The commercial markets for wireless technologies are clearly the largest markets for SDR and CR in terms of both units shipped and revenues. These commercial markets include: 1) The cellular market[1] including Beyond 3G and Long Term Evolution (LTE) [2], 2) The Wireless Local Area Network Market (WLAN, e.g., WiFi Market [2]), and 3) The Broadband Wireless Access Market, (BWA, e.g. WiMAX) [2]. The key SDR and CR opportunities in the commercial sector are improved spectrum efficiency and availability and cognitive support for network and terminal configurations to support the emerging triple/quadruple play, multimedia, and multi-radio initiatives. SDR-centric and CR-centric features appear essential to success of these commercial wireless market goals. The key SDR and CR stakeholder opportunities, and issues, are technology insertion consistent with overall industry goals and initiatives. It should be noted that many commercial sector stakeholders have expressed opposition to involuntary spectrum sharing (i.e., involuntary unlicensed operations in cellular bands). Industry prefers secondary market initiatives, where access is under operator business and technical parameters and control. Secondary market initiatives provide significant CR opportunities.

The SDR Forum's Public Safety SIG (Special Interest Group) has on-going activities to develop use cases for cognitive radio applications in public safety. The key public safety application for SDR and CR is interoperability. In many disaster events communication may not be available due to infrastructure damage. A key requirement for CR technologies is to reconfigure responders' radios as an ad hoc extension to the existing network to allow transmissions relayed

[1] Cellular: Terminals and Infrastructure, Prepared for The SDR Forum, by Jim Gunn Consultancy, June 2005
[2] WiFi, WiMAX, and Beyond 3G / 4G, Prepared for The SDR Forum, by Jim Gunn Consultancy, May 2007

from a disaster site along a network of individual responder radios providing access to the main radio network.

The defense community has been the leader of SDR and CR initiatives. Although international interests and initiatives exist, the military leader of SDR and CR initiatives has been the US Department of Defense in its DARPA XG (neXt Generation) program, and in other related programs. Military programs have a focus on Mobile Adhoc NETworks (MANETs) that require no supporting infrastructure. The Tactical Edge has various types of MANETs that are formed to support tactical operations using waveforms appropriate to units and missions. MANETs are deployed to support fluid wireless tactical networking operational requirements for voice and data waveforms based on Internet Protocol (IP) network technologies.

Two regulatory leaders of SDR and CR initiatives have been United States Federal Communication Commission (FCC) and the United Kingdoms Office of Communication (Ofcom). Some of the key recent releases by the FCC concerning CR and SDR initiatives include new SDR rules/regulations facilitating CR, unlicensed operations in TV bands, a CR spectrum sharing test-bed, and secondary licensing. Ofcom representatives have stated that “Research suggests that if licenses were more flexible this could increase the value the UK generates from the radio spectrum by nearly €1bn”[3]. In pursuit of this Ofcom has funded several studies on SDR and CR over the last several years. In a study report on CR released in February 2007 by Ofcom, it is stated that “two problems are identified to achieving full CR. The first is making a truly cognitive device with the ability to intelligently make decision based on its own situational awareness. The second is the evolution of SDR technologies to enable reconfigurability.”

An European CR program is the End-to-End Reconfigurability (E^2R) project sponsored by the European Commission. The program goals are to realize the full benefits of the diversity within the radio eco-space, composed of wide range of systems such as cellular, fixed, wireless local area and broadcast. The key objective of the E^2R project is to devise, develop, trial and showcase architectural design of reconfigurable devices and supporting system functions to offer an extensive set of operational choices to the users, application and service providers, operators, and regulators in the context of heterogeneous systems. The program is a CR project for commercial operator initiatives with extensive business model analyses.

Based on input and discussions from many sources we conclude that CR is an emerging technology that will become an essential enabling technology for key wireless market segments. As discussed herein, the commercial, public safety, and military markets have emerging requirements that we conclude can only be achieved through insertion of SDR and CR technologies. The essence of this report is to provide the information and rational leading to these conclusions.

[3] See Section 3.5

2 Introduction and Conclusions

This report entitled "Cognitive Radio Market" provides a comprehensive look at an emerging technology that offers promise to achieve the vision of multimedia wireless services anywhere, anytime, and with any device. The key near-term goal is spectrum efficiency, enabling spectrum availability to support emerging commercial, military, public safety, and new market opportunities. The longer-term goal is cognition not only for spectrum efficiency purposes, but to adaptively provide for user needs and efficiency. This report will be organized as follows:

1. Executive Summary and Conclusions
2. Introduction and Conclusions
3. Background/Definitions, Drivers and Issues
4. The Potential Cognitive Radio Market

Based on research documented in this report, the conclusions are that Software Defined Radio (SDR) and Cognitive Radio (CR) initiatives are essential enabling technologies for rapidly emerging requirements in key wireless market segments, including commercial, public safety, and military markets. It is envisioned that SDR and CR technologies will be substantial product and application differentiators and service enablers. Those who embrace SDR and CR will be positioned for application and market successes.

These three key markets exhibit the following attributes:

1. Commercial markets including cellular, Broadband Wireless Access (BWA, e.g. WiMAX), and Local Area Networks based on the popular WiFi technologies are evolving to become part of heterogeneous multimedia "system-of-systems" that provide "Seamless Mobility", "Always Best Connected", and "Always Best Experience" for subscribers. CR provides real time optimization and configuration for network and terminals in a subscriber-friendly "easy-to-use" manner. SDR enables band and mode flexibility.
2. The public safety market priority requirement is for CR interoperability. Improved spectrum flexibility and broadband service are also needed. In disaster events, requirements exist for relay of communication should the normal infrastructure not be available. Ease of use is critical for these capabilities as public safety personnel must focus on their primary, often stressful, public safety missions. SDR and CR are enablers of these characteristics.
3. The military, particularly the DARPA XG program, has been the international leader in SDR and CR. The key military requirement is for Mobile Adhoc NETworks (MANETs) that rapidly reconfigure to accommodate a fluid mobile force without infrastructure. They are interconnected by the Global Information Grid (GIG) based on satellite communication links to interconnect tactical edge operational elements with each other and their command and control elements. SDR and CR are enablers.

3 Cognitive Radio Definitions, Opportunities, Driving Forces, and Issues

As an emerging technology with an intriguing name, Cognitive Radio (CR) gives rise to the question "what is cognitive radio?" A popular source for technical definitions is Wikipedia[4], a web site that claims to be "an encyclopedia collaboratively written by many of its readers". The definition on the Wikipedia web site for Cognitive Radio is:

> Cognitive radio is a paradigm for wireless communication in which either a network or a wireless node changes transmission or reception parameters to communicate efficiently without interfering with the licensed users. This alteration of parameters is based on the active monitoring of several factors in the external and internal radio environment, such as radio frequency spectrum, user behavior, and network state.

Most standards organizations define CR and Software Defined Radio (SDR) as distinct, but complementary and mutually enabling, technologies. The Wikipedia definition for SDR, is:

> A software-defined radio (SDR) system is a radio communication system which can tune to any frequency band and receive any modulation across a large frequency spectrum by means of a programmable hardware which is controlled by software.

With emerging technologies such as CR and SDR, many organizations (often standards or technology advocacy organizations), such as the ITU, IEEE (e.g. P1900/SCC41), the SDR Forum, the European Commission's End-to-End Reconfiguration (E2R), offer variations of definitions for such technologies that reflect the needs of their constituencies or the opinions and interests of their contributors. We could consider a long list of such definitions here, but will refrain from doing so and only offer further refinements of definitions as appropriate to develop our market study discussions. It should be noted that very legitimate reasons and needs exist for variations in definitions to position various stakeholder motivations and goals. Users, equipment vendors, operators, various food chain vendors (sub-systems, components, and (support) service providers), regulators, and others have highly complementary, but different motivations and goals.

The key and most pervasively articulated driving force for CR is more efficient use of spectrum. Regulatory authorities appear almost exclusively focused on spectrum efficiency and availability. A key issue for them is how to provide regulatory initiatives supporting CR while assuring primary spectrum owners of their right to primary access whenever required. Most regulatory authorities appear interested in letting the competitive marketplace determine the most appropriate CR technologies and initiatives. CR visionaries appear to have broader goals for CR that includes cognitive or intelligent serving of market, regulatory, and user application needs, as well as enabling of these needs through spectrum efficiency.

[4] www.wikipedia.com

3.1. *The Commercial Markets*

Commercial wireless markets are clearly the largest markets for SDR and CR in terms of both units shipped and revenues. These commercial markets include:

1) The cellular market[5] including Beyond 3G and Long Term Evolution (LTE) [6]
2) The Wireless Local Area Network Market (WLAN) (e.g., WiFi Market) [6]
3) The Broad Wireless Access Market, (e.g. WiMAX) [6]

Other key synergistic initiatives contributing to enhanced commercial market SDR and CR opportunities are Personal Area Networks (PAN) (e.g. Bluetooth, Ultra Wideband, (UWB))[7] and Global Positioning System (GPS). Bluetooth and GPS are increasingly being integrated into commercial user terminals.

Perhaps the best place to start discussing CR commercial market opportunities is an overview of current general industry drivers. Since approximately 2000, the international cellular market has approached saturation in early adopter, high tier, economies such as Western Europe, Japan, Korea, North America and the United States. In these areas to varying degrees the market for voice subscribers is saturated with some countries (e.g. Italy) actually achieving over 100% penetration (i.e. subscriptions / population). Additionally, regulatory authorities have encouraged competition by awarding spectrum licenses to multiple companies. Thus, the historical business model for achieving revenue growth by adding new subscribers is no longer effective, exacerbated by decreasing voice ARPU (average revenue per user) generally as a result of increased competition. The 3rd Generation (3G) industry initiatives originated in the late 1990's with initial deployments occurring in the early 2000's (Japan's NTT DoCoMo was the first to deploy WCMDA in September 2001) addressed this issue by adding features and capabilities to support broadband wireless data including Internet/email access and mobile TV. The industry goal for 3G is to enable new wireless services that are sufficiently attractive to provide revenue growth from an operator's existing subscriber base. Nokia, in its 4th quarter 2006 financial report, announced that 4th quarter 2006 handset average selling price (ASP) was ~€89 (~US$116), which represents an ongoing decline in ASP. Services, terminals, and infrastructure are all experiencing declining ARPUs and ASPs.

A key emerging goal has been the creation of quadruple play market opportunities to compete as an integrated operator on converged core networks for cellular, internet access, music, games, and eventually TV revenue opportunities. Figure 3-1 illustrates this anticipated evolution from legacy stove pipe networks to converged core networks for the wireline businesses. Operators able to achieve multi-service successes will have substantially enhanced opportunities for revenue growth business models. This appears to especially be a goal of legacy wireline international operators (i.e. including the US) that are increasing experiencing subscription losses, ARPU declines, and generally declining opportunities in their legacy voice-centric business models.

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[5] Cellular: Terminals and Infrastructure, Prepared for The SDR Forum, by Jim Gunn, June 2005
[6] WiFi, WiMAX, and Beyond 3G / 4G, Prepared for The SDR Forum, by Jim Gunn, January 2006
[7] SDR Market Segmentation and Sizing, Prepared for The SDR Forum, by Jim Gunn, January 2005

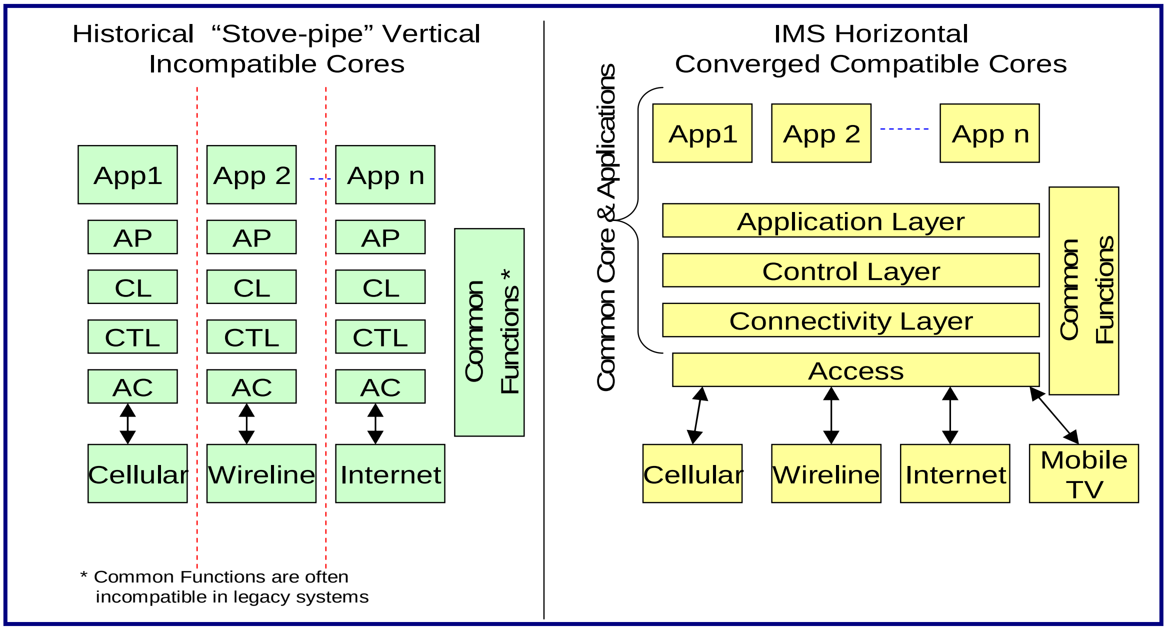

Figure 3-1 IP Multimedia Subsystem (IMS) Concept
(Source: Author Research)

While mature cellular markets in high tier economies are saturating, many emerging economies have been experiencing favorable economic growth. There, a growing middle class needs and demands cellular services, often their only available telecom service. Thus, international net subscriber additions (net adds) are occurring in emerging economies such as China, India, Caribbean and Latin America, Africa, and Eastern Europe**.** Reports indicate that, in 2006, 70-80% of net adds have been in such economies. The key characteristic of these markets is price sensitivity - affordable lower cost is more important to success than extensive services and terminal features. To address this goal, at 3GSM2005 in February in Cannes, France, the GSM Association (GSMA) announced a 1st award to Motorola to provide sub $40 units in its Emerging Market Handset (EMH) initiative with an eventual price goal of ~$30 in later rounds. A GSMA goal to support international "bridging the digital divide" initiatives is to provide 80% of the world's population access to mobile communications by 2010. Low cost handsets, services, and supporting networks and infrastructures are all essential to this initiative. In 4th quarter of 2006 Chinese and India operators reported average monthly ARPUs ranging from US$6 to $12. The compares to the US average ARPU of ~$50. Some Chinese (i.e. China Mobile) and India operators are reporting that their legacy, essentially urban, markets are saturating and these operators, like the higher tier economically legacy operators, are beginning to consider multimedia 3G service evolutions. Additionally, they are expanding their service coverage areas to even lower tier rural areas in their countries.

With evolution to multimedia wireless services a goal in both legacy and emerging markets, a strongly emerging requirement is multi-radio terminals as depicted in Figure 3-2. Multi-radio refers to units incorporating multiple air interfaces. As has been discussed in our previous reports, many wireless industry stakeholders are indicating that future cellphones, laptops, PDA, and other terminals will have as many as 11 or more integrated air interfaces. Infrastructure also appears to require multi-radio solutions to support the emerging multimedia era. This figure was presented by Nokia's CTO at the WiMAX World convention in October 2006. Similar needs for evolving to multi-radio technologies are being identified by many others.

Figure 3-2 Emerging Multi-radio Opportunity
(Source: Nokia Broadband Strategy Presentation at WiMAX World by Tero Ojanperä, Chief Technology Officer, October 2006)

Multi-radio offers many opportunities for CR. Historically; cellular terminals supported one or perhaps a few air interfaces such as multiple GSM frequency bands, Bluetooth, and GPS**.** In the emerging multimedia era, handsets, laptops, PDAs, and other devices will require multiple air interfaces to cost effectively support wireless or wired service anywhere at anytime. This will create a difficult problem for users and their service providers to select, configure, and communicate on the most appropriate and cost effective air interface. Subscribers want easy-to-use, intuitive user interfaces to make and configure these selections, a natural application for CR technologies.

Another problem facing operators in the evolutions to Beyond 3G and 4G is coverage.
An illustration of the importance of coverage is presented in information from Japan's NTT DoCoMo in Figure 3-3 where they provide information on their initiatives to improve coverage for their FOMA (WCDMA) service in Japan by adding additional indoor and outdoor systems Base Station Sites (BTS). DoCoMo indicates in the figure that improved coverage initiatives are in response to customer input.

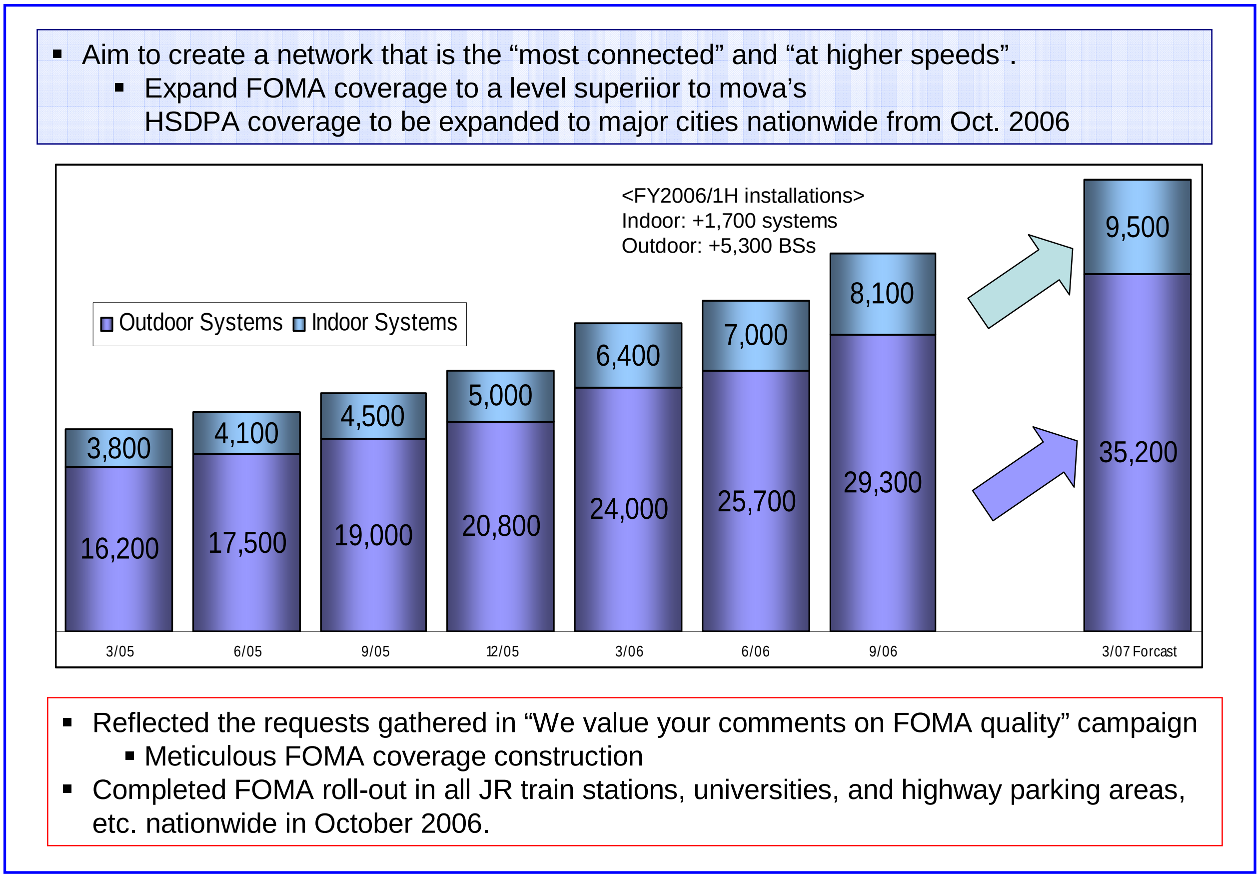

Figure 3-3 DoCoMo’s Evolution of Indoor and Outdoor Base Station Sites
(Source: Recreated/Adapted NTT DoCoMo Industrial Relations (IR) Presentation, January 2007)

DoCoMo, as the first operator to deploy WCDMA with their FOMA (Freedom of Mobile Multiledia Access) offering, is the bellwether of the industry to provide indicators of 3G customer preferences and experiences to make services attractive. As the figure indicates FOMA customer surveys indicate that coverage is an important satisfaction indicator. Coverage problems in advanced 3G/HSPA and planned future Beyond 3G/LTE/4G waveforms are exacerbated by the use of more advanced waveform such as OFDM and CDMA, including higher order modulations such as n-PSK, and n-QAM. As the order (n = 2, 4, 8, 16) of these modulations increase, the signal-to-noise ratio for target probability of demodulation (e.g. maximum error rate) increases[8]. Thus, higher bit rates for Beyond 3G enabled services will require more cell sites and/or coverage enhancing technologies such as smart antennas, enhanced sectorization, and MIMO (Multiple In, Multiple Out).

Subscribers also desire “easy-to-use” services that are not difficult to configure. CR technologies provide a solution to achieve “ease-of-use” for this added complexity. In fact many in the commercial sector indicate that the current 3G standards already utilize techniques that can be considered, including automated power control, modulation format selection, and error coding selection based on link conditions.

[8] `The SNR increase can be approximately estimated from Shannon Capacity Theorem: Bit Rate/Bandwidth = Bits/Sec/Hertz = log $_2$ (1+SNR), many text books, e.g., Digital and Analog Communcication Systems, ., Couch, Macmillan

Commercial market drivers for CR are:

1. New non-voice data, web/internet, and mobile TV services which present coverage needs addressed with more cell sites, smart antennas, MIMO technologies, and picocell, femtocel (home cell sites), and in-building sites. Configuration of infrastructure and user terminals must not be complex. Multi-radio will offer up to 11 or more waveforms in user terminals. Selection and use of appropriate service, bit rate, and resulting cost should take place without user intervention. The emerging proliferation of home and sometimes free municipal WiFi services could create a conflict between operators and their subscribers over control of subscriber terminals and selection of a provider for obtaining a particular service and available revenue. Low cost WiFi access with increasingly low cost broadband IP-based backhaul could be a significant competitive force. Similarly, emerging Broadband Wireless Access (BWA) such as WiMAX appears on track to become a competitive force by providing metro wireless access networks (MWAN). Mobile operators have problems keeping their networks optimized for changing customer usage patterns. A clear trend by many operators is to outsource their network operations expense (OPEX) and sometimes site-related capital expenditure (CAPEX) to network equipment vendors such as Ericsson, Nokia-Siemens, Alcatel-Lucent, Nortel, and Motorola. CR technologies offer solutions for these vendors to achieve operational and cost efficiencies in network operations, often with remote sensing and configuration.
2. Figure 3-1 illustrates the commercial sector trend toward converged compatible core networks that are access technology agnostic, accommodating cellular, Wireline, Internet, Mobile TV, and Wireless Local Area Networks (WLAN, e.g. 802.11x). These networks create requirements for cognitive capability synergistic with CR initiatives. We envision scenarios for CR in commercial applications including requirements for cognitive networks and applications in addition to the radio systems. As the figure also illustrates, applications or services are envisioned to be available “anywhere, on any access technology, and any time”. Cognition will be found in the radio wireless access technology, the core network, and applications.
3. Commercial networks have traditionally included a core network interconnected by fixed wire, fiber, or wireless (e.g. microwave) backhaul carefully configured to provide needed capacity and Quality of Service. In emergency situations many operators have emergency mobile base stations available to serve areas where Base Stations have failed and await repair. CR capabilities will provide needed flexibility in these situations, and even respond to unusual load situations, such as a sporting event.

3.2. *Public Safety Markets*

The public safety markets have received much attention in recent years as the result of terrorist attacks and natural disasters. Those receiving the most recent visibility and attention include:

- The 9/11/2001 plane hijackings and terrorist attacks on the World Trade Center in New York City and the Pentagon in Washington DC.
- The Katrina Hurricane in the New Orleans and Gulf Coast region of the United States in August 2005.
- The terrorist bombings of the London subway on July 7, 2005.

The post event analyses and conclusions have consistently identified significant problems due to lack of interoperability of communication assets of first responder organizations. First responder organizations usually refer to Law Enforcement, Fire, and Emergency Medical Service (EMS) personnel. Public Services, Highway/Roads,Water, Gas, Power, Telephone, and others have interoperability requirements in common with first responders.

As depicted in Figure 3-4 the public safety community is a diverse community consisting of various specialties from various levels of government. The figure is drawn from a US document, but input has indicated that similar communities exist internationally with added complexities due to international first responder interoperability requirements. Historically, each first responder organization at each level of government has independently procured, operated, and maintained its communication assets, with little regard for interoperability of non-local potential partner first responder organizations[9]. Interoperability adequate to current threat conditions requires a change, and CR has a significant role to play in the new directions.

[9] SDR Market Study: The US Public Safety Market, Prepared for The SDR Forum, by Jim Gunn Consultancy, May 2007

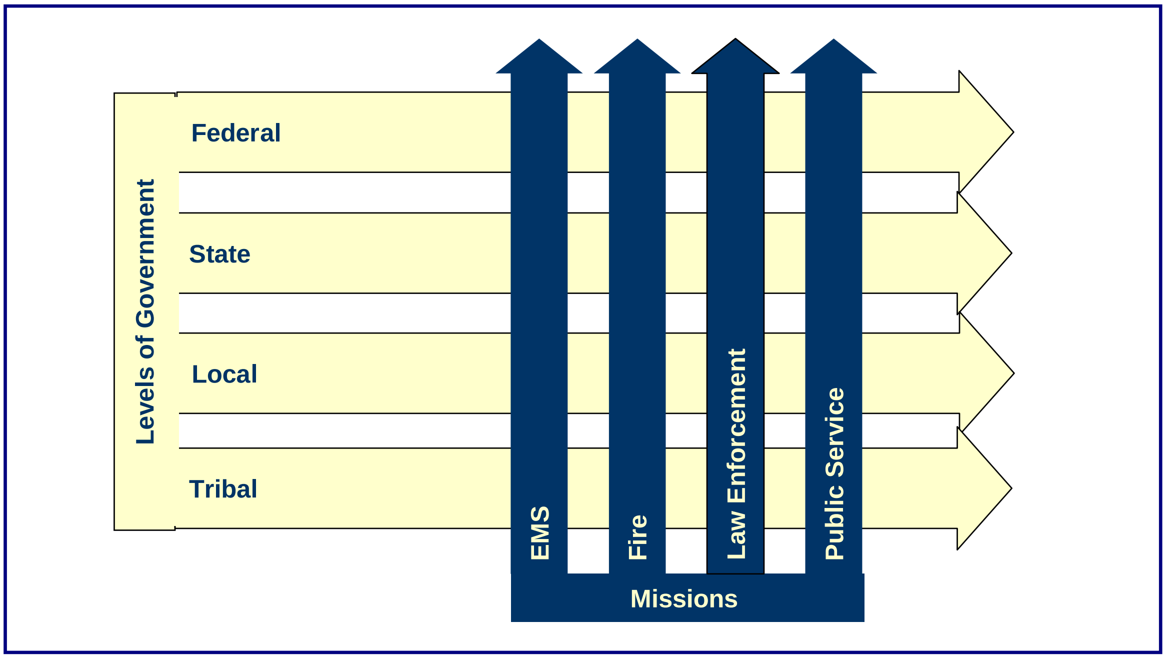

Figure 3-4 Diverse Public Safety Community
(Source: US Safecom Documents, www.safecom.gov)

Two dominant international voice-centric public safety wireless standards have been emerging in recent years: Terrestrial Trunked Radio (TETRA) and Project 25 (P25).

Terrestrial Trunked Radio (TETRA) is a digital trunked mobile radio standard[10] developed by the European Telecommunications Standards Institute (ETSI). The purpose of the TETRA standard is to meet the needs of traditional Professional Mobile Radio (PMR) user organizations such as Public Safety, Transportation, Utilities, Government, Military, Public Access Mobile Radio (PAMR), Commercial & Industry, and Oil & Gas. The standards for TETRA specify the air interfaces, network interfaces as well as the services and facilities in sufficient detail to enable independent manufacturers to develop infrastructure and radio terminal products that fully interoperate with each other. The ability for full interoperability between different manufacturer's products is a distinct advantage of open standards developed by ETSI. Because TETRA standards have been specifically developed to meet the needs of a wide variety of traditional PMR user organizations it has a scaleable architecture allowing economic network deployments ranging from single site local area coverage to multiple site wide area national coverage.

In several European countries, nationwide networks (some lacking complete coverage) have been deployed. In Britain the public sector TETRA system operates under the name Airwave[11]. In Belgium, the A.S.T.R.I.D[12] system uses TETRA. In the Netherlands, the TETRA system is called C2000[13]. In Sweden the RAKEL system uses TETRA. In Finland the VIRVE (short for VIRanomaisVErkko, loosely translated: "official network") network uses TETRA.

[10] Tetra Association, www.tetramou.com
[11] http://www.airwaveservice.co.uk/
[12] http://www.astrid.be/
[13] http://www.c2000.nl/?menuitemID[]=104&PHPSESSID=e654ad77f0917cce7f0fbefd94c2488b

Project 25 (P25)[14] is the designation used to identify standards developed by Telecommunication Industry Association's (TIA) TR-8 engineering committee for Mobile and Personal Private Radio applications. The engineering committee and its subcommittees develop and maintain standards for private radio communications systems and equipment for both voice and data applications. TR-8 addresses all technical matters for systems and services, including definitions, interoperability, compatibility, and compliance requirements. Project 25[15] is a steering committee for selecting voluntary common system standards for digital public safety radio communications.

P25 compliant radios can communicate in analog mode with legacy radios and in either digital or analog mode with other P25 radios. Additionally, the deployment of P25-compliant systems will allow for a high degree of equipment interoperability, compatibility and economy of scale. Specifically, P25 systems can be maintained and upgraded cost effectively over the system's life cycle, thus meeting user requirements, achieving interoperability and security, promoting committed manufacturers to provide compliant products, fostering competition and achieving cost-effective emergency/safety communications solutions. In light of recent worldwide terrorist activities, interoperability among first responders is a key initiative of many countries.
The P25 suite of standards involves digital Land Mobile Radio (LMR) services for local, state and national (federal) public safety organizations and agencies. P25 Phase II implementation involves time and frequency modulation schemes (e.g., TDMA and FDMA), with the goal of improved spectrum utilization. Significant attention is also paid to interoperability. Phase III activities are addressing the operation and functionality of a new aeronautical and terrestrial wireless digital wideband/broadband public safety radio standard that could be used to transmit and receive voice, video and high-speed data in a ubiquitous, wide-area, multiple-agency network.

The spectrum allocations for Tetra in Europe and P25 in the United States are presented in Figure 3-5.

[14] http://www.tiaonline.org/standards/technology/project_25/
[15] www.project25.org

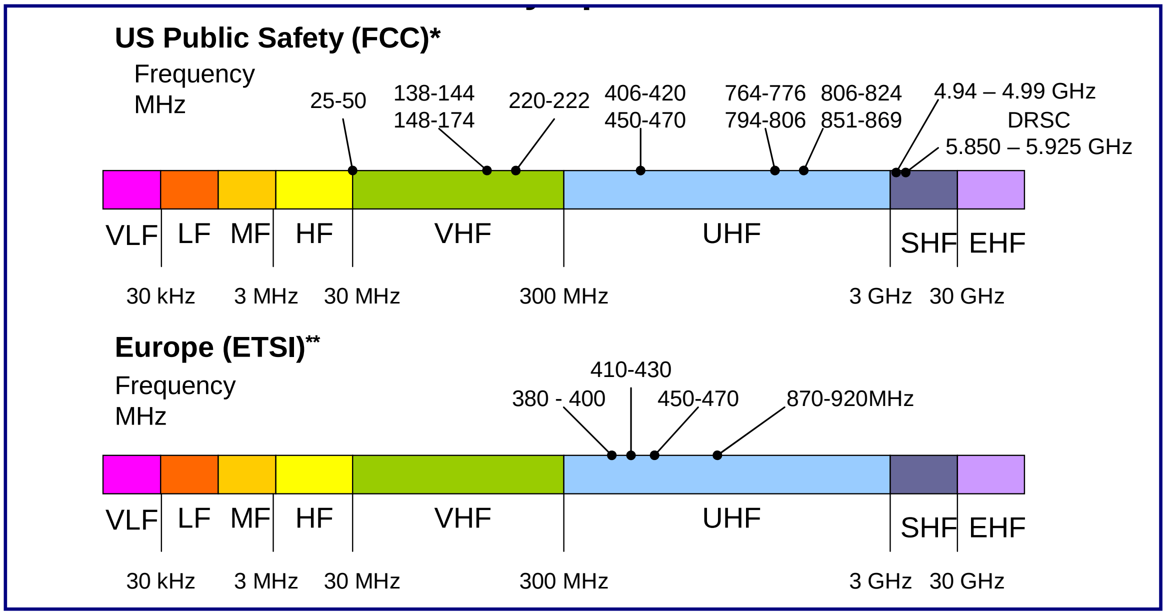

Figure 3-5 Public Safety Spectrum Allocations
(Source: * FCC Regulations and "Public Safety: Radio Spectrum: A Vital Resource for Saving Lives and Protecting Property", PSWN Program [now SAFECOM]); ** http://www.etsi.org)

Due to common needs and recognition for potential international economies of scale, ETSI and TIA have agreed to work collaboratively for the development of international next-generation mobile broadband specifications for public safety users. This international collaboration is known as Project MESA[16] (Mobility for Emergency and Safety Applications). These broadband standards target supporting transmission of maps, emergency medical data, photos, video, building plans, **etc.** to facilitate more efficient public safety operations.

The SDR Forum's Public Safety SIG (Special Interest Group) has an on-going activity to develop use cases for cognitive radio applications[17] in public safety. In many disaster events, independent of interoperable communication equipment, anticipated communication system coverage may not be available due to damage to infrastructure. One example of CR application to public safety involves network extension.

The concept for cognitive radio is to reconfigure responders' radios as an ad hoc extension to the existing network that would allow transmissions to be passed back from the an incident site that is outside the coverage area of existing infrastructure along a network of individual responder radios to a radio which can communicate with the main radio system/network. While initially motivated by a review of the challenges faced by responders in London during the 2005 bombing there, a similar requirement was identified in the experience of communications teams deployed in the response to Hurricane Katrina. In many places infrastructure was destroyed or severely damaged. Emergency portable resources were brought to the area to support the response but as these were newly deployed capabilities, the pattern of coverage changed frequently, making it difficult to determine extent of radio coverage to support operations. A capability to

[16] www.projectmesa.org
[17] **"**Use Cases for Cognitive Applications in Public Safety Communications Systems", currently in draft form.

automatically maintain communications using ad hoc networks to provide reach back would have enhanced the efficiency of the disaster response operation.

3.3. The Military Market

The US Department of Defense with its Joint Tactical Radio System (JTRS) program and DARPA XG (neXt Generation) program has been a leader in CR and SDR initiatives, although some international interests and initiatives do exist. A key difference for military programs is a focus on Mobile Adhoc NETworks (MANETs) that essentially have no supporting infrastructure.

Figure 3-6 presents an overview of the JTRS network architecture that notionally illustrates that JTRS provides "the transport to extend the Global Information Grid (GIG) to the tactical edge."[18] The tactical edge, as the figure illustrates has various types of networks that are formed to support the tactical operations using waveforms appropriate to units and missions. MANETs are deployed to support fluid wireless tactical networking operational requirements for voice and data waveforms based on modern Internet Protocol (IP) network technologies. The GIG is largely based on satellite communication links to interconnect tactical edge operational elements with each other and their command and control elements.

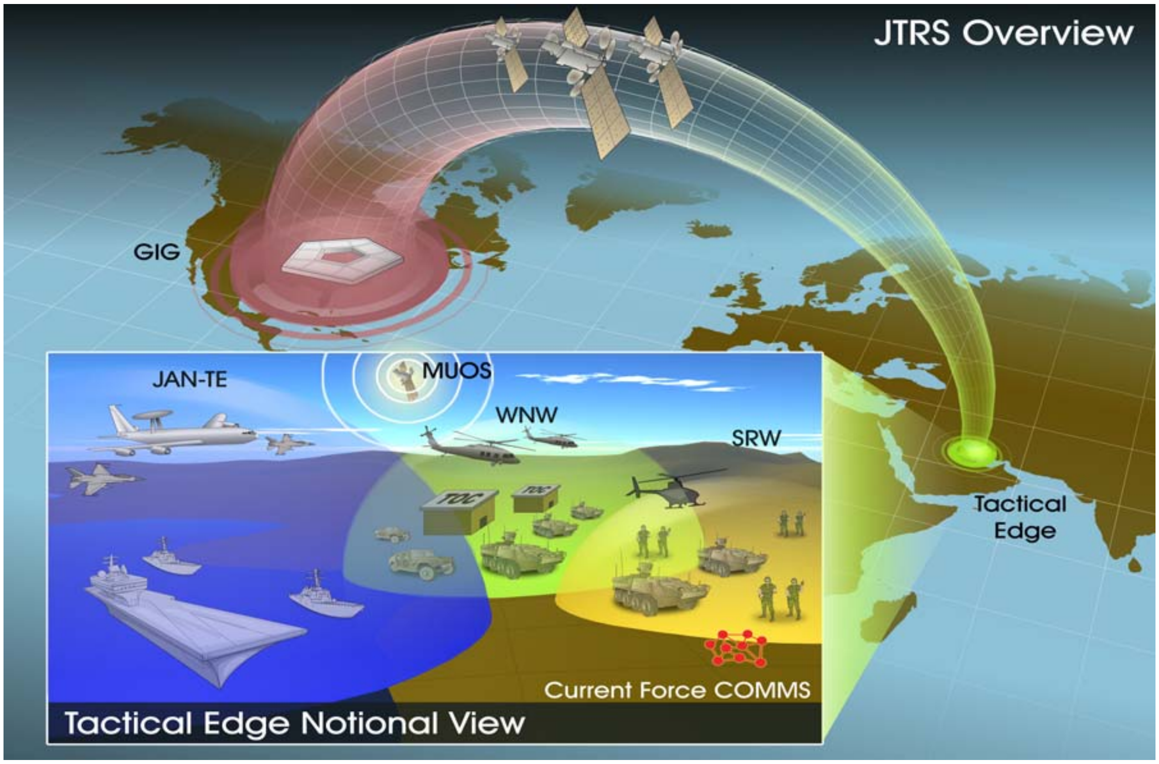

Figure 3-6 JTRS Network Overview, Increment 1
(Source: [18])

[18] "Joint Tactical Radio System – Connecting the GIG to the Tactical Edge", Dr. Rich North, etal; Milcom, Oct 2006.

The JTRS program has experienced significant schedule and cost problems. When JTRS was initiated in the late 1990's, the primary focus was on replacing an aging inventory of largely incompatible legacy radio systems with a single versatile system. However, "two factors worked against the initial JTRS approach: 1) the loose organization between highly dependent programs and 2) the JTRS mission evolved from legacy radio replacement to transformational wireless networking. Without strong centralized management, the growth in mission and requirements resulted in schedule and cost over-runs."[19] In February 2005, the collection of JTRS activities were placed under the leadership of the Joint Program Executive Office Joint Tactical Radio System (JPEO JTRS) of the Space and Naval Warfare Systems Command, (or SPAWAR) headquartered in the San Diego area. The redefined goals of JTRS are "To develop, produce, integrate, and field a family of interoperable, digital, modular, software-defined radios that operate as nodes in a network to ensure secure wireless communications and networking services for mobile and fixed forces."[20] A key initiative of the reorganized JTRS program has been to deploy JTRS in increments with a manageable number of waveforms and form factors for each increment that can be developed at moderate risk within retargeted scope, budget, and schedule goals. An overview of planned increment 1 waveforms and form factors are presented in Table 3-1. A glossary of terms is presented below the table. It should be noted that the waveforms and form factors planned for increment 1 represent approximately one third of plans prior to re-focusing of the program.

Waveform → Form Factor ↓	WNW	SRW Type 1 Secret	SRW Type 2 SBU	JAN-TE	SINC	SINC w/ INC	LINK 16	EPLRS	MUOS	HF	UHF SATCOM DAMA
Ground Vehicle (4Ch)	X	X	X		X	X		X		X	X
MIDS-J (4 ch)				X			X				
SFF A/H (IMS/UGS 1/2 ch)			X								
SFF D (UAV 1ch)			X								
SFF J (NLOS 2 ch)		X			X						
MAN Pack (2 ch)		X	X		X			X		X	X
Handheld (2 ch)		X	X		X			X			
SFF B (LW 2 ch)		X	X		X			X			
SFF C (LW 1 ch)			X								
SFF I (LW 1 ch)		X	X		X			X			
AMF M (4 ch)									X		X
AMF SA (2 ch)	X	X	X				X		X		

Table 3-1 Planned JTRS Increment 1: Waveforms and Form Factors, with glossary
(Source: [21])

Waveforms Glossary		**Form Factor Glossary**	
WNW	Wideband Networking Waveform	GMR	Ground Mobile Radio
SRW	Soldier Radio Waveform	MIDS-J	Multifunctional Information Distribution System for JTRS
JAN-TE	Joint Airborne Networking–Tactical Edge		Manpack
MUOS	Mobile User Objective System		Handheld
SINCGARS	Single Channel Ground and Airborne Radio System	AMF-SA	Airborne, Maritime and Fixed Site Small Airborne
	Link-16	AMF-MF	(Maritime/Fixed Site)
EPLRS	Enhanced Position Location Reporting System	SFF	Small Form Factor A&H (for Intelligent Munitions
	High Frequency (HF)		Systems and Unattended Ground Sensors in the Future

[19] See North, Note 18

[20] http://enterprise.spawar.navy.mil/body.cfm?type=c&category=27&subcat=60

[21] "JTRS Overview and Status Update" Presented to SDR Forum 2007, by Dr. Rich North Technical Director JPEO JTRS 16 January 2007, based on JTRS ORD 3.2.1 and the signed JROC 28 August 2006

HF SATCOM	Combat System) SFF B, C and I (for Ground Soldier Systems) SFF D (for Aerial Systems) SFF J (for Networked Missile Launcher)

JTRS increment 1 includes currently deployed legacy waveforms and frequency bands as well as more modern waveforms focused on adding ad hoc networking capabilities based on IP network technologies. An overview of the legacy and modern waveforms and their band is presented in Figure 3-7 and illustrates the JTRS 2 MHz to 2 GHz band requirements. The modern waveforms are in frequency bands from 12 MHz to 2.1 GHz and include the following waveforms:

1. Wideband Networking Waveform (WNW),
2. Soldier Radio Waveform (SRW),
3. Joint Airborne Network – Tactical Edge (JAN-TE), and
4. Mobile User Objective System (MUOS).

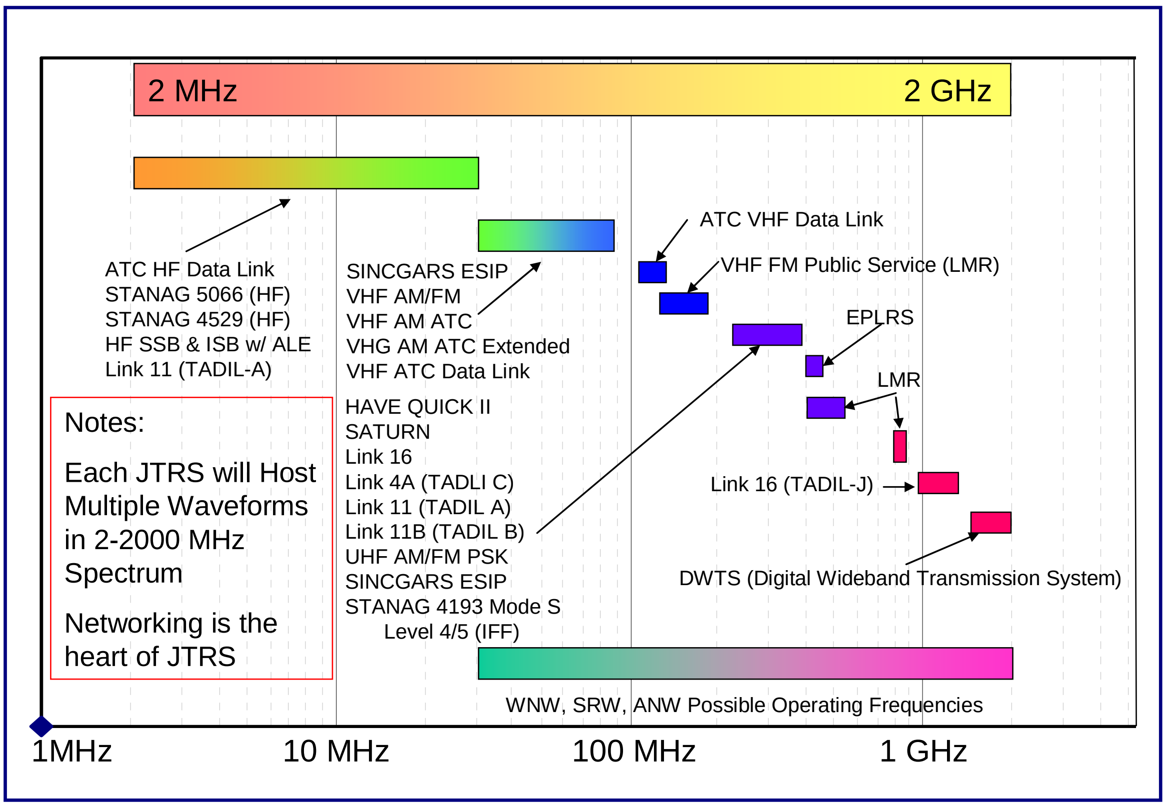

Figure 3-7 JTS Spectrum: 2 - 2000 MHz
(Source: Adapted from "JTRS Overview for CCEB Spectrum Task Force"; Draft Review; Joint Program Executive Office, Joint Tactical Radio System (JPEO JTRS); by Len Schiavone, Mitre; May 5, 2006)

A key goal of JTRS is interoperability achieved using several approaches:[22]

1. JTRS products are based on DOD and commercial standards, as depicted in Figure 3-8.

[22] See North, Note 17

2. All JTRS products "reuse" the same waveform software with their associated JTRS Infrastructure Standards.
3. JTRS products must pass the Joint Interoperability Test Center's (JTIC) waveform conformance and interoperability waveforms.

JTRS products are based on SDR technologies. Software for JTRS will be based on an open systems modular architecture with a standardized JTR Infrastructure as presented in Figure 3-9. Elements of this JTR infrastructure include the Software Communication Architecture (SCA), Application Program Interfaces (APIs), software coding standards, and Modem Hardware Abstraction Layer (MHAL). Proprietary legacy waveforms have lacked openness and effective standards, frustrating attempts at reuse and competitive procurements. Thus, the JTRS program will establish the JTRS Information Repository that will make "JTRS software and artifacts"[23] available for reuse by multiple vendors under Government Purpose Rights.

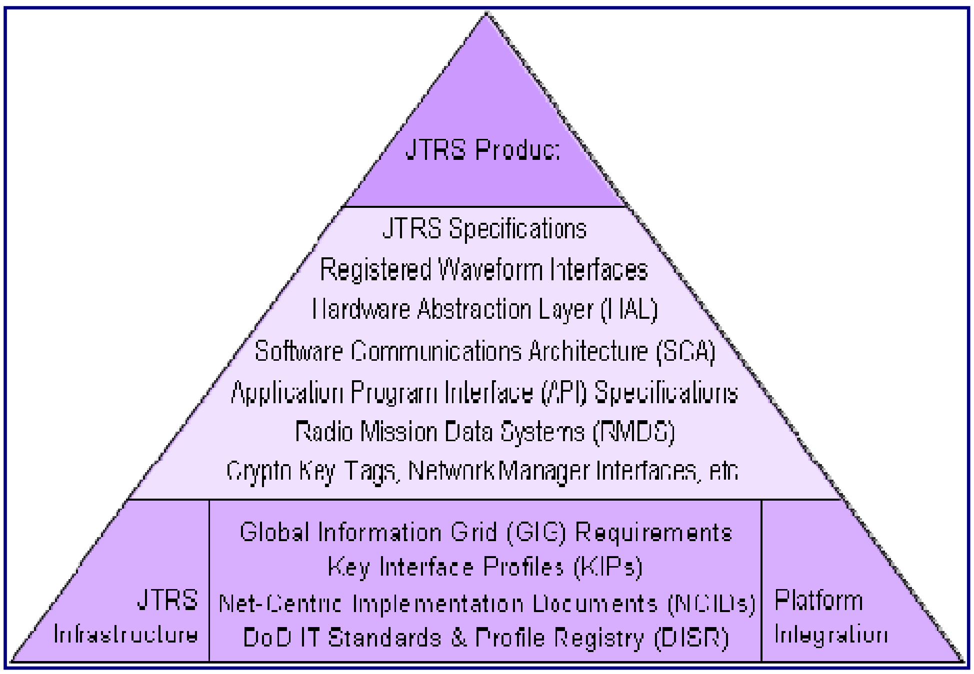

Figure 3-8 JTRS Standards
(Source: 21)

[23] See North, Note 17

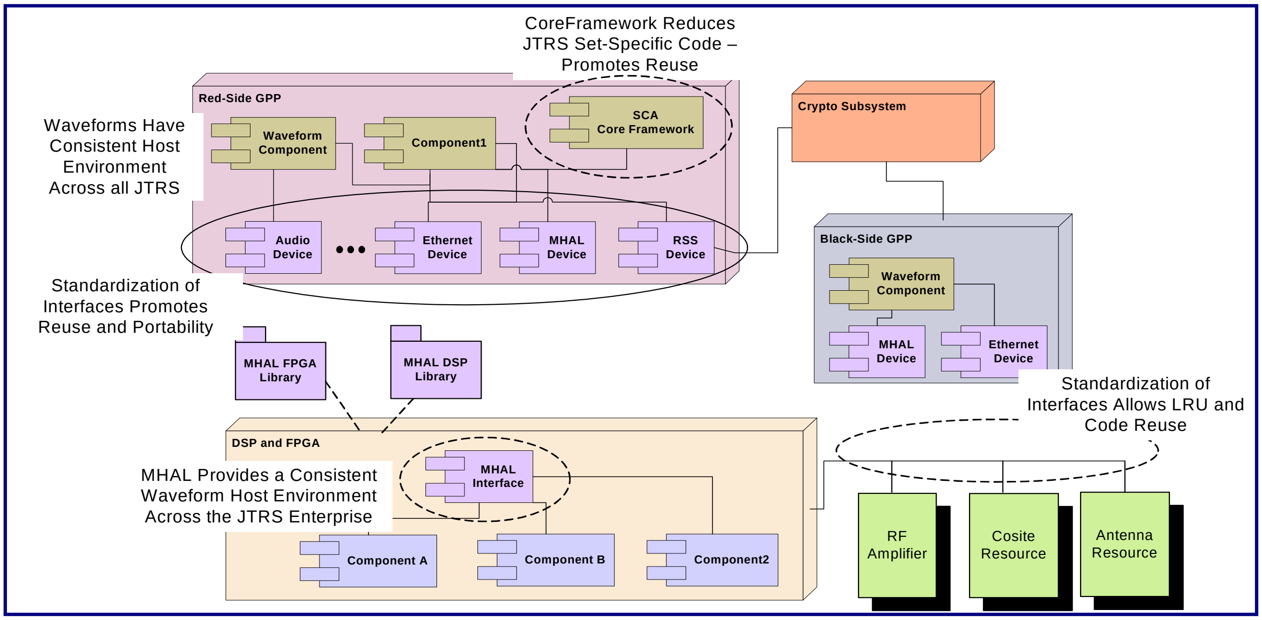

Figure 3-9 Standardization of JTR Infrastructure
(Source: 21)

A goal of JTRS, often not emphasized, is reuse of common hardware, common software modules, and related components. Perhaps overly emphasized has been the connotation in the military community of “2 MHz to 2 GHz” as the essence of the SDR definition. In actuality, JTRS and the international military community share with the commercial and public safety communities a more extensive SDR connotation to include frequency and mode (i.e. waveform) flexibility as well as reuse to facilitate time-to-market, manufacturing efficiencies, and cost goals.

The use of “tactical edge” MANETs in JTRS creates a significant requirement for Cognitive Radio technologies to support effective and “easy-to-use” equipment for military users that are focused on their military missions, not high tech communications equipment.

DARPA’s neXt Generation (XG) and related programs are conducting research to enable more effective modern military communication. We base our discussions of the XG program on input in telecoms with Dr. Preston Marshall, DARPA’s XG program manager and on material in several of his presentations.

Figure 3-10 presents DARPA’s director vision of communication technology evolution and provides a list of key DARPA research programs that have and are contributing to US military evolution the GIG and tactical edge initiatives. As the figure illustrates, cognitive radio technology including MANET cognitive networking is a key goal to achieve dynamic spectrum allocation and network adaptation and optimization. The XG program goals are “to develop both the enabling technologies and system concepts to dynamically redistribute allocated spectrum along with novel waveforms in order to provide dramatic improvements in assured military communications in support of a full range of worldwide deployments. The XG program approach is to develop the theoretical underpinnings for dynamic control of the spectrum, the technologies and subsystems that enable reallocation of the spectrum, and the system appliqué prototypes to demonstrate applicability to legacy and future DOD radio frequency emitters. …

The program goals are to develop, integrate, and evaluate the technology to enable equipment to automatically select spectrum and operating modes to both minimize disruption of existing users, and to ensure robust operation of U.S. systems. The result of the XG program will be to develop and demonstrate a set of standard dynamic spectrum adaptation technologies for legacy and future emitter systems for joint service utility." [24]

The Wireless Network after Next (WNaN) program is a DARPA open solicitation for future research. Figure 3-11 presents an overview of anticipated WNaN technologies to be developed. The WNaN goal[25] is "to develop and demonstrate technologies and system concepts enabling densely deployed networks in which distributed and adaptive network operations compensate for limitations of the physical layer of the low-cost wireless nodes that comprise these networks. WNaN networks will manage node configurations and the topology of the network to reduce the demands on the physical and link layers of the nodes. The technology created by the WNaN effort will provide reliable and highly-available battlefield communications at low system cost. The WNaN program will develop a prototype handheld wireless node that can be used to form high-density ad hoc networks and gateways to the Global Information Grid. This program will develop robust networking architecture(s) that will exploit high-density node configurations from related DARPA programs. This program will culminate in a large-scale network demonstration using inexpensive multi-channel nodes. WNaN technology is planned for transition to the Army in 2010." A key goal of WNaN is to develop cognitive radio technologies that support cross layer optimization and deep packet inspection that have significant commercial interests, albeit that the military is more focused than the commercial market on MANET technologies. WNaN has a cost goal of $ 500 for a 4 channel node, that is spectrally adaptive, employs MIMO and beamforming technologies, can be a member of four simultaneous sub-networks, with ultra low latency. [26]

[24] http://www.darpa.mil/sto/smallunitops/xg.html
[25] http://www.darpa.mil/sto/strategic/wireless.html
[26] "DARPA Progress in Spectrally Adaptive Radio Development" Presentation by Preston Marshall, DARPA, at SDR Forum Expo, November 2006

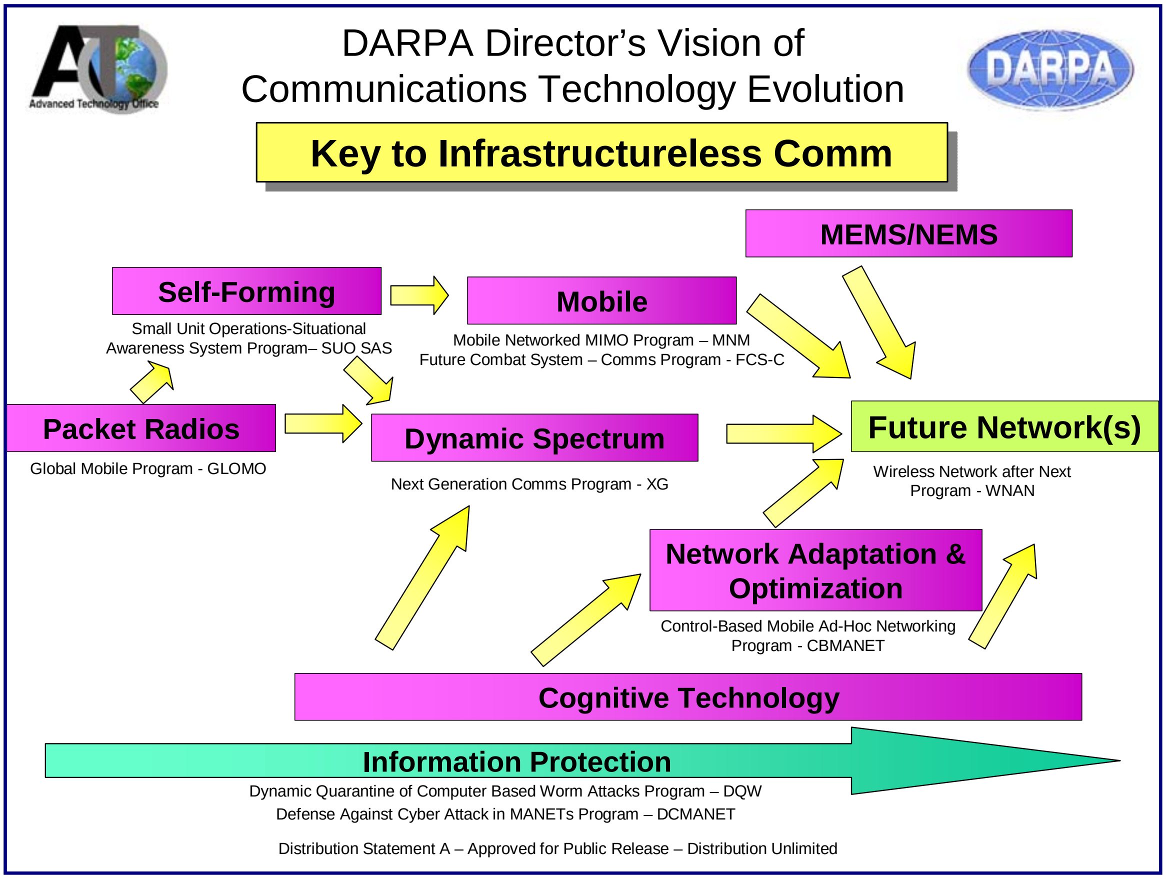

Figure 3-10 DARPA Director's Vision of Communication Evolution
(Source: [27])

Preston Marshall offered several comments on CR:

1. The first thing CR technologies attack is spectrum management.
2. Many opportunities exist in the non-DOD sectors:
   a. White space exists in TV bands with the transition to digital TV (DTV)
   b. Most spectrum does not have consistent national allocations
3. There should be many refarming opportunities soon including Public Safety, Broadcast, and TV.
4. It is key to develop CR dynamic spectrum technologies that exploit these needs and opportunities, but do not cause harmful interference. Highly effective and reliable interference avoidance is essential.
5. Sensing is important to understand the environment and adapt, but is more than MAC layer considerations.
6. XG contractor Shared Spectrum's spectrum analysis activities clearly illustrate that most of the spectrum is in use less than 10% of the time at any given location. Significant opportunities exist to achieve spectrum efficiencies by exploiting time, geographic, and frequency opportunities.

[27] "Cognitive Radio Panel, What are the next Research Challenges?" Presentation by Preston Marshall, DARPA, at SDR Forum Expo, November 2006

7. In reality, CR adds statistical multiplexing efficiencies to RF spectrum management as has been effectively used in wireline links for many years.
8. It seems possible in entry level radio for military to adequately sense for CR, spectrum management purposes, with a 2 MHz wide IF capable of hopping to various frequencies every 5 microseconds.

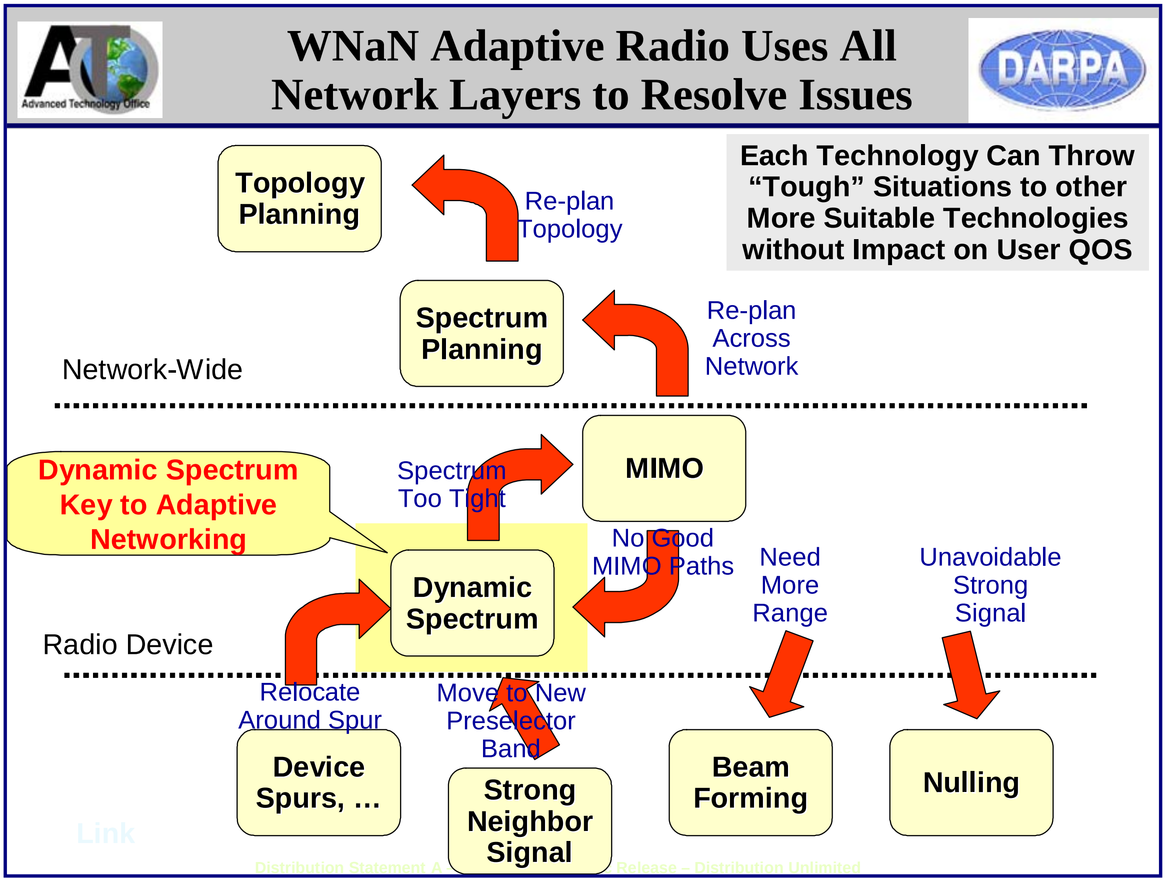

Figure 3-11 WNaN Adaptive Radio Uses All Network Layers to Resolve Issues
(Source: [27])

3.4. *US FCC's Cognitive Radio Initiatives*

The United States Federal Communication Commission (FCC) has been an international regulatory leader in Software Defined Radio (SDR) and Cognitive Radio (CR) initiatives. This section looks at these initiatives. The FCC sequence of events in modifying its rules adoption typically includes:

1. Public notice requesting comments on proposed rule making
2. Public notice of proposed rule making and order (i.e. proposed new rules). This seeks comments from potential stakeholders.
3. Report and Order. Explanation of rationale of new rules and presentation of actual rules.

Some of the key more recent releases by the FCC concerning CR and SDR initiatives include new SDR rules/regulations facilitating CR,[28] unlicensed operations in TV bands,[29] a CR spectrum sharing test-bed,[30] and secondary licensing.[31]

The regulatory focus of the FCC for CR and SDR are targeted at interference mitigation, as this is the fundamental goal of regulatory initiatives. Thus, a SDR is defined[28] as:

> "A radio that includes a transmitter in which the operating parameters of frequency range, modulation type or maximum output power (either radiated or conducted), or the circumstances under which the transmitter operates in accordance with Commission rules, can be altered by making a change in software without making any changes to hardware components that affect the radio frequency emissions."

While the focus of the regulatory SDR and CR definitions is on the transmitter, receiver selectivity also has a critical role and should be part of SDR and CR definitions and considerations for business model and technology purposes.

In a 2005 FCC report and order[28] the rules for SDR were modified with a central goal of market based technology development by industry unencumbered as much as possible by regulations. The most significant changes are (paraphrased):

- A radio must be certified as SDR if its RF-affecting software is designed or expected to be modified by a third-party other than the manufacturer.
- A SDR manufacture must take steps to ensure that only RF- affecting software that has been approved with a SDR can be loaded into the radio and that the security measures should prevent operations outside approved operating frequencies, output power, modulation types, or other RF parameters that are not approved. Security measures must be incorporated in the SDR to prevent unauthorized software loading and operations. Specifics are left to the expertise of the manufacturer, but the method must be described in application for equipment authorization.
- Instead of requiring submission of the RF-affecting software code, applications for certification must include a high level operational description or flow diagram of the RF-affecting software.
- The rules for modification of approved RF-affecting software for Class III permissive changes require only providing the FCC with a description of the changes and test results showing compliance with applicable rules.

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28 Report and Order: "Facilitating new technologies and services as well as permit more intensive and efficient use of the spectrum." ET Docket No. 03-108; 3/11/2005;

29 "Unlicensed operation in the TV Broadcast Bands, Additional Spectrum for unlicensed devices below 900 MHz and the 3 GG\Hz band", ET Docket Nos. 04-186 & 02-380; 10/18/2006

30 Public Notice: "Federal Communication Commission seeks public comment on creation of a spectrum sharing test-bed;" 6/8/2006

31 Second report and order, order on reconsideration, and second further notice of proposed rulemaking; Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets; WT Docket No. 00-230; 9/2/2004

- These rule changes do not permit Telecommunication Bodies (TCBs) to certify SDRs for the time being. The FCC indicated it would reconsider this at a later date after more experience has been gained. Many submitting comments favored TCB certification as a preferred method of protecting required confidential information submitted in the certification process.

Cognitive Radio initiatives were addressed by the FCC in a 2003 NPRM[32] (Notice of Proposed Rule Making) and a FCC R&O[28]. In the R&O, CR features that may be incorporated to facilitate more efficient and flexible spectrum utilization include:
“

- Frequency Agility - the ability of a radio to change its operating frequency to optimize use under certain conditions
- Dynamic Frequency Selection (DFS) – the ability to sense signals from other nearby transmitters in an effort to establish a low interference operating environment
- Adaptive Modulation – the ability to modify transmission characteristics and waveforms to exploit opportunities to use spectrum.
- Transmit Power Control (TPC) – to permit transmission at full power limits when necessary, but constrain the transmitter power to a lower level to allow greater sharing of spectrum when higher power operation is not necessary.
- Location Awareness - the ability for a device to determine its location and the location of other transmitters, and first determine whether it is permissible to transmit at all, then to select the appropriate operating parameters such as the power and frequency allowed at its location.
- Negotiated Use - a cognitive radio could incorporate a mechanism that would enable sharing of spectrum under the terms of a prearranged agreement between a licensee and a third party. Cognitive radios may eventually enable parties to negotiate for spectrum use on an ad hoc or real-time basis, without the need for prior agreements between all parties.

”

Identified applications[28, 32] for CR include:

- Rural markets and unlicensed devices
- Secondary Markets / Interruptible spectrum leasing
- Dynamically Coordinated Spectrum Sharing
- Facilitating interoperability between communications systems
- Mesh Networks

In an October 18, 2006 First Report and Order and Further Notice of Proposed Rulemaking,[29] the FCC revealed additional CR plans and initiatives. This notice targets unlicensed operations in TV bands that will be vacated by the FCC mandated date of February 17, 2009 for completion of transition to digital TV (DTV) channels by broadcasters when their full service analog TV service must cease, making their analog channels available for other purposes. The report concludes that “Although the record filed in response to the Notice provides a sufficient basis for

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[32] “Facilitating opportunities for flexible, efficient, and reliable spectrum use employing cognitive radio technologies, Authorization and use of software defined radio technologies” FCC Notice of Proposed Rule Making and Order, ET Dockets Nos. 03-108 and 00-47, December 2003.

the Commission to conclude that properly regulated devices could operate without causing harmful interference to incumbent operations, the record does not contain sufficient information to adopt final rules for their operations." The notice goes on to explain that sufficient technical information was not offered by industry in comments on the details of methods for various interference mitigation approaches. Thus the FCC deferred final rules and issued Further Notice of Proposed Rule Making and indicated that it intended to adopt a second R&O in the fall of 2007 to provide time for the FCC and industry to develop standards for TV-band products as well as provide lead time for design and to develop new products. The FCC requested comments and data on unresolved issues that include:

1. Licensed vs. Unlicensed Operation – In earlier Notices and Orders, the FCC had not proposed licensed operations. Although the FCC seems to favor unlicensed operation, it did offer an interesting observation as when licensed works best. "The licensed model is more efficient in many cases, and tends to work best when spectrum rights are (1) clearly defined, (2) exclusive, (3) flexible, and (4) transferable. When spectrum rights lack these attributes, potential licensees face uncertainty and may lack incentive to invest in a license or offer service. In those circumstances, the unlicensed model may better optimize spectrum access and utilization."
2. Spectrum sensing and other technical requirements – Spectrum sensing has been adopted by the FCC for unlicensed national information infrastructure (U-NII) devices at 5 GHz[33] using dynamic frequency selection (DFS) to detect military radar and avoid operation if a radar is present. However, it was pointed out that radar's transmitter and receiver are collocated with a known signal. This will not be true for TV band devices. Thus, detection threshold levels will have to be much less than the -64 dBm specified in the U-NII regulation. The FCC pointed out that the IEEE 802.22 group developing standards for these applications is considering detection thresholds as low as -116 dBm. The hidden node problem is cited as contributing to this problem when there is an obstruction between the sensing receiver and the signal transmitter. Other problems are identified and include: 1) Channels over which sensing is required, 2) bandwidth considerations, 3) antenna considerations, 4) transmit power control, 5) master/client operation, 6) spectrum sharing, and measurement procedures.
3. Geo-location / data base approach – The FCC has proposed that fixed TV band access devices could use geo-location methods such as GPS to determine location and then access a data base to identify available spectrum at its location. A first problem is inaccuracies of GPS in indoor or obstructed locations. A second problem is that the FCC does not maintain a complete data base of TV stations and their location parameter that could be accessed in real time by a large number of TV-band devices. Alternative data base access would have to be developed, probably by 3rd party providers. Professional installation was another identified method.
4. Control signal approach – a control signal could be broadcast by FM, TV, or CMRS transmitter that would list available vacant TV channels in an area. A TV-band device would only be allowed to transmit on a frequency in the list.
5. Due to operations of PLMRS/CMRS[34] in 13 metropolitan areas of the country, operation of TV-band devices on channels 14-20 are not allowed in all parts of the country. Similarly, channels 2-4 are commonly used by VCR, cable, satellite TV receivers to provide video

[33] 46 C.F.R paragraph 15.407(h)
[34] PLMRS - Public Land Mobile Radio Service; CMRS – Commercial Mobile Radio Service

signals to TVs and could be interfered with. The FCC is leaving this open for possible later decisions if it can be determined that interference can be avoided.

6. Types and applications of devices – these might include TV-band fixed devices, mobile/portable devices, and perhaps other types of devices. Each type of device and application might require different interference mitigation methods.
7. Out of band emission limits – The FCC proposed that TV-band device emissions comply with the limits defined in Part 15.209. Comments were received indicating that this might not be adequate to mitigate interference to emerging DTV receivers.
8. Direct TV pickup interference and receiver desensitization- The FCC indicated that no test results and data had been submitted to substantiate this possibility, but it will be part of ongoing considerations.
9. Certification by Telecommunication Certification Bodies (TCB) – the FCC or a TCB must certify a device before it can be marketed in the US. The FCC indicated that it will not initially allow TCB certification until it has gained more experience with TV-band certification. It will be reconsidered at a later date.
10. Unlicensed use in border areas near Canada and Mexico – No operations of TV-band devices will be allowed in designated border areas until a later date to allow for development of details and negotiations.

In June 2006, the FCC released a public notice[35] seeking comments on a CR initiative for a test-bed for concept demonstration and testing. This is a joint activity of the FCC and the National Telecommunication and Information Administration (NTIA) to "evaluate methods for spectrum sharing among disparate users to enable more intensive use of the finite radio spectrum." It should be noted that the NTIA is responsible for managing the federal government's use of radio spectrum. The FCC is responsible for regulating interstate and international communications by radio, television, wire, satellite and cable. The FCC requested comments concerning the test-bed on subjects including:

1. Goal and scope of the test-bed program – should the test-bed goals address CR techniques, public safety CR methods, spectrum coordination process between federal and non-federal users? Should the test-bed answer questions about CR supporting technologies such as smart antennas; measuring spectral efficiency methods, **etc.** ? Should a single or multiple experiments be conducted?
2. Logistics to create and implement the test-bed program –what criteria should be used to identify candidate frequency bands for the program. A minimum of 20 MHz (10 MHz by the FCC and 10 MHz by NTIA) is proposed for the program. What relationships among the bands should be considered in selecting bands and how much should be provided. What geographic area(s) should be authorized?
3. Conclusions and evaluation of the test-bed program – What metrics should be used to evaluate the program? If successful, should the program be expanded to other bands or locations? If successful, should the program transition to permanent usage or rulemaking proceedings by the FCC?

[35] "Federal Communication Commission seeks public comment on creation of a spectrum sharing innovation test-bed", FCC 06-77, June 8, 2006.

The SDR Forum submitted a response[36] to the FCC on this test-bed program that is available on its website. In summary the SDR Forum recommendations included:

1. The proposed spectrum time sharing innovation test-bed will improve spectrum utilization and efficiency.
2. The FCC should authorize multiple candidates to utilize the test-bed.
3. The FCC and NTIA should establish 2 test-beds. One below 1 GHz and one in the 5 GHz band.
4. Participates should be provided maximum flexibility to engage in a wide variety of experiments.
5. The FCC should delay adaptation of specific metrics that will determine the success of the test-bed program.

The SDR Forum indicated that it fully supports the creation and implementation of a spectrum sharing innovation test-bed.

In a second report and order and further notice[37] in September 2004, the FCC expanded the rules on secondary markets for spectrum and provided information and requested comments for future rules. Secondary market refers to leasing of spectrum by a licensee to other parties. The FCC believes that such leasing potentially might "further enhance opportunities for spectrum access, efficiency, and innovation by removing unnecessary regulatory barriers and implementing more market-oriented policies that would facilitate moving spectrum to its highest valued uses." In earlier rule making the FCC established two different spectrum leasing approaches. The first "spectrum manager" leasing allow parties to enter into spectrum leasing arrangements without prior Commission approval so long as the licensee maintains control of the license and control over the leased spectrum. In the second "transfer" leasing the licensee retains control of their licenses while control over the use of the leased spectrum, and associated rights and responsibilities, are transferred to the lessees. Parties may enter into either long-term or short-term de facto transfer leases, with some variation in the policies and procedures that apply to each type. In this order the FCC implemented rules that provided for:

- Spectrum Leasing Arrangements
- Policies to Facilitate Advanced Technologies
- License Assignments and Transfers of Control
- The Commission's Role in Providing Secondary Markets Information and Facilitating Exchanges

This order is extensive and very detailed. Readers are referred to the reference for more details. Needless to say that the commercial sector is very negative on "involuntary spectrum sharing" (involuntary unlicensed operations) initiatives of CR. Secondary market initiatives offer a potential method for their cooperative participation.

[36] FCC ET Docket 06-89, Comments of the SDR Forum, July 10, 2006

[37] Second Report And Order, Order On Reconsideration, And Second Further Notice Of Proposed Rulemaking: Promoting Efficient Use of Spectrum Through Elimination of Barriers to the Development of Secondary Markets; WT Docket No. 00-230; Released: September 2, 2004

In its notice and order,[32] the FCC received many comments from industry that provide insight into CR. The following will provide summaries of these comments.

Shared Spectrum Company on its web site[38] indicates that the company "has devised and implemented pioneering solutions for a wide variety of communications, RF receiver, and dynamic spectrum sharing problems." The company has been a key member of the US's DARPA neXt Generation (XG) program. In comments to the FCC[39], the company indicated the following about CR initiatives:

1. Initial operation of smart radios should take place on a centrally controlled system basis
2. Sufficient spectrum should be authorized for cognitive radio
3. Secondary markets should be opened to existing licensees but not allowed to become a vehicle for monopoly control
4. Interference management should be based on receiver levels rather than transmitter level
5. Dynamic sharing will bring substantial public benefits

In later reply comments[40] the company stated that "Cognitive Radios should be operated on an independent basis and not subjected to the control of existing licensees, -- pursuant to well-established Commission and Congressional policy in favor of competition and the Constitutional policy of promoting free speech. Existing licensees were not granted property rights in every thing that goes on in the frequency bands they use but merely the right to offer their licensed services free from harmful interference. … The technical arguments by licensees seeking recognition of monopoly status over the bands they use are highly flawed with erroneous assumptions about their own services contrary to the Commission's previous decisions and even more erroneous assumptions about cognitive radio. Avoidance of interference to services using frequency pairs merely requires monitoring each of the paired frequencies. Use of packets by cognitive radio permits monitoring of primary use even after cognitive radio transmissions have begun. For the small number of services characterized by passive receivers, Shared Spectrum had previously addressed the so-called "Hidden-Node: problem."

Not surprisingly, wireless operators and their equipment vendors have different opinions. One such opinion was expressed by Verizon Wireless[41] commenting (paraphrasing key points) that:

1. "The Commission should continue its policy of letting markets and not regulators determine the highest and best use of spectrum"
2. "Parties that support "involuntary sharing" of licensed spectrum offer no details or support for their conclusions that such use will not cause harmful interference to licensed services" (i.e. FCC records including industry comments are inadequate at that time)

[38] www.sharedspectrum.com
[39] "Comments of Shared Spectrum Company" to FCC ET Docket No. 03-108, [32] By Mark McHenry etal, April 5, 2004
[40] "Reply Comments of Shared Spectrum" to FCC ET Docket No. 03-108,[32] By Mark McHenry etal, June 1, 2004

[41] "Reply Comments of Verizon Wireless" " to FCC ET Docket No. 03-108,[32] By Scott etal, June 1, 2004

3. “”Nothing in these few comments should persuade the Commission that it should allow “non-voluntary” invasion of spectrum licensed on an exclusive, flexible basis.”
4. “CTIA, for example” suggests that a better way than forcing sharing to facilitate access to spectrum and encourage the further development of cognitive radio technologies is to “foster a robust secondary market.”

Motorola offered the following comments. [42] In its opening paragraph, the company states:

> Motorola believes there are benefits associated with cognitive radio that should be explored. However, the technology is still under development and there are many questions regarding implementation that must be answered before it can be implemented effectively. The protection of existing services, including public safety communications and other licensed services, must be a priority in considering the introduction of this new technological approach. Further, the Commission should not view cognitive radio as a replacement for sound spectrum management. Rather, it is yet another tool to maximize the efficient use of spectrum, consistent with operational requirements. In addition, Motorola supports the development of software-defined radio (SDR) policies and guidelines. Such guidelines should be intended to facilitate the development of SDR and should not impede the flexibility of manufacturers to develop new technology or increase the cost or cycle time of equipment certification. Ensuring that rules for SDR provide for the efficient manufacture and deployment of equipment will benefit the public by minimizing costs and delay.

Further “Policies for cognitive radio deployment should be assessed in a broader analytical framework, but rules for actual deployment must be assessed and defined on a band-by-band, service-by-service basis.” In another comment, “Motorola urges the commission to make more spectrum available to facilitate public safety interoperability.”

Ericsson asserted[43] “Ericsson believes that cognitive radio technologies do and will in the future provide additional degrees of spectrum efficiency and access; however, significant research is necessary to determine what specific role a cognitive radio technology can potentially play without the risk of creating additional interference and unreliability.” Ericsson’s comments address the proposal to promote a secondary market using public safety spectrum and its potential risk to public safety networks in critical operations. “Additionally, the use of cognitive technologies to allow unlicensed use in licensed bands or high-powered use in unlicensed bands could allow additional interference and introduce uncertainty in the band.” Overall, Ericsson

> … submits that the proposals in the NPRM to rely on cognitive technology in the manners proposed for spectrum efficiency are premature and alternative proposals should be considered to achieve the desired goals. Ericsson cautions that the NPRM proposes to change the Commission’s rules without fully considering the impact of the changes on non-cognitive radio operations. In addition, progress is being made in the marketplace in the development and application of cognitive technologies. Applying additional rules and regulations could delay its continued progress. For these reasons, Ericsson submits these comments, urging the Commission to embrace the marketplace and allow it to continue forward with the development of cognitive radio technologies.

[42] “Comments of Motorola, Inc,” to FCC ET Docket No. 03-108,[32] By Sharkey etal ,May 3, 2004
[43] “Comments of Ericsson, Inc.” to FCC ET Docket No. 03-108,[32] By Racek etal ,May 3, 2004

On interruptible public safety leasing Ericsson commented: “The Commission can attain public safety spectrum efficiency through far more reliable, cost effective, and less complex means. Specifically, Ericsson proposes that the Commission encourage public safety spectrum efficiency by supporting public safety entities’ use of commercially available systems for those functions and applications that do not require dedicated access to spectrum.”

Intel Corporation submitted the comment:[44]

> Intel believes that the Commission can address legitimate regulatory concerns raised by cognitive radios, if it bases its rules on clear definitions of the rights and responsibilities of both licensed and unlicensed spectrum users, particularly with respect to interference and interference protection. … As Intel has stated in the Commission’s inquiry into unlicensed use of vacant TV channels (ET Docket No. 03-201), today’s unlicensed allocations are successful because they create a structure of primary and secondary users and give de facto control of the secondary use to the owner of the immediate physical area (business, campus, or home).

Concerning higher power for rural markets and unlicensed devices Intel commented that “Intel agrees that permitting unlicensed devices to operate at higher power levels in rural areas could help provide improved access to spectrum in those areas by permitting greater transmission range and coverage area, but believes the Commission should proceed cautiously.” The historical unlicensed rules have been effective due to “The combination of low power limits and propagation characteristics in the unlicensed bands that limit the effective range of these devices has created a workable environment.” Intel expressed concern that interference problems could occur in high power unlicensed rural operations.

[44] “Comments of Intel Corporation ” to FCC ET Docket No. 03-108,[32] By Chartier etal

3.5. *Ofcom Cognitive Radio Initiatives*

Office of Communication (Ofcom) in the United Kingdom has been a very active international regulatory leader in Software Defined Radio (SDR) and Cognitive Radio (CR) initiatives. This section will provide discussions of these initiatives. Most of the information that follows is based on a very recent Cognitive Radio study final report released by Ofcom on February 26 on their web site.[45] An additional source of information on Ofcom's CR initiatives are papers[46] presented at the 2006 SDR Expo. However, we will start by reviewing discussions in a paper authored by Dr. William Webb, Head of Research and Development at Ofcom, in a recent paper.[47]

The lead theme of the paper asserts: "Research suggests that if licenses were more flexible this could increase the value the UK generates from the radio spectrum by nearly €1bn". The paper explains that licenses are currently issued "more or less specific to a particular technology or application" An example would be that GSM licenses in Europe in cellular and PCS bands must be used for mobile services and employ GSM standards. Also note that while flexibility seems essential for the future, this inflexible licensing strategy was probably essential for Europe when adopted in the 1990's and has propelled GSM to become the dominant international standard today.

The paper states that the "key reason for managing spectrum is to avoid interference between users" and the reasons for current inflexibility are that regulators are concerned that greater flexibility might lead to interference. It outlines the modes of interference (in terms of user "A" interfering with user "B") as:

1. Geographical interference. In this case both A and B are using the same frequencies, but in different locations. If A moves too close to B, signals from A's transmitters can interfere with reception on the edge of B's coverage area.
2. Out-of-band interference. In this case, A and B are located in the same geographical area, using separate but nearby frequencies. If A's transmissions in its own frequency bands spill out into neighboring bands then they can be received by B's receivers as interference. (i.e., the transmit filter does not effectively attenuate out of band signals)
3. In-band interference. Again, A and B are located in the same area with nearby frequencies. In this case, B's receivers are not perfect and also pick up some of the signal A transmits in its own bands causing interference. (i.e. the receiver filters do not affectively attenuate out of band signal)

The paper concludes that a superior method to license spectrum is "to specify in the license the interference that a license holder is allowed to cause rather than the signal he or she is allowed to

[45] Cognitive Radio Technology: A Study for Ofcom Final Report, by QinetiQ LTD, Multiple Access Communication Limited, University of Surrey, University of Strathclyde, and Red-M., dated February 12, 2007, http://www.ofcom.org.uk/research/technology/overview/emer_tech/cograd/

[46] "A Summary of Cognitive Radio Work Performed for the UK Regulator Ofcom," presented by Julie Bradford, QinetiQ, SDR Forum Expo, November 15, 2006.

[47] "A license to do (almost) anything you want", by William Webb, Head of Research and Development, Ofcom; in IET Communication Engineer, December/January/2006/2007

transmit. The license then directly controls the interference rather than indirectly as is the case today." This method allows users flexibility to change use or technology as long as interference to neighboring users is within license constraints. This interference approach is called Spectrum Usage Rights (SURs).

The paper concludes by stating that "Ofcom's vision for the longer term is that, with users allowed to trade their licenses, change their technology and use and negotiate changed limits between them, the market will determine the use of radio spectrum, and the role of the regulator will diminish to that of a spectrum policeman. SURs might be an important step towards that vision and one we are currently working with key stakeholders to develop further." Figure 3-12 presents graphically a goal stated by Ofcom to evolve to 71.5% licensing by market mechanisms by 2010.

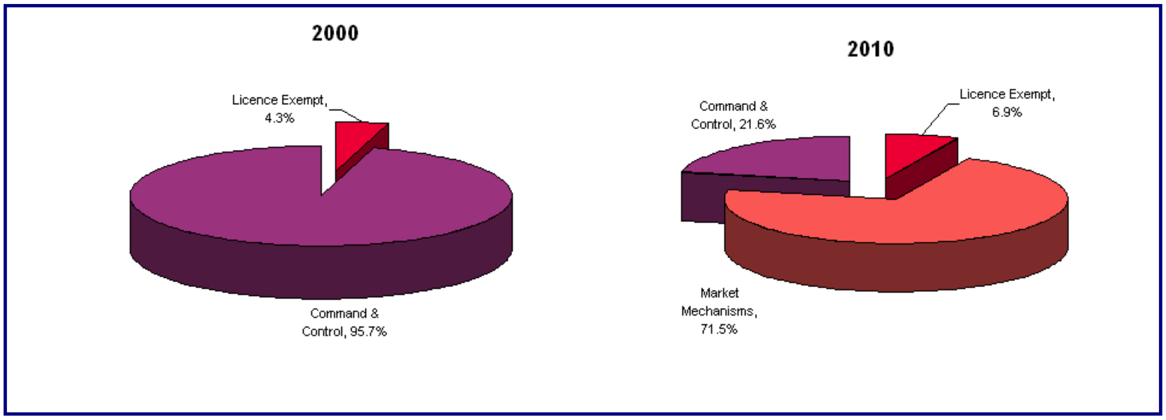

Figure 3-12 Regulatory Goals: From Ofcom Spectrum Framework Review 2004
(Source: SDR Forum paper and presentation[45])

In late February 2007, a final report was published by Ofcom[45] that provided results of a Cognitive Radio Study conducted by a consortium of companies and universities. The report states that the study was commissioned by Ofcom to "enable it to develop its strategic response to the emerging Cognitive Radio (CR) debate, both nationally and internationally." In the report it is stated that this study builds on previous SDR studies by Ofcom and "considers aspects such as CR terminology, technologies, potential development timescales, user scenarios, and regulation."

The report discusses the relationship between CR and the 7 OSI layers as depicted in Figure 3-13. The conclusion is that the CR implies intelligent signal processing (ISP) at the physical layer that "performs functions such as communication resource management, access to the communication medium, etc. . " A conclusion is offered that ISP at higher layers of the OSI stack is required to achieve fully optimized spectrum efficiency. The report then concludes that the complexity of adding intelligence to all seven layers of the OSI stack, as required for full (denoted Mitola CR after CR visionary Joe Mitola) CR might not be achievable for many years.

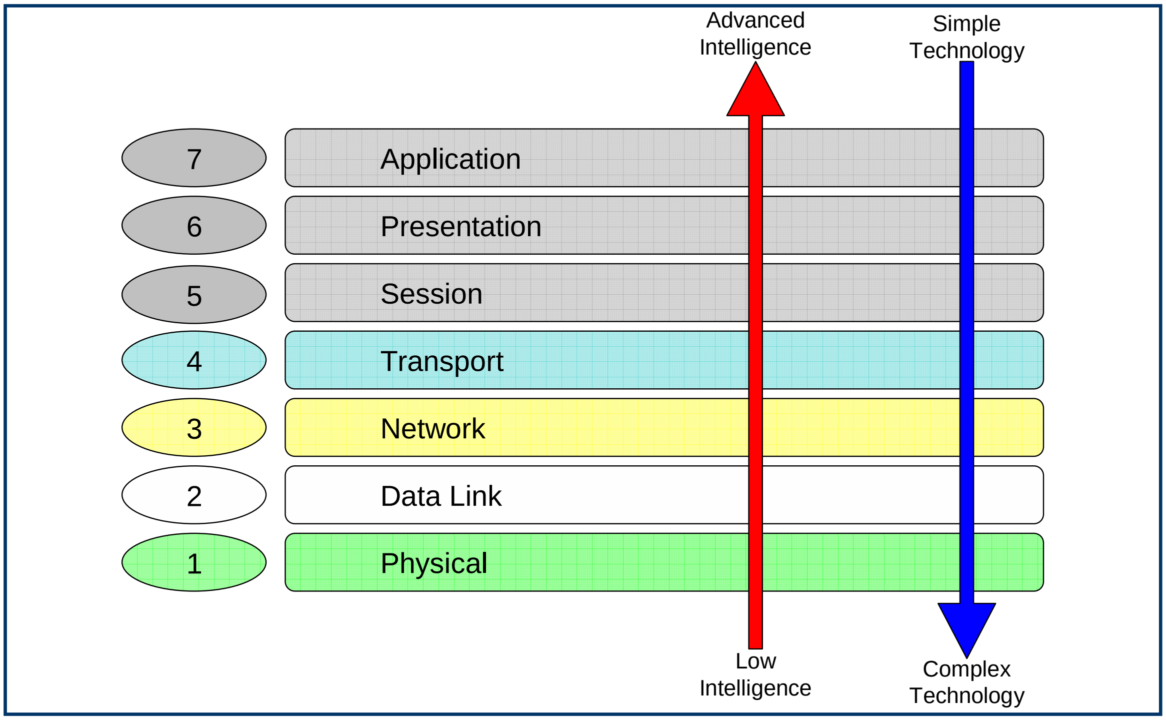

Figure 3-13 Cognitive Radio and the 7 OSI Layers
(Source: Ofcom Report [45])

Two problems are identified to achieving full CR. The first is making a truly cognitive device with the ability to intelligently make decisions based on its own situational awareness. The second is the evolution of SDR technologies to enable reconfigurability. The need for SDR radios capable of operating flexibly in any frequency band up to 3 GHz are cited as desirable and are not anticipated being available until 2030.

However, the study concludes that "true cognition" at all levels of the OSI stack may not be required to provide value as "simple intelligence at the physical layer, coupled with basic reconfigurable technologies (i.e. SDR), could provide significant benefits over traditional types of radio." Thus it is anticipated that the evolution to full CR will be gradual, and that some CR features are already in deployed radios. These features include adaptive allocation of frequencies, adaptive power control, and multiple input multiple output (MIMO) antenna techniques. Early CR feature enhancements are anticipated to be SDR frequency flexibility with decreasing hardware limitations. (i.e., reducing or eliminating the need for multiple RF/analogue front ends and switches). An identified key CR capability will be the development of rules to define how differing CR devices, networks, and services can co-exist in the same spectrum and space. The IEEE 1900-B working group activities are recognized as developing "protocol standards that can be transmitted to CRs to enable heterogeneous networks to optimize their behaviors and hence co-exist with other radio systems."

Based on a UK stakeholder workshop, four applications were identified as most promising CR applications:

- Mobile multimedia downloads (for example, download of music/video files to portable players) which require moderate data rates and near-ubiquitous coverage;
- Emergency communications services that require a moderate data rate and localized coverage (for example, video transmission from firemen's' helmets);
- Broadband wireless networking (for example, using nomadic laptops), which needs high data rates, but where users may be satisfied with localized "hot spot" services;
- Multimedia wireless networking services (e.g. audio/video distribution within homes) requiring high data rates.

Potential spectrum suitable for CR technologies deployments was identified as:

- 148 – 470 MHz, Analogue land mobile radio band
- 300 - 1000 MHz, Digital Video Broadcasting – Terrestrial (DVB-T)
- Non-continuous radar system bands
- 2000 - 11000 MHz, Fixed Wireless Access Spectrum, particularly 802.16h

Three main challenges to the widespread deployment of CR are identified as:

1. Ensuring that CRs do not interfere with other primary radio users – i.e. solving the hidden node problem.
2. Security issues associated with SDR, such as authenticity, air-interface cryptography and software certification, also apply.
3. Developing control techniques for CRs.

CR is viewed as a potential enabler of new market-based approaches to spectrum management to achieve spectrum efficiencies and secondary market access.

The key regulatory and security issues to CR included several items. First, a liberalized spectrum environment must be created in which multiple users can share spectrum. However, licensing restrictions must not be fully eliminated. Interfaces between radios must be standardized to ensure radios cooperate with each other on a local, national, or international scale. Spectrum data bases must be available, and may be available only from regulators or 3rd party spectrum managers. A great deal of CR research is needed and spectrum should be allocated for these purposes, including CR control and secondary licensing methods. CR spectrum policy will require SDR technology.

The report concluded that determination of the economic benefits of the CR and spectrum sharing applications was not possible due to the lack of available economic and usage data. An example was evaluated based on the competitive cellular market. It was assumed that at a future date cellular spectrum would become insufficient and cellular congestion would occur. CR would be deployed to achieve needed extra capacity. Simulations performed showed that maximum call volume increases of between 3.1% and 10% could be obtained in the GSM and UMTS expansion band using CR. An economic analysis of the potential development and deployment of CR techniques showed that an investment of 5% of the expected annual revenue in 2025 would be required. With a conservative assumption that the investment depreciates completely after only 3 years, an estimated call volume increase of 3.7% was obtained for the economic benefit of CR to consumers to outweigh the investment cost, a figure close to the minimum estimated to be achieved with CR techniques. (See Section 4.) In the analysis, it was concluded that based on cellular congestion predictions, cellular-CR may not be required until 2025 to 2030, but once implemented, the CR economic benefits to consumers would conservatively be expected to exceed the investment costs. It should be noted that this analysis is based on a UK scenario.

3.6. *E2R Cognitive Radio Initiative*

The End-to-End Reconfigurability (E²R) program is an Integrated Project (IP)[48] of the 6th Framework Programme of the European Commission. The project addresses the strategic objective for "Mobile and wireless systems and platforms beyond 3G". The first phase of E2R contract was initiated March 1, 2004. Motorola Labs, Paris, was selected to lead the project consisting of "many key players in the domain of reconfigurability, software defined radio (SDR), and cognitive radio (CR)." The second phase of E2R[49] started on January 1, 2006 and is scheduled to complete in December 2007. The consortium consists of 32 organizations and 14 countries. The budget for the phase 2 is 11.6 Million euros and has contractual outcomes consisting of 38 deliverables and 45 milestones.[50]

> The End-to-End Reconfigurability (E^2R) project aims at realizing the full benefits of the diversity within the radio eco-space, composed of wide range of systems such as cellular, fixed, wireless local area and broadcast. The key objective of the E^2R project is to devise, develop, trial and showcase architectural design of reconfigurable devices and supporting system functions to offer an extensive set of operational choices to the users, application and service providers, operators, and regulators in the context of heterogeneous systems. Innovative research, development and proof of concept are to be pursued from an end-to-end perspective, stretching from user device through all system levels. Furthermore reconfigurability support for intrinsic functionalities, such as management and control, download support, spectrum management, regulatory framework and business models complete the project scope.[48]

Often articulated key goals of commercial Beyond 3G (B3G) initiatives include "Seamless Mobility", "Always Best Connected", and "Always Best Experience" for users. Figure 3-14 presents a very succinct graphic of anticipated E2R reconfigurability as an enabler of this seamless experience. As the figure depicts B3G systems are anticipated to include heterogeneous systems, devices, and environments and contexts. The emerging communication technologies that are anticipated to be WLAN; WiMAX; cellular including 2G, 2.5G, 3G, B3G, and 4G; Digital Video Broadcast (DVB); Digital Audio Broadcast (DAB); and others. In an SDR Forum expo presentation[49], E2R representatives indicated that "End-to-End Reconfigurability is the key enabler for providing seamless experience to the end-user and the operator:

- Managing and increasing resilience of growing complex architectures
- Reducing costs of deployments, evolution, and operation of large communication systems

[48] http://e2r2.motlabs.com/; March 2007
[49] "E2R II: Convergence of Unitied Business Model (UMB) and Responsibility Chain", by Didier Bourse etal, SDR Forum Expo Presentation; November 15, 2006.
[50] Thanks to Dr. Didier Bourse, E2R program manager, for guidance on these discussions.

- Providing opportunities to develop and experiment rapidly new services and applications."

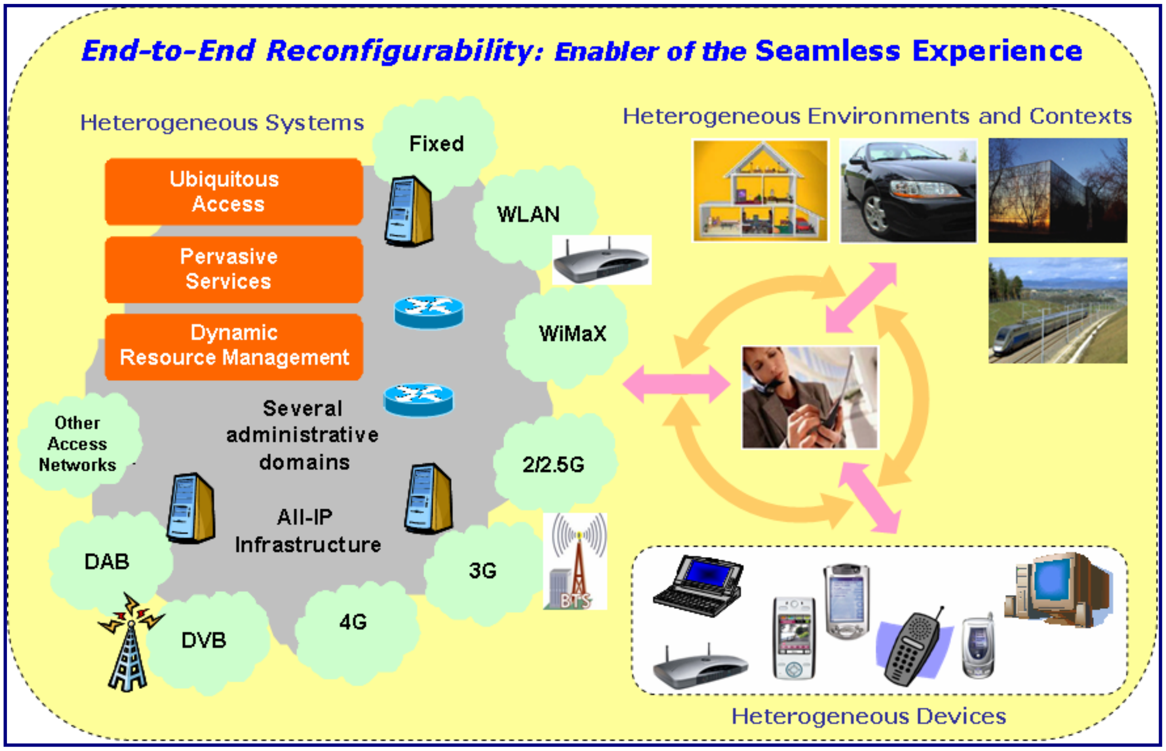

Figure 3-14 E2R: end-to-end reconfigurability: Enabler of the Seamless Experience
(Source: various E2R web site papers and presentations; Thanks to Dr. Didier Bourse, E2R program manager, for graphics)

An E2R white paper[51] discusses unified scenarios for autonomic (i.e. self governing) communication systems that include 4 basic categories of capabilities:

- Self-management: Profile interpretation, policy-based management, autonomic decision making, formation of network compartments, self-protection,
- Self-knowledge: Resource management, profile management, RAT[52] discovery & selection, cognitive service provision/discovery, traffic load prediction, network monitoring,
- Self-configuration: Self-healing, self-protection, self-configuring protocols, software download, base station configuration,
- Self-optimization: Resource allocation, traffic load balancing, dynamic spectrum allocation, flexible spectrum management, dynamic extension of network coverage.

The paper identifies business challenges as

[51] "E^{2}R II Scenario on Autonomic Communication Systems for Seamless Experience", e2r2.motlabs.com, November 2006
[52] RAT: Radio Access Technology

- Autonomics:
  Reference is made to an IEEE P1900.B concept that distributes decisions in new ways. Existing cellular systems make decisions almost exclusively in the (traditionally highly centralized) core network. WiFi networks allow terminals to make most decisions. P1900.B targets distributed decision making to facilitate more optimal use of resources.
- Pricing/Billing:
  User preferences may not be aligned with traditional business models and charging models. Users will prefer cheaper WiFi networks when available, yet they may be using a subsidized commercial operator mobile terminal. Various levels of emerging QoS may involve differing pricing plans
- Value Proposition:
  Operators will have to decide on investments to achieve spectrum efficiency. These include considerations such as throughput, capacity, and coverage.

Key aspects of E2R II initiatives focus on commercial business model opportunities, and issues for reconfigurability (and CR), as addressed in a paper[53] published in October 2006. The analysis in the paper used the Business System Architecture Process (BSAP) methodology to help achieve better customer value understanding by identifying key competitive differentiators needed to compete effectively in the market. It says "BSAP uses role based value mapping to understand the economic dynamics among roles within a business ecosystem." Figure 3-15 from the paper provides a simple illustration of a wireless business ecosystem.

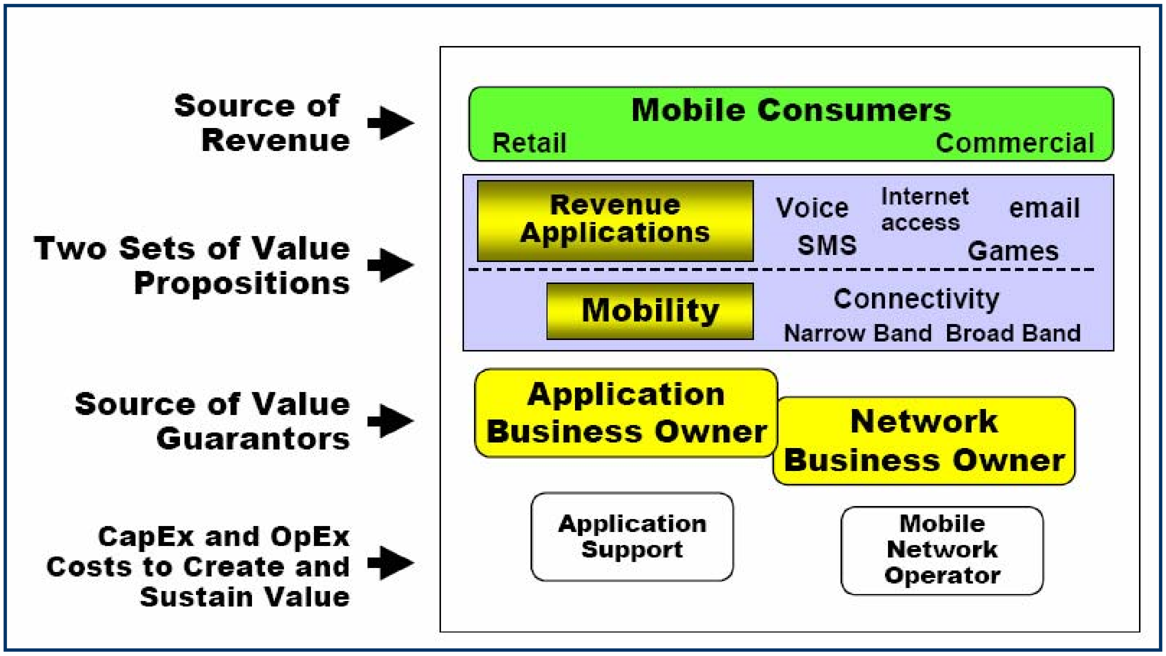

Figure 3-15 Wireless Business Ecosystem
(Source: E2R2 white paper[53])

Developing business models has been ongoing in E2R in both phase 1 and phase 2. Figure 3-16 presents the enhanced unified business model from the paper. The figure identifies the players

[53] "The E2R II Business Outlook: Framework, Instantiations and Challenges for Reconfigurability", www.e2r2.motlabs.com; October 2006

and the relationship of their roles from a business model perspective. Three instantiations of Unified Business Model (UBM) roles and relationships are discussed in the paper.

The paper states that its scope is "the presentation of the E2R II Unified Business Model (UMB), targeted to capture the challenges emerging from B3G telecommunication environments and advanced concepts, including cognitive and autonomic networking." In a previous SDR Forum report[54], multi-radio was identified as an important trend in the commercial wireless sector. These E2R initiatives are providing additional confirmation of this trend.

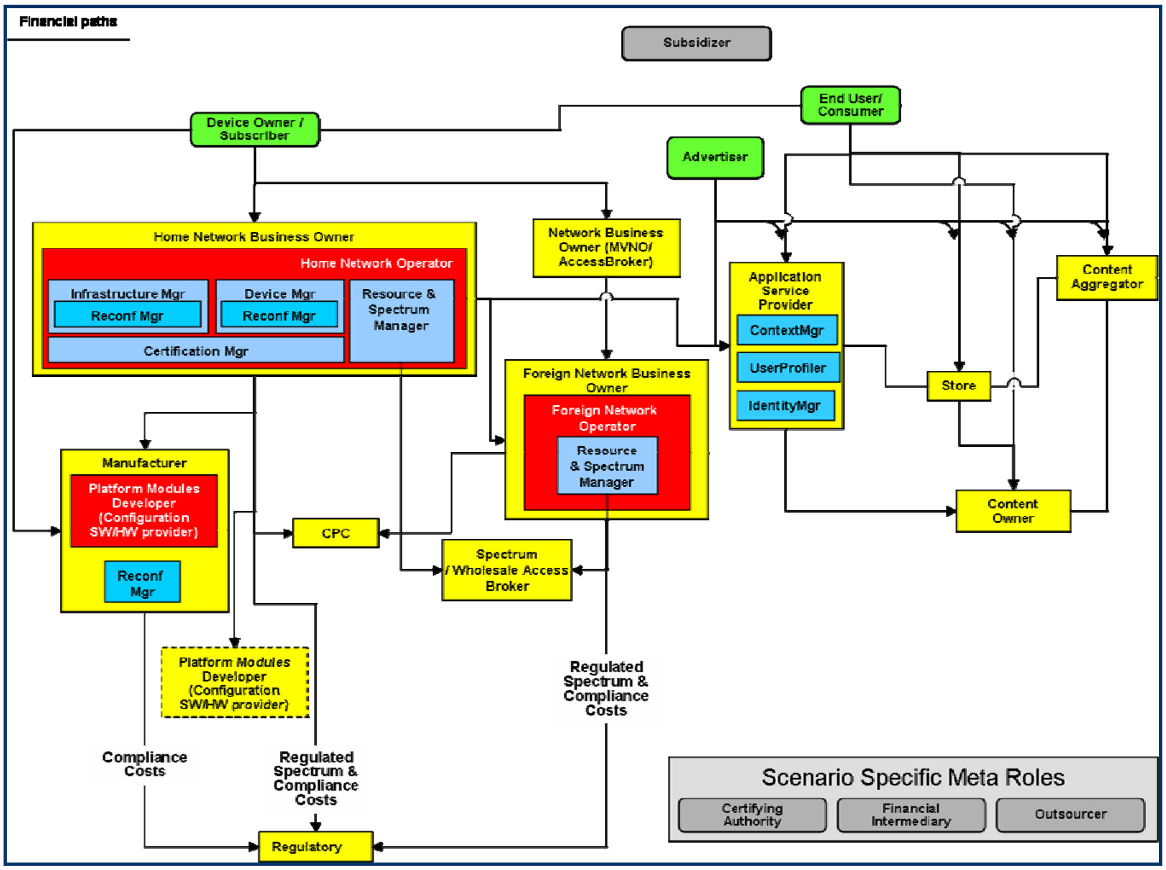

Figure 3-16 Enhanced Unified Business Model (UBM v2.0)
(Source: e2r2 white paper[53]; Thanks to Dr. Didier Bourse, E2R program manager, for graphics)

In addition to the E2R II papers discussed above, several additional phase 2 white papers are planned:

- E2R II Flexible Spectrum Management
- E2R II Transceiver Architecture
- E2R II Cognitive Radio
- E2R II Cognitive Networks
- E2R II Responsibility Chain

54 SDR Market Study, Task 3: WiFi, WiMAX and Beyond 3G / 4G, by Jim Gunn, SDR Forum Market Study Report, May 2007

As stated in Section 3.1, the commercial market segments are anticipated to be the largest market for CR and the E2R CR initiatives are anticipated to significantly contribute as an essential enabling technology to the evolution to market responsive features and services.

3.7. *Visionary Cognitive Radio*

Dr. Joe Miltola of the Mitre Corporation[55] is credited with creating the Cognitive Radio (CR) concept and the first published coining of the name Cognitive Radio (CR) in an IEEE Personal Communication article[56] in 1999. He published his Ph.D. dissertation[57] on CR in 2000. He has since actively published[58, 59, 60] on the subject. Dr. Mitola is also credited with defining Software Defined Radio (SDR) technologies and terminologies in the early 1900's and has published and researched SDR extensively since.

An early paper entitled "Cognitive Radio: Making Software Radios More Personal"[56] provides insight into the vision and long range potential of CR. More personalized service concepts are identified as:

- Understands user's goals (space, time, things)
- Understands self
- Understands networks
- Understands radio

A key ingredient of these concepts is the inclusion of cognition features for user goals including space, time, and things. Most CR initiatives, especially regulatory initiatives, focus on spectrum efficiency and better spectrum licensing access, and are essentially physical layer (PHY), the MAC/Link layer, and general lower OSI layer features. Dr. Mitola envisions not only these lower layer CR features, but also more extensive application layer features that cognitively anticipates and serves user needs. In Section 3.5 Ofcom study discussions refers to this as full cognition (or Mitola Cognition) and indicates that evolution to this full cognition will probably not occur until perhaps 2030, although less extensive CR features are already emerging. Dr. Mitola indicates that CR includes "sensing and perception capabilities in the user domain, not just the radio domain."

As illustrated in Figure 3-17, the CR Architecture (CRA) augments SDR with computational intelligence and learning capacity. The CRA consists of hardware and software (consisting of

55 Dr. Mitola's affiliation is for identification purposes only and does not imply the endorsement of MITRE nor any of its sponsors of his views.
56 "Cognitive Radio: Making Software Radios More Personal"; Joseph Mitola and Gerald McQuire, IEEE Communication Magazine, August 1999, p13
57 Mitola, Joseph III, Cognitive Radio: An Integrated Agent Architecture for Software Define Radio, Royal Institute of Technology (KTH) Stockholm, Sweden, May 8, 2000
58 "Software Radio Architecture: A Mathematical Perspective," Motila, IEEE JSAC, Vol 17, #4, April
59 Cognitive Radio Architecture: The Engineering Foundations of Radio XML, Joseph Mitola, Wiley, 2006
60 "Cognitive Radio Architecture", Joseph Mitola, Chapter 14 of Cognitive Radio Technology, Bruce Fette, Newnes, 2006

SoftWare Radio (SWR) modules. CR features add cognition. The figure also illustrates the importance of languages to CR evolution and identifies eXtensible Markup Language (XML) and Radio eXtensible Markup Language (RXML) as potential CR languages. Research on languages for CR is ongoing in academia, DARPA's XG program, and other organizations.

In discussions[60,59] Dr. Mitola introduces "the fundamental design rules by which software-defined radio (SDR), sensors, perception, and automated machine learning (AML) may be integrated to create Aware, Adaptive, and Cognitive Radios (AACRs)." The discussions introduce five complementary perspectives of Cognitive Radio Architecture, that are called CRA I through CRA V. The CRA I perspective defines six functional components that are identified as black boxes that provide first-level decomposition of AACR functions and important connecting interfaces. The components for a simple CRA are presented in Figure 3-18.

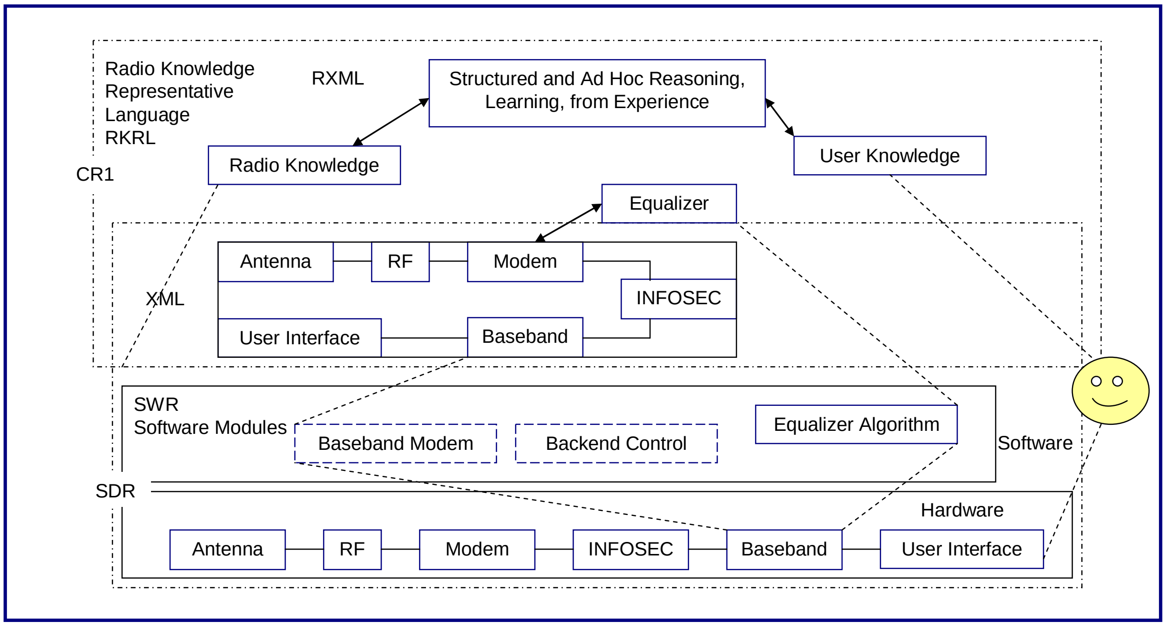

Figure 3-17 CRA augments SDR with computational intelligence and learning capacity
(Source: © Dr. Joseph Mitola III, used with permission)

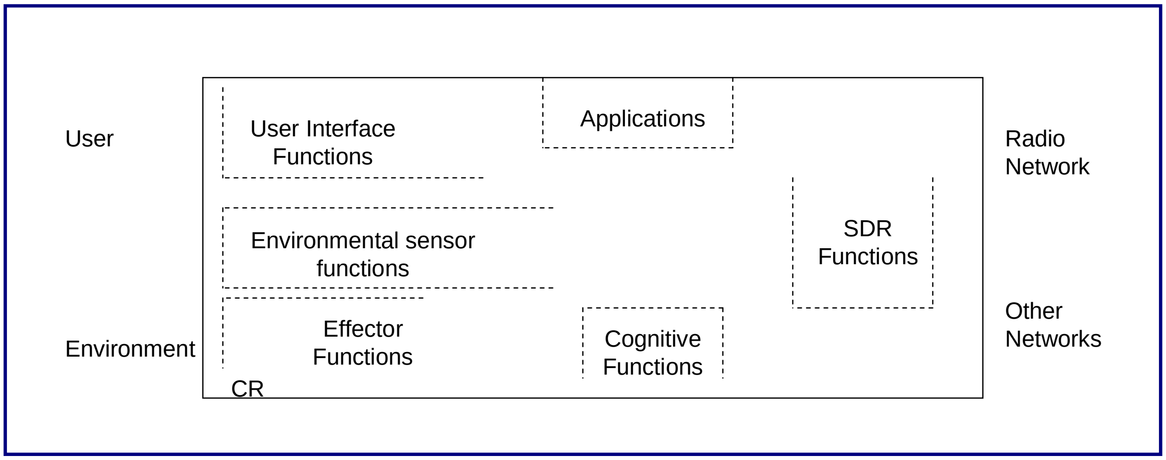

Figure 3-18 Minimal AACR node architecture
(Source: © Dr. Joeseph Mitola III, used with permission)

The functional components identified in the figure are described as:

1. The user sensory perception (SP), which includes haptic (touch), acoustic, and video sensing and perception functions.
2. The local environment sensors (temperature, location, acceleration, direction).
3. The system applications, including user professional support, information delivery, and media-independent services such as network games.
4. The SDR functions, which include RF sensing and SDR applications.
5. The cognition functions (symbol grounding for system control, planning, and learning).
6. The local effectors functions (speech synthesis, text, graphics, and multimedia displays).

3.8. *Cognitive Radio Policy and Spectrum*

Spectrum licenses are issued by the appropriate regulatory agency in a nation and authorize a band of use, a geographic region of use, and allowable operational parameters. For licensed spectrum there is a level of interference protection from other users. Unlicensed devices that are also referred to as license-free and licensed-by-rule are authorized frequency bands and transmission characteristics, but are not provided regulatory protection from interference.

Spectrum is generally allocated by type of use, frequency bands, and transmission parameters. Allocations are specified by individual nations, but are guided by international agreements including ITU agreements. Within the allocations, user assignments provide individual licensees with a specific set of parameters within an allocation.

Three basic types of assignment methods are employed.

1.)Command and control, where the regulatory agency awards a license to a licensee according to criteria specific to national goals. This has been the method used historically.

2.) Auction, where prospective licensee's bid on the right to a license. The license is awarded to the highest bidder. This is believed to facilitate use of market dynamics to maximize commercial benefit to society.

3.) Protocols and etiquettes, where licensees do not have specific frequency assignments. Unlicensed devices and amateur licensees are examples. Devices and licensees are provided a band of operation, but not specific frequencies for operations. Protocols and etiquettes are used for frequency selection in a manner to accommodate/avoid interference.

Dr. Paul Kolodzy, Kolodzy Consulting, and formerly a senior spectrum policy advisor at the FCC's Office of Engineering and Technology (OET), offers a discussion[61] of communication policy and spectrum management. CR is identified as offering the opportunity in spectrum management for radio devices to transition from the current manual oversight process to an

[61] Chapter 2 of Cognitive Radio Technology, Bruce Fette, Newnes, 2006

automated process that will facilitate more intensive use of spectrum. CR delivers four capabilities that will help enable dynamic use of spectrum: flexibility, agility, RF sensing, and networking.

He states that "Regulations based on static broadcast geometries cannot address the spatial, numeric and spectral dynamics of future radio technology." Further, "Technologists must begin to address not only how to construct such new technologies, but also to address how to bring dynamics into the regulatory framework."

Dr. Preston Marshall, DARPA, also describes[62] spectrum management as historically being a static process based on conservative assumptions. Spectrum planners have to assume that:

- Interfering signals will propagate to the maximum possible range.
- Desired signals will be received without unacceptable link margin degradation.

With these conservative static assumptions, interfering signals are considered to propagate to the maximum and desired signals propagate to the minimum. CR adds ability to sense and adapt to actual conditions and potentially optimize performance. A desired signal needs to propagate only as far required to maintain the signal-to-noise ratio needed for the desired error rate decoding. But the distance this signal continues to interfere is until it is attenuated below the noise/interference floor, which can be 4 times the maximum use distance. By adding CR, dynamic sensing and adaptation can provide improved performance over current static techniques.

3.9. *Software Defined Radio Forum Cognitive Radio Initiatives*

The Cognitive Working Group of the SDR Forum has published a paper on CR definitions and nomenclature[63]. SDR Forum members have access to this paper and details will not be repeated. However, some of the discussions provide supportive information and will be discussed.

SDR and benefits of Cognitive SDR are identified in the paper as:

1. Interoperability and Coexistence
2. Reduced demand on user, reduced user control burden
3. Greater Spectrum Efficiency through improved access.
4. More robust, seamless application interface for communication tasks
5. Dynamic Regulatory Compliance
6. Radio performance optimization
7. User based Cognitive Adaptation (i.e. Application layer and cognitive user preferences)

"The basic function of a cognitive radio is matching the radio link requirements of a higher layer application for user needs with available device, spectral and infrastructure resources." The

[62] See Section 3.3 and Chapter 5 of Cognitive Radio Technology, Bruce Fette, Newnes, 2006
[63] "Cognitive Radio Definitions and Nomenclature", SDR Forum Cognitive Radio Working Group

conceptual view of Cognitive SDR Radio Architecture to achieve this is presented in Figure 3-19. In this model the policy and cognitive engine are separated from the respective Rule-set to facilitate easy updates.

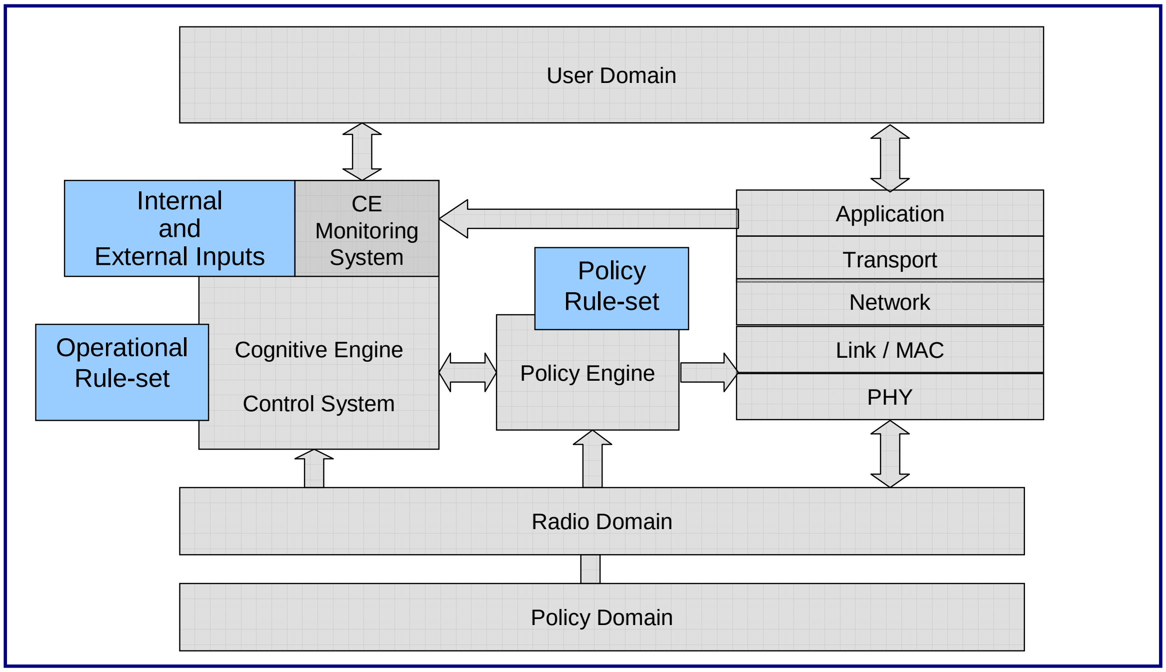

Figure 3-19 Conceptual view of Cognitive Radio Architecture
(Source: SDR Forum paper[63])

The attributes of a CR are identified as:

- Aware: Understands RF environment, geolocation, and associated spectrum use policies.
- Adjustable Can change frequency, power, modulation and other radio parameters and adjust to improve efficiency or optimize; on border crossing can adjust to comply with local crossing.
- Autonomous Does not require user intervention to exploit local spectrum opportunities while complying with local regulations.
- Adaptive Can learn from user patterns of use and respond and anticipate user needs.

The identified hierarchies of cognition are presented in Figure 3-20. As indicated in the figure, the evolution of CR technologies is anticipated to be incremental in functionality. As indicated in Figure 3-19, CR will, over time, offer CR facilities in all layers of the OSI stack, including learning and adaptation to user needs.

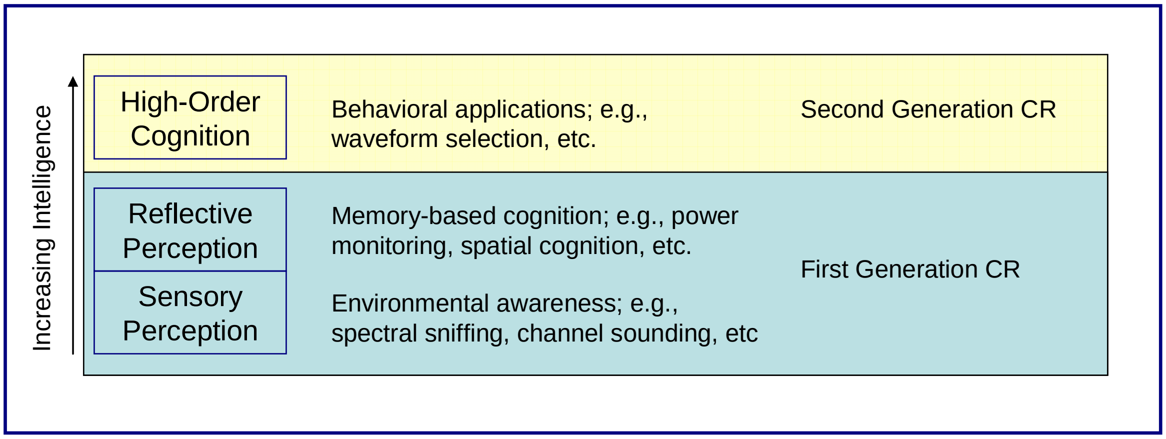

Figure 3-20 Hierarchy of Cognition and phases of deployment
(Source: adapted from SDR Forum CR WG paper[63])

3.10. *Commercial Network Optimization*

At key goal of Cognitive Radio technology is spectrum efficiency. To assess current commercial operator initiatives to achieve spectrum efficiency an interview was conducted with Bill Clift, CEO, of Optimi headquartered in Atlanta Georgia. Bill is a 30-year veteran of the wireless industry. Before joining Optimi in September 2005, he served as Chief Technology and Strategy Officer for Cingular Wireless.

Optimi[64] is a global wireless network performance management solutions provider. The company develops cutting-edge network simulation, prediction, and service monitoring and optimization applications for wireless carriers, network equipment manufacturers and engineering consulting firms. The company claims that its unique, customer-centric approach allows users of its applications to balance capacity, coverage and quality with sound financial management. The company has more than 200 employees that are skilled in RF optimization, end-to-end performance management, network operations and network cost analysis.
Bill summarized current general steps in commercial cellular network optimization. The steps include:

1. 2G Frequency Planning
2. Software Parameter Optimization
3. Physical Characterization of Cell Sites

2G frequency planning involves assigning carrier frequencies by cell site and sector according to the reuse plan to control interference. In fact, maximum performance/capacity comes from ad-hoc frequency plans rather than following a fixed pre-planned system-wide reuse pattern. The key metrics for frequency planning are quality and capacity. GSM, the dominant 2G technology is a time division multiplexed technology similar to IS-136 TDMA. The quality performance parameters for this include dropped calls, origination failures, blanking, and muting**.** Optimi has

[64] www.optimi.com

software tools to automate the process of optimizing frequency planning, the physical characteristics of cell sites (antenna type, height, downtilt, etc. .) and parameter optimization. The dynamics of a growing network, new sites, physical changes to sites, additional capacity to existing sites, and seasonal changes to foliage, require frequent reoptimization of the system to ensure maximum performance. During ongoing changing operations, frequency changes can be implemented on clusters of sites until the cumulative changes in the network become sufficient to warrant a replan. At total system retune typically takes several weeks.

UMTS, also known as WCDMA, is a CDMA based technology, and does not require frequency planning, per se, as 1 of 1 reuse is possible. However, CDMA requires even more attention to interference management to avoid negative impacts on capacity, coverage and data throughput.

Software parameter optimization involves setting the parameters of a Network vendor's infrastructure equipments and includes such items as handoff biasing and maximum power budgets. These parameters can typically be set remotely and vary from vendor to vendor. If these are not properly configured, users can experience poor quality of service, including dropped calls and origination failures.

The physical characteristics of the cell sites include such things as antenna positioning, beamwidth, height, and total available power. They have traditionally required a physical site visit for adjustment. However, electronic techniques, with better remote adjustment capabilities, are being deployed for some of them.

Bill stated that optimization for voice and data are different. Voice is more predictable and stable. Data, with its bursty nature, is less predictable and stable. Data is more sensitive to interference. Operators currently lack experience on emerging data traffic profiles and resulting RF network characterization.

Today operators need an ability to measure, plan, and change optimization in a near real time basis. Legacy physical capacity tools are back office tools that can take anywhere from several minutes to several hours to run, often on a daily or weekly basis.

The opportunities for cognitive radio to provide more real time assessment and configuration appear significant as the emerging multimedia voice, data, and video networks emerge. As 3G initiatives continue to evolve operators will need to improve their processes.

3.11. *Licensing and Coordination*

Sections 3.4 and 3.5 discussed cognitive radio initiatives from a regulators' perspective. The section will present the perspective of Comsearch,[65] of Ashburn, Virginia, a company that "provides innovative spectrum management solutions to the global market for fixed, mobile and broadband wireless applications." Since 2003, Comsearch has been part of Andrew Corporation[66]. The discussions in this section are based on discussions with Mark Gibson, Director, Business Development, at Comsearch. These discussions were supplemented by information on Comsearch's web site.

Comsearch states that it "is the industry leader in spectrum management, including frequency analysis and licensing, protection, sharing, and field services. We offer full life cycle engineering, including program management, network planning, RF engineering, site development, equipment installation and testing, system optimization and performance evaluations, and site audits in support of all wireless communications technologies, including PCS, cellular, microwave, satellite, fixed wireless, and broadband networks."

Types of license issued in the US by the Federal Communication Commission (FCC) include:

1. Full Scale Licensing: This has been the historical method of licensing by the FCC that typically requires coordination before a license is issued in shared-spectrum bands. The most significant examples of services are Land Mobile Radio (LMR), FCC Part 90; Microwave, FCC Part 101, and Satellite, FCC Part 25. These services have extensive (but differing) coordination requirements and generally exact coordinates of base station deployments must be reported to the FCC.

2. License by auctioning: This has been a more recent and popular method of licensing. It has been used extensively internationally for cellular PCS, and 3G/UMTS/WCDMA spectrum licensing. The US's initial auction was in 1994. The licenses are typically for a block geographic area (as opposed to a specific location) and have much simplified coordination requirements (e.g. borders of area and international border, Canada and Mexico). The FCC's web site[67] lists 82 closed or completed auctions as of 3/1/2007. The cellular services are licensed under FCC part 22 and the PCS services are licensed under FCC part 24. It is not required in the PCS bands in the US to report exact coordinates of a base station site to the FCC.

3. Unlicensed with coordination: This refers essentially to services in the unlicensed PCS (UPCS) bands at 1910 – 1930 MHz. This is often referred to as UTAM[68] bands or UPCS. The 1910-1920 MHz sub band was designated for asynchronous devices and the1920-1930 MHz sub band was designated for isochronous applications. Since 1994 over 1,100 active,

[65] www.comsearch.com
[66] www.andrew.com
[67] http://wireless.fcc.gov/auctions/default.htm?job=about_auctions&page=1
[68] After UTAM, Inc (www.utam.org) an organization designated to serve as spectrum coordinator for this UPCS band. UTAM is derived from "Unlicensed Transition and Management."

licensed, point-to-point microwave links have been relocated to clear the band. UTAM cleared 99% of the band of active microwave links and on April 5, 2005 the remaining microwave link lost their primary status making the deployment of nomadic devices, such as cordless phones, possible. The FCC rules for UPCS are in Part 15 and require device certification by device manufacturers.

4. Unlicensed, No Coordination: This is the extensively deployed and very popular unlicensed operations that are governed by FCC Part 15 rules and includes the unlicensed ISM and NII bands[69]. While no coordination is required for operation, equipment manufactures are required to obtain device certification.

5. License by Rule: A special case of unlicensed, such as the Wireless Medical Telemetry Service (WMTS) that is covered under CFR Part 95[70] rules. The FCC designated the American Society for Healthcare Engineering of the American Hospital Association (ASHE/AHA) to serve as the exclusive WMTS frequency coordinator. Wireless medical telemetry systems include devices to measure patients' vital signs and other important health parameters (e.g., pulse and respiration rates) and devices that transport the data via a radio link to a remote location, such as a nurses' station, equipped with a specialized radio receiver. WMTS equipment may be used only within a health care facility. The FCC currently does not allow home use of WMTS equipment because of a concern that temporary use of such equipment at many dispersed locations would make it difficult to coordinate the operating frequencies, resulting in harmful interference. Another example of license by rule is Broadband over Powerline (BPL). Coordination is required to avoid interference with incumbent operations in the BPL spectrum. A third-party database was developed to assist, and is supported by the United Power Line Council.[71] (BPL has been the target of a great deal of criticism because of the broad interference emitted by its systems.)

Spectrum Management services are the expertise offered by Comsearch. On their web site Comsearch offers several tables on the steps in the spectrum management process for different services including microwave, mobile, satellite, and broadband. An adaptation of the table for mobile is presented in Table 3-2.

An important component of spectrum management is frequency coordination. Oriented toward frequency coordination between sovereign nations, the ITU definition[72] is:

"The frequency coordination is a bilateral or multilateral process, conducted between administrations, which comprise the following activities:

- identification of the administrations whose assignments are likely to be affected and with which prior coordination must be sought or agreement obtained;

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69 ISM – Industrial, Scientific, and Medical; and NII - National Information Infrastructure

70 47 CFR Part 95: (Code of Federal Regulation)part of Personal Radio rules, see http://wireless.fcc.gov/services/index.htm?job=service_home&id=wireless_medical_telemetry

71 http://www.uplc.org/

72 http://www.itu.int/ITU-R/terrestrial/faq/index.html#i013

- use of standardized methods for calculating the potential for interference;
- application of standardized steps of a well-defined and transparent procedure comprising, inter alia, the exchange of a sufficient number of data elements in a prescribed format, communicating comments within a prescribed period, and, when appropriate, publication of the results of the coordination procedure in the appropriate Circular of the ITU/BR."

This definition is oriented toward coordination between sovereign nations, but is also applicable for coordination among entities occupying shared spectrum.

Table 3-2 Spectrum Management Process for Mobile

Step	Description	Discussion
1	Band Information	Technical and regulatory information about the PCS and cellular frequency bands.
2	Equipment Selection	Locate antenna manufacturers.
3	Preliminary RF Design	Determine the initial site layout.
4	Spectrum Sharing and Microwave Relocation	Identify potential interference problems with point-to-point microwave systems.
5	Detailed Design & Site Selection	Analyze and rank candidate sites. Locate an existing structure or a site location for a ground build.
6	Network Interconnection	Identify network connectivity options.
7	Radiation Safety Compliance	Radiation safety guidelines and your obligations.
8	Installation & Construction	Find a company to help with the installation and construction of your system.
9	System Optimization / Performance Evaluation	Ensure that your system achieves network quality goals.
10	In-Building Coverage	Provide focused coverage in important high-traffic dead zones.

(Source: Adapted from http://www.comsearch.com/pcs_cellular)

Comsearch[73] outlines the frequency coordination process for microwave systems by license applicants. Microwave systems require a very thorough coordination.

The Frequency Coordination Process involves several distinct but interrelated elements; interference analysis, notification, and response.

- Interference Analysis - The first step in the frequency coordination process is interference analysis. The FCC requires that applicants engineering a new system or making modifications to an existing system must conduct the appropriate studies and analyses to avoid interference in excess of permissible levels to other users. This interference analysis is performed by the applicant prior to issuing a prior coordination notice (PCN) and is also performed by recipients of a PCN to verify noninterference. Interference Analysis is an iterative process that involves computerized simulation of potential interference and an engineering analysis to eliminate interference cases. The process begins with a tentative frequency selection consistent with the established frequency plan in place. High-speed, automated calculations are conducted utilizing Telecommunication Industry Association (TIA) Bulletin 10 criteria and industry developed guidelines. These calculations include co-channel and adjacent channel interference, threshold degradation,

[73] "Fundamentals of Microwave Frequency Coordination", Comsearch White Paper, April 2005

adjacent spectrum interference; and potential interference from inter modulation products. In frequency bands shared with satellite earth stations, an interference analysis is conducted with the applicable ground and space segments.

- Notification - Once an interference analysis has been completed, and prior to system implementation, an operator is required to notify all "potentially affected parties". The industry defines an operator as potentially affected if his facilities (including proposed, applied-for, or operating) fall within a defined coordination distance and operate in the same frequency band. This notice is referred to as a prior coordination notice (PCN) and contains the technical operating parameters and a general description of the proposed system. The FCC Rules make allowance for two types of notification, both oral and written. The "written" PCN is the standard type and is conveyed by mail, fax or electronic media. The PCN includes a requested response date to coincide with the 30-day period allowed under FCC Rule.
- Response - As stated previously, the recipient of a PCN has 30 days in which to analyze the proposal and respond. Every attempt should be made by the receiving party to respond as soon as possible. In most cases, operators utilize an outside agent, commonly referred to as a "protection agent" to administer this function. The response to a PCN should include an affirmation of the proposal, or if there are objections, a detailed description of the reasons why. Typically, a response raising concerns will contain technical data sufficient to substantiate the objection.

The party issuing the PCN then is required to resolve all potential conflicts raised to the satisfaction of the objecting party. This may require several rounds of discussion, technical analysis, and negotiation. When both parties have reached an agreeable resolution of the cases, the coordinator of the proposed system issues a document called a Supplemental Showing. The Supplemental Showing is a signed affidavit in which the coordinator attests to satisfactorily completing coordination. When conflicts remain unresolved after repeated attempts to negotiate a solution, the Rules require that it be noted on the Supplemental Showing. Once coordination is satisfactorily completed, the signed Supplemental Showing is attached to the license application.

In general before submitting for a license in LMR, microwave, or satellite, the applicant must show frequency coordination (note that LMR coordination is slightly different from microwave coordination). The FCC has over time ceased to provide frequency coordination and has delegated this responsibility to appropriate industry organizations or frequency coordination service companies. These frequency coordinators are listed in various places on the FCC's web for the various services[74].

Additional comments by Mark Gibson include:

- CR white space initiatives could be License by Rule, although Unlicensed with coordination is possible.
- In Advanced Wireless Cellular applications, CR, supported by SDR, makes sense but may create data base issues. The data bases for PCS maintained by the FCC do not contain site-

[74] http://www.fcc.gov/pshs/spectrum/coord.html

specific data. Thus, knowledge of base station locations and configurations may have to be developed through alternate means.
- Television and AM and FM radio stations are licensed based on FCC Tables of Allocation for a geographic area and typically do not require extensive coordination with each other. The digital transitions may change procedures, but tables of allocations will probably still be the method.
- In general, the FCC's licensing data bases, as currently maintained, are not sufficiently complete and accurate to reliably serve CR flexible usage initiatives.
- CR will require integrating radio functionality with appropriate data bases.
- GSM already has some CR functionality as GSM has overhead functions that download operating parameters on every power-on that include frequencies and protocols to employ in the utilized cell/sector.

3.12. *IEEE P1900 Standards Group*

The IEEE P1900 Standards Group[75] was established in the first quarter 2005 jointly by the IEEE Communications Society (COMSOC) and the IEEE Electromagnetic Compatibility (EMC) Society. The objective is to develop supporting standards dealing with new technologies and techniques being developed for next generation radio and advanced spectrum management.

IEEE P1900 is currently being restructures as Standards Coordinating Committee (SCC)41. Its previous structure consisted of the following working groups:

- IEEE 1900.1 Working Group on Terminology and Concepts for Next Generation Radio Systems and Spectrum Management
- IEEE 1900.2 Working Group on Recommended Practice for Interference and Coexistence Analysis
- IEEE 1900.3 Working Group on Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules
- IEEE 1900.4 Working Group on Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks
- IEEE 1900.A Working Group on Dependability and Evaluation of Regulatory Compliance for Radio Systems with Dynamic Spectrum Access

According to a presentation[75] by Jim Hoffmeyer, chair of P1900.1 WG, a common concern of regulatory authorities around the globe is increasing demands for access to more spectrum. That requires addressing issues of:

- More efficient use of the spectrum
- Spectrum trading
- Dynamic frequency sharing
- Interrelationship of developments in technology, market and regulatory practices

[75] IEEE P1900 web site, www.ieeep1900.org, March 2007

- Need for a new spectrum management paradigm
- Pace of technology development – regulation has to keep up or get out of the way

P1900.4 is the working group focusing on CR standards. In discussions with Soodesh Buljore, chair of P1900.4 WG, the February 2007 Madrid meeting and presentation[75] were reviewed. According to the presentation, the 1900.4 WG Scope is defined as:

- The standard defines the building blocks comprising
  i) network resource managers,
  ii) device resource managers and
  iii) the information to be exchanged between the building blocks,
- for enabling coordinated network-device distributed decision making
- which will aid in the optimization of radio resource usage, including spectrum access control,
- in heterogeneous wireless access networks.
- The standard is limited to the architectural and functional definitions at a first stage.
- The corresponding protocols definition related to the information exchange will be addressed at a later stage.

And the 1900.4 WG purpose "is to improve overall composite capacity and quality of service of wireless systems in a multiple Radio Access Technologies (RATs) environment,

- by defining an appropriate system architecture and protocols which will facilitate the optimization of radio resource usage,
- in particular, by exploiting information exchanged between network and mobile Terminals,
- Whether or not they support multiple simultaneous links and dynamic spectrum access."

The IEEE P1900.4 WG PAR (Project Authorization Request) was approved in December 2006, commencing formal WG activities. According to the presentation the schedule envisions balloting starting in July 2008 and submission to the IEEE IEEE-SA Standards Board Standards Review Committee (RevCom) in February 2009.

The WG envisioned commercial scenarios as is depicted in Figure 3-21 that applies CR techniques for 802.11n, WiMAX, and CAP UMTS operations.

The P1900 web site referenced a Wikipeida article on the definition of frequency assignments as:

- Authorization, given by an administration, for a radio station to use a radio frequency or radio frequency channel under specified conditions.
- The process of authorizing a specific frequency, group of frequencies, or frequency band to be used at a certain location under specified conditions, such as bandwidth, power, azimuth, duty cycle, or modulation. A synonym is radio frequency channel assignment.

The source for the definitions was indicated as from Federal Standard 1037C and from MIL-STD-188.

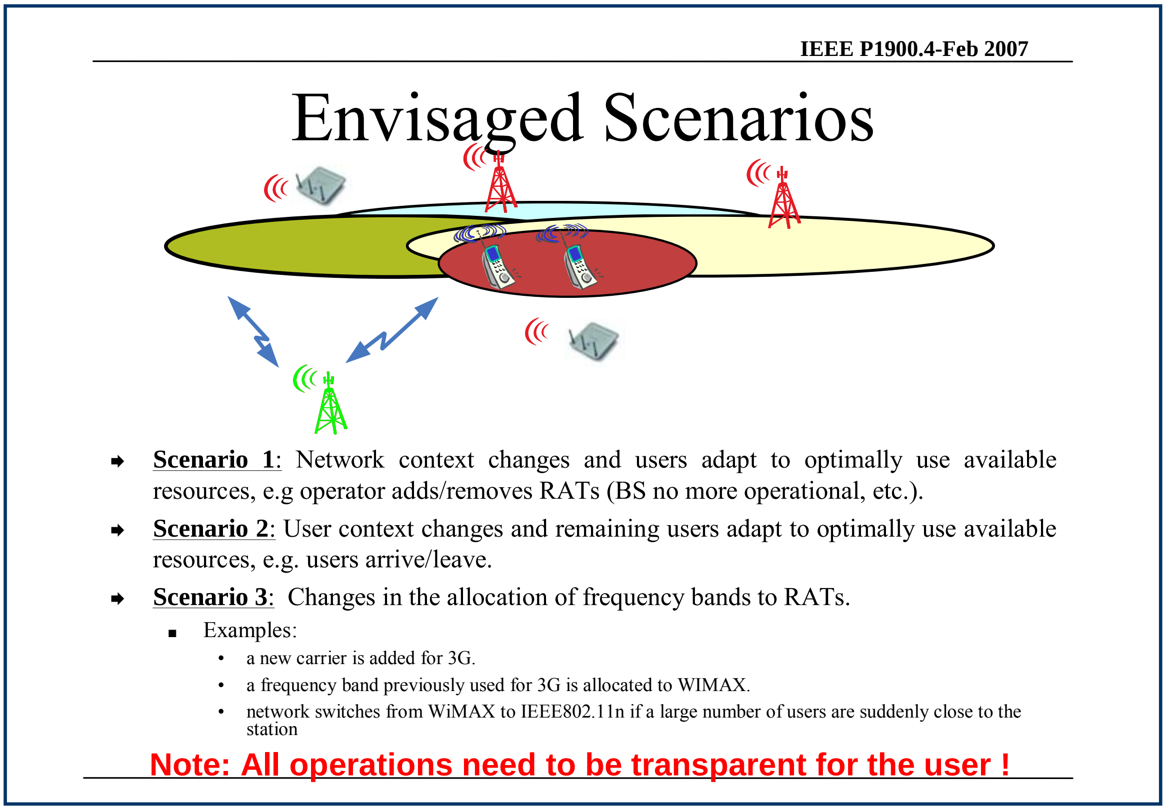

Figure 3-21 IEEE P1900.4 Envisioned Scenarios
(Source: IEEE P1900.4 Madrid Meeting Presentation, February 2007)

AP
802.11n

4 The Potential Cognitive Radio Market

Cognitive Radio (CR) is a technology that will be used in many markets including cellular, BWA, public safety, and military. In the emerging CR era, cellular phone, PDA, laptop, and other terminal purchases will be motivated by user applications such as mobile TV, wireless web access, location based services (LBS), games, and of course voice. We do not envision purchase of a radio product motivated by CR as the primary application or market driver. However, SDR-centric and CR-centric features are emerging as an essential technology to enable primary application market feasibility. We envision that CR technologies will be substantial product and application differentiators. Those that embrace SDR and CR should be positioned for superior market successes.

We view CR as an essential enabler of several key wireless market trends and requirements:

- The commercial market is evolving to converged (wire and wireless) networks that provide any service, any where, and time, and over any available media (fiber, wire, or wireless). Multi-radio is a key trend that offers on a single platform multiple air interfaces such as traditional cellular, HSPA, BWA/WiMAX, WLAN/WiFi, PAN/Bluetooth, GPS, and Mobile TV. Ease of use and access to the best available (cost and performance) air interface(s) will be critical to users. Optimization of resources will be very important to operators.
- The Public Safety market, as has been well documented since 9/11/2001, has a significant requirement to improve interoperability of their deployments. CR offersa number of opportunities for improved interoperability. Broadband capabilities are being planned for deployment which will require spectrum resource optimization and user terminal configuration. Disaster and emergency events may require ad hoc networking to provide coverage in the event of normal infrastructure unavailability.
- The military market in the JTRS program is evolving to a concept based on “tactical edge” consisting of Mobile Adhoc Networks (MANETs). These MANETs will have very fluid RF and networking adaptive requirements that provides the essence of CR motivations for easy of use, rapid configuration of fixed and mobile terminals for missions, and spectral efficiencies. An important goal is an open competitive environment that solves legacy intellectual property issues. Reuse to reduce costs is important.
- Regulators seem to recognize that technology such as SDR and CR provide best value when market forces, and not excessive regulation, are empowered with potential business incentives to motivate deployments.
- In all of the above, sufficient spectrum for emerging multimedia services is a big concern. MANETs, white space, and data bases are CR-centric solutions proposed to increase spectrum efficiency and capacity and create flexible spectrum access and network solutions. Ease of use is an essential requirement. CR is well positioned to achieve these goals.

Figure 4-1 provides plots of results of the economic benefits of CR from a recent Ofcom report[46] discussed in Section 3.5. The “investment cost of cognitive radio” axis is specified as percent of revenues in the 1st year of CR deployment. The “Minimum proportional capacity increase k” axis is the estimated capacity increase resulting from CR techniques for a cellular system operation near the limit of spectrum capacity. T in the figure is the assumed years of depreciation. Thus, if the investment cost of CR is .48 % of 1st year revenues, then the capacity increase required for breakeven for T=3, 5, or 7 can be estimated from the figure. The study estimates CR spectrum efficiency improvements ranging from ~ 3% to 10%, thus indicating a probable positive economic return on investment. The Ofcom report bases the analysis on the assumption of capacity shortage, but concludes on conservative voice-only (GSM) assumptions that the UK will not experience voice capacity shortage until the 2025-2030 timeframe. At that time CR could provide a 3% to 10% capacity improvement and a corresponding 3% to 10% revenue (or economic) benefit. We think the analysis is excellent, but the underlying assumptions are quite conservative. As will be discussed below, the telecommunication industry is in evolution to convergence, multimedia, and multi-radio era targeting access to any service, any media, any where, and any time era. Capacity is only one of many SDR and CR benefits. SDR and CR are essential to achieve capacity as well as expanded industry service and revenue goals.

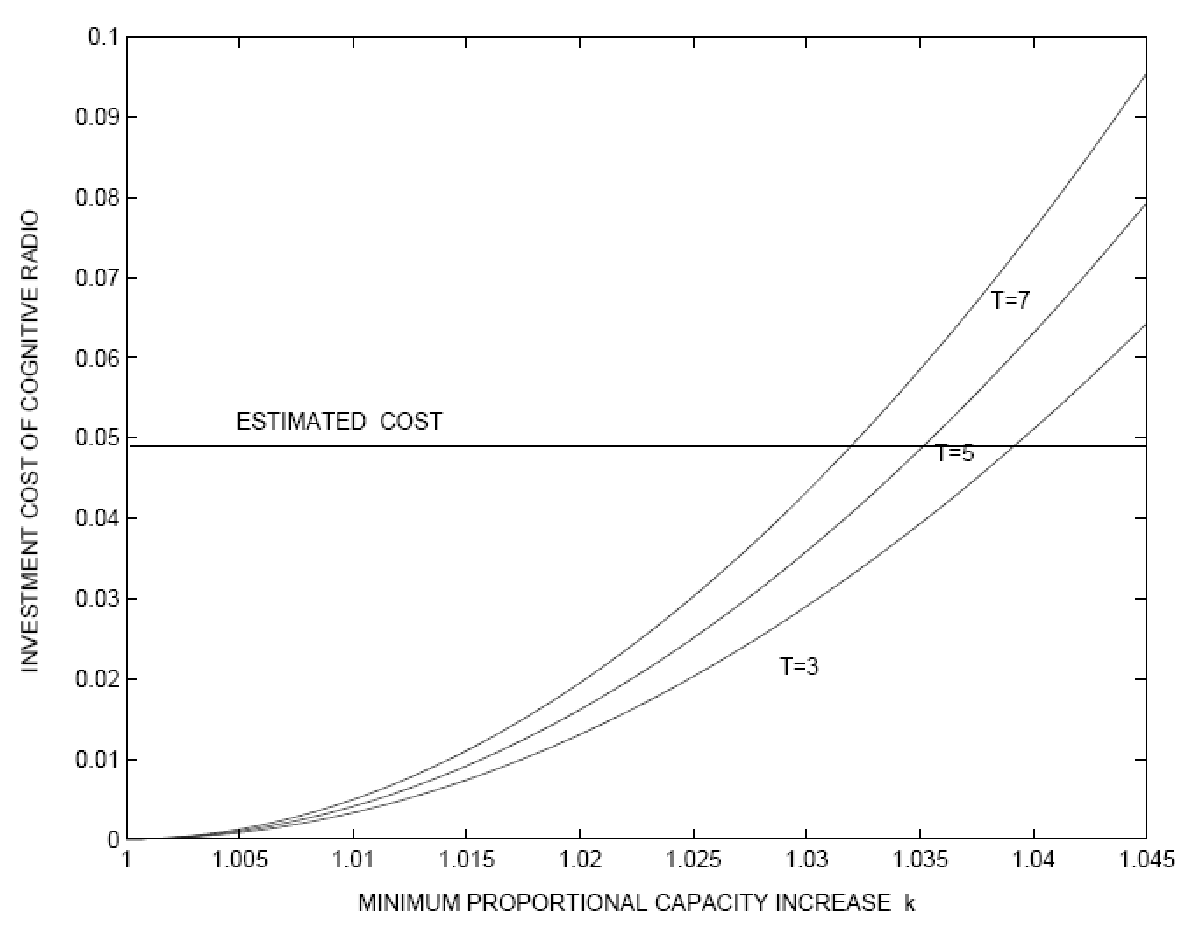

Figure 4-1 Cognitive Radio Economic Benefits
(Source: Paper and Presentation[46] at SDR Forum Expo)

The commercial cellular industry's 3G initiatives are targeting enhanced average revenue per unit (or user) (APRU) through the addition of non-voice services. Table 4-1 presents reported APRU and percentage of non-voice revenues for year-end 2006 for several international operators. The industry has been experiencing flat to declining voice ARPUs for several years.

This is attributed to the saturation of many markets and a highly competitive market requiring competitively lower monthly APRU rates to attract and retain subscribers.

Operator	Percentage non-voice Revenues	ARPU Monthly
Vodafone Germany	22.9%	$27.17
Vodafone Italy	18.7%	$33.54
Vodafone Spain	15.3%	$45.89
Vodafone UK	23.2%	$46.49
Japan DoCoMo	30.1%	$58.90
US Verizon	15.8%	$50.78
China Mobile	19.0%	$11.65

Table 4-1 Operator ARPU and % non-voice revenues
(Source: Company Financial Reports year-end 2006)

In previous reports[76,77] estimates and forecasts were provided for international cellular subscribers; service revenues for total, voice, and non-voice services; operator Capital Expenditures (CAPEX) including total CAPEX and CAPEX awarded to network equipment vendor for equipment and services; and terminal units and revenues. These estimates and forecasts have been updated with historical data through year-end 2006 and are presented in Table 4-2. The table also includes estimates of potential CR service enhancement revenues as graphically presented in Figure 4-2.

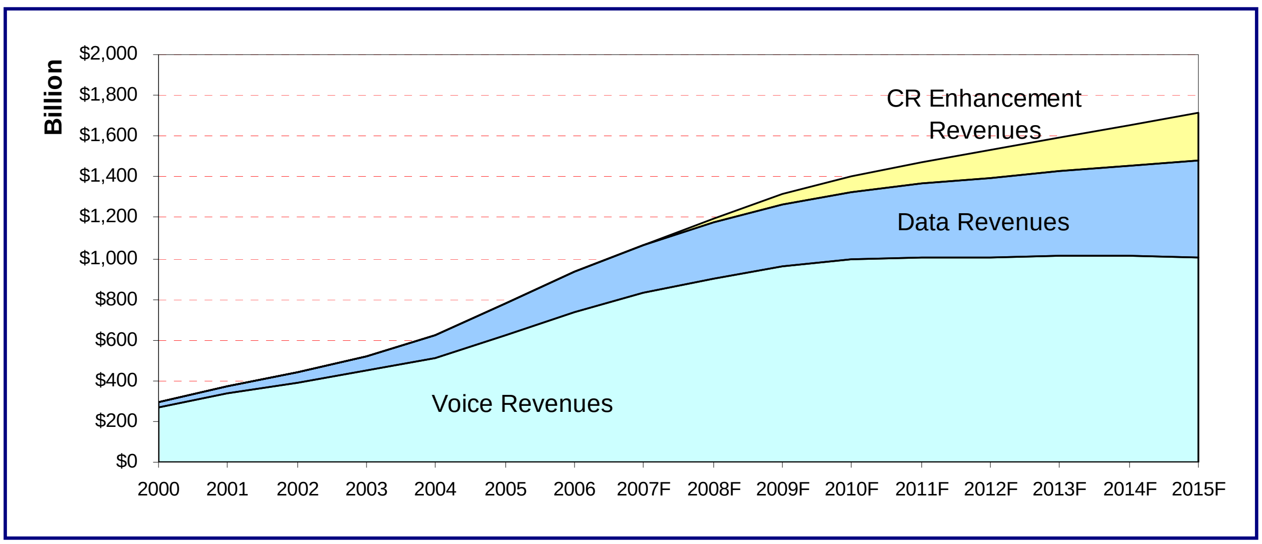

Figure 4-2 Voice, Date, and CR Enhancement ARPU Estimates
(Source: Adaptation and update of data from [76])

Unfortunately, other than the Ofcom report, no data or analyzes were identified quantifying how or how much CR might enhance revenue opportunities or reduce costs. CR is an emerging technology and only qualitative high level information has been identified to date. Thus it was

[76] SDR Market Study: Cellular: Terminals and Infrastructure, by Jim Gunn, Prepared for the SDR Forum, June 2005
[77] WiFi, WiMAX, and Beyond 3G / 4G, by Jim Gunn, Prepared for the SDR Forum, May 2007

assumed that a 2% increase of revenues is achieved staring in 2008 and increases 2% per year through 2015. Under these assumptions, CR economic cumulative enhancement benefits between 2008 and 2015 inclusively are:

CR Service Enhancement Revenues:	$1,013 B
CR Operator Enhancement CAPEX:	$152 B
CR Network Equipment CAPEX:	$76 B
CR Terminal Enhancement Revenues:	$97 B
Total CR Economic Benefit	$1,338 B

In estimating total operator CAPEX and network equipment CAPEX, the method outlined in a previous report[77] was utilized. It makes use of information in a Nokia paper that indicates various operator cost allocations as percentages of revenues and is presented in Figure 4-3. As the figure indicates, operators typically allocate approximately 15% of revenues for depreciation which is yearly allocation of previous years of CAPEX expenditures. As analyzed in previous cellular market studies,[78, 76] we have observed that the maturing cellular market yearly operator cash flow CAPEX budgets were trending toward the 15% depreciation allocations in income statements. Thus we have used 15% CAPEX in our forecasts. As also reported in those reports, network equipment vendor expenditures have been approximately 50% of total CAPEX expenditures.

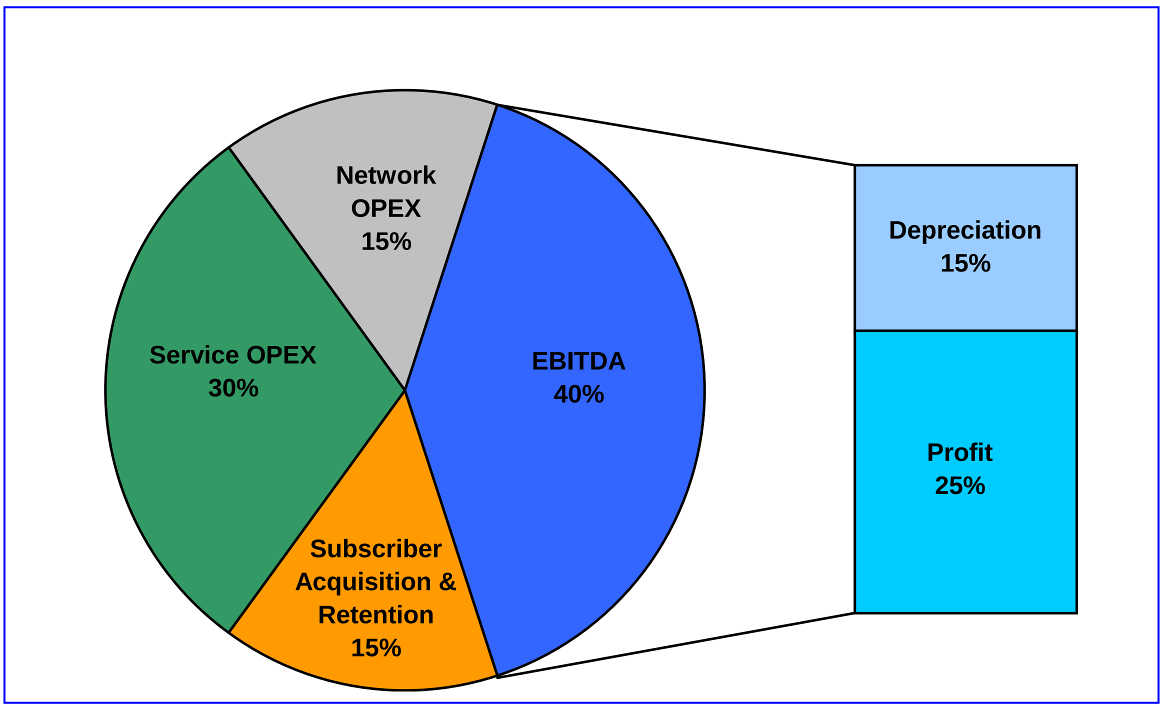

Figure 4-3 Typical Cellular Operator Expense Components
(Source: Recreated from Nokia, "The Prerequisites for Profitable Entry Business," April 2004, www.nokia.com)

78 Wireless Infrastructure Technology and Markets: The Challenge of 3G, by Jim Gunn, Published by Forward Concepts

We believe, based on our studies including the many inputs documented in this report that the above analysis is based on conservative assumptions. Some of the specifics for these conclusions include:

- It is widely reported that current 3G initiatives, while achieving impressive network equipment and terminal deployments, have been somewhat disappointing to date in helping operator's achieve non-voice revenue goals. As presented in Figure 4-2 and Table 4-2, estimated international percentage of non-voice revenues was approximately 21% at year end 2006. And much of this is from Short Message Service (SMS), that while very attractive and profitable, does not provide the pervasive revenue opportunity suite that operators desire. Pricing for many non-voice services has not yet declined to levels valued by mass market subscribers, constraining usage volume. Another reason is that QoS of wireless networks for internet access[79] still lags behind less costly wireline networks that are available to subscribers. CR offers significant potential to offer solutions to better enable these initiatives.
- In section 3.10, Bill Clift, CEO of Optimi, a company that offers network optimization services and software, stated that optimization in wireless networks is different for voice and data. He also stated that current tools are back office and thus are only utilized on infrequent intervals less than weekly or even monthly. Thus, emerging multimedia networks have significant requirements for CR-enabled real-time optimization to improve capacity and Quality of Service (QoS).
- Perhaps one of the reasons that pricing for non-voice services has so far remained high is that operators are concerned that high capacity data service, with lower ARPU market potential, will consume capacity needed for historically higher ARPU voice services. Thus, pricing is maintained at a higher level to restrain network loading. CR offers the potential provide a solution by off-loading wide area networks where feasible to WiFi, Bluetooth, WiMAX, **etc.** networks. As presented in Figure 3-3, international 3G industry leader Japan's NTT DoCoMo has been deploying indoor sites to enhance coverage and QoS. NTT indicates that these are being identified in customer surveys as important to customer satisfaction. Other complementary initiatives are macro cells, picocells, and femtocels[80] to provide coverage and QoS in focused areas. These also unload wide area networks (WANs). CR-centric features are considered essential to configure and create an easy-to-use subscriber experience.
- As discussed in Sections 3.5 and 3.7, full CR as first described by Dr. Joe Mitola provides cognition for anticipating and adapting to user needs and provides CR features at all levels of the OSI stack (see Figure 3-19). Ofcom states that full CR will probably not be available until 2025-30, although evolutionary CR features will be available in the interim.

The needs for CR are pervasive and thus there seems little doubt that SDR and CR are essential enabling technology for evolution to the goals of WiFi, WiMAX, and Beyond 3G as discussed in our previous report[6]. We can not envision the Converged, Triple or Quadruple play, Multimedia era targeting "Any Where" "Any Time", "Any media", and "Any Service" benefit to subscribers progressing without CR. It appears essential for capacity enhancement, ease-of-configuration, improved licensing, plus many other essential features.

[79] An opinion discussed in telecom with John Chapin of Vanu, Inc in late March 2007
[80] A Femtocel is a home base station, typically on cellular frequencies, and IP internet wireline backhaul

Subscribers by Technology - M	2000	2001	2002	2003	2004	2005	2006	2007F	2008F	2009F	2010F	2011F	2012F	2013F	2014F	2015F
Total	739.4	960.0	1154.8	1403.8	1709.3	2168.4	2656.5	3129.4	3554.9	3942.4	4267.7	4528.0	4777.1	5025.5	5281.8	5545.9
% Growth	50.20%	29.84%	20.30%	21.56%	21.75%	26.86%	22.51%	17.80%	13.60%	10.90%	8.25%	6.10%	5.50%	5.20%	5.10%	5.00%
World Population - M	6,073.3	6,149.1	6,224.2	6,299.3	6,375.0	6,451.4	6,528.1	6,605.0	6,682.5	6,760.2	6,838.2	6,916.7	6,995.4	7,074.0	7,152.3	7,230.0
Penetration (%)	12.17%	15.61%	18.55%	22.29%	26.81%	33.61%	40.69%	47.38%	53.20%	58.32%	62.41%	65.46%	68.29%	71.04%	73.85%	76.71%

International Revenues	2000	2001	2002	2003	2004	2005	2006	2007F	2008F	2009F	2010F	2011F	2012F	2013F	2014F	2015F
ARPU per month - $	$ 33.00	$ 32.34	$ 31.69	$ 31.06	$ 30.44	$ 29.83	$ 29.23	$ 28.36	$ 27.51	$ 26.68	$ 25.88	$ 25.10	$ 24.35	$ 23.62	$ 22.91	$ 22.22
ARPU per year - $	$396.00	$388.08	$380.32	$372.71	$365.26	$357.95	$350.79	$340.27	$330.06	$320.16	$310.56	$301.24	$292.20	$283.44	$274.93	$266.68
Industry Service Revenue $B	$292.8	$372.5	$439.2	$523.2	$624.3	$776.2	$931.9	$1,064.8	$1,173.4	$1,262.2	$1,325.4	$1,364.0	$1,395.9	$1,424.4	$1,452.1	$1,479.0
Voice Revenues - $B	$269.4	$337.2	$390.9	$448.9	$515.1	$622.5	$735.3	$827.4	$896.4	$961.8	$992.7	$1,002.5	$1,006.4	$1,009.9	$1,009.2	$1,007.2
Data Revenues - $B	$23.4	$35.4	$48.3	$74.3	$109.3	$153.7	$196.6	$237.5	$276.9	$300.4	$332.7	$361.5	$389.4	$414.5	$442.9	$471.8
% Non-Voice Revenues	8.0%	9.5%	11.0%	14.2%	17.5%	19.8%	21.1%	22.3%	23.6%	23.8%	25.1%	26.5%	27.9%	29.1%	30.5%	31.9%
CR Enhancement Revenues - $B									$23.5	$50.5	$79.5	$109.1	$139.6	$170.9	$203.3	$236.6
% CR Enhancement Revenues									2%	4%	6%	8%	10%	12%	14%	16%

International CAPEX	2000	2001	2002	2003	2004	2005	2006	2007F	2008F	2009F	2010F	2011F	2012F	2013F	2014F	2015F
Capex - $M	$99	$87	$76	$82	$94	$116	$140	$160	$176	$189	$199	$205	$209	$214	$218	$222
Network Equipment CAPEX - $B	$55	$53	$46	$44	$52	$58	$70	$80	$88	$95	$99	$102	$105	$107	$109	$111
Incremental CR Capex - $B									$4	$8	$12	$16	$21	$26	$30	$35
Incremental CR Network Equip. Capex - $B									$2	$4	$6	$8	$10	$13	$15	$18

International Terminal Units & Revenues	2000	2001	2002	2003	2004	2005	2006	2007F	2008F	2009F	2010F	2011F	2012F	2013F	2014F	2015F
Total Cellular Terminal Units - M	409.5	399.0	410.5	520.5	640.3	795.2	978.2	1,203.3	1,471.7	1,767.5	2,083.8	2,393.3	2,694.8	2,977.8	3,275.6	3,603.1
Terminal ASP (Aver. Sell Price)	$205	$195	$178	$155	$137	$131	$125	$115	$110	$106	$102	$98	$96	$95	$94	$94
Terminal Revenues - $B	$83.9	$77.8	$73.1	$80.7	$87.7	$104.2	$122.3	$138.4	$161.9	$186.5	$211.5	$119.5	$121.1	$122.3	$123.4	$124.1
Incremental CR Enhancement Revenues - $B									$3.24	$7.46	$12.69	$9.56	$12.11	$14.68	$17.28	$19.86

Table 4-2 Commercial Wireless: Subscribers, Service Revenues, CAPEX, and Terminal Revenues
(Source: Report [76] , Updated by Company Reports and Author Research)

In the cellular market, voice has, and continues, to be the killer application as Figure 4-2 illustrates. Perhaps there will be no killer data or other non-voice applications. Possibly the long term opportunity is a flexible suite of more tailored applications that collectively provide significant non-voice service revenues for operators. In this scenario, CR and SDR technologies appear essential. We comment on the most frequently identified non-voice services that are candidates to create potential CR opportunities.

A promising non-voice service initiative is MobileTV. The key standards and initiatives are Digital Video Broadcast – Handheld (DVB-H and –Terrestrial DVB-T) that is the dominant international standard, Integrated Services Digital Broadcasting (ISDB-T) that is expected in Japan, Terrestrial Digital Multimedia Broadcast (T-DMB) a less extensive international standard, and MediaFLO a technology that is championed by Qualcomm in the US. A key consideration is to multicast or broadcast and what frequency band is used for broadcast. MediaFLO is on a dedicated band in the US.

Location-based services (LBS) are services that may be offered by operators that can send custom advertising, provide concierge services and other information subscribers based their location. Location is typically determined by GPS although triangulation and other methods are possible. A closely related service is Telematics that typically offer emergency, navigation, and diagnostic services in automobiles. Perhaps the best example of this is OnStar offered by General Motors on an increasing number of their vehicle models. GM offers free OnStar services for one year on equipped models. Similar services have recently been offered by Lexus.

Telematics, while attracting much attention, has yet to achieve the success anticipated. We believe that LBS and telematics will eventually achieve critical mass and become pervasively more successful. It is not clear that they will come to be considered a killer app. Business models need refinement and time to successfully mature. CR is anticipated to be a significant enabler for LBS and telematics. Given that next generation automobiles may have as many as 17 radios, it seems likely that CR and SDR will play a significant role in this market.

Concierge Services provide personal services to individuals, typically those traveling. Historically, organizations providing these services have been hotels. The services usually involve support in obtaining tickets to events or local transportation, restaurant information and booking, local shopping possibilities, errands, plus more. CR with access to the cellular network and LBS services could provide very effective anticipation and service of the needs of travelers. We contacted the IT department of IHG, Inc (e.g. Intercontinental Hotel, Holiday Inn and others) about concierge services. They indicated that often concierge services are offered on the hotel internet web services as well as by assigned lobby personnel. They indicated that concierge services are cost centers and not revenue centers. Thus, it is not clear, based on this input, how much subscribers will pay much for such services. Advertising, outsourced wireless hotel concierge services, as well as direct consumer concierge services are possible sources of revenues.

Wireless Internet Service (WIS) is another attractive non-voice service. Many international wireless operators have been launching WIS. These have been most pervasive on emerging 3G networks based on CDMA-2000-1x-EV-DO and WCDMA. These services typically require the purchase of a computer plug-in card and separate service commitment. To date, pricing for these services have been sufficiently high to restrict penetration to only the more affluent or must-have mobile users such as real estate agents and business travelers. Mass market uptake to date has been limited to date.

Another emerging service is financial services, whereby subscribers can make purc

Unlike cellular, the public safety and military markets have not traditionally generated service revenues. Obviously, there are significant and comparable markets for systems, network equipment, terminals, and related services. A recent trend has been for state-wide shared public safety systems, in some cases operated by private operators, leasing back services to public entities. However, these do not yet appear sufficiently pervasive to influence and guide market estimates. We can not currently identify that CR will necessarily increase the available market in terms of units. We provide discussion in sections 3.2 and 3.3 of the drivers for these segments and believe that CR will be an essential enabler and differentiator for many of the emerging goals and initiatives that are ongoing. For Public Safety the key goals are interoperability, evolution to broadband features, and an ad hoc network configuration for unavailable infrastructure during disasters.

The SDR Forum's Public Safety SIG[81] has significant ongoing CR initiatives that are addressing many requirements for the sector. In our Public Safety Report[82], we found that a key issue in the US market is funding and slowness in development of needed standards. In this report an estimate of the total replacement value of deployed US Infrastructure and terminals was provided. However, we found that much current equipment is antiquated due to lack of funding and current market run rates appear to be more a function of available funding than actual needs and market requirements. We anticipate that over time CR will be essential and widely deployed in Public Safety equipment and terminal, but will be an essential technology feature and not necessary drive more demand. Demand run rates could be influenced by CR providing features that create confidence in benefits, and perhaps lower pricing, to aid in achieving authorization of public funding for deployments. US Homeland Security activities are targeting potential funding for these deployments.

For the military the goals are interoperability, reuse, and MANETS. The DARPA XG program was discussed in Section 3.3 and in SDR Forum EXPO presentations by Preston Marshall in November 2006. It targets significant CR technologies and appears to be a technology leader for CR as well as SDR. However, like the public safety market, these initiatives are financed by public funds and do not have service revenues (at least on access tactical links). Thus CR technologies do not appear to increase demand for systems, equipment and terminals. The demand (other than R&D) appears driven by funding, the US and world war situation, and related requirements. However, CR technologies appear essential to achieve requirements (e.g. JTRS and related initiatives) and will be important differentiators.

[81] http://www.sdrforum.org/pages/committeesAndGroups/marketsCommittee.asp
[82] SDR Market Study: The US Public Safety Market, Prepared for The SDR Forum, by Jim Gunn Consultancy, May 2007

5 Acronyms

2G	2^{nd} Generation
2.5G	2.5 Generation
3G	3^{rd} Generation
4G	4^{th} Generation
AACR	Aware, Adaptive Cognitive Radio
AHA	American Hospital Association
AI	Artificial Intelligence
AM	Amplitude Modulation
AMF-SA	Airborne, Maritime and Fixed Site Small Airborne
AP	Access Point
API	Application Program Interface
ARPU	Average Revenue per Unit (or user)
ASHE	American Society for Healthcare Engineering
ATC	Air Traffic Control
AWS	Advanced Wireless Service Spectrum
BPL	Broadband over Powerline
BS	Base Station
BWA	Broadband Wireless Access
CAP UMTS	CAMEL Application Part UMTS
CAPEX	Capital Expense
CFR	Code of Federal Regulations (US)
CMRS	Commercial Mobile Radio Service (US)
COMSOC	IEEE Communications Society
CR	Cognitive Radio
CRA	Cognitive Radio Architecture
DAB	Digital Audio Broadcasting (Eureka 147)
DFC	Dynamic Frequency Control
DTV	Digital Television
DVB	Digital Video Broadcasting
DVB-H	Digital Video Broadcast – Handheld – T Terrestrial
DWTS	Digital Wideband Transmission System
E2R	End-to-End Reconfigurability
EHF	Extremely High Frequency
EMC	IEEE Electromagnetic Compatibility Society
EMS	Emergency Medical Service
EPLRS	Enhanced Position Location Reporting System
ETSI	European Telecommunication Standards Institute
FCC	Federal Communication Commission (US)
FM	Frequency Modulation
FOMA	Freedom of Mobile Multimedia Access (Japan DoCoMo)
GHz	Giga (10^9) Hertz
GIG	Global Information Grid
GMR	Ground Mobile Radio

GPS	Global Positioning System
GSM	Global System for Mobile Communication
GSMA	GSM Association
HF	High Frequency
HSPA	High Speed Packet Access
IF	Intermediate Frequency
IMS	IP Multimedia System
INFOSEC	Information Security
IP	Integrated Project (E2R)
IP	Intellectual Property
IP	Internet Protocol
ISDB-T	Integrated Services Digital Broadcasting – Terrestrial
ITU	International Telecommunication Union
JAN-TE	Joint Airborne Networking–Tactical Edge
JPEO	Joint Program Executive Office (JTRS)
JTIC	Joint Interoperability Center
JTRS	Joint Tactical Radio System
kHz	kilo (10^3) Hertz
LAN	Local Area Network
LBS	Location Based Service
LF	Low Frequency
LMR	Land Mobile Radio
LTE	Long Term Evolution
MAN	Metro Area Network
MANETs	Mobile Adhoc Networks
MESA	Mobility for Emergency and Safety Applications
MHAL	Modem Hardware Abstraction Layer
MHZ	Mega (10^6) Hertz
MIDS-J	Multifunctional Information Distribution System for JTRS
MUOS	Mobile User Objective System
Net Adds	Net Additions (Subscribers)
NPRM	Notice of Proposed Rule Making
NTIA	National Telecommunications and Information Administration
OET	Office of Engineering and Technology (FCC)
Ofcom	Office of Communication (UK)
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operating Expenses
PAN	Personal Area Network
PAR	Project Authorization Request (IEEE)
PHY	Physical Layer (OSI Layer 1)
PLMRS	Private Land Mobile Radio Service
PSK	Phase Shift Key
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
R&O	Report and Order (FCC)
RAT	Radio Access Technology

RF	Radio Frequency
RKRL	Radio Knowledge Representative Language
RXML	Radio eXtensible Markup Language
SCA	Software Communication Architecture
SDR	Software Defined Radio
SFF	Small Form Factor
SHF	Super High Frequency
SIG	Special Interest Group
SINCGARS	Single Channel Ground and Airborne Radio System
SMS	Short Message System
SNR	Signal to Noise Ratio
SP	Sensory Perception
SRW	Soldier Radio Waveform
SWR	Software Radio
TCB	Telecommunication Certification Body
TDMA	Time Division Multiple Access
T-DMB	Terrestrial Digital Multimedia Broadcast
TETRA	Terrestrial Trunked Radio
TIA	Telecommunication Industry Association
TPC	Transmit Power Control
UHF	Ultra High Frequency
UMA	Unlicensed Mobile Access
UMB	Unified Business Model (E2R)
UMTS	Universal Mobile Telecommunication System
UWB	Ultra Wideband
VHF	Very High Frequency
VLF	Very Low Frequency
WAN	Wide Area Network
WCDMA	Wideband Code Division Multiple Access
WG	Working Group
WiFi	WLAN brand (Wireless Fidelity)
WiMAX	Worldwide Interoperability for Microwave Access
WIS	Wireless Internet Service
WLAN	Wireless Local Area Network
WMTS	Wireless Medical Telemetry Service
WNAN	Wireless Network After Next (DARPA)
WNW	Wideband Networking Waveform
XG	neXt Generation
XML	eXtensible Markup Language