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Introducing Adaptive, Aware, and Cognitive Radios

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Spectrum is the lifeblood of RF Communications[1]

In the late 1990s, nearly all telecommunications radios were built using digital signal processor (DSP) processors to implement modulation and signal processing functions, and a General Purpose Processor (GPP) to implement operator interface, network signaling, and system overhead functions. This architecture is attractive to a manufacturer because the same basic electronics can be used over and over for each new radio design, thereby reducing engineering development, enabling volume purchasing, and optimizing production of a common platform, while retaining the flexibility for sophisticated waveforms and protocols. A few manufacturers called their radios "Software Defined Radios" (SDRs), recognizing the power and market attractiveness of the customer community being able to add additional functionality that is highly tuned to market specific applications.

In the early 2000s, a few of these vendors made application layer software functionality available for additional value added functions to aid the user. Users could add music, games, or other applications, as long as the radio waveform functions remained untampered.

Similarly, in the late 2000s, many radios will make the software functionality available for various classes of adaptivity and significantly extend user support functionality. This will initiate the generation of "Cognitive Radios". Thus, with minimal additional hardware, additional software features will enable users, network operators, spectrum owners, and regulators to accomplish much more than with the fixed application radios of an earlier generation.

To understand this important design trend, we must first understand the background, history, and terminology.

[1] Quote originally from Cognitive Radio Technologies, Chapter 5 by Preston Marshall, B.A. Fette, editor, Newnes, 2006.

H. Arslan (Ed.), Cognitive Radio, Software Defined Radio, and Adaptive Wireless Systems, 1–16.

1.1 In the Beginning

The field of radio architecture has recently undergone a revolution of design, significantly enabled by Moore's law of computational evolution, where sufficient computational resources are available in DSPs and GPPs to implement the modulation and demodulation and all of the signaling protocols of a radio as a software function. This threshold was crossed in 1992 when the Department of Defense issued a contract called Speakeasy I and subsequently Speakeasy II to demonstrate that SDR was feasible. It was demonstrated by General Dynamics C4 Systems' Speakeasy II equipment in 1997, and gradually morphed from Speakeasy to Programmable Modular Communication System (PMCS), to Digital Modular Radio (DMR), to Joint Tactical Radio System (JTRS).

The SDR Forum industry group[2] was formed to guide the industry at large in standards to make the industry practical. Joe Mitola of Mitre Corporation and Wayne Bonser of Air Force Research Labs were the visionaries who started this organization and brought the industry together to work these hard design problems, and to begin establishing the new standards it would require. During this time, Joe Mitola was performing his Ph.D. research at the KTH Royal Institute of Technology, University of Stockholm,[3] and began his study of what would be possible once radios were software defined radios (SDRs). He recognized that it is feasible for a radio to become aware of its user, aware of its network (choices and features), and aware of its spectral environment. In fact, it could then be adaptive, and ultimately could have the software to learn various adaptations to its current environment that are desirable support to the user, network, operators, spectrum owners, and regulators. Dr. Mitola introduced the terms "aware", "adaptive", and "ideal Cognitive Radio" (iCR) to reflect the different levels of cognitive capability.

Paul Kolodzy of the Federal Communications Commission (FCC), and Preston Marshall of the Defense Advanced Research Programs Agency (DARPA) developed multiple programs to demonstrate the possibilities and the significance of these capabilities. One very significant demonstration is a demonstration of dynamic spectral access (which subsequently spawned an IEEE conference called DYSPAN) and Interference Avoidance (IA). The International Telecommunications Union (ITU), the IEEE P1900 study group, and the European Union End to End Reconfigurability Project (E2R) have subsequently launched several significant studies into the technical and economic issues of cognitive capability.

[2] SDR Forum was first called Modular Multifunctional Information Transfer System Forum (MMITS Forum) to reflect that these systems are capable of being far more than just a radio, and was initiated by Wayne Bonser of AFRL.

[3] Joseph Mitola III, *Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio* (Stockholm: KTH, The Royal Institute of Technology) June 2000.

1.1.1 Support for the User

Ultimately, it is the user of the radio who must see incremental value in using his radio. In fact, there is a yearly upward spiral of utility in the industry. Each year new functions are recognized as "must-have killer applications" that nearly all customers will want. Unique musical ring tones were extremely popular, just so everyone could recognize their own phone from all the other cell phones. Camera phones, to send your smile to Grandma, came next. Then Bluetooth wireless and hands-free connections to the earphone became popular. Every year, these new user support features extend market demand and fuel growth.

Cognitive Radio envisions that the radio will have sufficient ability to recognize common user activities so that it begins to learn to assist the user and the network with common tasks. Mitola likens this to Radar O'Reilly,[4] who recognizes what tasks the Colonel must perform and is always ready to support those functions. A radio with sufficient flexibility can recognize that the selection of wireless access methods is a function of location and time, and can remember locations where cellular service, WiFi service, WiMAX service, Bluetooth, and other services are available and useful.

Awareness may also be able to help the user locate services when he travels in a new country (i.e., please help me find the: restroom, baggage, car rental, train, taxi, next flight to ..., restaurant, tickets to the opera, etc.). Concierge services are easy for a radio to provide, if the radio has location awareness. More sophisticated services are readily provided by database servers, each of which has a narrow but sufficient depth to be truly helpful to its subscribers (Mitola provides the example of airline reservation services). Language translation is another example of such as a service.

1.1.2 Support for the Network

Radios, just like computer networks, generally have a full protocol stack running from the physical layer to the application. The ISO standard defines seven layers for protocol. Other stack models combine some of these layers resulting in a four layer model. Of these layers, only the physical and MAC layers are intimately designed and specific to radio/wireless protocols. Higher layers frequently follow protocols that have been developed for the wired world including Internet Protocols (IP), or telephony protocols (SS7, for example). Many years of optimization have gone into these wired network layer protocols; re-optimizing them for wireless networks is a current research topic. Cognitive radios operate on the principle that by measuring the performance metrics of each layer, those layers and other layers can be optimized. However, the physical layer and MAC layer are very specific to radio/wireless applications, and

[4] Radar O'Reilly from the TV series Mash 1973–1982.

optimization of these layers as a real time activity based on measurements of local spectrum is the dominant part of Cognitive Radio research and design at this time.

Radio systems are often supported by a vast but unseen network. For example, "the array of towers synonymous with the cellular wireless telephony network will each be associated with base stations, which must be linked to a core network infrastructure containing the billing system and through which connectivity to the terrestrial wireline telephone network is made".[5] Even taxi and police radio functions usually include transmitter and receiver sites, interconnect, dispatch operators, terrestrial telephony connections, and a rich support network. On the university campus, it is common to have a network of WiFi access points and a wired network to aggregate traffic to the internet service point, to the university computer and database servers.

The network layer of the smart radio can be an important contributor to the stability and robustness of the network. The radio can select an access point which has less traffic, or where the traffic load presented consumes less total resource, at least in instances where there is more than one access point available. Similarly, the radio can shape its traffic load so that no user experiences unacceptable network performance variations.

The radio can also select the most appropriate network for the service requests of the user. For example, the radio can select a Bluetooth network access for a local printer, rather than using the WiFi access point, while using the WiFi access point for internet database searches. Similarly, voice or video traffic can be provided through the most appropriately resourced network.

1.1.3 Support for the Network Operator

Some network operators have recognized the benefit of convergence of wireless services delivered through multiple access networks. Thus, cellular, WiFi, WiMAX, Bluetooth, broadcast digital audio, and video are bundled so that the service provider selects which resource is most efficiently able to accommodate a user's current needs, and that the transition across different network access is both seamless and economical for the user and for the network operator. This topic is likely to become the differentiating feature of successful network operators over the next decade.

1.1.4 Support for the Regulatory Organization(s)

GSM cellular radio access has been harmonized across much of the globe. However, many other radio technologies have not. Each of the nearly 200 different countries has different regulatory rules and procedures for designing radios, defining spectral mask of each radio application waveform, manufacturing radios, and acquiring rights to use various parts of spectrum. Vendors

[5] Personal communication, Stephen Hope, 1/19/07.

who sell the radios would like to be able to manufacture a common design, and must have the ability to adapt the design as required for each country, where they have the right to utilize the design.

Cognitive radios include a policy engine. The policy engine's role is to be aware of the utilization rules for all countries where the equipment is licensed, and to assure that the radio only operates in those allowed modes in those geographic regions. The policy engine can also include additional rules that define network usage policy, network operator policy, and even manufacturer policy. For example, if software download is allowed into one of the processors in the radio, the policy may state the provisions and requirements to enable the downloaded software. Such a policy may be country specific, allowed by the regulators, and the software may need to be exhaustively validated by the manufacturer as compliant to regulations and non-deleterious under all network conditions, ranging from innocuous to abnormal.

We assume that the policy and downloaded software will follow security guidelines, assuring that the software cannot be modified by unauthorized sources, and that it is validated and un-tampered as required by all parties. Generally this involves exhaustive testing and validation, use of standardized protocols and software sources, cryptographic sealing, signatures, and certification authorities, as described in SDR Forum Security literature.

1.1.5 Support for the Spectrum Owner & Users

The physical and MAC layers of wireless are now undergoing significant research on real time optimization given the ability to measure the spectral environment. Through such measurements, it is possible to minimize interference while supporting very significant increases in traffic density. Measurements suggest that cognitive radio systems should be able to increase traffic density at ratios between 7:1 and over 20:1 (spectrum efficiency is often measured in number of spectrum users supported by measuring bits per second per square kilometer per MegaHertz of spectrum used). In addition to supporting significant increase in users, use of spectrum awareness and adaptation techniques can also indicate interference properties, multipath properties, signal strength, and in turn, these real time measurements can guide adaptation of the transmission waveforms to be more robust, providing the user improved quality of service in multiple dimensions.

Many organizations are now involved in the issue of dynamic spectrum allocation, which is unquestionably the field where cognitive radio is receiving the greatest attention. Dynamic spectrum allocation is attracting the same degree of attention that Internet Protocols and optimization received ten years ago. Activities range from analysis, to testbeds, to languages for specifying regulatory policy, and many new activities are now being funded by research organizations around the world.

All of this now converges in the commercial electronics world, as the next generation of Personal Digital Assistants (PDAs) assimilate cellular connectivity, WiFi, WiMax, Zigbee, and Bluetooth wireless network access and wireless protocols. Users will expect these devices to efficiently select amongst these networks to accomplish the user's most important objective of the moment, and to do it cost effectively. Cellular connectivity may swap with WiFi or WiMax connectivity as the user moves about his activities. Since the availability, range, throughput, and economics are vastly different models, users will come to expect the system to make cost effective and performance sensitive decisions. Eventually users will expect these decisions to be automatic.

1.2 Economics of Cognitive Radio

Many things are technically possible, but what justifies the time and effort to advance various degrees of cognitive functionality into the radio network, either in subscriber equipment or in the network infrastructure is the economics. In this section, we will scratch the surface of cognitive applications and the revenue stream.

Since adaptive spectrum has gained so much attention we will study it first.

1.2.1 Value of Spectrum

Without spectrum, no wireless telecommunications or wireless internet services would be possible. The telecommunications industry is now a 1 Trillion (10^{12}) dollar per year industry,[6] and the wireless part is growing very rapidly, while the wired telecommunication services are experiencing a relatively flat business. As of 2006, the wired and wireless businesses were approximately equal in revenue. Spectrum is required to support these wireless businesses. In the United States, the continuing increase in cellular telephony demand is supported by increasing density of cellular infrastructure.

However, in some regions of the globe, the cellular infrastructure is at peak capacity and increased infrastructure density is impractical. In these early warning hot spots, other means to support continued growth of demand is necessary to continue serving the market demand. Technologies that enable continued growth include adaptivity, smart antenna technology, and more efficient use of existing spectrum. More efficient use of spectrum in these high demand hot spots translates immediately into continuing to support the growing revenue stream for the network operators.

There are also regions which are under-served by the wired community, and the wireless community. In mainly rural regions, where fiber or cable

[6] Research and Markets, "2004 Telecommunications Market Review and Forcast – Trends, Analyses and Projections to 2007"; http://www.researchandmarkets.com/reportinfo.asp?report_id=226592.

is uneconomical to install, and where there is nearly no spectrum use (for example, in many rural areas, a single broadcast TV source may be nearly 200 miles away and there is little or no local TV service) there are significant opportunities to provide internet and telecommunication services using this under-utilized spectrum.

In each of these cases there are ways in which to utilize cognitive radio principles to make additional spectrum available. These methods are being thoroughly analyzed, and business cases are being examined.

1.2.2 Spectrum Adaptivity

Current research in selection of waveforms or protocols that provide higher throughput, and reduce interference to adjacent channels has focused on the exploitation of Orthogonal Frequency Division Multiplex (OFDM) types of waveforms. In these waveforms, high data rates are achieved through use of multiple carriers. Furthermore, the order of modulation may be adaptive so that the number of bits delivered on each carrier is adapted to the noise floor and the propagation performance at each carrier frequency. OFDM is already in use for Digital Audio Broadcast (DAB) and High Definition TV (HDTV) and is a research topic rich with additional opportunity.

1.2.3 Smart Antennas

One way to get enhanced spectral density and user density is with smart antennas. Smart antennas can provide narrow beam patterns for either transmitter or for receiver or both. In the Industrial Scientific and Medical (ISM) band frequencies of 2.4 GHz, practical narrow beam antennas can provide 9 dB of gain, and reduce interference to other communication activity off the sidelobes of the antenna beam patterns. Even more significantly, smart antennas can also be used for interference nulling, and can provide up to 30 dB of null depth. Either of these strategies significantly increases the feasible user density. Smart antenna techniques may be economically costly for certain applications, and may be impractical for certain form factors, but much research attention must be focused on this topic, as it provides the greatest opportunities for increased user density.

1.2.4 MIMO

Multi-Input Multi-Output (MIMO) is a communication technique in which the multipath properties of the channel are utilized to support greater data throughput. In a MIMO system, the transmitter transmits multiple channels of data traffic through multiple antennas; the receiver learns the channel behavior between the transmitter's multiple antennas and the receiver's multiple antennas, and uses signal processing to compute what waveform was transmitted by each transmitting antenna, and the corresponding data stream.

In this way, the same frequency is reused in the same geographic region to deliver greater amounts of data traffic than could be expected from a single transmitting and receiving antenna (SISO) system. Some MIMO systems also have the ability to learn to suppress interference from unrelated transmitters, further enhancing network performance. These MIMO techniques are practical when sufficient space for mounting antennas on the radio or platform are available.

1.2.5 Spectrum Subleasing, Sharing

In dense urban applications, there is opportunity to sublease spectrum from spectrum owners whose loading is temporarily light. Such owners can define access rules, and economics of such transactions, as well as rules to take back spectrum should demand or emergency arise. SDR Forum, IEEE, and others are working to establish standardized protocols to enable such transactions. For lightly loaded system, spectrum owners may be able to recover up to 60% of the cost of spectrum ownership in this fashion. In the public safety market, there have been discussions that some organizations might pay for new public safety infrastructure in exchange for shared spectrum access on a guaranteed non-interfering basis. This clearly shows just how valuable the spectrum is.

In rural applications, there has been discussion of using the relatively unused rural UHF TV broadcast bands for adhoc/mesh networks to deliver internet and other data services. Protocols to assure non-interference are currently under evaluation. However, concern from TV broadcasters that such techniques will eventually cause interference to broadcast TV, at the rural–suburban boundaries where such wireless networks will fail to recognize presence of the TV signal, or where local area networks may deliver spotty performance. Given that much of rural areas are served by S Band satellite TV, it is not clear what long range outcome of this debate will be.

Policy Assurance of Behavior to the Economic Stakeholders

Several significant studies have been performed on the economics of dynamically adaptive spectrum.[7] However, this work has also generated a great deal of concern, on the part of regulators, network operators, and spectrum owners. It is therefore important to understand the basic architecture of a cognitive radio. As shown in Fig. 1.1, a cognitive radio must include a variety of sensors, many of which support the user, a learning capability (possibly accomplished remotely), and a set of rules based on a policy engine which allow and disallow actions. It is the job of the policy engine, to define inviolable rules and behaviors of each stakeholder. Each stakeholder's rules will be expressed as

[7] "Software Radio: Implications for Wireless Services, Industry Structure, and Public Policy," W. Lehr, S. Gillett, F. Merino, *Communications and Strategies*, IDATE, Issue 49 (1st Quarter 2003) 15–42.

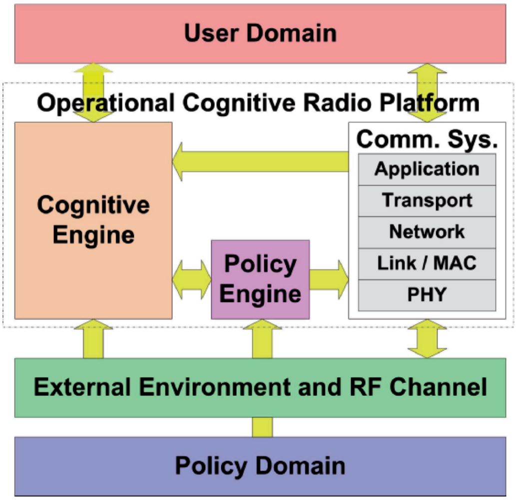

Fig. 1.1. Architecture of a cognitive radio. Figure 1.1 includes a cognitive function to analyze existing spectrum users, and measure properties of its own communication channels, and a set of rules expressed through a policy engine which define what the radio is allowed to do, and what it is not allowed to do.[8]

policies: policies for the regulator, for the spectrum owner, for the network operator, for the manufacturer, and for the user.

While policy engine languages are now a subject of R&D development throughout the industry, and in SDR Forum in particular, notionally, each policy engine must perform an analysis of actions proposed by the radio's cognitive engine, and must determine that the proposed action is allowed by at least one rule, and that the action is not disallowed by any rules. All actions which are allowed by the policy engine may then be compared and contrasted for spectrum efficiency, interference, quality of service and battery drain considerations, and the best choices applied. For example, if the cognitive engine were to propose that idle spectrum is available for a telephone call at 107.9 MHz, using a CDMA waveform, and a Universal Mobile Telecommunications System (UMTS) protocol, transmitting to close a link over 5 km, in Alamogordo, New Mexico, at 0.5 W, the policy engine will examine whether the user is entitled to perform that function at that frequency with that waveform, at that location and that power level. There must be one rule that allows it, and no rules that disallow it before the radio can implement the proposed adaptation. In this example, we assume that a regulatory policy would disallow use of an FM broadcast frequency within the continental U.S. for telecommunications applications, but it might be allowable in countries where there is no FM band broadcast activity. Thus the policy engines will disallow all

[8] Cognitive Radio Technologies, Chapter 7, Rondeau & Bostian, edited by B. Fette, Newnes 2006.

behaviors not in keeping with all stakeholders. Similarly, the network operator, spectrum owner, and user may all have various policy expressions, and each must approve before the radio would execute the mode.

A policy engine is an efficient encoding of these rules, but most importantly, an efficient method for managing radio functionality across the entire globe. If the location of the radio changes, then the radio can look up the rules for its new location. If the rules in a certain country change in order to allow a new capability, then an update of the policy database can allow the radio to perform new capabilities. Therefore, a cognitive radio will not learn or perform unacceptable behaviors, because those behaviors will be disallowed by the policy engine.

A very important consideration is that changes of policy must be prevalidated to assure reliable and stable performance under both reasonable and unreasonable conditions and must be administered by those trusted to distribute policies. Thus, the stakeholders must place their trust in the policy engines to enforce the rules of behavior, etiquette, and protocol to assure their participation in the revenue stream.

Value of Spectrum to the Stakeholders

"Spectrum is the lifeblood of communication systems."[9] Without spectrum, there is no electromagnetic communications. Many significant papers have addressed the value of spectrum. Each country has defined different mechanisms to assess and manage spectrum, radio production and use of spectrum, and the associated revenue. Some countries have recognized spectrum as publicly owned, and a value to be shared by all. In such a regulatory environment, spectrum should be used for the greatest public value. As such the primary issue is to prioritize current needs and grant access to spectrum best matched to most valued public need (higher frequencies to shorter range applications, etc.).

In the United States, and in many other countries, spectrum access is a source of federal government revenue. However, costs of spectrum auction are passed on to users as an increase in cost of services with incremental overheads of all participants in the value chain. In the United States it is assumed that the free market forces will assure that spectrum access, as a result of spectrum auction, will result in greatest cost effectiveness use of valuable spectrum.

Since July 1994, the FCC has conducted 33 spectrum auctions raising over $40 billion.[10] European auctions conducted in 2000 raised nearly $100 billion. Clearly the value of a spectrum license depends on many dimensions, including:

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[9] Quote originally from Cognitive Radio Technologies, Chapter 5 by Preston Marshall, B.A. Fette, editor, Newnes, 2006.

[10] Peter Crampton, "Spectrum Auctions", *Handbook of Telecommunications Economics*, Elsevier Science, Chapter 14, 2002.

1. amount of bandwidth in MHz (directly related to the ability to service as many subscribers as possible, number of subscribers within the service region;
2. demand within the service region;
3. duration of the contract;
4. opportunity for growth of services within the service region and:
5. cost of installing and providing service. As a calibration, auctions of 2×10 MHz (paired spectrum) +5 MHz (unpaired Spectrum) range from $2.60 per subscriber per year to $107.20 per subscriber per year.

Network operators provide a rough guideline of cost of spectrum access versus cost of subscriber equipment. In the United States, one network operator reported that the subscriber pays approximately twice as much per year for the subscriber equipment as he pays for the spectrum. In Europe, one operator indicated that the subscriber pays approximately twice as much for the spectrum, as he pays for the subscriber equipment. While such numbers are not published, we can consider spectrum access to range between 50% and 200% of the cost of subscriber equipment as a guideline.

In Fig. 1.2, Forward Concepts presents the 2006 handset revenue by waveform/protocol type. It is clear that the global telecommunications market uses more than 11 protocols, and that the total subscriber hardware market is $130B ($1.3 \times 10^{11}$). So we can project that spectrum access ranges between $65B and $260B in yearly cost to subscribers. So very clearly, the subscriber and the network operator have much to gain in lowering spectrum access costs. We can also conclude that one radio design capable of supporting 11 protocols, knowing which country to use them in, and how to register for access would support global requirements.

This shows a clear and significant value of spectrum to enable valuable applications. It also reflects a cost to the user, which will be paid with interest over the lifetime of the license, and a future revenue stream opportunity to the operator that acquires the spectrum.

Spectrum owners consist of many communities, each with different interests such as AM, FM, and TV broadcast operators, Federal State and Local public services (police, fire, FAA, FBI, etc.), Telecommunications network operators (cellular phone providers), the Department of Defense (Army, Navy Air Force, Marines, Coast Guard, others), and dispatch service providers (taxi, UPS, FED X, etc.). There are also spectrum users which are authorized by a license passed through the manufacturer to private citizens to use or as a public commons (Citizens band, Family Radio Service, WiFi, UWB, etc.). Existing spectrum owners are understandably reluctant to give up spectrum regardless of whether it is used or unused for public good, while advocates of cognitive radio argue that unused spectrum can be put to productive use without impacting primary existing users.

Much has been published about the distribution of spectral activity. However, there is a very clear trend. Between 1% and 15% of the spectrum is busy,

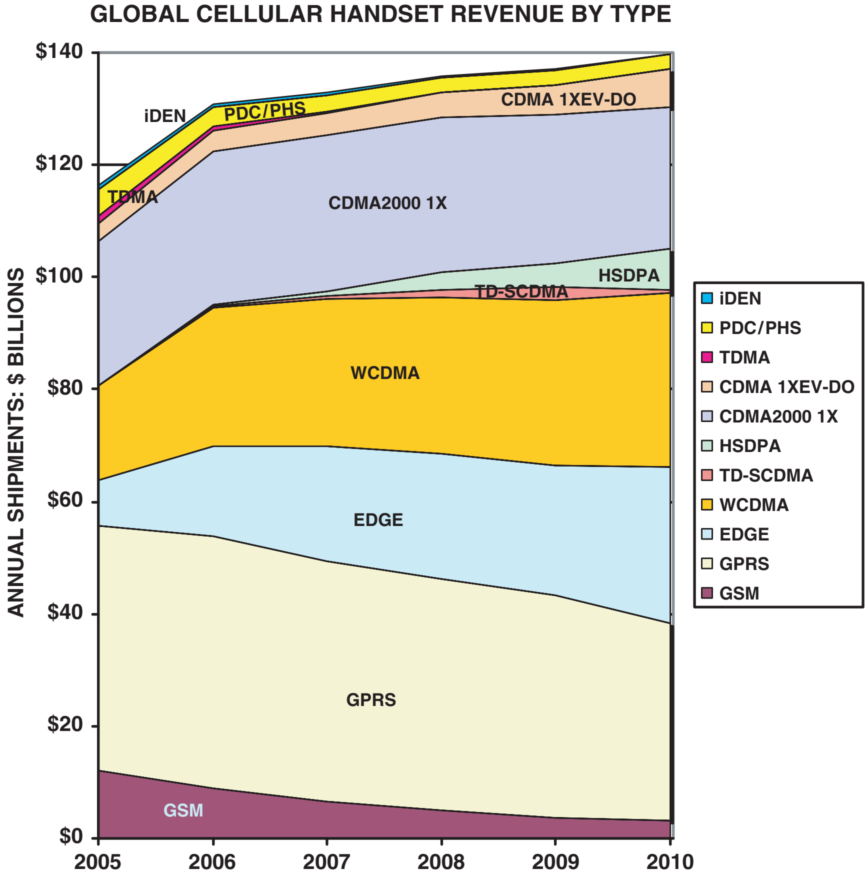

Fig. 1.2. Cellular handset market analysis, Forward Concepts DSP Market Analysis, 2006.

depending on what location the measurement is made in, what frequency the measurement is made at, and over how much time, frequency and geographic space the averaging is performed.[11] The implication is that while spectrum owners have paid dearly to own these time–frequency–space spectrum blocks, it is not put to 100% utilization. Nor would we necessarily want it to be fully utilized. In order to accommodate peak needs, and instant access, we must retain reserve capacity somehow. How much reserve capacity should be retained to accommodate peaking? This is a function of localized statistics, reserve access protocol, access latency, and urgency.

[11] Survey performed by Mark McHenry of Spectrum Signal Processing, as part of the Darpa XG program, and also funded by SDR Forum to survey spectrum use at the Republican National Convention September 2004.

1.2.6 Local Statistics

The Bell Telephone Company did extensive studies of call capacity and blocking probability on circuit switched telephony in the 1940s and 1950s, defining a unit of call bandwidth as an Erlang. In this work, the probability of dropped, lost, or blocked call decreases as the ratio of capacity to average demand increases. Their goal was to keep call blocking probability under 1% across each management region. In this case, the only resort beyond use of the full capacity of all existing trunk lines was to install more trunk lines – an unacceptably long access latency for unexpected peak capacity requirements. In these systems, normal daily peak utilization is about 30% of peak capacity (Mother's Day peak utilization usually exceeds capacity).

In today's modern age, cellular telephony operates with a somewhat higher ratio of average daily peak utilization to peak capacity. However, cellular systems have interesting local statistics. Airports have very high capacity requirements, and experience huge peaks as a consequence of delayed flights. Sports stadiums have extremes of peak to average traffic ratio, with the end of game resulting in very high peaks in traffic. Finally, traffic jams are also a source of high peak to average call ratios.

1.2.7 Peaking Support

Capacity to support a demand peak can be provided in many different ways. In the context of cellular telephony, additional demand can be supported by other nearby base stations until all channel capacity of all nearby base stations has also been consumed. In the context of laptop computers performing internet data access, additional demand is supported by reducing the available throughput support to all subscribers. In the case of FM broadcast, new capacity is being added as FM broadcasters add DAB subcarriers thereby offering new audio and data services. Where do police, fire, and other emergency departments get additional capacity? Within urban jurisdictions, they plan additional capacity for likely peak events such as emergencies. However, if the scope of an emergency exceeds the planned peak capacity, there is generally not any method to access additional spectrum. This occurred in both New York City and Washington D.C. on September 11, 2001. In remote regions, peaking capacity for emergencies (such as in rural Montana, rural Arizona, and rural Texas) is often supplied by cellular telephony if available, or by satellite transponder. It usually takes a few days to lease, deliver, and install the satellite transponder base station equipment.

1.2.8 Spectrum Leasing

Spectrum leasing is a way to support demand peaking, such that the ratio of the average utilization to peak capacity can be higher. In this scenario, multiple services either sublease from a spectrum owner for a time-frequency-spatial block, or owners cross license their current unused capacity to each other giving each the opportunity to support demand peak, or to prioritize access to spectrum depending on greatest public need.

At least one serious business proposal has been made to set up a spectrum leasing business. However, as of this time, no cellular subscriber equipment has the flexibility of frequency, waveform and protocol to accommodate varying spectral assignment, nor have industry accepted protocols been adopted to perform these transactions.

1.2.9 Spectrum Awareness Databases

Many radios can capture their local view of spectrum activity, position, and time. That information can be directly shared. It can also be aggregated into a regional database, that provides for awareness of local emitters, local policies, and knowledge of areas where signal dropouts are likely, resulting in radio performance predictions. One such data structure, developed by Zhao and Le is called a Radio Environment Map (REM). Such a database can be a significant aid to cognitive radios both in time to locate and allocate unused spectrum to a specific purpose, and time to acquire the policies of network access for local services.

1.2.10 Value of Concierge Services

Densely populated and popular urban areas lend themselves to concierge services. Tourists and business travellers can create significant demand because they are unfamiliar with local services. This is why major hotels have concierge desks to provide assistance with local arrangements. Concierge desks are often required to function around the clock. However, visitors may be unwilling or unable to use the local concierge service because of language barriers or unavailability of the identified need.

One company has been successfully selling concierge services as an internet service, and reports $77M/year revenues.[12] Another reports combining concierge services with telematics, location, and vehicle tracking as a successful business.[13] A third company reports the global concierge Ecommerce business as $12B/year with a 30% compound annual growth rate, and have established a monthly fee structure to test the market.[14] Frost and Sullivan has a market report focused specifically on telematics (concierge services focused specifically on luxury car owners). Their report, in short, indicates that of 250M cars on the road in the US, 30M are telematics capable, and 10M actually use the service. That service is reported as a $1.3B/year market.

[12] MetroOne Telecommunications.
[13] Skynet Telecom.
[14] Agillion http://www.businessweek.com/ebiz/0011/ec1107.htm.

With attention to convergence of voice and data services, this could easily grow from 30% market acceptance to a far larger market.

From this we conclude that making the radio sufficiently location and position aware to be able to assist in concierge services for the radio user has a significant international value to the users, and to the value added service providers, and is a cognitive radio market immediately serviceable with existing technology.

1.2.11 Cognition

Learning is a significant part of cognitive radio research. Rondeau and Bostian have studied the use of Genetic Algorithm (GA) to learn how a radio might best respond to a spectral environment given a set of objective metrics. They have developed prototypes that show that a radio can successfully learn proper adaptions to a spectral environment that optimize for the objective metrics. Neel and Reed have studied how to apply game theory to a radio as a member of a cognitive network. With game theory they were able to analyze protocols to determine whether cognitive radio behavior could result in stable network behavior, and they conclude that it can. Mitola, Kokar, and Kovarik have independently studied knowledge representation (Ontology) that a cognitive radio would need to perform reasoning functions. Mitola proposes that a radio should be able to reason about the owner's voice and visual characteristics, should be able to take verbal commands, should be able to visually recognize locations and conditions. Kovarik describes the difficulty of building a sufficiently large information database that a radio would be usefully intelligent to be able to reason over any but the narrowest range of topics. Mitola concludes that narrow fields of human activity can be captured with sufficient depth of knowledge representation to be useful. Thus niche markets will develop by creating a deep representation of requirements for specific services. Where these can be brought forward as an economically successful business, we will see new products and services offered even before general cognition is practical in a radio.

Radios that have learned or adapted to local spectrum, channel, waveform, or protocol conditions can share their learning with other radios that have not yet learned these local optimizations. This learning can be infused to other radios via a network database which provides local optimization, or it can be shared directly from radio to radio. Since network operators correctly worry that the network behavior be stable, and predictable, and within FCC guidelines, it is most appropriate that learned behaviors be shared from a database, where they can be checked, and validated as producing a net benefit to the network before being used. It seems that the Radio Environment Map is an example of a method for providing such services.

Thus we conclude that cognition can be local to the radio, or can be served as a download of knowledge structures (or software) from other radios which have performed the learning and now make it available. Market studies have not yet characterized the value of cognitive radio learning technology. However, if learning to use spectrum wisely is an example, it will be very valuable.

1.3 Summary

In summary, we conclude that Cognitive Radio technology is a way in which one radio or even a network of radios are able to learn a useful degree of adaptivity, that aids the user, the network, and/or the spectrum owner. There are powerful economic incentives to provide new capabilities, through existing telecommunications infrastructure, and cognitive radios will provide those capabilities. As new services are offered, more spectrum will be needed and cognitive radios will provide the means for radios to communicate with greater spectrum efficiency.