بسم الله الرحمن الرحيم

Cognitive Radio Technologies

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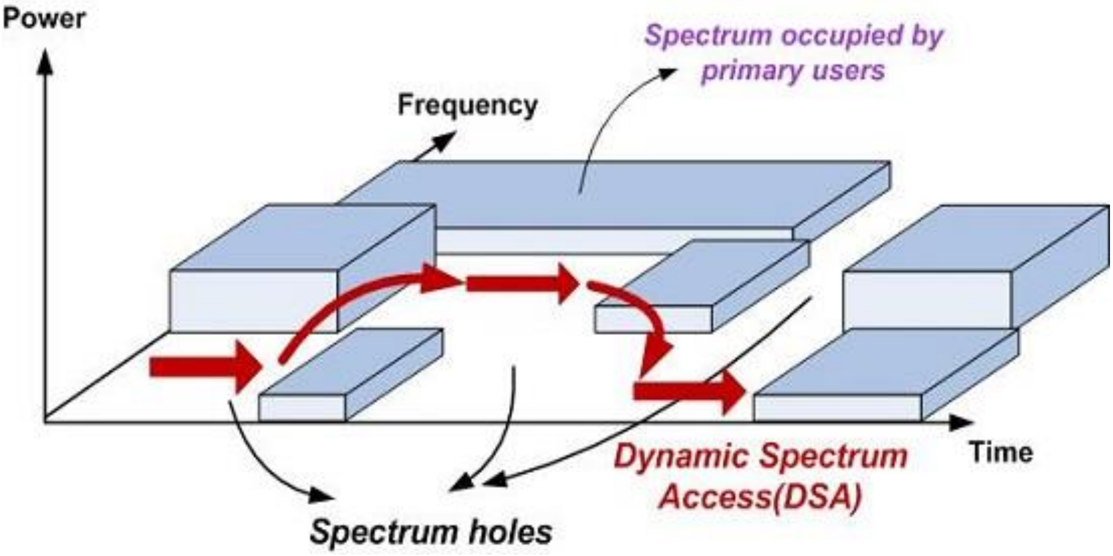
CHAPTER 1

Introduction

Chapter 1: Introduction

The radio spectrum is divided into licensed and unlicensed frequencies. The licensed spectrum is for the exclusive use of designated users. For instance, it includes the UHF/VHF TV frequency bands.
The unlicensed spectrum can be freely accessed by any user, following certain rules (e.g., not exceeding a defined limit for transmission power). It includes, for instance, the ISM (Industrial, Scientific and Medical) and U-NII (Unlicensed National Information Infrastructure) frequency bands. ISM is shared by technologies such as IEEE 802.11 for wireless local area networks (WLANs), Bluetooth .

The key enabling technology of dynamic spectrum access is cognitive radio (CR) has emerged as one of the keys that can help addressing the inefficient usage of the radio spectrum. It exploits unused licensed radio frequencies, often designated as spectrum holes see (Figure 1). or white spaces. CR aims to enable secondary users to autonomously access spectrum holes in the entire spectrum to increase performance, as long as they do not harmfully interfere with primary users. Basically, at a given time and location.



(Figure 1) spectrum holes

In order to share the spectrum with licensed users without disturbing them, and meet the diverse quality of service requirement of applications, each CR user in a CRN must:
* Determine the portion of spectrum that is available, which is known as Spectrum sensing.
* Select the best available channel, which is called Spectrum decision.
* Coordinate access to this channel with other users, which is known as

Spectrum sharing.
* Vacate the channel when a licensed user is detected, which is referred as Spectrum mobility.
See figure (1) Cognitive Cycle .

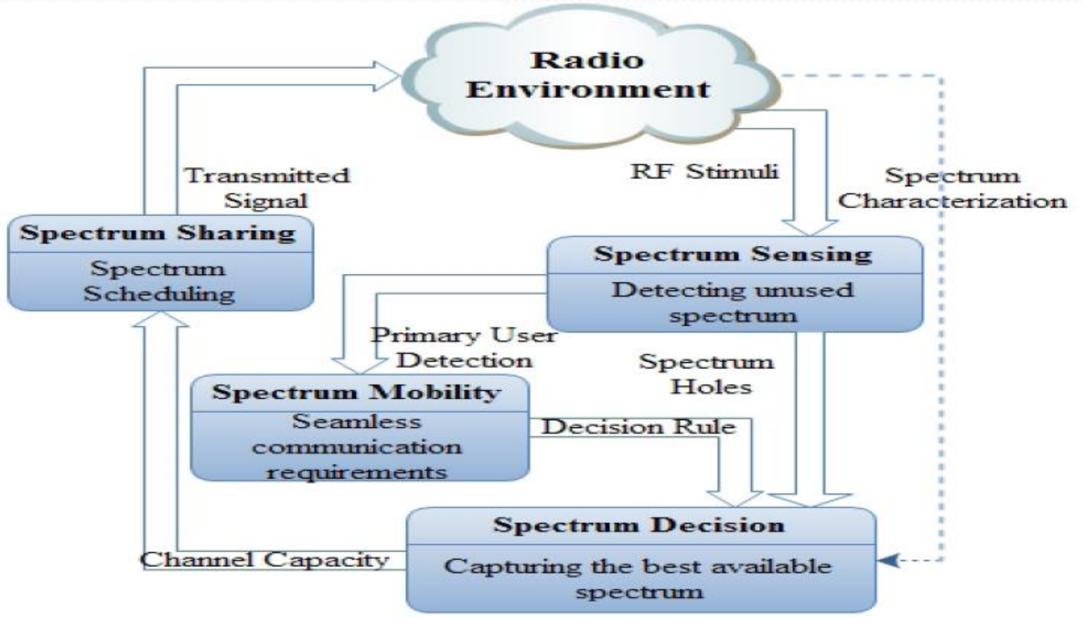


figure (1) Cognitive Cycle

CHAPTER 2

History of Cognitive Radio

Chapter 2: History of Cognitive Radio Technology

2.1 The Vision of Cognitive Radio

Just imagine if your cellular telephone, personal digital assistant (PDA), laptop, automobile, and TV were as smart as “Radar” O’Reilly from the popular TV series M*A*S*H.1 They would know your daily routine as well as you do. They would have things ready for you as soon as you ask, almost in anticipation of your need. They would help you find people, things, and opportunities; translate languages; and complete tasks on time. Similarly, if a radio were smart, it could learn services available in locally accessible wireless computer networks, and could interact with those networks in their preferred protocols, so you would have no confusion in finding the right wireless network for a video download or a printout. Additionally, it could use the frequencies and choose waveforms that minimize and avoid interference with existing radio communication systems. It might be like having a friend in everything that’s important to your daily life, or like you were a movie director with hundreds of specialists running around to help you with each task, or like you were an executive with hundred assistants to find documents, summarize them into reports, and then synopsize the reports into an integrated picture. A cognitive radio is the convergence of the many pagers, PDAs, cell phones, and many other single-purpose gadgets we use today. They will come together over the next decade to surprise us with services previously available to only a small select group of people, all made easier by wireless connectivity and the Internet.

2.1 Background Leading to Cognitive Radio

The sophistication possible in a software-defined radio (SDR) has now reached the level where each radio can conceivably perform beneficial tasks that help the user, help the network, and help minimize spectral congestion. Radios are already demonstrating one or more of these capabilities in limited ways. A simple example is the adaptive digital European cordless telephone (DECT) wireless phone, which finds and uses a frequency within its allowed plan with the least noise and interference on that channel and time slot. Of these capabilities, conservation of spectrum is already a national priority in international regulatory planning. This book leads the reader through the technologies and regulatory considerations to support three major applications that raise an SDR’s capabilities and make it a cognitive radio: 1. Spectrum management and optimizations. 2. Interface with a wide variety of networks and optimization of network resources. 3. Interface with a human and providing electromagnetic resources to aid the human in his or her activities.

These technologies represent a wide swath of contributions upon which cognitive technologies may be considered as an application on top of a basic SDR platform. To truly recognize how many technologies have come together to drive cognitive radio techniques, we begin with a few of the major contributions that have led up to today’s cognitive radio developments.

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[1]“Radar” O’Reilly is a character in the popular TV series M*A*S*H, which ran from 1972 to 1983. He always knew what the colonel needed before the colonel knew he needed i

The development of digital signal processing (DSP) techniques arose due to the efforts of such leaders as Alan Oppenheim [1], Lawrence Rabiner [2, 3], Ronald Schaefer [3], Ben Gold, Thomas Parks [4], James McClellen [4], James Flanagan [5], fred harris [6], and James Kaiser. These pioneers2 recognized the potential for digital filtering and DSP, and prepared the seminal textbooks, innovative papers, and breakthrough signal processing techniques to teach an entire industry how to convert analog signal processes to digital processes. They guided the industry in implementing new processes that were entirely impractical in analog signal processing. Somewhat independently, Cleve Moler, Jack Little, John Markel, Augustine Gray, and others began to develop software tools that would eventually converge with the DSP industry to enable efficient representation of the DSP techniques, and would provide rapid and efficient modeling of these complex algorithms [7, 8]. Meanwhile, the semiconductor industry, continuing to follow Moore's law [9], evolved to the point where the computational performance required to implement digital signal processes used in radio modulation and demodulation were not only practical, but resulted in improved radio communication performance, reliability, flexibility, and increased value to the customer. This meant that analog functions implemented with large discrete components were replaced with digital functions implemented in silicon, and consequently were more producible, less expensive, more reliable, smaller, and of lower power [10]. During this same period, researchers all over the globe explored various techniques to achieve machine learning and related methods for improved machine behavior. Among these were analog threshold logic, which lead to fuzzy logic and neural networks, a field founded by Frank Rosenblatt [11]. Similarly, languages to express knowledge and to understand knowledge databases evolved from list processing (LISP) and Smalltalk and from massive databases with associated probability statistics. Under funding from the Defense Advanced Research Projects Agency (DARPA), many researchers worked diligently on understanding natural language and understanding spoken speech. Among the most successful speech-understanding systems were those developed by Janet and Jim Baker (who subsequently founded Dragon Systems) [12], and Kai Fu Lee et al. [13]. Both of these systems were developed under the mentoring of Raj Reddy at Carnegie Mellon. Today, we see Internet search engines reflecting the advanced state of artificial intelligence (AI). In networking, DARPA and industrial developers at Xerox, BBN Technologies, IBM, ATT, and Cisco each developed computer-networking techniques, which evolved into the standard Ethernet and Internet we all benefit from today. The Internet Engineering Task Force (IETF), and many wireless-networking researchers continue to evolve networking technologies with a specific focus on making radio networking as ubiquitous as our wired Internet. These researchers are exploring wireless networks that range from access directly via a radio access point to more advanced techniques in which intermediate radio nodes serve as repeaters to forward data packets toward their eventual destination in an ad hoc network topology.

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[2]This list of contributors is only a partial representative listing of the pioneers with whom the author is personally familiar, and not an exhaustive one

All of these threads come together as we arrive today at the cognitive radio era (see Figure 1.1). Cognitive radios are nearly always applications that sit on top of an SDR, which in turn is implemented largely from digital signal processors and general-purpose processors (GPPs) built in silicon. In many cases, the spectral efficiency and other intelligent support to the user arises by sophisticated networking of many radios to achieve the end behavior, which provides added capability and other benefits to the user.

2.1 A Brief History of SDR

An SDR is a radio in which the properties of carrier frequency, signal bandwidth, modulation, and network access are defined by software. Today's modern SDR also implements any necessary cryptography; forward error correction (FEC) coding; and source coding of voice, video, or data in software as well. As shown in the timeline of Figure 1.2, the roots of SDR design go back to 1987, when Air Force Rome Labs (AFRL) funded the development of a programmable modem as an evolutionary step beyond the architecture of the integrated communications, navigation, and identification architecture (ICNIA). ICNIA was a federated design of multiple radios, that is, a collection of several single-purpose radios in one box.

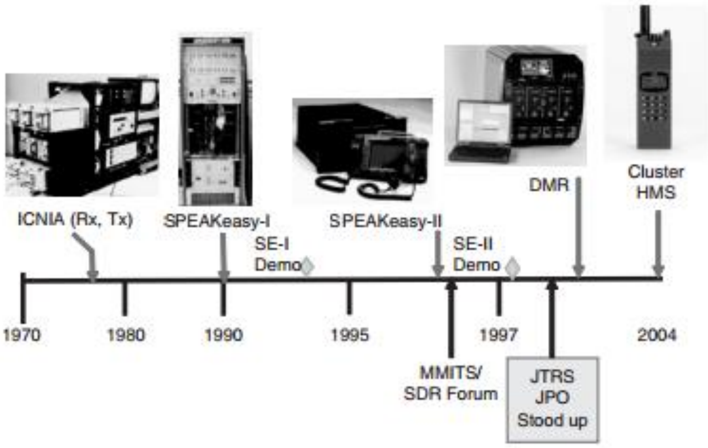

Figure 1.2: SDR timeline. Images of ICNIA, SPEAKeasy I (SE-I), SPEAKeasy II (SE-II), and Digital Modular Ratio (DMR) on their contract award timelines and corresponding demonstrations. These radios are the early evolutionary steps that lead to today's SDR.

Today's SDR, in contrast, is a general-purpose device in which the same radio tuner and processors are used to implement many waveforms at many frequencies. The advantage of this approach is that the equipment is more versatile and costeffective. Additionally, it can be upgraded with new software for new waveforms and new applications after sale, delivery, and installation. Following the programmable modem, AFRL and DARPA joined forces to fund the SPEAKeasy I and SPEAKeasy II programs. SPEAKeasy I was a six-foot-tall rack of equipment (not easily portable), but it did demonstrate that a completely software-programmable radio could be built, and included a software-programmable cryptography chip called Cypress, with software cryptography developed by Motorola (subsequently purchased by General Dynamics). SPEAKeasy II was a complete radio packaged in a practical radio size (the size of a stack of two pizza boxes), and was the first SDR to include programmable voice coder (vocoder), and sufficient analog and DSP resources to handle many different kinds of waveforms. It was subsequently tested in field conditions at Ft. Irwin, California, where its ability to handle many waveforms underlined its extreme usefulness, and its construction from standardized commercial off-the-shelf (COTS) components was a very important asset in defense equipment. SPEAKeasy II subsequently evolved into the US Navy's digital modular radio (DMR), becoming a four-channel full duplex SDR, with many waveforms and many modes, able to be remotely controlled over an Ethernet interface using Simple Network Management Protocol (SNMP). These SPEAKeasy II and DMR products evolved not only to define these radio waveform features in software, but also to develop an appropriate software architecture to enable porting the software to an arbitrary hardware platform, and thus to achieve hardware independence of the waveform software specification. This critical step allows the hardware to separately evolve its architecture independently from the software, and thus frees the hardware to continue to evolve and improve after delivery of the initial product. The basic hardware architecture of a modern SDR (Figure 1.3) provides suffi- cient resources to define the carrier frequency, bandwidth, modulation, any necessary cryptography, and source coding in software. The hardware resources may include mixtures of GPPs, DSPs, field-programmable gate arrays (FPGAs), and other computational resources, sufficient to include a wide range of modulation types.

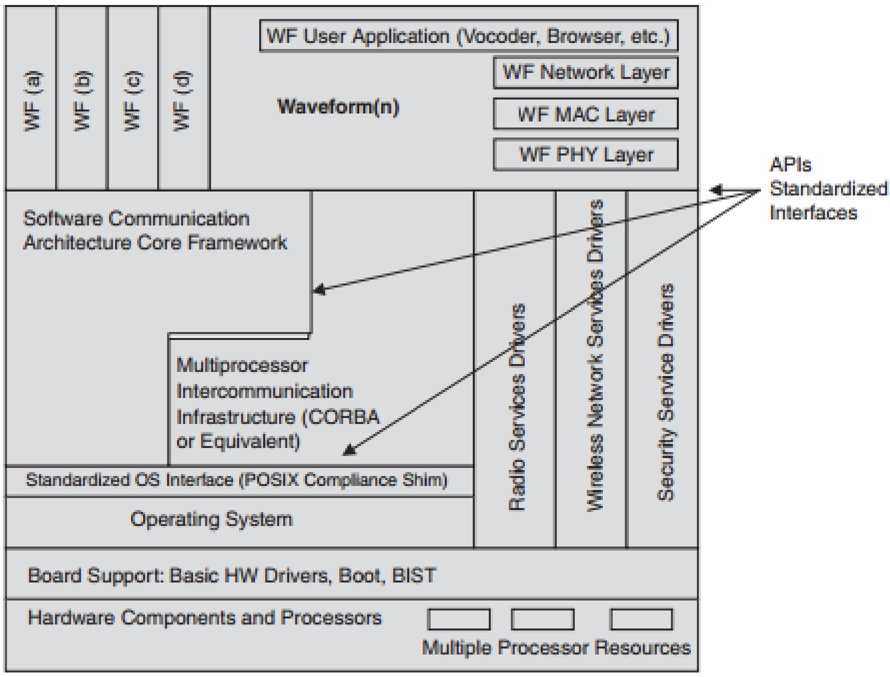

Figure 1.3: Basic software architecture of a modern SDR.[3] Standardized APIs are defined for the major interfaces to assure software portability across many very different hardware platform implementations. The software has the ability to allocate computational resources to specific waveforms. It is normal for an SDR to support many waveforms in order to interface to many networks, and thus to have a library of waveforms and protocols.

[3] BIST: built-in self-test; CORBA: Common Object Request Broker Architecture; HW: hardware; MAC: medium access control; OS: operating system; PHY: physical (layer); POSIX: Portable Operating System Interface; WF: waveform.

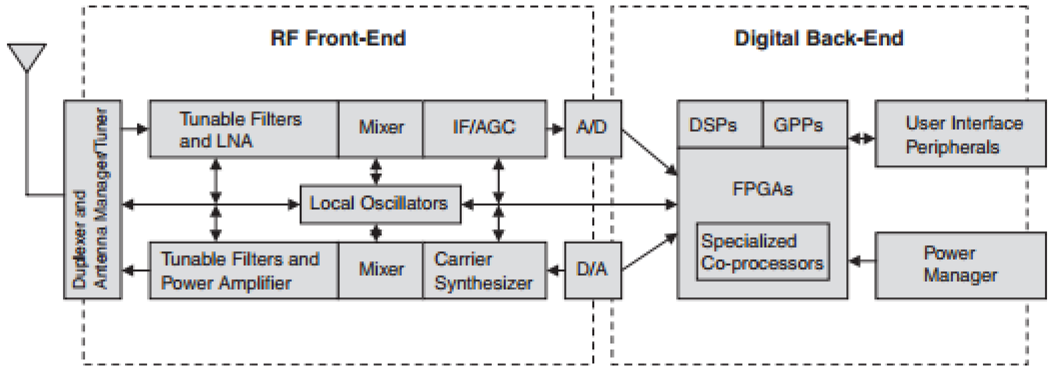

Figure 1.4: Basic hardware architecture of a modern SDR.[4] The hardware provides sufficient resources to define the carrier frequency, bandwidth, modulation, any necessary crypto- graphy, and source coding in software. The hardware resources may include mixtures of GPPs, DSPs, FPGAs, and other computational resources, sufficient to include a wide range of modulation types.

In the basic software architecture of a modern SDR (Figure 1.4), the application programming interfaces (APIs) are defined for the major interfaces to assure software portability across many very different hardware platform implementations, as well as to assure that the basic software infrastructure supports a wide diversity of waveform applications without having to be rewritten for each waveform or application. The software has the ability to allocate computational resources to specific waveforms (see Section 1.4.2). It is normal for an SDR to support many waveforms in order to interface to many networks, and thus to have a library of waveforms and protocols. The SDR Forum was founded in 1996 by Wayne Bonser of AFRL to develop industry standards for SDR hardware and software that could assure that the software not only ports across various hardware platforms, but also defines standardized interfaces to facilitate porting software across multiple hardware vendors and to facilitate integration of software components from multiple vendors. The SDR Forum is now a major influence in the SDR industry, dealing not only with standardization of software interfaces but many other important enabling technology issues in the industry from tools, to chips, to applications, to cognitive radio and spectrum efficiency. The SDR Forum currently has a Cognitive Radio Working Group, which is preparing papers to advance both spectrum efficiency and cognitive radio applications. In addition, special interest groups within the Forum have interests in these topics. The SDR Forum Working Group is treating cognitive radio and spectrum effi- ciency as applications that can be added to an SDR. This means that we can begin to assume an SDR as the basic platform upon which to build most new cognitive radio applications.

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[4] A/D: analog to digital; AGC: automatic gain control; D/A: digital to analog; IF: intermediate frequency; LNA: low-noise amplifier; RF: radio frequency

2.1 Basic SDR

In this section, we endeavor to provide the reader with background material to provide a basis for understanding subsequent chapters

2.4.1 The Hardware Architecture of an SDR

The basic SDR must include the radio front-end, the modem, the cryptographic security function, and the application function. In addition, some radios will also include support for network devices connected to either the plain text side or the modem side of the radio, allowing the radio to provide network services and to be remotely controlled over the local Ethernet. Some radios will also provide for control of external radio frequency (RF) analog functions such as antenna management, coax switches, power amplifiers, or special-purpose filters. The hardware and software architectures should allow RF external features to be added if or when required for a particular installation or customer requirement. The RF front-end (RFFE) consists of the following functions to support the receive mode: antenna-matching unit, low-noise amplifier, filters, local oscillators, and analog-to-digital (A/D) converters (ADCs) to capture the desired signal and suppress undesired signals to a practical extent. This maximizes the dynamic range of the ADC available to capture the desired signal. To support the transmit mode, the RFFE will include digital-to-analog (D/A) converters (DACs), local oscillators, filters, power amplifiers, and antenna-matching circuits. In transmit mode, the important property of these circuits is to synthesize the RF signal without introducing noise and spurious emissions at any other frequencies that might interfere with other users in the spectrum.

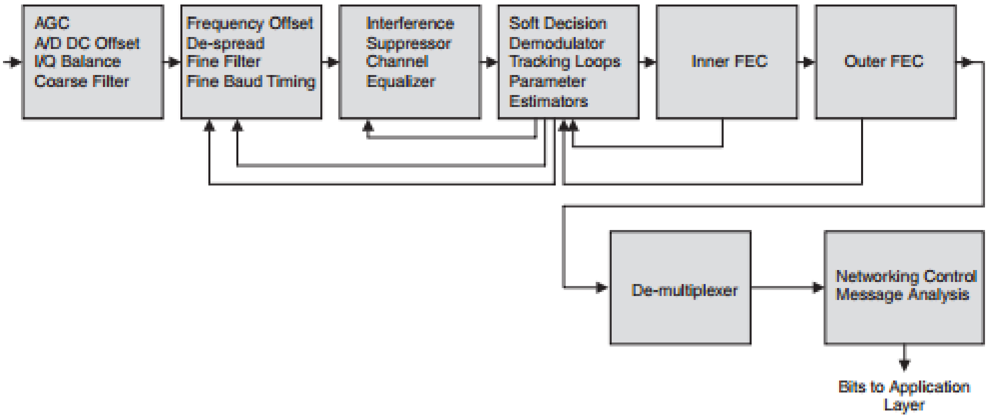

Figure 1.5: Traditional digital receiver signal processing block diagram.[5]

The modem processes the received signal or synthesizes the transmitted signal, or both for a full duplex radio. In the receive process (Figure 1.5), the modem will shift the carrier frequency of the desired signal to a specific frequency nearly equivalent to heterodyne shifting the carrier frequency to direct current (DC), as perceived by the digital signal processor, to allow it to be digitally filtered. The digital filter provides a high level of suppression of interfering signals not within the bandwidth of the desired signal.

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5 I/Q, meaning “in phase and quadrature,” is the real part and the imaginary part of the complexvalued signal after being sampled by the ADC(s) in the receiver, or as synthesized by the modem and presented to the DAC in the transmitter.

The modem then time-aligns and de-spreads the signal as required, and refilters the signal to the information bandwidth. Next the modem time-aligns the signal to the symbol or baud time so that it can optimally align the demodulated signal with expected models of the demodulated signal. The modem may include an equalizer to correct for channel multipath artifacts, and for filtering and delay distortions. It may also optionally include rake filtering to optimally cohere multipath components for demodulation. The modem will compare the received symbols with the possible received symbols and make a best possible estimate of which symbols were transmitted. Of course, if there is a weak signal or strong interference, some symbols may be received in error. If the waveform includes FEC coding, the modem will decode the received sequence of encoded symbols by using the structured redundancy introduced in the coding process to detect and correct the encoded symbols that were received in error.

The process the modem performs for transmit (Figure 1.6) is the inverse of that for receive. The modem takes bits of information to be transmitted, groups the information into packets, adds a structured redundancy to provide for error correction at the receiver, groups bits to be formed into symbols, selects a wave shape to represent each symbol, synthesizes each wave shape, and filters each wave shape to keep it within its desired bandwidth. It may spread the signal to a much wider bandwidth by multiplying the symbol by a wideband waveform which is also generated by similar methods. The final waveform is filtered to match the desired transmit signal bandwidth. If the waveform includes a time-slotted structure such as time division multiple access (TDMA) waveforms, the radio will wait for the appropriate time while placing samples that represent the waveform into an output first in, first out (FIFO) buffer ready to be applied to the DAC. The modem must also control the power amplifier and the local oscillators to produce the desired carrier frequency, and must control the antenna-matching unit to minimize voltage standing wave radio (VSWR). The modem may also control the external RF elements, including transmit versus receive mode, carrier frequency, and smart antenna control. Considerable detail on the architecture of SDR is given by Reed [14].

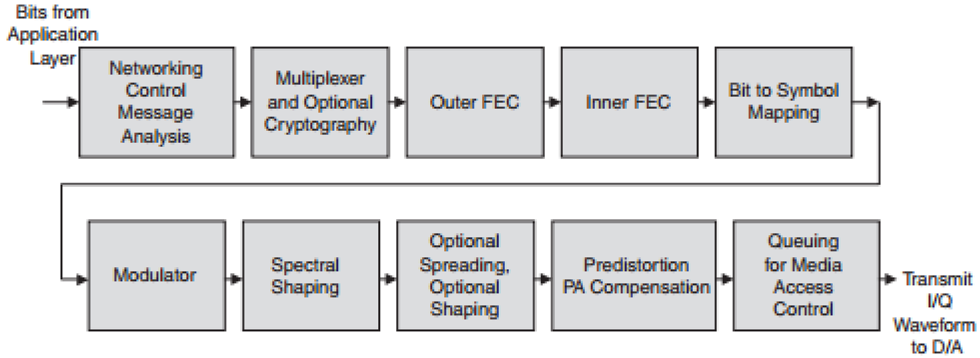


Figure 1.6: Traditional transmit signal processing block diagram.

The cryptographic security function must encrypt any information to be transmitted. Because the encryption processes are unique to each application, these cannot be generalized. The Digital Encryption Standard (DES) and the Advanced Encryption Standard (AES) from the US National Institute of Standards and Technology (NIST) provide example cryptographic processes [15, 16]. In addition to providing the user with privacy for voice communication, cryptography also plays a major role in assuring that the billing is to an authenticated user terminal..

In the future, it will also be used to authenticate transactions of delivering software and purchasing services. In future cognitive radios, the policy functions that define the radios' allowed behaviors will also be cryptographically sealed to prevent tampering with regulatory policy as well as network operator policy. The application processor will typically implement a vocoder, a video coder, and/or a data coder, as well as selected web browser functions. In each case, the objective is to use knowledge of the properties of the digitized representation of the information to compress the data rate to an acceptable level for transmission. Voice, video, and data coding typically utilize knowledge of the redundancy in the source signal (speech or image) to compress the data rate. Compression factors typically in excess of 10:1 are achieved in voice coding, and up to 100:1 in video coding. Data coding has a variety of redundancies within the message, or between the message and common messages sent in that radio system. Data compression ranges from 10 to 50 percent, depending on how much redundancy can be identi- fied in the original information data stream. Typically, speech and video applications run on a DSP processor. Text and web browsing typically run on a GPP. As speech recognition technology continues to improve its accuracy, we can expect that the keyboard and display will be augmented by speech input and output functionality. On cognitive radios with adequate processors, it may be possible to run speech recognition and synthesis on the cognitive radio, but early units may find it preferable to vocode the voice, transmit the voice to the base station, and have recognition and synthesis performed at an infrastructure component. This will keep the complexity of the portable units smaller.

2.4.2 Smart Antennas in a Cognitive Radio

Current radio architectures are exploring the uses of many types of advanced antenna concepts. A smart radio needs to be able to tell what type of antenna is available, and to make full use of its capabilities. Likewise, a smart antenna should be able to tell a smart radio what its capabilities are.

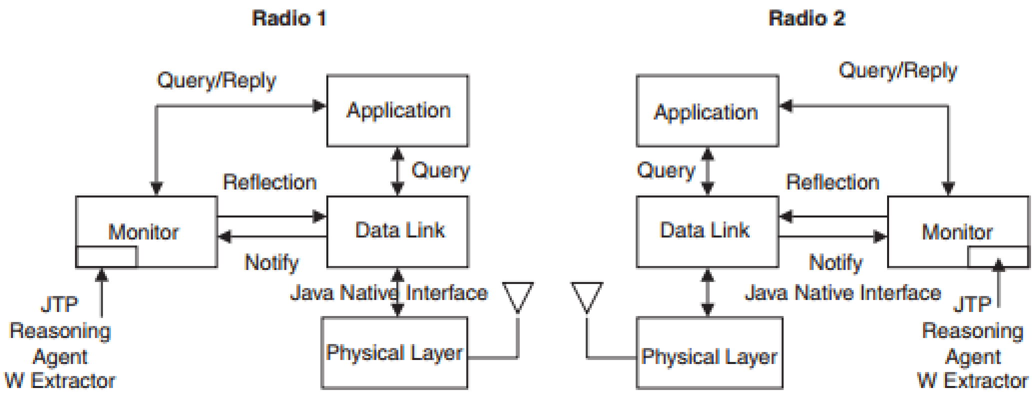


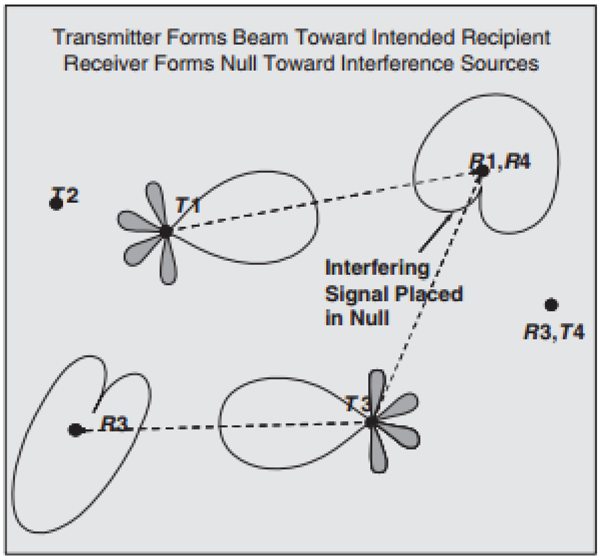
Figure 1.7: Java reflection allows the receiver to examine the state variables of the transmit and receive modem, thereby allowing the cognitive radio to understand what the communications channel is doing to the transmitted signal [19]. Copyright 2003 SDR Forum.

Smart antennas are particularly important to cognitive radio, in that certain functionalities can provide very significant amounts of measurable performance enhancement.

if we can reduce transmit power, and thereby allow transmitters to be closer together

on the same frequency, we can reduce the geographic area dominated by the transmitter, and thus improve the overall spectral efficiency metric of MHzkm2 .
A smart transmit antenna can form a beam to focus transmitted energy in the direction of the intended receiver. At frequencies of current telecommunication equipment in the range of 800–1800 MHz, practical antennas can easily provide 6–9 dB of gain toward the intended receiver. This same beamforming reduces the energy transmitted in other directions, thereby improving the usability of the same frequency in those directions. A radio receiver may also be equipped with a smart antenna for receiving. A smart receive antenna can synthesize a main lobe in the desired direction of the intended transmitter, as well as synthesize a deep null in the direction of interfering transmitters. It is not uncommon for a practical smart antenna to be able to synthesize a 20 dB null to suppress interference. This amount of interference suppression has much more impact on the MHzkm2 metric than being able to transmit 20 dB more transmit power. The utility of the smart antenna at allowing other radio transmitters to be located nearby is illustrated in Figure 1.8.

Figure 1.8: Utility of smart antennas. A smart antenna allows a transmitter (*T*) to focus its energy toward the intended receiver (*R*), and allows a receiver to suppress interference from nearby interfering transmitters.



CHAPTER 3

Technology Enablers and their

Chapter 3: Technology Enablers and their Effects

3.1 Cognitive Radio Technology Enablers

The development of wideband power amplifiers, synthesizers, and analog-to-digital converters (ADCs) is providing a new class of radios: the software-defined radio (SDR) and its software and cognitive radio cousins. Although at the early stages of development, this new class of radio ushers in new possibilities as well as potential pitfalls for technology policy. The flexibility provided by the cognitive radio class of radios allows for more dynamics within radio operations. The same flexibility poses challenges for certification and the associated liability through potential misuse. SDRs provide software control of a variety of modulation techniques, wideband and narrowband operation, transmission security (TRANSEC) functions (such as hopping), and waveform requirements. In essence, components can be under digital control and thus defined by software. The advantage of an SDR is that a single system can operate under multiple configurations, providing interoperability, bridging, and tailoring of the waveforms to meet the localized requirements. SDR technology and systems have been developed for the military. The digital modular radio (DMR) system was one of the first SDR systems. Recently the US Defense Advanced Research Projects Agency (DARPA) developed the Small Unit Operations Situational Awareness Systems (SUO SAS), which was a man-portable SDR operating from 20 MHz to 2.5 GHz.
SDRs exhibit software control over a variety of modulation techniques and waveforms. Software radios (SRs) specifically implement the waveform signal processing in software. This additional caveat essentially has the radio being constructed with a RF front-end, a down-converter to an intermediate frequency (IF) or baseband, an ADC, and then a processor. The processing capacity therefore limits the complexity of the waveforms that can be accommodated. A cognitive radio adds both a sensing and an adaptation element to the software defined and software radios. Four new capabilities embodied in cognitive radios will help enable dynamic use of the spectrum: flexibility, agility, RF sensing, and networking [1]. ● Flexibility is the ability to change the waveform and the configuration of a device. An example is a cell tower that can operate in the cell band for telephony purposes but change its waveform to get telemetry from vending machines during low usage, or other equally useful, schedulable, off-peak activity. The same band is used for two very different roles, and the radio characteristics must reflect the different requirements, such as data rate, range, latency, and packet error rate. ● Agility is the ability to change the spectral band in which a device will operate. Cell phones have rudimentary agility because they can operate in two or more bands (e.g., 900 and 1900MHz). Combining both agility and flexibility is the ultimate in “adaptive” radios because the radio can use different waveforms in different bands. Specific technology limitations exist, however, to the agility and flexibility that can be afforded by current technology. The time scale of these adaptations is a function of the state of technology both in the components for adaptation as well as the capacity to sense the state of the system. These are classically denoted as the observable/controllable requirements of control systems. ● Sensing is the ability to observe the state of the system, which includes the radio and, more importantly, the environment. It is the next logical component in enabling dynamics. Sensing allows a radio to be self-aware, and thus it can measure its environment and potentially measure its impact to its environment. Sensing is necessary if a device is to change in operation due to location, state, condition, or RF

environment. ● Networking is the ability to communicate between multiple nodes and thus facilitate combining the sensing and control capacity of those nodes. Networking, specifically wireless networking, enables group-wise interactions between radios. Those interactions can be useful for sensing where the combination of many measurements can provide a better understanding of the environment. They can also be useful for adaptation where the group can determine a more optimal use of the spectrum resource over an individual radio.
These new technologies and radio classes, albeit in their nascent stages of development, are providing many new tools to the system developer while allowing for more intensive use of the spectrum. However, an important characteristic of each of these technologies is the ability to change configuration to meet new requirements. This capacity to react to system dynamics will require the development of new spectrum policies in order to take advantage of these new characteristics.

3.2 Technology Impact on Regulation

Regulations based on static broadcast geometries cannot address the spatial, numeric, and spectral dynamics of future radio technology. 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.
Four basic geometries affect the type of technical and social/economic issues that are addressed in wireless communications policy: fixed or mobile transmitters combined with fixed or mobile receivers: ● Fixed Transmitter, Mobile Receiver(s) ● Fixed Transmitter, Fixed Receiver(s) ● Mobile Transmitter, Fixed Receiver(s) ● Mobile Transmitter, Mobile Receiver(s). Fixed Transmitter, Mobile Receiver(s) Fixed transmitter, mobile receiver systems include broadcasting, radio position determination, and standard time and frequency signal services. Broadcasting comprises a large fraction of the consumer devices such as radio (AM, FM, TV, etc.). Radio position determination includes radio navigation and radio beaconing services such as GPS. Standard time and frequency signal services include WWVB, the National Institute of Standards and Technology (NIST) long-wave standard time signal, which continuously broadcasts time and frequency signals at 60 kHz. The carrier frequency provides a stable frequency reference traceable to the national standard. A time code is synchronized with the 60 kHz carrier and is broadcast continuously at a rate of 1 bit per second (bps). Emission-only devices, such as those for ISM purposes, including microwave ovens, magnetic resonance equipment, and industrial heaters, are included in this category. The important feature of these systems is that there are small numbers of high power transmitters at fixed and potentially known locations. The economic challenge is to put most of the complexity (i.e., cost) in the transmitter since the ratio of receivers to transmitters is more than 1 million to 1.
The policy challenge with fixed transmitter, mobile receiver systems is to determine the allowable transmission parameters (power, location) that prevent interference at the receivers and provide for the potential of an economicallyviable business. The trade-offs for broadcasting services include the number of stations in a given region and the viability of the service (number of customers). The trades are exceptionally complex. The station density could be increased by reducing transmission power and greater frequency reuse. However, that would decrease the coverage area and thus the number of potential customers. The station density could be increased by using closer band spacing between stations. However, that would increase the out-of-band

rejection by the receivers.

Fixed Transmitter, Fixed Receiver(s) Fixed transmitter, fixed receiver systems include point-to-point, point-tomultipoint, and radio astronomy services. Both endpoints are in fixed locations and could either be a one-way (transmitter to receiver) or a two-way (transceiver to transceiver) configuration. A point-to-point communication system is defined as having two fixed transceivers. Private operational-fixed microwave may use an operational-fixed station, and only for two-way communications related to the licensee's commercial, industrial, or safety operations. Point-to-multipoint includes multipoint distribution systems (MDSs) and multichannel, multipoint distribution systems (MMDSs) that are generally used for one-way data broadcasting. Originally, the primary MMDS application was "wireless cable" to deliver TV programs. Advances in antenna development allowed for two-way digital subscriber link (DSL) applications to be implemented with MMDS. Radio astronomy is the scientific study of celestial phenomena through measurement of the characteristics of radio waves emitted by physical processes occurring in space. The radio telescopes that are used for astronomical work are extremely large because the signal strength coming from the distant stellar objects is low and many of the frequencies that are observed are below 3 GHz. The challenge is in addressing the location of fixed receiver, radio astronomy systems that take decades to plan and construct. Originally located in places away from population centers to minimize the potential for interference from commercial systems, these systems now find themselves surrounded by population centers. The policy-makers are essentially facing an issue of whether to keep "radio-free zones" around the telescopes or to find other means to provide interference-free operation. Fixed transmitter, fixed receiver systems are the most straightforward to determine the transmission parameters to prevent interference with other systems. However, the complexity occurs with mobile transmitters interfering with these systems. Because the location of the fixed transceivers is generally unknown to mobile users, mobile transmitters can potentially interfere with a receiver operating close to the noise floor due to out-of-band emissions or lack of out-of-band rejection by the receiver. However, the policy trades are quite straightforward because the RF environment and the geometry are fixed. Mobile Transmitter, Fixed Receiver(s) Mobile transmitter, fixed receiver systems include monostatic active as well as passive meteorological and Earth exploration systems. These systems are mobile (either airborne or space based). In the passive sensing configuration, the operational area is unknown, as it has similar characteristics to radio astronomy. In the active sensing configuration, the transmission location is unknown but the receiver is co-located with the transmitter. Mobile transmitter, fixed receiver systems generally employ extremely sensitive receivers. Due to the mobility of the transmitter, the geographic region impacted is fixed in size and moves with the transmitter. The policy challenges are that the amount of frequency needed for these systems is large but the specified frequency use is very small. Also, the operational frequencies are specific to the physical attributes of the chemicals that are to be sensed. The sensitivity of the receivers also requires all adjacent channel systems to have an extremely low outof-band emission. This is usually accomplished through guard bands. The challenge to the policy-maker is to determine the relative values of consumer services compared with scientific investigation and Earth exploration. Those values provide input as to whether to find mechanisms to access the unused spectrum in one location while the sensor is operating in another location. Mobile Transmitter, Mobile Receiver(s) Mobile transmitter, mobile receiver systems include a wide range of mobile services as well as portable unlicensed devices. These systems include radiotelephony (e.g., cellular, personal communication system (PCS), wireless communication, and specialized mobile radio (SMR)) and private land mobile radio (PLMR) services. PLMR services are for state and local governments, and for commercial and nonprofit organizations to use for mobile and ancillary fixed communications to assure the safety of life and property and to improve productivity and efficiency. Personal radio services include CB radios, Family Radio Service (FRS), and remote control. Unlicensed devices, also known as licensed-by-rule, license-free, or “Part 15” devices as denoted in the FCC rules, are included. The important feature of these systems is that there are potentially large numbers of moderate (100W) and extremely large numbers of low power (1 mW–1W) transceivers that are mobile. Both the mixture of powers and the unknown geometries between receivers and transmitters make it impossible to provide absolute assurance of interference-free operation without specifying a minimum separation distance. Mobile transmitter, mobile receiver systems involve by far the most complex geometries for policy-makers to address. Currently, all computations for interference assume a minimum separation distance between devices (and it differs from device to device). The assumption is that these distances represent the space in which the user has full control and thus can directly impact the presence of interference. As with the mobile transmitter, fixed receiver systems, the mobility of the transmitters creates the uncertainty of the geometry between the transmitters and receivers. The mobility also creates spectral regions in time, space, and frequency that are not used. The policymaking challenge is to maximize the use of the spectrum, encourage the development of new technologies and services, and to provide certainty (spectrum access, interference, etc.) for the service providers to encourage investment.

CHAPTER 4

Cognitive Radio Network Applications

Chapter 4 : Cognitive Radio Network Applications

Cognitive Radio Networking and Opportunistic Spectrum Access can be used in different applications:

1- Cognitive Mesh Networks
2- Public Safety Networks
3- Disaster Relief and Emergency Networks
4- Battlefield Military Networks
5- Leased Networks .

1- Cognitive Mesh Networks
Multi-hop wireless mesh networks have recently gained significant popularity as a cost-effective solution for last-mile Internet access. Traditional wireless mesh network are challenged by the scarcity of the wireless bandwidth needed to meet the high-speed requirements of existing wireless applications.
by allowing the mesh nodes to dynamically explore any available spectral opportunities. Such cognitive mesh networks are meant be used to provide broadband access to rural, tribal, and other under-resourced regions. See figure (1.C) explain Cognitive Mesh Networks

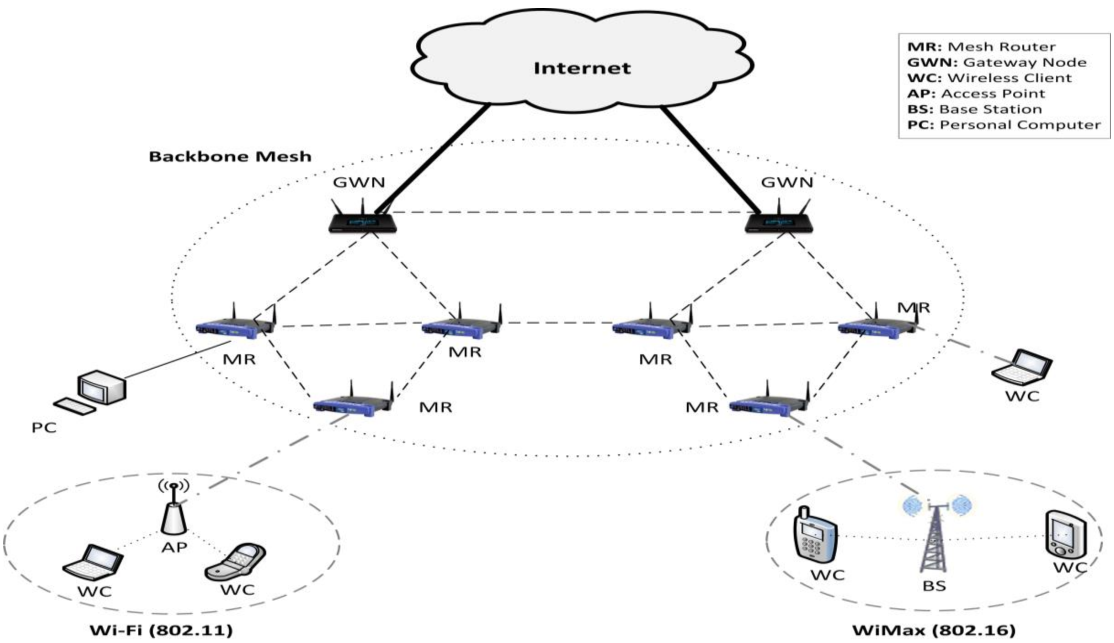


figure (1.C) Cognitive Mesh Networks

2- Public Safety Networks
Public safety networks are used for communications among police officers and fire and paramedic personnel. Such networks are also challenged by the limited amount of allocated spectrum. Even with the recent extensions of the allocated public safety spectrum bands, the public safety personnel do not have the technology to dynamically operate across the different spectrum segments. Recall that public safety licensees have a wide variety of bands available (VHF-

Low, VHFHi,220MHz, UHF below 800, UHF-800, etc.). The cognitive radio technology can offer public safety networks more bandwidth through Opportunistic Spectrum Access. Furthermore, a public safety CRN can provide a substantial communication improvement by allowing the interpretability across different public safety services while smartly adapting to the high peak-to-average nature of the traffic carried out by such networks. See figure (2.P)

figure (2.P) Public Safety Networks

3- Disaster Relief and Emergency Networks

Natural disasters such as hurricanes, earthquakes, wild fires, or other unpredictable phenomena usually cause the communications infrastructure to collapse. For example, some base stations of cellular networks can fall, the connectivity between sensor nodes and the sink node in static wireless sensor networks can be lost, existing Wireless Local Area Networks (WLANs) can be damaged, etc. This results in a set of partially or fully damaged coexistent networks that were previously deployed and then became disconnected. Meanwhile, there is an urgent need for a means of communications to help the rescue teams to facilitate organized help, rehabilitation efforts, and to locate the disaster survivors. CRNs can be used for such emergency networks.
provide a significant amount of bandwidth that can handle the expected huge amount of voice, video, and other critical and time-sensitive traffic
See figure (3.D)

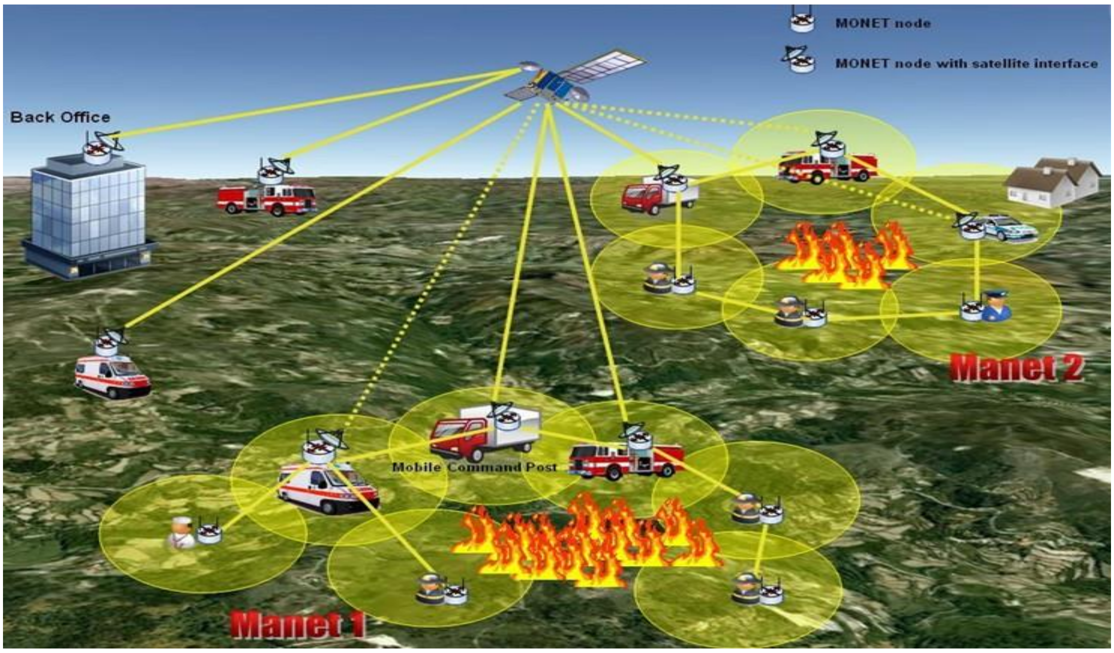


figure (3.D) Disaster Relief and Emergency Networks

4- Battlefield Military Networks

Unfortunately, the recent advances in wireless technologies made the job of communication jamming and/or hacking much easier. Consequently, achieving reliable and secure communications in modern battlefields has become a more challenging task. Recall that a battlefield communication network provides the only means of communications between soldiers, armed vehicles, and other units in the battlefield amongst themselves as well as with the headquarters. This implies that such networks do not only require significant amount of bandwidth, but also mandate secure and reliable communications to carry vital information. The cognitive radio is the key enabling technology for realizing such densely deployed networks which use distributed Opportunistic Spectrum Access strategies to fulfill the bandwidth and reliability needs . see figure (4.B)

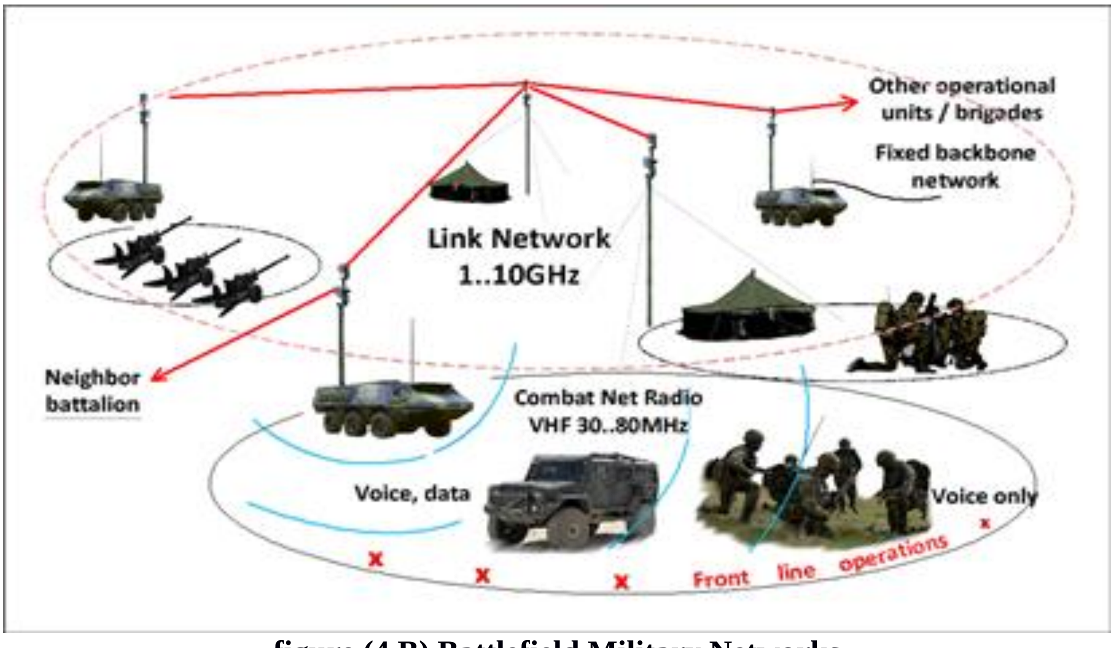
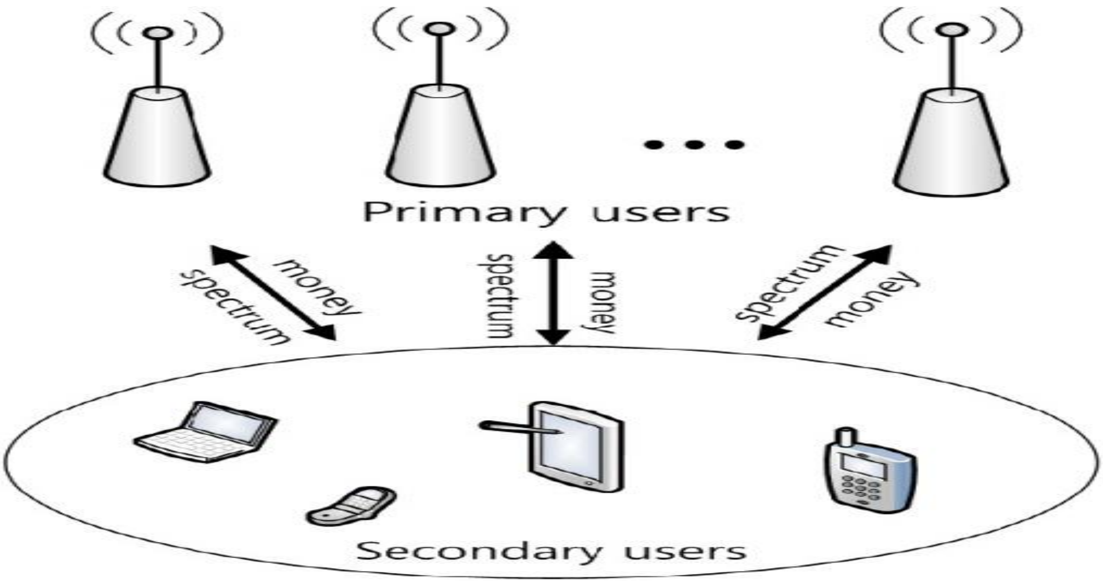


figure (4.B) Battlefield Military Networks

Note that, the dynamic nature of OSA makes the ability to track and jam a communication more difficult. Thus motivated, DARPA initiated the Wireless Network after Next (WNaN) program aiming at creating a flexible architecture for military communications The main goal of the WNaN program is to develop a low-cost handheld cognitive radio terminal that is capable of selecting its own frequencies and forming a dense network within a large battlefield area.

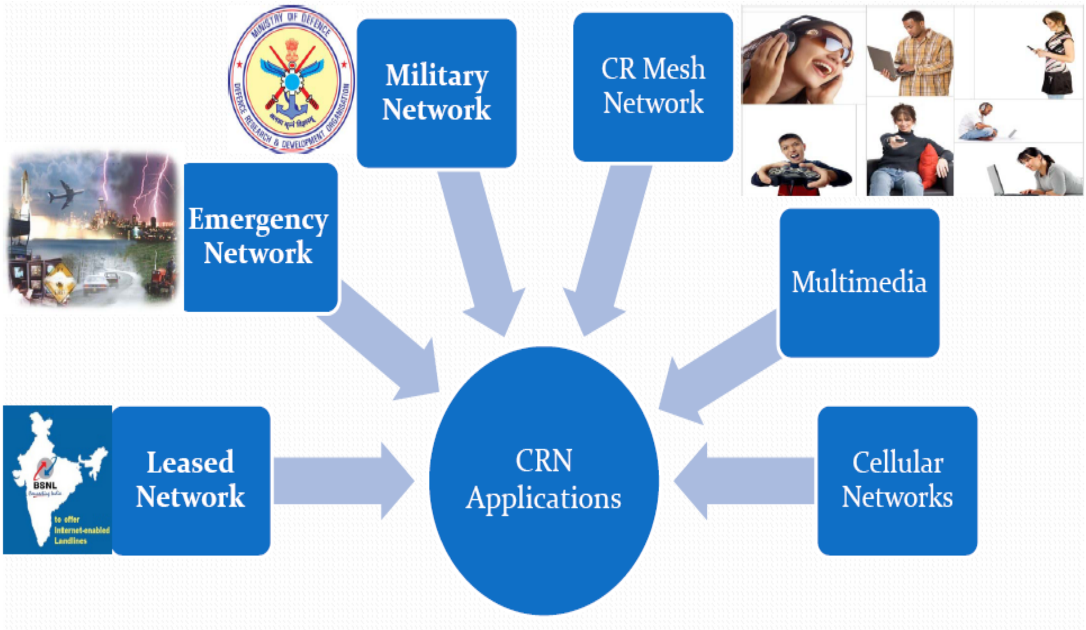
5- Leased Networks

All of the aforementioned CRN applications have the secondary users exploiting the resources of the primary networks without being beneficial to the primary networks in any way. However, a primary network can benefit from leasing a fraction of its licensed spectrum to secondary operators adopting cognitive radio technology to opportunistically access the spectrum. The entrance of the secondary operator to the market of the incumbent primary network can increase the revenue of the primary licensed operator. See figure(5.L)



figure(5.L) Leased Networks

The primary users treat the set of secondary users as a spectrum consumer. Each primary user sells an unused portion of its spectrum (e.g., time slots in TDMA based wireless system) to the market at price p_i (i=1,2,…,N). In this market, the demand of secondary users depends on the prices of per-unit spectrum. Each primary user chooses its own strategy p_i to induce the subscription of the secondary users.



Military Network
CR Mesh Network
Emergency Network
Multimedia
Leased Network
CRN Applications
Cellular Networks