A Comparison Between SDR and CR Platforms (both in military and commercial applications)

By Andrew Gamulja

I. Introduction

Digital communications are an important aspect in any modern society. They are a technology that we have become accustomed to and depended upon in executing our everyday life applications. Some of these applications include social interactions, entertainment, education and financial transactions. In particular, wireless devices today are capable of performing many advanced functions that empower them to support services such as voice telephony, web browsing, video conferencing, data transfer and streaming media. With the rapid advancement of microelectronics, wireless transceivers are becoming more flexible, powerful and portable. This has enabled the development of *software-defined radio* (SDR) technology, a radio that has its functionality defined by the software running in it. The benefit of an SDR system is that much of the digital signal processing of data signals are implemented in software, which empowers the flexibility of the radio on performing many different functionalities. Its ability to switch function however can only be done on demand and the system is not capable of reconfiguring itself into the most effective form without the programmer's intervention. This is where the cognitive radio (CR) technology takes the extra step of having the ability to autonomously adapt to different surrounding conditions.

In this project, the capabilities of the two platforms will be examined and compared. The first half talks about the SDR platform and discusses some of the challenges in transitioning from hardware radios. We analyze the basic transceiver architecture and its implementation for commercial application. This will be followed by the discussion on the open software framework that governs the SDR implementation for military applications. This open framework is called the Software Communications Architecture (SCA) and it is now managed by the recently established organization: the Joint Tactical Networking Center (JTNC). The second part of this project talks about the CR platform. The project will only focus on the CR system that implements dynamic spectrum access (DSA). The concept of spectrum opportunity and its performance measures will be analyzed. This is followed by the discussions on CR systems that are currently being implemented in both, commercial and military sectors.

II. Software Defined Radio

2.1 Background

Software Defined Radio (SDR) is a radio in which some or all of the OSI model layers functionalities are implemented in software, thus enabling it to be reconfigurable. In order to understand how an SDR system works, it is crucial to first understand the basic building blocks that makes the software-defined radio system. Fig.1 below shows the top level structure of a typical SDR system, which consists of five sections [1]:

- **The Antenna**: responsible for receiving/transmitting electromagnetic waves and the conversion into/from electrical signals.
- **The RF Module**: performs the conversion of radio frequency signal to/from intermediate frequency signal.
- **ADC/DAC Module**: performs the conversion of analog signal to/from digital signal.
- **DDC and DUC Module**: performs the digital-down conversion (bandpass to baseband) and the digital-up conversion (baseband to bandpass).
- **Baseband Processing Module**: performs operations such as equalization, channel coding/decoding, spreading/de-spreading, link layer protocol, etc.

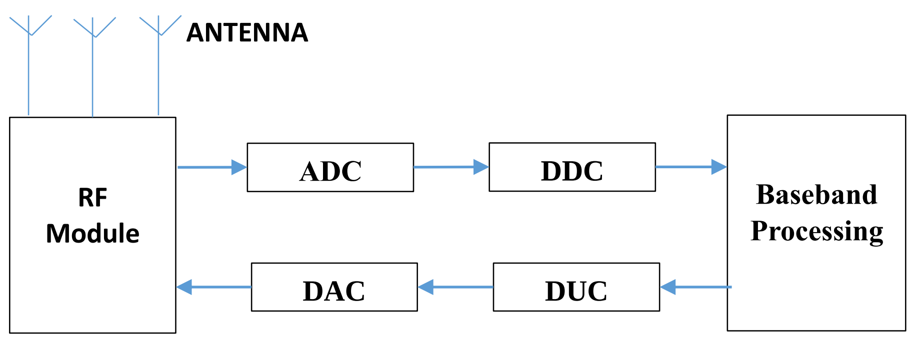

Fig. 1. Top-level Structure of an SDR System [1].

Much of the heavy computations are executed in the DUC/DDC and the Baseband Processing modules. Essentially, these are the main modules that dictate the operation characteristics of the device. The functionalities of these modules are executed by software components running on field programmable gate arrays (FPGAs), Digital signal processors (DSPs) or general purpose microprocessors. Both the DDC/DUC and the Baseband Processing blocks can be programmable, hence they can perform operations such as channel coding, spreading, different modulation types, frequency band selection, etc. The operations can be changed at will, simply by loading a new software to these modules. The framework of Fig.1 enables the implementation of various physical-layer (as well as other layers within the OSI model) formats and protocols into a single radio.

2.2 Challenges

Although Software-defined radio offers a remarkable benefit of 'one-design fits all' feature, there are however a number of disadvantages of the technology [1]. The first is the heavy computational nature of software applications. Software applications typically run on top of a microprocessor that executes a sequence of instructions and tends to be power hungry. This is certainly not an ideal case for a battery powered device and is one of the key reasons why software-defined radios have yet to be deployed in commercial end-user devices. Base stations and access points however can take advantage of external power source and are therefore more suitable for SDR implementation. Although power consumption is certainly not an issue in FPGA devices, the technology however requires a significant portion of the silicon to be dedicated in achieving programmability, which results in a much larger chip area compared to ASICs. This is also a major drawback for end-user devices, where keeping the device small is an important design aspect.

The second challenge is the location where the ADC/DAC conversion takes place. The location of the converter within the radio system determines what radio functions can be done in software and hence how reconfigurable a radio can be made. In an ideal SDR, the RF signal is directly sampled at the antenna output. This however has a significant drawback since state-of-the-art analog-to-digital converters are not available today. Digitization of the RF signal requires the incoming signal to be sampled at least at a rate that is determined by the Nyquist frequency, which means a very high sampling rate is required to digitize today's high-bandwidth, high-frequency RF transmissions. Because today's analog to digital converter operates at much lower rates, a common approach is to mix down the RF signal to intermediate frequency (IF) before converting it into a digital signal for processing; a procedure that is performed by the RF module in Fig.1. To give an example, the typical channel used by an 802.11 WiFi device is 20 MHz wide carried on a 2.4 GHz frequency. If analog-to-digital conversion was to be implemented at the antenna output, it would require a sampling rate as well as signal processors operating in the gigahertz range. A more practical approach is to mix down the RF signal to an IF, where the 20 MHz analog signal set by the IF filters is captured without aliasing artifacts by the ADC that can use a lower rate of 40 million samples per second (Msps).

The third challenge in transitioning into an SDR platform is cost. SDR devices are expensive because they typically require programmable devices like FPGAs, as opposed to the mass-produced, single-purpose ASICs that are used in most consumer devices today. Although SDR has started to find its way into the commercial sector, the technology is mainly used in military applications where cost is less of a constraint.

2.3 Commercial Presence

In the commercial sector, cellular networks were considered as the most obvious and profitable market that SDR could penetrate. The plethora of wireless standards being used makes SDR platform an attractive solution because it has the added functionality and interoperability of supporting multiple standards. Other benefits also include future-proofing and easier bug fixes through software upgrades. As was mentioned previously, SDR system however has the major drawback of being power hungry and is therefore more suitable to be implemented in base-station transceiver where it can take advantage of external power source. There are companies like Vanu, ZTE, AirSpan and Etherstack currently offering SDR products for cellular base stations. The first FCC-certified commercially available SDR device was the Anywave GSM base station developed in 2005 by a U.S-based company, Vanu Inc. The device runs on a general purpose processing platform and provides a software implementation to a lot of the base transceiver station's functionalities.

In general, software-defined radios can be classified into the following categories [2]:

(i) *Multi-band system:* supports more than one frequency band used in wireless standard (e.g., LTE 850 MHz, LTE AWS (1700 MHz), LTE 1800 MHz, LTE 2100 MHz).

(ii) *Multi-standard system:* supports more than one wireless standard. The system can work within one standard family (e.g., UMTS, HSPA+, DC-HSDPA) or across different network families (e.g., CDMA EV-DO, 802.11, DECT).

(iii) *Multi-media system:* supports different services (e.g., voice, data, video streaming).

For simplicity, the basic front-end architecture of multimode systems (combination of multi-band and multi-standard systems) is analyzed in this report.

Architecture

The receiver architecture will be analyzed first followed by the transmitter. Also the operations of the baseband processing module of the SDR platform (which involves equalizer, channel coding/decoding, spreading/dispreading) will not be discussed in this project. A lot of information about the baseband processing module can be found in the literature [3]. The focus of this section is on the hardware implementation of the SDR front-end architecture, which include the RF module, ADC/DAC and DDC/DUC blocks of Fig. 1. To give it a more versatile functionality, an SDR platform can also be designed in a way that it can be reconfigured on the go. Such configuration is called a *parameter-controlled* (PaC) *SDR* [2], which guarantees that operation characteristics can be changed instantaneously if necessary.

Receiver

Fig. 2 shows the basic architecture of a base-station software radio receiver at the frond-end module. The receiver has a control bus where the operating parameters can be supplied, allowing it to be configurable on the go.

We start the discussion with the gray shaded block which represents the tunable modules that accept the parameter input from the control bus. This involves two things: the oscillators and the bandpass filters. The received signal from the antenna is first filtered by a pre-selection filter that selects the complete frequency range, which is in the UHF range for commercial applications (e.g., 800 – 2600 MHz as specified by the UMTS-FDD standard). The signal is then amplified and mixed with the frequency $F = RF+IF1$.

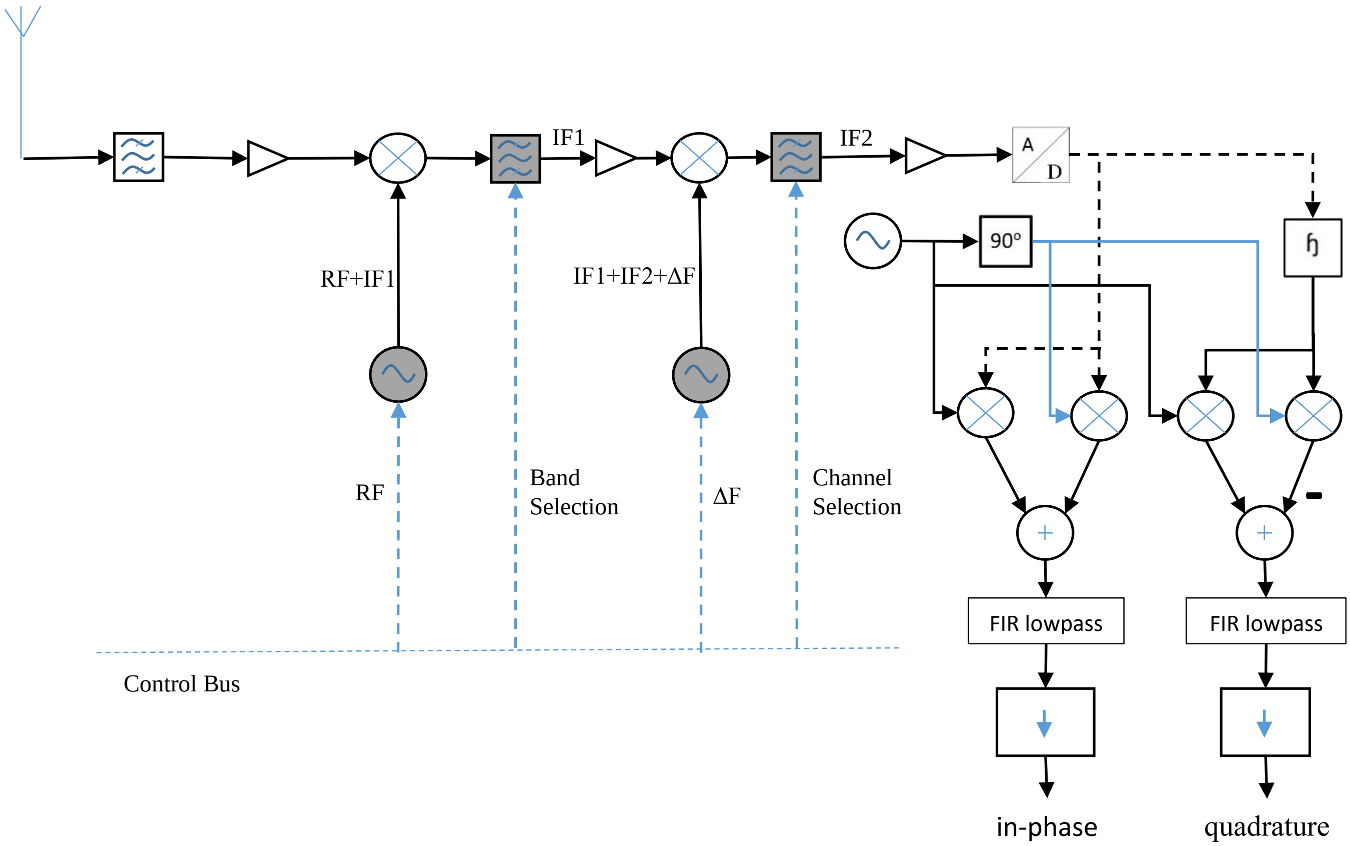

Fig. 2. SDR Receiver architecture at the Front-end.

The control bus supplies the *RF* frequency parameter which essentially tells the SDR device the frequency band that it is interested in. For example, T-Mobile USA operates in the AWS frequency band for their 3G service. For uplink transmission, this is in the range between 1710 – 1755 MHz. The control bus should then supply the center frequency parameter of *RF* = 1732 MHz (mid-point of the AWS uplink band).

After the first mixing, this center frequency is brought down to *IF1* and the signal is bandpass filtered so that only those received signals in the band of interest around *IF1* are outputted. The programmable bandwidth is set in accordance to TABLE I, which shows a compact list of frequency allocation for different cellular standards.

After the IF1 filter, the signal is again amplified and mixed the second time with the frequency *F = IF1+IF2+ΔF*. Note that *IF1* and *IF2* are fixed intermediate frequencies. *ΔF* is the difference between the carrier frequency of the specific band and the center frequency of the channel of interest. The reason that *ΔF* parameter is needed is because there are many channels within a band, and *ΔF* instruct the SDR device to select the specific channel to communicate with. At the output of the second mixer, the carrier frequency of the signal is shifted to *IF2*. The signal is then fed to a second bandpass filter, where the bandwidth is again set in accordance to TABLE I. This bandwidth value depends on which wireless standard being used. For example, the third generation UMTS-FDD standard uses DS-CDMA air interface for channel access which operates on a wide channel bandwidth of 5 MHz. The new Long Term Evolution (LTE) standard however requires a scalable channel bandwidth from 1.4 MHz to 20 MHz for faster data throughput.

After the IF2 filter, the signal is amplified again and fed into the analog to digital converter. The A/D conversion is then performed, satisfying the Nyquist criterion to avoid aliasing artifacts. The first digital signal processing (implemented in software) is to convert the digital bandpass signal out of the A/D converter to the complex baseband, i.e., generate its in-phase and quadrature components. This is done by using a Hilbert transform filter (the ‘ђ’ block of Fig. 2) and a sinusoidal signal at frequency *IF2*. Mathematically, the in-phase and quadrature components can be calculated as follows:

$$\begin{aligned} x_i(t) &= x(t)\cos(2\pi f_0 t) + \hat{x}(t)\sin(2\pi f_0 t) \\ x_q(t) &= \hat{x}(t)\cos(2\pi f_0 t) - x(t)\sin(2\pi f_0 t) \end{aligned} \tag{1}$$

where x_i and x_q are the in-phase and quadrature components respectively, x is the received signal out of the A/D converter, $\hat{x}$ is the Hilbert transformed signal and f_0 is equal to *IF2*. The two components are then lowpass filtered before feeding them into the down samplers. The purpose of the down sampling block is to reduce the unnecessary high sampling rate used in the A/D conversion so that the digital baseband processing can be carried out at a lower rate.

Table I. Frequency allocation and channel access interface to various third and fourth-generation cellular standards

<table>
<tr><th>Standard</th><th>Frequency Range (MHz)</th><th>IF1 Filter Bandwidth</th><th>IF2 Filter Bandwidth</th><th>Channel Access</th></tr>
<tr><td>LTE (Band 1)
UMTS-FDD (Band 1)
CDMA2000 (Band 6)</td><td>Uplink: 1920 – 1980
Downlink: 2110 – 2170</td><td>60 MHz</td><td rowspan="4">LTE
Scalable from 1.4 – 20 MHz

UMTS-FDD
5 MHz

CDMA2000
1.25 MHz</td><td rowspan="4">LTE
SC-FDMA for uplink
OFDMA for downlink

UMTS-FDD
DS-CDMA

CDMA2000
CDMA and TDMA</td></tr>
<tr><td>LTE (Band 3)
UMTS-FDD (Band 3)
CDMA2000 (Band 8)
(DCS)</td><td>Uplink: 1710 – 1785
Downlink: 1805 – 1880</td><td>75 MHz</td></tr>
<tr><td>LTE (Band 4)
UMTS-FDD (Band 4)
CDMA2000 (Band 15)
(AWS)</td><td>Uplink: 1710 – 1755
Downlink: 2110 – 2155</td><td>45 MHz</td></tr>
<tr><td>LTE (Band 5)
UMTS-FDD (Band 5)
(CLR)</td><td>Uplink: 824 – 849
Downlink: 869 – 894</td><td>25 MHz</td></tr>
</table>

Transmitter

The block diagram for the transmitter branch is shown in Fig. 3. Again, only the front-end module is discussed in this project. Operations such as channel coding, baseband modulation and spreading are all implemented in software in the baseband processing module. The baseband processing module outputs the in-phase and quadrature components. The transmitter branch of the SDR front-end starts by converting these components into analog signals. Both signals are then fed to a tunable lowpass filter, of which the bandwidth is tuned according to the wireless standard being used. The in-phase component is modulated into the carrier frequency, while the quadrature component is modulated into the same carrier frequency that is shifted in phase by 90°. The sum of these two signals forms the bandpass RF signal, which is amplified and filtered to the standard before it is radiated over the antenna.

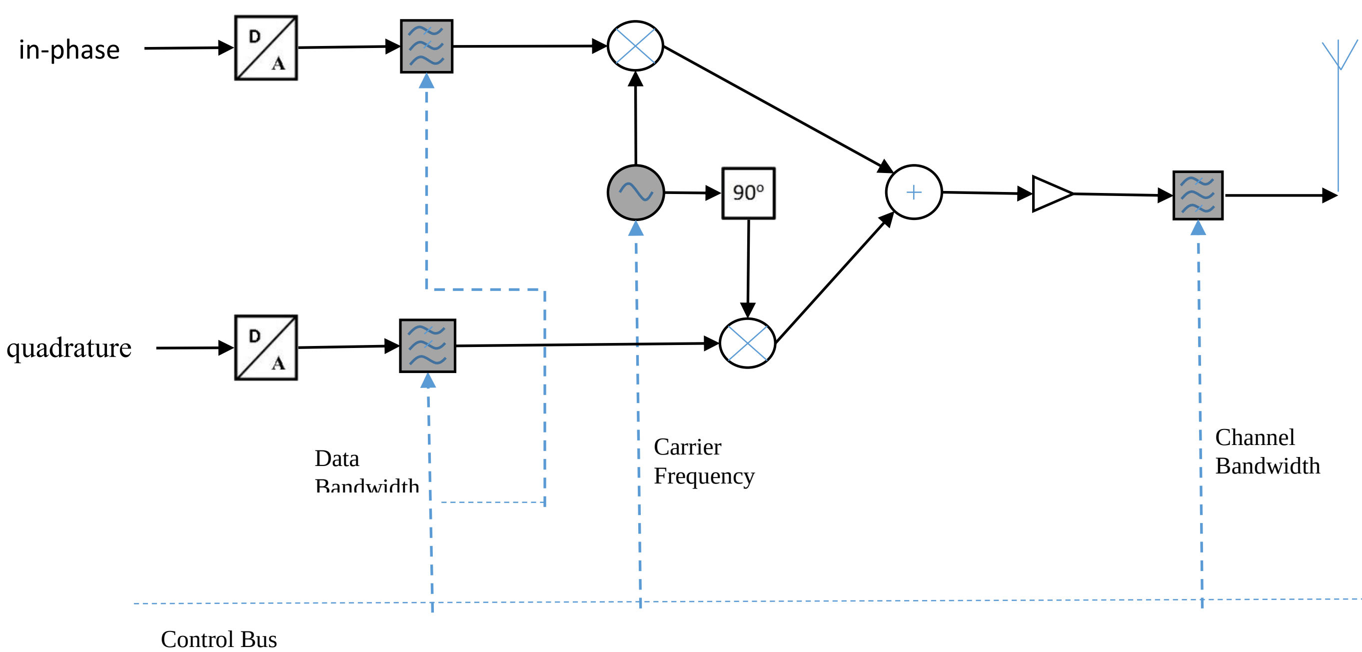

Fig. 3. SDR transmitter architecture at the front-end.

2.4 Military Presence

There is no doubt that establishing communication in the battlefield is crucial, and without it coordination and battle plans would not be effective. Military radio communications has progressed substantially beyond those crackly sound we see often in old movies. Today, software-defined radios are increasingly being implemented into military radios. This is because they can adapt to a wide variety of communications protocols that are used among different military services and allied forces. While legacy military radios have been designed in hardware with specific and limited functionality, SDR implements radio functionality in software. The software programs in SDR technology that determine operation functionality (such as frequency range, security, frequency-hop scheme, etc) are often called *waveforms*. These waveforms must run on top of an operating system, much like many software applications that run on top of Windows operating system. For the U.S military's software-defined radio, the standard operating system is called the Software Communications Architecture (SCA). It is an open development framework that specifies how hardware and software are to operate together within an SDR system.

SCA was managed by the Joint Program Executive Office for the Joint Tactical Radio System (JPEO JTRS). The JPEO JTRS project however was cancelled in October 2011 by the United States Undersecretary of Defense, stating that "*it is unlikely that the products resulting from the JTRS GMR development program will affordably meet service requirements, and may not meet some requirements at all. Therefore termination is necessary* [4]." In less than a year later, the United States Undersecretary of Defense approved the organizational restructure, which established the transitioned organization, designated as the Joint Tactical Networking Center (JTNC). This new organization is officially active as of October 1, 2012 and is now the responsible body for development and sustainment related to SDR waveforms and network management for the U.S military. It also continues to manage the SCA framework as well as develop software waveforms standard built on the SCA.

2.4.1 Waveforms

One of the main difference from commercial radios is that the transmission frequencies of military radios do not fall entirely in the ultra-high frequency (UHF) region, but extends from high-frequency to extremely high frequency (EHF) region (2 MHz – 300 GHz). The reason for the wider range is that there are many types of military applications out there and that different applications tend to be best used at different frequency region. For example, high frequency (HF) band between 3 to 30 MHz have longer wavelengths and the radio waves have the property of being able to be reflected back to Earth by the ionosphere layer in the atmosphere. The band is therefore more suited for long distance communication. On the other hand, super high frequency (SHF) band between 3 to 30 GHz have shorter wavelengths from ten to one centimeter, which makes is suitable to be used in radar transmitters and line of sights communications where wave diffraction phenomenon is less likely to occur.

In this section, several waveforms that will be supported by the JTNC program are discussed. Some of the basic physical layer attributes of each waveform is also examined. It is important to note that a waveform is also defined by the data link and network layer of the OSI model, but those are beyond the scope of this project and will not be discussed here.

Wideband Networking Waveform (WNW)

The WNW is designed to operate in a mobile ad-hoc network (MANET). This means that the network does not require a lot of pre-planning for nodes to join and leave. The links between devices are therefore dynamic because each node is free to move independently in any direction. Each node in an ad-hoc network can be treated as a router itself because they must also forward traffic unrelated to its own use. The wideband networking waveform is primarily intended to establish the backbone communication between ground and air vehicles in this ad-hoc mobile network. The use of high transmission bandwidth and sophisticated networking algorithm are therefore crucial for WNW system. Since the device is normally mounted on the vehicles, it has the power, size and weight infrastructure available to support this demanding communication setup.

According to the physical layer implementation developed by L-3 Communications Nova Engineering [5], the waveform operates in one of the four bandwidth modes (1.2, 3, 5 and 10 MHz), and can achieve data rates of up to 23.0 Mbps through the use of OFDM encoding method. There are two modulation orders: 16-DPSK and QPSK. To enhance reliable high data rates communication, the WNW waveform employs two forward error correction schemes: Reed-Solomon and Turbo-code. Also WNW system draws from a wide portion of the available spectrum (2 MHz – 2 GHz) to transmit and network information. The waveform can be used to transmit digital voice, video and image data.

Soldier Radio Waveform (SRW)

The Soldier Radio Waveform is also designed to operate in a mobile ad-hoc network for land combat operations. It is focused on delivering a networked wideband communications to warfighters that are travelling on foot and is therefore optimized for size, weight, and power (SWaP) constrained devices. The waveform packs a lot of networking into a very small package and allows that to be integrated into hand-held radios. Because it operates in an ad-hoc network, SRW works well in providing connectivity for dispersed forces.

The SRW operates in one of the two wideband frequency range: UHF (225 – 450 MHz) and the L-band (1250 – 1390 MHz and 1710 – 1850 MHz). It is designed to efficiently use the spectrum in 1.2 MHz bandwidth allotments, which can provide throughputs of up to 225 kbps. There are two modulation orders: QBL-MSK and CPM. The waveform will also support voice, video and data communications in the immediate area of operations and will be able to interface with the WNW for long-haul operation.

Single Channel Ground and Airborne System (SINCGARS)

SINCGARS is a critical operational waveform that hosts battalion voice command and fire networks. It is currently the most used waveform by the U.S and allied military forces, and has been supporting operations in Iraq and Afghanistan. The waveform has been constantly upgraded (since its early development in the 80s) to meet ever-changing battlefield demands and is currently in its sixth generation.

SINCGARS operates in the VHF band (30 – 88 MHz) and uses a bandwidth of 25 kHz to handle voice and data communications. There two modes of operation: single channel or frequency-hopping mode. Single channel only uses one carrier frequency out of the available 2320 channels, while frequency-hopping mode can rapidly switch carrier at a configurable speed (up to 111 times per second).

Enhanced Position Location Reporting System (EPLRS)

EPLRS is primarily used to distribute tactical information through a secure, jam resistant, computer controlled communications network. It is also used for position location and reporting. The waveform enhances command and control of tactical units by providing commanders with the location of friendly units.

EPLRS utilizes 3 MHz of bandwidth, operating in the 420 – 450 MHz frequency range. There are four modes of channel access: CSMA, TDMA, CDMA and FDMA.

Physical layer characteristics of other legacy waveforms [6]:

HAVEQUICK II:
Center-frequency range: 225 – 400 MHz
Bandwidth: 25 kHz
Data rates: 16 kbps

DAMA SATCOM MIL-181/ 182/ 183
Center-frequency range: 225 – 400 MHz
Bandwidth: 5 and 25 kHz
Data rates: variable up to 56 kbps
Modulation: FSK, SBPSK, BPSK, SOQPSK, DEQPSK and CPM

Link 16
Center-frequency range: 960 – 1215 MHz
Bandwidth: 3 MHz
Data rates: 118/236 kbps
Waveform type: fast frequency-hopping, TDMA/CPSK

Above lists some of the broad range of waveforms used in the military, with each having its own unique physical layer implementation. The waveforms also have different network, data link and security layer implementation, which makes it impossible for hardware specific device to communicate with other device standards. The solution to this problem is to use a software-defined radio that is built on top of a common framework: the Software Communications Architecture.

2.4.2 Software Communications Architecture (SCA)

While industrial communications software and hardware suppliers continue to compete on development, production and delivery of radio products, JTRS guided these suppliers towards reaching for the most interchangeability of components. The tool used is the *Software Communications Architecture (SCA)*, an open framework standard that assist suppliers in the development of software-defined radio communication systems [7]. The existence of SCA would also promote competition amongst hardware (and software) manufacturers so that costs of SDR devices can be reduced.

Architecture overview of SCA

As was discussed earlier, software-defined radio is in essence a radio system whose output signal is determined by software. The functionality of software itself is virtually limitless in that any types of signal can be produced by simply changing the code. Therefore, there is a large dependency placed on the ability of the hardware to cope with what the software can do. JTNC has a standard list of hardware requirements and the organization has the authority to certify devices that are considered as being capable to run the SCA framework. The role of the SCA is therefore to provide a common infrastructure for managing the software and hardware elements present in certified devices. This function is accomplished by defining a set of interfaces that isolate the system applications from the underlying hardware. The set of interfaces is referred to as the Core Framework of the SCA and they consists of [7]:

- Base Application Interfaces.
- Base Device Interfaces.
- Framework Control Interfaces.
- Framework Services Interfaces.

Fig. 4 shows the architecture layer of the SCA framework. The Application Component is the software component that manipulates input data and determines the output waveform. It does this by implementing the Base Application Interfaces of the core framework. System Component consists of software modules (often called *devices*) that can provide access to the hardware resources; and this is done by implementing the Base Device Interfaces of the core framework. An application as a whole normally consists multiple software components, and together they are managed by an implementation of the Framework Control Interfaces (shown as the Control Component block in Fig. 4) of the core framework. An implementation of the Framework Control Interfaces is also used to manage multiple system software components (devices). Framework Services Interfaces (part of the Control Component block in Fig. 4) provide additional support functions and services (such as file system and management) to the application software and devices. From this figure, we can see that the application components and devices communicate with the Framework Services Interfaces through the CORBA middleware. CORBA stands for Common Object Request Broker Architecture, and it is a standard defined by the Object Management Group (OMG) that enables software components written in multiple computer languages and running on multiple computers to work together. Finally, AEP in Fig. 4 stands for Application Environment Profile. It is basically an enumerated set of OS functionality that the application software can access. System components however do not have this restriction on accessing the OS functionality because these components are in general device specific that could require low level software operations.

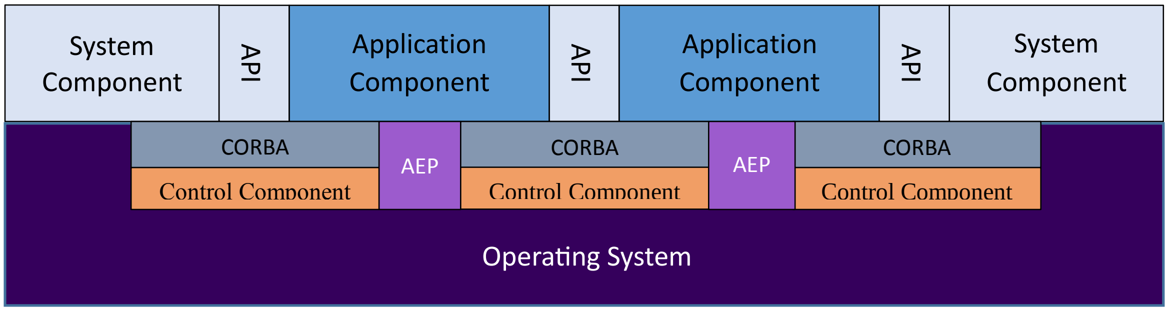

Fig. 4. Architecture layer of the SCA [7].

Waveform implementation on SCA

Because software components tend to be connected to one another, the connections between waveform applications and the SCA framework are essentially given by the APIs (Application Programming Interfaces) [2]. Standardized APIs are essential because they enable the use of same software code to implement a certain waveform across multiple devices. APIs however are waveform specific because using the same set of APIs to implement all waveforms would be inefficient. That is, not all waveform requires the same set of resources of the device. The goal for JTNC is therefore to develop a standard set of APIs for each waveform. The waveform specific APIs are composed of individual API that is used to implement functionalities on each layer of the OSI model. For example, a physical layer API provides the necessary code for converting bandpass signal into two baseband (in-phase and quadrature) components on the receiver, and takes care of the transmission from baseband to bandpass signal on the transmitter. A data link layer API supports the MAC function (e.g. timeslot control in TDMA), as well as all of the waveform’s link layer performance. A network layer API makes available an interface for waveform’s network performance on software component level. This API layer is especially crucial when implementing WNW and SRW waveforms as they rely heavily on communications that can establish a mobile network. Also, the security layer API serves for the software implementation of data security functions.

III. Cognitive Radio

The programmability of a software-defined radio technology enables radio to switch its functionality. However, an SDR system can only do this on demand and it is not capable of reconfiguring itself into the most effective form without the programmer's intervention. This is where the cognitive radio technology takes the extra step of having the ability to autonomously adapt to different surrounding conditions. The concept of Cognitive Radio was first proposed by Joseph Mitola III [8], which he described as "the intersection of personal wireless technology and computational intelligence." Mitola outlined that a CR can reconfigure itself through an ongoing cycle of awareness, perception, reasoning and decision making, similar to an analogy with the mental process of cognition. In a sense, this terminology applies to a broad range of applications, which can lead us to the impression that a CR must be a complex device that can help overcome all problems in our everyday lives. Of course this vision is strongly intended to stimulate future research and development.

Today however, there are many definitions of cognitive radio that have more of a pragmatic view. The U.S. Federal Communications Commission (FCC) uses a narrower definition: "a radio that can change its transmitter parameters based on interaction with the environment in which it operates." Also there is another popular definition by the Wireless Innovation Forum: "a radio in which communication systems are aware of their internal state and environment, such as location and utilization on RF frequency spectrum at that location. They can make decisions about their radio operating behavior by mapping that information against predefined objectives." These pragmatic definitions have three things in common in that a CR system need to be:

- Adaptive: being able to be reconfigured for different operational characteristics.
- Aware: being able to sense and interpret the surroundings.
- Autonomous: being able to maximize predefined objectives without user intervention.

Being adaptive requires CR to have a flexible radio device. An ideal platform (although not necessary) for a CR system to be built on is the software-defined radio platform. Specifically the parameter-controlled SDR would be a suitable candidate because it guarantees that operation characteristics of the radio can be changed instantaneously. Awareness in CR requires the system to be equipped with sensors. Depending on the applications and objective, the type of sensors used can be of spectrum sensing, network sensing and/or many others. Being autonomous requires the system to have a cognitive unit. The cognitive unit tries to find a solution or optimize a performance goal based on inputs received from the sensors.

There are many range of applications that a CR system can implement. For example, a CR system can be built for a jamming device that can learn and block multiple channels of a certain communication protocol [9]. There can also be a CR system that sense whether a particular channel is jammed and tries to find other "clean" channels to maintain communication, which would be valuable in military applications. Most research work however revolves around Dynamic Spectrum Access (DSA) and it is the focus topic for CR technology in this project. In the next section, the concept of spectrum opportunity, its performance measures and implementations are discussed.

3.1 Dynamic Spectrum Access (DSA)

In the past, fixed spectrum assignment policy has generally served well because mobile communications did not have many demanding applications that require the use of high channel bandwidth. Today, there is a dramatic increase in the access to the limited spectrum for mobile services, which causes the growing need for communication system to efficiently utilize this scarce and expensive resource. However, most current wireless networks characterized by fixed spectrum assignment policies are known to be very inefficient. This is because communications transmissions tend to be bursty and that there are moments in time when the resource blocks are unused. Measurements done by Federal Communications Commission for example showed some evidence indicating the shortage of spectrum that is mainly caused by spectrum access problem [10]. Cognitive radio has the potential to solve this spectrum underutilization problem because the system has the ability to sense transmission opportunity and "borrow" the spectrum that is unused by the primary user. This type of operation is often referred to as dynamic spectrum access (DSA).

When accessing these unoccupied frequencies, the secondary wireless device must ensure that it does not interfere with the operations of the primary user transmissions. Also, due to the time-varying nature of the wireless channel, a spectrum that might be occupied at one time instant could potentially be unoccupied at a subsequent time instant. A cognitive radio should therefore be aware of its environment and be able to rapidly reconfigure its parameters to prevent secondary user interference of primary user transmissions. A critical component of DSA is thus its spectrum sensing ability. Together with the decision making component, they constitute the cognitive unit of a CR system.

3.1.1 Spectrum Sensing

There are two types of spectrum sensing: primary signal detection and spectrum opportunity detection. Primary signal detection simply deals with the detection of whether or not the primary users are currently using the spectrum. The basic idea is that the CR system sense a particular spectrum of interest for the existence of any signals transmitted by the primary users. If there is no such signal detected, the secondary users would then use that channel to communicate; otherwise it would consider the channel as being occupied and will not use it. This scenario can be best represented by a binary hypothesis test. That is, the channel is idle under the null hypothesis (H_0) and busy under the alternate (H_1):

$$\begin{aligned} H_0&:\ x(k) = n(k) \\ H_1&:\ x(k) = s(k) + n(k) \end{aligned} \quad (2)$$

where $x(k)$is the received sampled signals, $s(k)$and $n(k)$ are the sampled primary and ambient noise signal respectively.

Spectrum opportunity detection however is more complicated. It involves interference constraint imposed by the primary network that a pair of secondary users must not violate. The secondary users decide that the channel is an opportunity when they can communicate successfully without violating this constraint. Therefore, the existence of a spectrum opportunity is determined by two logical conditions: the reception at the secondary receiver being successful and the transmission from the secondary transmitter being "harmless" [12]. This definition has significant complications in cognitive radio networks where primary and secondary users are geographically distributed and wireless transmissions are subject to path loss and fading.
To get a better illustration of spectrum opportunity detection, consider the case where a pair of secondary users (A and B) seeking to communicate in the presence of primary users as shown in Fig. 5. User A is the transmitter, while user B is the receiver. The area inside the solid circle of A represents the space area that has interference above the constraint to any active primary receivers as a result of A's transmission. That is, if an active primary receiver is located outside of this solid circle, A's transmission would not cause any interference to it. The area inside the dashed circle of B represents the space area that would cause significant interference to B from any active primary transmitters. That is, if an active primary transmitter is located outside of this dashed circle, the signal strength received at B would be considered as negligible that B can A's transmission clearly.

Spectrum opportunity detection can also be considered as a binary hypothesis test. Let *ξ(A, rx)* be the event that there exist active primary receivers at which signal receptions will be corrupted by transmissions from A, and let *ξ(B, tx)* be the event that there exist active primary transmitters whose transmissions interfere with the reception at B. The binary hypothesis is given by [12]:

$$\begin{aligned} &H_0\ (opportunity\ exist)\colon\ \overline{\xi(A,rx)} \cap \overline{\xi(B,tx)} \\ &H_1\ (no\ opportunity)\colon\ \xi(A,rx) \cup \xi(B,tx) \end{aligned} \tag{3}$$

where $\overline{\xi(.,.)}$ denotes the complement of event $\xi(.,.)$.

The figures of merit for both types of spectrum sensing at the physical layer are similar, and they are given by the probabilities of false alarm P_{FA} and miss detection P_{MD}. False alarm occurs when the channel is idle (opportunity exist) but is detected as busy (no opportunity). Similarly, miss detection occurs when the busy (no opportunity) channel is detected as idle (no opportunity), which could potentially lead to a collision with the primary users and wasted transmissions for all users. Mathematically, they can be represented as:

$$\begin{aligned} P_{FA} &= Prob\{Decide\ H_1 | H_0\} \\ P_{MD} &= Prob\{Decide\ H_0 | H_1\} \end{aligned} \tag{4}$$

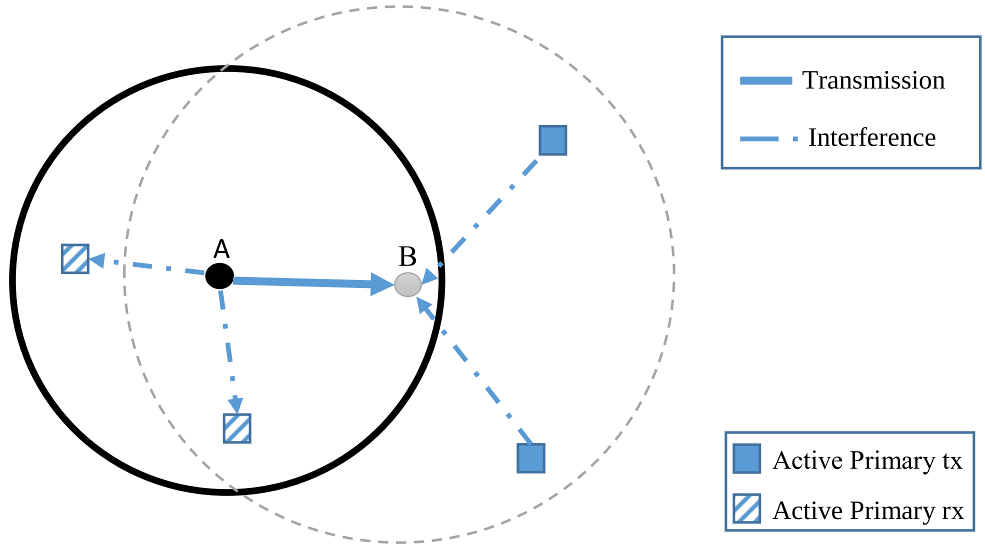

Fig. 5. The occurrence of interference in spectrum opportunity detection [11].

3.1.2 Listen Before Talk (LBT)

Perfect spectrum opportunity detection requires the cooperation with primary users. For example, the event $\xi(A, rx)$ depends on the primary receiver to inform the secondary transmitter A that its transmission violates the interference constraint. The user A would then make the decision that there is no opportunity for channel use in that instance of time. Listen Before Talk (LBT) is the approach where there is no cooperation between users, and that the responsibility of detecting spectrum opportunity falls entirely to the secondary transmitter. Essentially, LBT approach is to detect spectrum opportunities by detecting primary signals. That is, the secondary transmitter (A) sets out a detection range r_D and infers the existence of spectrum opportunity from the absence of active primary transmitters within this range. This can be seen in Fig. 6. Note that the detection range can be adjusted by changing a certain threshold of A's detector device.

If we let $\xi(A, tx)$ be the event that there exist active primary transmitters in the vicinity of r_D, the LBT performance measures at the physical layer are:

$$\begin{aligned} P_{FA} &= Prob\{\xi(A, tx)|H_0\} \\ P_{MD} &= Prob\{\overline{\xi(A, tx)}|H_1\} \end{aligned} \tag{5}$$

Uncertainties however are bound to happen to a CR system that employs LBT technique, even if the secondary transmitter (A) listens to the primary signals with perfect ears (i.e., perfect detection of active primary transmitters within its detection range r_D). That is, even in the absence of additive noise and fading, the geometrical distribution and traffic pattern of primary users have significant impact on the performance of LBT. To illustrate how different geometrical distributions of primary users can result in false alarm or miss detection, consider the disk interference model shown in Fig. 6.

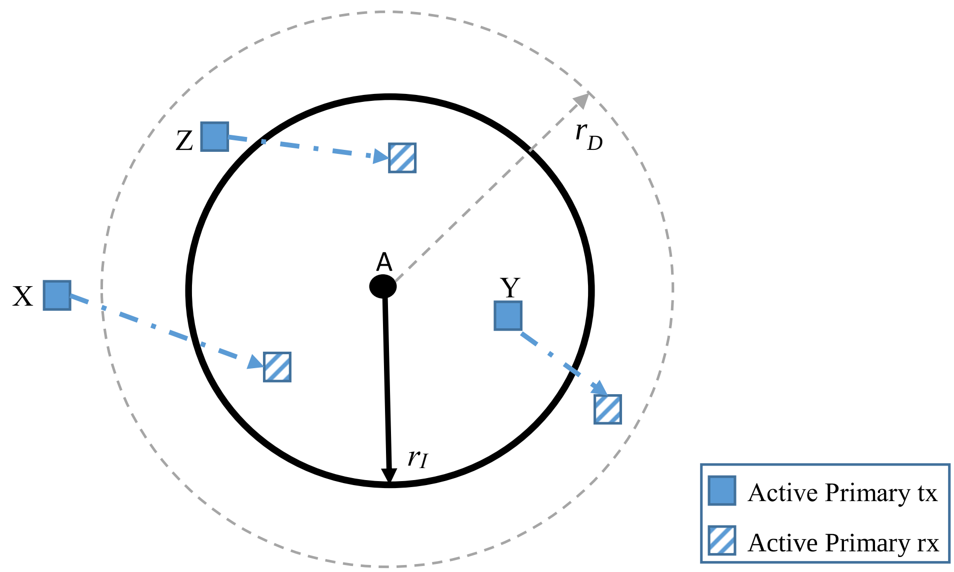

Fig. 6. Disk Interference Model of LBT [11].

r_I (area inside the solid circle) is the area where signal reception at the active primary receivers will be corrupted by transmission from A. r_D (area inside the dotted circle) is the detection area of any nearby active transmitter. The transmission from X is a source for miss detection because X is located outside of the detection region r_D, while its receiver is located inside the interference region of A (r_I). The transmission from Y, however is a source of false alarm because while Y is located inside of the detection region, the corresponding receiver is outside of the interference region (hence any transmission from A would not corrupt with its reception). The transmission from Z however is safe from these errors because it is located inside the detection region and that its receiver is located inside the interference region.

We can see that measuring this type of CR system is fairly complicated as it depends on the geographical distribution of primary users. In [11], Ren et al. analyzed the performance of LBT with perfect ears for spectrum opportunity detection in a Poisson primary network. That is, the primary users are distributed according to a two-dimensional homogeneous Poisson process where in each transmission slot, each primary user has a certain constant probability of becoming a transmitter. The authors then derived the overall probability of false alarm and miss detection, and plotted the relationship between the two. An important point to note is that there exist a trade-off between the probability of missed detection and the probability of false alarm, as shown in Fig. 7. This relationship is crucial in the design of cognitive radio system. The choice of an operating point becomes a matter of optimization, where a cap is usually placed on the allowed probability of missed detection. The optimization problem then is to minimize the probability of false alarm, subject to a constraint on the probability of missed detection. For example, when a maximum cap for P_{MD} is known (which is equivalent to a minimum cap of P_D =

$1 - P_{MD}$), the detection region r_D should be decreased to the point where P_{FA} is at the lowest level.

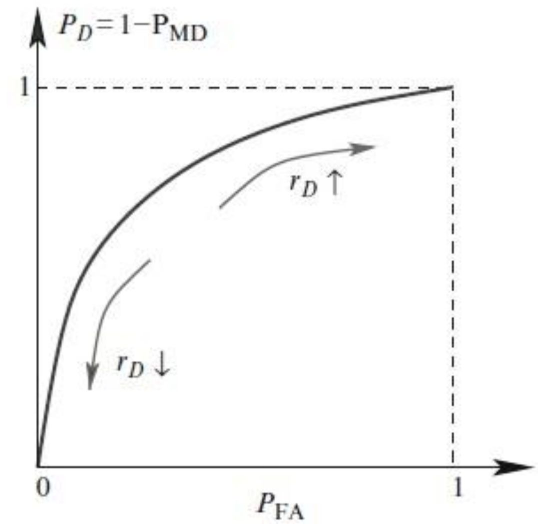

Fig. 7. A Typical receiver operating characteristic (ROC) of spectrum opportunity detection [11].

3.1.3 Types of Primary Signal Detector

Varying the detection region r_D to choose the operating point within the ROC curve is achieved by varying certain threshold limit of the primary user detector. Two of the most common types of detectors are energy and cyclostationary-feature detectors.

Energy Detector

Energy detector is often used when the signaling scheme of the primary users are unknown to the secondary users. The received signal can then be modelled as a zero-mean stationary Gaussian process, independent of the noise. Consider the binary hypothesis test shown previously in (2). If we assume that the channel is AWGN, *s(k)* and *n(k)* are both zero-mean complex Gaussian random variables. It can be seen that the detector decides H_1 (busy) if

$$z = \frac{1}{2n{\sigma_0}^2} \sum_{k=1}^{n} |y(k)|^2 > \tau \qquad (6)$$

where τ is the threshold level, σ_0 is the noise variance, n is the number of observed samples and z is a scaled version of a standard χ^2 random variable with n degrees of freedom. The choice of threshold τ therefore depends on the probability of missed detection [12]:

$$P_{MD} = 1 - \Gamma(a, u) \qquad (7)$$

where $a = \frac{u\tau}{1+snr}$ and $u = \frac{n}{2}$ and $\Gamma(.,.)$ is the upper incomplete gamma function defined by:

$$\Gamma(a, u) = \int_{a}^{\infty} t^{u-1} e^{-t} dt \tag{8}$$

For fading environment, one can determine the allowed average missed detection probability and set the threshold level accordingly. Several closed form expressions for average detection probability under different types of fading channel are derived in [13].

Cyclostationary-feature detector

Modulated signals in general have built-in periodicity because they are often coupled with sine wave carriers, pulse train, repeating spreading or cyclic prefixes. Even though the data itself is a stationary random process, the modulated signal can be characterized as a wide-sense cyclostationary process because its mean and autocorrelation are periodic. The periodicity would cause the cyclostationary signals to exhibit correlation between widely separated spectral components. A way to capture this correlation is by observing its spectral correlation function (SCF) defined as [17]:

$$S_x^{\alpha}(f) \triangleq \lim_{\Delta f \to 0} \lim_{T \to \infty} \frac{1}{T.\Delta f} \int_{f-\Delta f/2}^{f+\Delta f/2} X_T(t, v + \frac{\alpha}{2}) X_T^*(t, v - \frac{\alpha}{2})\, dv \tag{9}$$

where α is the cycle frequency, T is the observation length, Δf is the size of the smoothing window, and X_T is the time-variant Fourier transform defined as:

$$X_T(t, f) \triangleq \int_{t-T/2}^{t+T/2} x(u) e^{-j2\pi f u} du \tag{10}$$

x here is the received wide-sense cyclostationary signal.

The proposed primary user signal detection in [17] uses the cycle frequency domain profile (CDP) and a threshold-test method. The authors defined the CDP as:

$$I(\alpha) \triangleq \max_f |C_x^{\alpha}(f)| \tag{11}$$

where $C_x^{\alpha}(f)$ is the correlation coefficient of the SCF shown in (9), which is commonly known as the spectral coherence (SC).

The threshold-level test uses CDP for comparison. The threshold C_{TH} is first calculated when no signal is present, i.e., the case where $x(k) = n(k)$ in (2),

$$C_{TH} = \max(I(\alpha)) / \sqrt{\sum_{\alpha=0}^{N} I^2(\alpha)/N} \tag{12}$$

where N is the observation length that determines the FFT size. Following the binary hypothesis test in (2), the proposed signal detection test is performed as follows:

$$\begin{aligned} C_I \leq C_{TH} &: Declare\ H_0 \\ C_I > C_{TH} &: Declare\ H_1 \end{aligned} \tag{13}$$

CDP has a nice uniqueness property for different modulation schemes. Because of this, it can also be applied to classify modulation types without demodulating the signal.

3.2 Commercial Presence

802.22 WRAN

The success of unlicensed band in accommodating a range of devices and services (e.g., the 2.4 GHz for IEEE 802.11 WiFi) has led the FCC to consider opening further bands for unlicensed use. In the contrary, the licensed bands are underutilized due to the fixed spectrum policy that prevents secondary users to exploit spectrum opportunity. Realizing that CR technology has the potential to efficiently exploit underutilized bands without causing interference to the primary users, the FCC released a Notice of proposed rulemaking (NPRM) on May 2004, which would allow unlicensed radios to use white spaces in the TV frequency spectrum. In response to this, the Institute of Electrical and Electronics Engineers (IEEE) formed the IEEE 802.22 working group for implementing wireless regional area network (WRAN) on October 2004. It is the first worldwide effort to define a standardized air interface based on CR techniques for the opportunistic use of TV bands on a non-interfering basis. The 802.22 standard aimed to facilitate sharing of geographically unused spectrum allocated for TV broadcast service and utilization of free spectrum to bring broadband services to low population density remote areas. The standard was published in July 2011.

The WRAN network topology operate in a point to multipoint basis (P2MP). That is, the network is formed by a base station and a number of client stations (referred to as customer-premises equipment (CPE)) that are attached to it. Each station in an 802.22 network is required to perform spectrum sensing. The base station controls the whole sensing operation and all of the spectrum sensing results are reported to it. The base station rely on the information gathered to evaluate whether a change in channel used is necessary, or in the contrary, if it should stay transmitting and receiving in the same one. This type of sensing technique is known as *cooperative spectrum sensing*, where spectrum opportunity decisions are based not only on the measurements reported by a single user but also on information from other cognitive users.

The standard does not mandate the use of a specific signal processing technique, instead it mandates specific sensing performance and a standardized reporting structure. Some of the physical layer implementation and spectrum sensing requirements are as follows [12]:

- Operate in the UHF/VHF TV bands between 54 and 862 MHz.
- OFDMA modulation scheme for both uplink and downlink.
- Bandwidth of 6 MHz (7 or 8 MHz in some countries).

- Maximum allowed detection time of 2 seconds.
- Required to sense analog television, digital television and wireless microphones.
- Required probability of missed-detection and probability of false alarm of 0.1.
- Sensing receiver sensitivity requirements are shown in Table II.

Table II. Detection sensitivity requirements for the 802.22 WRAN.

	Analog TV	**Digital TV**	**Wireless Microphones**
Detection threshold	-94 dBm	-116 dBm (over 6 MHz)	-107 dBm (over 200 kHz)
SNR	1 dB	-21 dB	-12 dB

Implementations in LTE-A

Long term evolution (LTE) standard was designed to improve the performance of mobile broadband, mainly to support high data rates communications in a cellular system. However, the road towards the next generation LTE-Advanced (LTE-A) introduces more challenging requirements (e.g., peak data rates up to 1 Gbps) and there are many different techniques still being considered by the 3rd Generation Partnership Project (3GPP) committee that can reach or go beyond these requirements. The preferred solution to achieve higher data rates transmission is the use of carrier aggregation, and it is the most distinct feature of LTE-Advanced. Carrier aggregation allows the use of concurrent carriers for a single transmission so that the expansion of effective bandwidth can be delivered to the user terminal.

Despite the potential advantageous of carrier aggregation, a major problem is the scarcity of the spectrum. Carrier aggregation demands extra resource bandwidth (up to 100 MHz) that might not be available. The cognitive radio has been proposed as a feasible solution to this problem in that the technology has to ability to “borrow” from frequency bands that are underutilized. In [14], Osa et al. proposed a cooperative opportunistic access framework for LTE-A, with a great deal of emphasis paid on the practical issues related to the implementation. The authors proposed the adoption of a geo-located database (Geo-DB) containing the available spectrum holes in a certain frequency band at a given time. The use of geo-localization of spectrum sensing measurements not only enables the detection of white spaces at a particular time, but also the location of those white spaces. The authors proposed a low-cost solution by identifying the set of tools available in LTE-A standard which enables the opportunistic spectrum access of cognitive radio. This set of tools is used for spectrum sensing, sensing data report and user positioning.

Spectrum sensing

For the purpose of handover, there are some user measurement capabilities that are being considered for the LTE-A standard. These capabilities can be exploited to sense the state of the channel. The measurement gap length (MGL) is the timing parameter defined in the standard for end user measurement. During this time, the scheduler does not allocate any resource to the user and the time spent is solely for the purpose of measurement. Therefore, this is the ideal time for spectrum opportunity detection to be executed. According to the standard, MGL is fixed (6 ms) but the periodicity of this measurement occurring is configurable to allow the choice in the trade-off between system throughput and up-to-date sensing. During this measurement gap, LTE-A end users are capable of measuring the so called Received Signal Strength Indicator (RSSI). This measurement provides the necessary feature of detecting the presence of any active primary user in the frequency band of interest.

Sensing data reporting

In a cooperative spectrum sensing, the spectrum sensing measurements from all user equipment (UE) must be reported back to a centralized processing node where decision for opportunity access can be made. This centralized approach requires a new-node in the LTE-A network, which the authors referred to as the cognitive resource manager (shown as CRM in Fig. 8). The proposed reporting procedure uses the IEEE 802.21 protocol (also known as the Media-Independent Handover (MIH)) for its popularity and the availability of open source implementations. MIH is a standardized application layer protocol normally used for handling IP sessions among many wireless access technologies. In this case, the protocol is used for exchanging spectrum sensing measurements data. This provides the necessary interface between the cognitive UEs and the CRM.

User positioning

As mentioned earlier, the benefit of using geo-localization spectrum sensing is that it enables the detection of the location of white spaces. Fortunately, location positioning of UEs is a feature of an LTE-A standard that has been ratified. In an LTE-A network architecture, two nodes are responsible for getting the location of each UEs: the mobile management entity (MME) and the enhanced serving mobile location center (E-SMLC). MME is the main controller that is responsible for getting and providing subscriber's data, providing handover support, handles authentication, as well as tracking the location of UEs. E-SMLC receives a location service request from the MME and execute the positioning procedure. The LTE-A specification considers the use of LTE Positioning Protocol (LPP) for executing this procedure.

Proposed architecture

The proposed LTE-A network architecture with cooperative spectrum opportunity sensing is shown in Fig. 8. The Geo-DB contains valuable information about which frequency bands can be used by a given eNodeB at a specific moment of time. It also specifies the maximum coverage range from the eNodeB in order not to interfere with the active primary users. The CRM collects the sensing information from the UEs and the positioning information provided by the MME. The entity then updates the database after a cooperative decision.

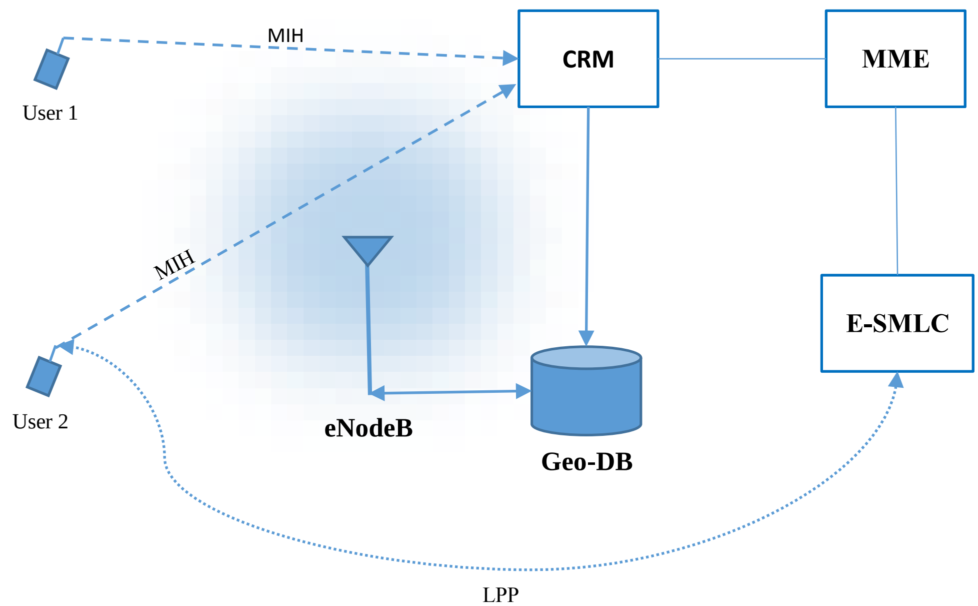

Fig. 8. Proposed LTE-A network architecture [14].

3.3 Military Presence

neXt Generation communications (XG) program

Perhaps the most notable cognitive radio work for military applications is the next Generation communications (XG) program funded by the Department of Defense's (DoD) Defense Advanced Research Projects Agency (DARPA). The XG program is developing technology and system concepts for military line-of-sight radios to dynamically access spectrum in order to establish and maintain communications. The XG technology assesses the spectrum environment and dynamically uses spectrum across frequency, space and time. It is also designed to be successful in the face of jammers and not to interfere with commercial, public service, and other military communications system.

In 2005, Shared Spectrum Company (SSC) was awarded the prime contract for Phase III of the XG program. Since then, the company has made a significant progress in developing its Dynamic Spectrum Access (DSA) software. Its current implementation supports multiple DSA modes: Listen-Before-Talk (LBT), Group Behavior and Policy Control [15]. Group behavior mode combines multiple measurements from cognitive units to extend the system's detection distance. Policy control enables the separation of all the policy software from the rest of the radio software. This allows multiple controlling authorities to provide spectrum access policies to any DSA radio.

The SSC's DSA system architecture is shown in Fig. 8. This architecture has four main components: the DSA engine, the environmental sensing, the communications subsystem and a policy module/enforcer.

The DSA engine forms the brain (i.e. cognitive unit) of the whole cognitive radio system. The engine can be further broken down into three subcomponents: spectrum manager, scheduler and rendezvous functions. The spectrum manager is responsible for managing the list of candidate channels. This is where the policy compliance and the decision making about opportunistic access of a channel is made. The scheduler manages the operation of the detectors and collects spectrum sensing measurements. Rendezvous process uses the list of candidate channels developed by the spectrum manager for network discovery and frequency negotiation with other cognitive nodes in the network.

The policy modules loads the spectrum access policies that govern the operation of the spectrum manager. The detector API provides the interface to the sensing devices at a software component level. Similarly, the radio API provides the necessary software interface to a specific radio device.

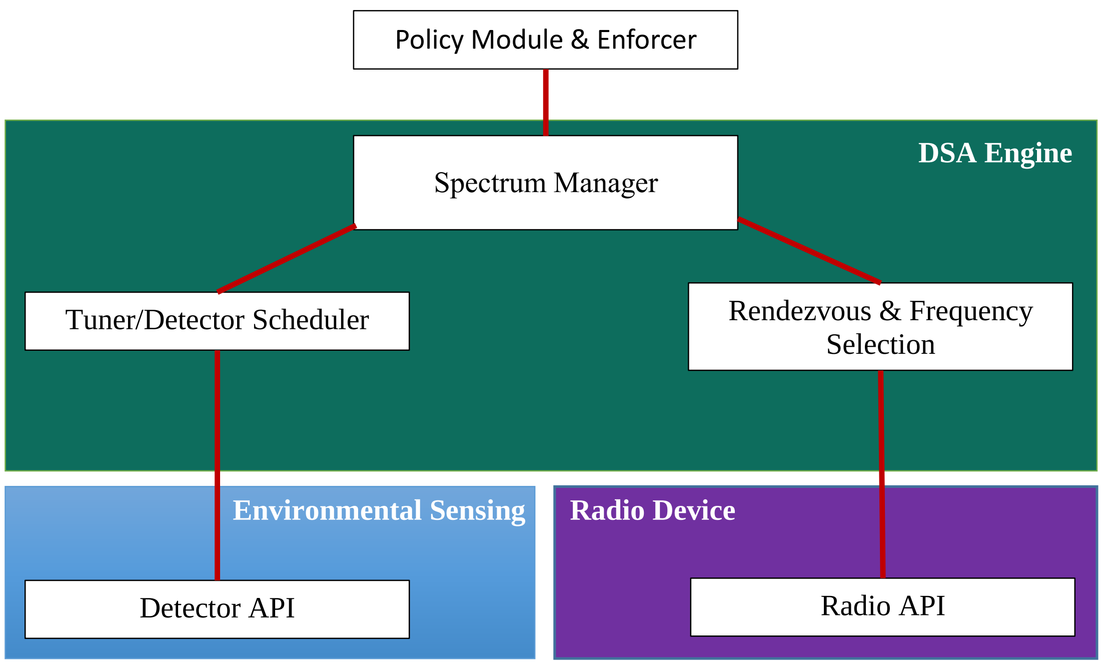

Fig. 9. SCC's DSA architecture [15].

Software-defined radio is an important step toward achieving full XG capabilities. XG technology is being built based on the assumption that technologies such as SDR system developed by the Joint Tactical Networking Center (JTNC) will succeed. As the SDR technology is mastered, DARPA plan to transition and integrate XG into the JTNC program. Part of this early transition process begins in 2008, when SSC's XG contract with the U.S. government was modified to have the company analyze existing and future military communications system, including the JTNC SDR system [16]. SCC has also entered into an agreement with Harris Corporation to conduct a joint study of integrating its dynamic spectrum access software into the Harris Falcon III military radios. The Harris Falcon III AN/PRC-152 handheld radio is the first JTRS-approved radio to be certified as fully compliant with Software Communications Architecture (SCA) version 2.2.

Future work and testing is yet to be done, but it is clear the direction in which XG program is heading: developing military cognitive radio system built on top of a software-defined platform, namely the SCA framework. This integration will deliver the added functionality to the JTNC SDR program, in that the system will possess a cognitive ability in determining the most effective form of the military communication.

IV. Conclusion

Some of the capabilities of software defined radio and cognitive radio platforms are examined and compared. SDR technology provides the flexible framework for switching functionality, which is made possible by the programmable application software. The basic transceiver architecture of SDR platform is shown and some of the physical layer operation parameters for the third and fourth generation cellular standards are tabulated. This gives an example on how a cellular SDR base station typically operates in the front-end module. In the military sector, SDR system for the U.S. military continues to be developed under the supervision by the Joint Tactical Networking Center (JTNC). The JTNC is responsible for developing and managing military waveforms as well as maintaining the Software Communications Architecture (SCA) framework. The physical layer parameters of several military waveforms are addressed and a brief overview of the SCA architecture is discussed.

In the second part of the project, CR technology that implements opportunity spectrum access is analyzed. The concept of opportunity access is explained and that its physical layer performance depends on two probability measures: false alarm and missed detection. Two of the most commonly used primary signal detections are analyzed. They are the energy detector and the cyclostationary-feature detector. Unlike SDR, the CR platform has mostly found its way into the commercial sector. This is because a lot of the licensed spectrums owned by many companies are underutilized. The CR technology is therefore an ideal solution to solve this problem since it has the ability to borrow unused spectrum without causing much interference to the primary users. This is the concept used for implementing the IEEE 802.22 WRAN standard. The opportunistic spectrum access technique is also being considered for 3GPP’s next generation LTE-Advanced cellular standard. Finally, the architecture of DARPA’s neXt Generation (XG) communications program is discussed. The program is developed for the sole purpose of implementing CR technology into the radios used by the U.S. military.

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