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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

EC8071 –COGNITIVE RADIO

(REGULATION -2017)

UNIT I

INTRODUCTION TO SOFTWARE-DEFINED RADIO AND COGNITIVE RADIO

Evolution of Software Defined Radio and Cognitive radio: goals, benefits, definitions, architectures, relations with other radios, issues, enabling technologies, radio frequency spectrum and regulations.

Ref. 1) Alexander M. Wyglinski, Maziar Nekovee, Thomas Hou, ―Cognitive Radio Communications and Networks‖, Academic Press, Elsevier, 2010.

Software Defined Radios – Concept

- The basic concept of the SDR software radio is that the radio can be totally configured or defined by the software so that a common platform can be used across a number of areas
- There is also the possibility that it can then be re-configured as upgrades to standards arrive, or if it is required to meet another role, or if the scope of its operation is changed.

what Software is….

- Software, is that part of a computer system that consists of encoded information or computer instructions, in contrast to the physical hardware from which the system is built.

What Radio is…

- Radio is the technology of using radio waves to carry information, such as sound, by systematically modulating some property of electromagnetic energy waves transmitted through space, such as their amplitude, frequency, phase, or pulse width.

When radio meets software…

- Data communication networks plays a vital role in any modern society.
- They are used in numerous applications, including financial transactions, social interactions, education, national security, and commerce.
- With the exponential growth in the ways and means by which people need to communicate - data communications, voice communications, video communications, broadcast messaging, command and control communications, emergency response communications, etc.
- Modifying radio devices easily and cost-effectively has become business.

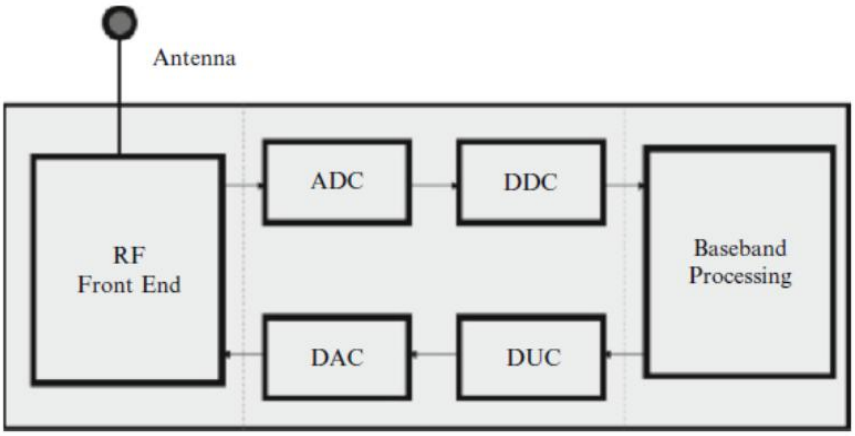
Why Software Meets Radio?

There are certain crucial drawbacks with pure radio systems.

- Least Flexibility
- Design Cost is High
- Possibility of Updating to new technologies is difficult.
- These Drawbacks are addressed by incorporating Software along with the Hardware Radios

What Is Software-Defined Radio?

- A number of definitions can be found to describe Software Defined Radio, also known as Software Radio or SDR. The SDR Forum, working in collaboration with the Institute of Electrical and Electronic Engineers (IEEE) P1900.1 group, has worked to establish a definition of SDR that provides consistency and a clear overview of the technology and its associated benefits.
- "The Radio in which some or all of the physical layer functions are software defined"
- As the name suggests, a software defined radio is a radio system where the majority of baseband processing (Physical Layer Functions) are done in software which includes modulation, forward error correction, spreading, filtering, frequency, timing synchronization, and so on.
- Simple way to understand SDR, have a look at the digital radio shown in Figure.



(Image Source : Ref.book)

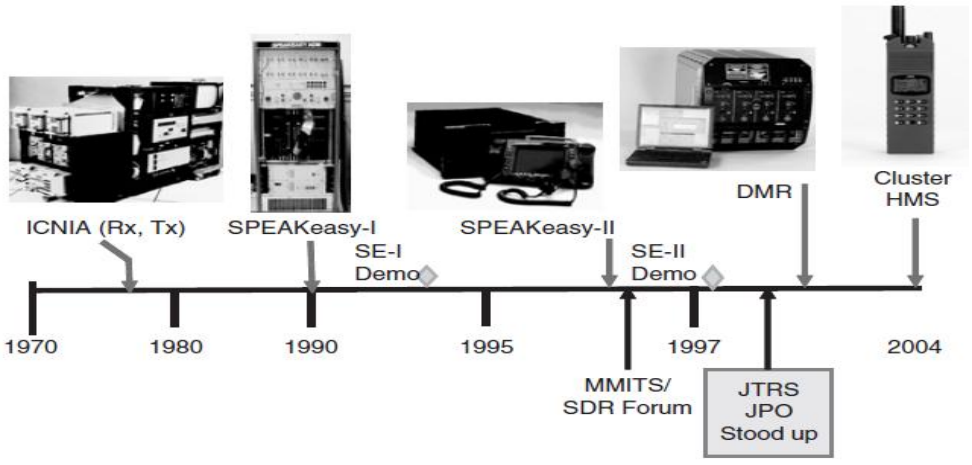
Block diagram of a generic digital radio consists of five sections:

- The antenna section, which receives (or transmits) information encoded in radio waves.
- The RF front-end section, which is responsible for transmitting/receiving radio frequency signals from the antenna and converting them to an Intermediate frequency (IF).
- The ADC/DAC section, which performs analog-to-digital/digital-to-analog conversion.
- The digital up-conversion (DUC) and digital down-conversion (DDC) blocks, which essentially perform **modulations of the signal** on the transmitting path and **demodulation of the signal** on the receiving path.

- The baseband section, which performs operations such as connection setup, equalization, frequency hopping, coding/decoding, and correlation, while also implementing the link layer protocol.
- The DDC/DUC and baseband processing operations require **large computing power,** and in a conventional digital radio are implemented in dedicated hardware.
- Software-defined radio refers to technologies wherein these functionalities are **performed by software modules** running on field programmable gate arrays (FPGAs), digital signal processors (DSP), general-purpose processors (GPP), or a combination there of.
- This enables programmability of both DDC/DUC and baseband processing blocks.
- SDR is currently used to **build radios that support multiple interface technologies** (e.g., CDMA, GSM, and WiFi) with **a single modem** by reconfiguring it in software.
- SDR is currently used mostly in military applications, where cost is less of a constraint.

EVOLUTION OF SOFTWARE-DEFINED RADIO

- Two decades ago most radios had no software at all, and those that had it didn't do much with it. In a remarkably visionary article published in 1993, **Joseph Mitola** III envisioned a very different kind of radio.
- A digital radio that could be reconfigured in fundamental ways just by **changing the software code running on it**.
- He dubbed this *software-defined radio.*



(Image Source : Ref.book)

- A few years later **Mitola's vision** started to become reality. In the **mid-1990s military radio systems were invented** in which software controlled most of the signal processing digitally, enabling one set of hardware to work on many different frequencies and communication protocols.
- The first (known) example of this type of radio was the
- U.S. military's SPEAKeasy I (not easily portable) &
- SPEAKeasy II radios, which allowed units from different branches of armed forces to communicate for the first time.
- SPEAKeasy II was a much more compact radio, the size of two stacked pizza boxes, and was the **first SDR with sufficient DSP** resources to handle many different kinds of waveforms.
- In the late 1990s **Cellular networks** were considered as the most obvious and potentially most lucrative market that SDR could penetrate.
- in 2005 **GSM base station**, which became the *first SDR product to receive approval under the newly established software radio regulation.*
- In March 2005 Airspan released the first commercially available **SDR based IEEE 802.16** base station.
- The AS.MAX base station uses **picoarrays** and a reference software implementation of the **IEEE 802.16d standard**. The **picoarray** is a reconfigurable platform that is **10 times** faster in processing power than today's **DSP**s.
- The AS.MAX base station promises to be **upgradeable to the next generation mobile 802.16e** standard and so has the potential to offer a future-proof route to operators looking to **rolling out WiMAX services.**
- **GNU radio** is an **open-source architecture** designed to run on **general-purpose** computers.
- Gnu radio has been extensively used as an **entry-level SDR** within the research community.
- Due to its **high demand** on computation and processing, **SDR** technology has *worked only in devices that have less constraint in size and power consumption*, such as base stations and moving vehicles.
- However, as new processing platforms emerge that overcome power and size constraints, it is very likely that SDR will make its way into portable devices.

POTENTIAL BENEFITS OF SDR

- The usage of software defined radio offers various advantages over the hardware radios.
- Few of the advantages are mentioned below
- SDR offers the greatest flexibility
- SDR provides Software Reusability
- Testing and Analysis made easy using SDR

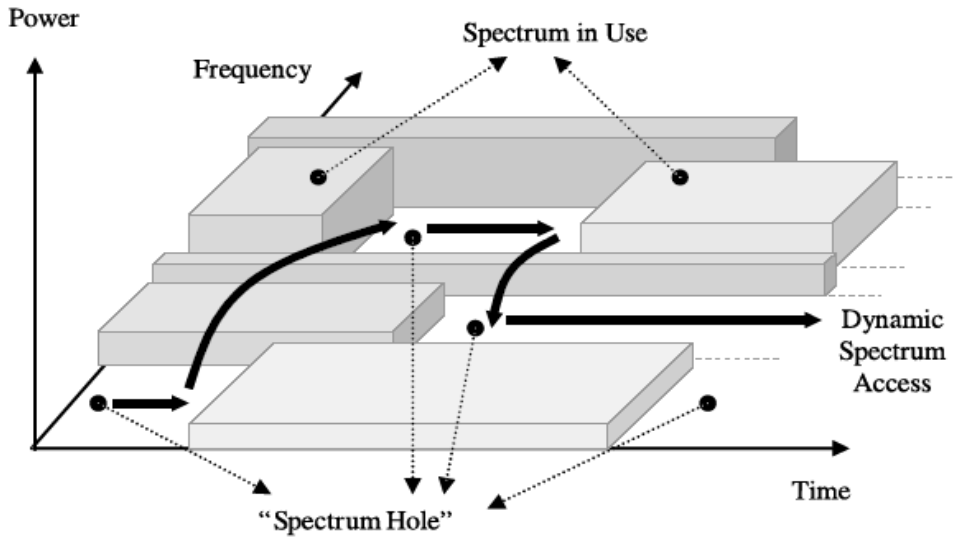
EVOLUTION OF COGNITIVE RADIO

- The main precursors for CR research was the seminal work by Mitola and Maguire in 1999 and early spectrum measurement studies conducted as early as in 1995 to **quantify the spectrum use, both in the licensed and unlicensed band.**
- CR research focused quickly on dynamic spectrum access (DSA) and secondary use of spectrum as the **main objectives** of the initial research.
- In the standardization domain, *three major groups* have emerged to work on relevant technologies and architectures: **IEEE 802.22** and **SCC41** (formally P1900) working groups and more recently **ETSI's** Reconfigurable Radio Systems Technical Committee on CRs and SDRs.
- The most advanced standardization activity is IEEE 802.22 and related research that aims to **provide dynamic access to vacant TV spectrum**.
- In the United States, the FCC already proposed to allow opportunistic access to TV bands in 2004.
- After extensive tests, the FCC adopted in November 2008 a Second Report and Order that establishes rules to allow the operation of cognitive devices in TVWS on a secondary basis.
- (TVWS)-TV White Spaces refer to frequencies allocated to a broadcasting service but not used locally
- The U.K. regulator, Ofcom, is proposing to "allow licence exempt use of interleaved spectrum for cognitive devices"
- On February 16, 2009, Ofcom published a new consultation providing further details of its proposed cognitive access to TVWS.

- With both the United States and United Kingdom adapting the cognitive access model, and the emerging 802.22 standard for cognitive access to TV bands being at the final stage
- **FCC(Federal Communications Commission) assigns** spectrum to licensed holders, known as *primary users (PU).*
- Users who have no spectrum licenses, known as *secondary users (SU).*
- FCC has been considering more flexible and comprehensive uses of the available spectrum, through the use of *cognitive radio* technology.

DYNAMIC SPECTRUM ACCESS

- CR Technology works on the principle of dynamic spectrum access, where secondary users utilize spectrum holes.
- A spectrum hole (shown in figure) is a band of frequencies assigned to a primary user, but, at a particular time and specific geographic location, the band is not being utilized by that user.



(Image source : Ref.Book)

How is a Cognitive Radio Different from Other Radios?

Conventional Radio

- Supports a fixed number of systems
- Reconfigurability decided at the time of design
- May support multiple services, but chosen at the time of design

Software Radio

- Dynamically support multiple variable systems, protocols and interfaces
- Interface with diverse systems
- Provide a wide range of services with variable QoS

Cognitive Radio

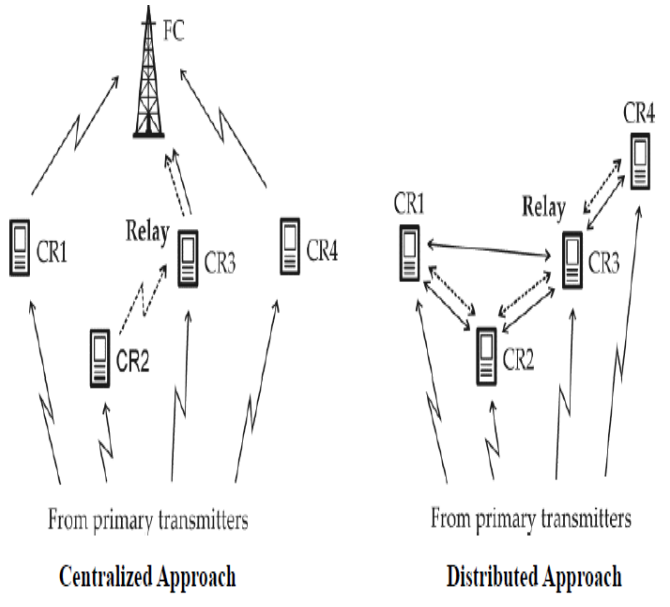
- Can create new waveforms on its own
- Can negotiate new interfaces
- Adjusts operations to meet the QoS required by the application for the signal environment
- SDR+intelligence

CR ARCHITECTURE

- The architecture of CR networks can either be centralized or distributed.

Centralized Approach – Spectrum allocation and access are controlled by a central entity (e.g., a base station).

Distributed Approach – Spectrum Allocation and access controlled by CR users.



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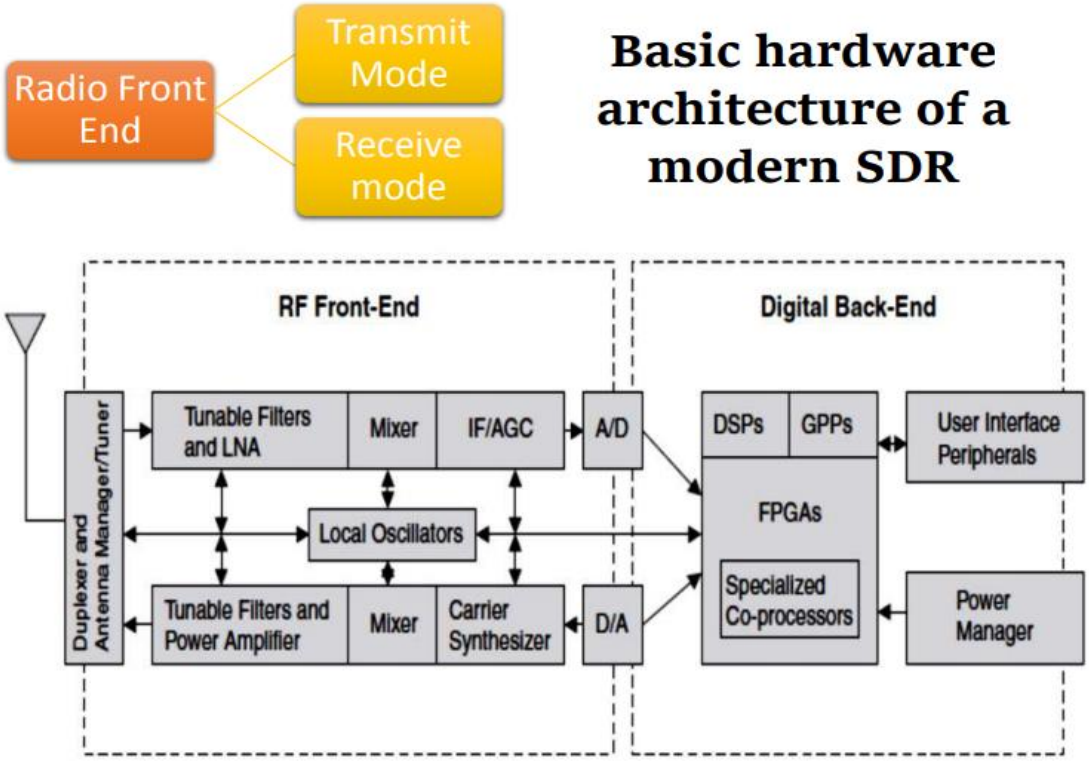
SDR - Hardware Architecture



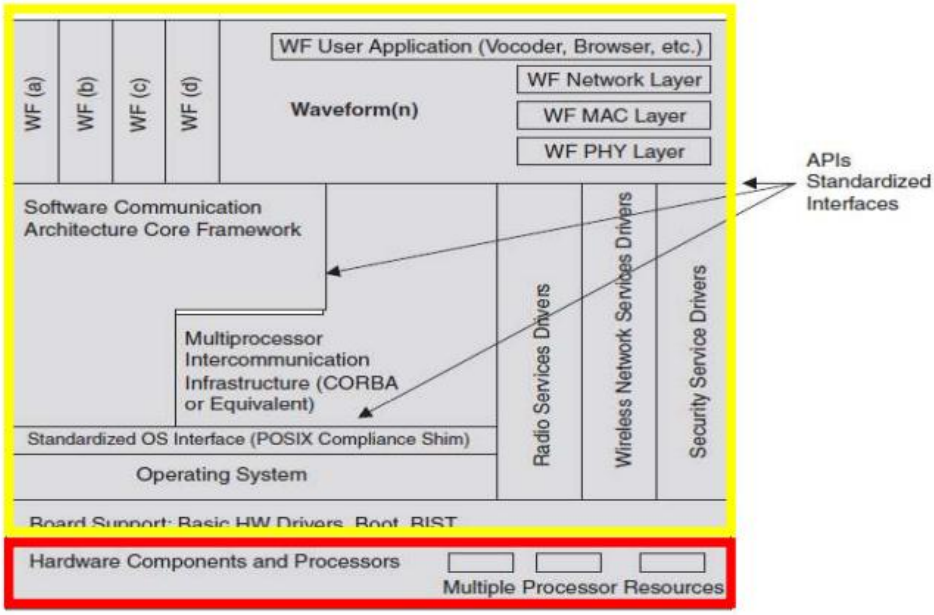
(Image Source : Online)

- The RF front-end (RFFE) consists of the following functions to support the receive mode:
- Antenna-matching unit, Low-noise amplifier, Filters, Local oscillators, Analog to-digital (A/D) converters (ADCs) to capture the desired signal and suppress undesired signals to a practical extent.
- 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.

SOFTWARE ARCHITECTURE

- The objective of the software architecture in an SDR is to place waveforms and applications onto a software-based radio platform in a standardized way.

- These waveforms and applications are installed, used, and replaced by other applications as required to achieve the user's objectives.
- The Software radio is decomposed into a stack of hardware and software functions, with open standard interfaces. As shown in Figure
- stack starts with the hardware and the one or more data buses that move information among the various processors.



(Image Source :Ref.book)

The Software Framework includes several layers, they are:

- Board Support -contains the input / output drivers which controls each interface
- Operating systems -the low-level software that supports a computer's basic functions, such as scheduling tasks and controlling peripherals
- Standardized OS Interface

POSIX - The Portable Operating System Interface -This is a standard for maintaining the compatibility between operating systems

- Multiprocessor intercommunication infrastructure

CORBA - Common Object Request Broker Architecture - (CORBA) is an architecture and specification for creating, distributing & managing distributed program objects in a network.

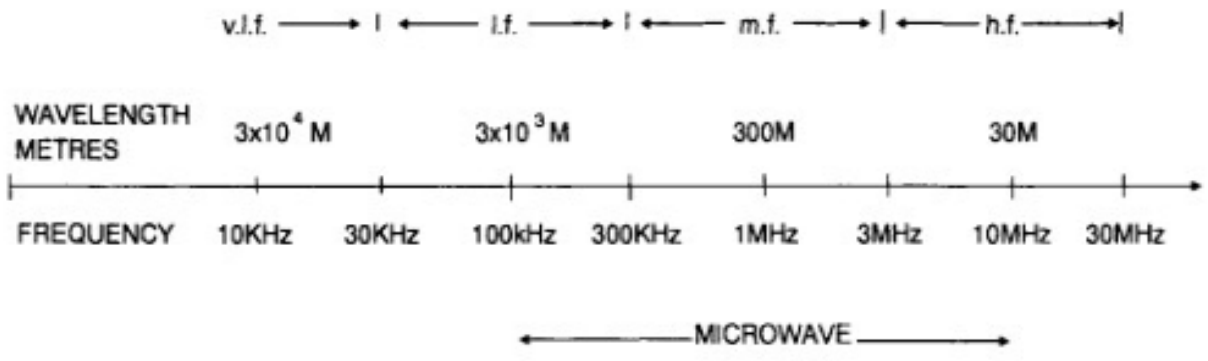
- Software communication Architecture core frame work

The SCA is a core framework to provide a standardized process for identifying the available computational resources of the radio, matching those resources to the required resources for an application.

RADIO FREQUENCY SPECTRUM AND REGULATION

Radio frequency spectrum

- The radio frequency spectrum is an abundant natural resource that uniformly covers the planet and is available for a wide variety of useful purposes.
- Beyond the historic voice communications and increasingly dominant multimedia and data networking focus of this text, this spectrum is regularly used for a diverse array of applications, including radar for finding large and small objects.
- Even cooking food in the microwave oven in your home.
- The radio frequency spectrum is divided into a number of bands which have been given designations such as l.f., m.f., h.f. etc. for ease of reference.



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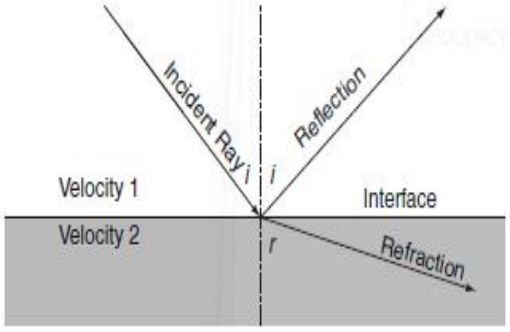
Physical characteristic of spectrum

- The radio frequency spectrum is formed by a virtually infinite set of discreet frequencies characterized as waves with wavelengths corresponding to the frequencies.
- according to the simple formula, frequency equals the speed of light divided by the wavelength, or

$$f = c/\lambda$$

- Like all elements of the electromagnetic spectrum, the radio frequency component of this spectrum has the wavelike characteristics of reflection, refraction, diffusion, absorption, and scattering.



- With appropriate care and at times considerable ingenuity, these characteristics can be used to enhance the capabilities of the radio frequency source (i.e., the transmitter) either by enabling its transmissions to reach receivers that are otherwise hidden from the transmitter (i.e., non–line of sight or NLOS)

COGNITIVE REGULATION

- Cognitive regulation refers to the self-directed regulation of cognitions (thoughts, beliefs, affects) toward the attainment of goals.

Regulatory History and Successes

- The history of spectrum regulation closely followed the early development and deployment of the first wireless communications systems, the wireless telegraph pioneered by Marconi and others in the late 1800s.
- The first international wireless standards meeting, the International Radiotelegraph Conference, was organized by the International Telegraph Union (ITU), the governing body for wired telegraph operation, and held in 1906 in Berlin.

- At the International Radiotelegraph Convention, which established the basic standards for wireless telecommunications, particularly between ships and land-based stations.
- These regulations have been expanded and revised over the years and continue today as the Radio Regulations, now updated based on the outcomes of the quadrennial World Radio communications Conference (WRC).

Radio Regulations

- RR is a single set of international regulations on spectrum/orbit use
- RR is intergovernmental treaty. Ratified by governments
- Define the rights and obligations of Member States in respect of the use of spectrum/orbit resources and explains how these rights may be obtained and kept
- Updated every 3-4 years by World Radio communication Conferences, WRCs
- Main goals of the RR:
- - interference free operation of stations
- - harmonization of spectrum usage RR is a single set of international regulations

Era of Increasing Regulatory Challenges

- The military and emergency services need real-time information to better plan, coordinate, direct, execute, and assess their various activities.
- Finally, government and nongovernment social service organizations and educational organizations are seeking to improve their effectiveness and efficiency in providing their services.
- The four elements of the quadruple whammy are listed and elaborated as:
- **Applications**
- **Coverage**
- **Duty Cycle**
- **Performance**

Allocation, Reallocation, and Optimization

- With a finite supply of spectrum and an ever-increasing demand for that spectrum, the value of the spectrum has risen and will continue to rise; and that rise will be directly related to the increasing demand.
- This is obviously an extremely difficult task.

1)Move to government auctions

- This market-based approach is currently being extended to allow entities that have obtained spectral resources to resell or lease these resources to others on a long-term or temporal basis.
- By using these methods the market should be able to "move" spectrum ownership to those users and applications that value it the most rather than requiring the regulator to make a judgment on the optimal use of the spectrum.

2) The other approach, called *dynamic spectrum access networks*

- This approach is based on the important observation that most of the spectrum, in most of the places, most of the time is completely unused based on the measurements performed in various spectrum occupancy studies less than 20% of the spectral capacity is actually being used.
- To help reconcile there are many well-established wireless
- Applications with long-term spectral band assignments that are rarely used or are used only in specific spatial locations. For example, ship-to-ship and ship-to shore radios are rarely used.
- The various initiatives directed toward identifying and supporting more efficient dynamic sharing mechanisms for the world's scarce spectrum resources.

ENABLING TECHNOLOGY

- **Enabling** technologies are characterized by rapid development of subsequent derivative technologies, often in diverse fields.

SDR

- SDR is a key **enabling technology** to realize cognitive radios.
- Until development of cognitive radio technology, SDR has been mainly proposed to **realize multi-mode and multi-standard wireless devices.**
- However, the **role of SDR in cognitive radios is very essential**, which is the realization of cognition features (e.g. awareness, sensing, etc.) in cognitive radios.

- As discussed one of the **main characteristics** of cognitive radio is the **adaptability** where the radio parameters (including frequency, power, modulation, bandwidth) can be **changed depending on** the radio **environment**, user's situation, network condition, geolocation, and so on.
- SDR can provide a very flexible radio functionality by avoiding the use of application specific fixed analog circuits and components.
- **Therefore, cognitive radio needs to be designed around SDR.**
- "A cognitive radio is an SDR that is aware of its environment, internal state, and location, and autonomously adjusts its operations to achieve designated objectives."
- Compared to hardware radio, SDR which is capable of **operating with many different bandwidths** over a wide range of frequencies and using many different modulation and waveform formats.

SDR Forum

- The SDR Forum **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 Working Group is treating cognitive radio and spectrum efficiency as applications that can be added to an SDR.

GEOLOCATION

- Geolocation is an important CR enabling technology due to the wide range of applications that may result from a radio being aware of its current location and possibly being aware of its planned path and destination.
- Geolocation is the identification or estimation of the real-world geographic location of an object, such as a radar source, mobile phone, or Internet-connected computer terminal.
- Geolocation through the use of GPS

NETWORKING PROTOCOLS

- Cooperative groups (a multiagent model) have the potential to increase capabilities in a variety of ways.
- A network of CRs enables other significant increases in capabilities. Software for Mobile Ad hoc Networking (MANET), although maturing slowly, is a key enabling technology.
- An interesting application of CR is the ability to learn how to network with other CRs and adapt behavior to achieve some QoS goal such as data rate below some BER bound, bounded latency, limited jitter, and so forth.

DYNAMIC SPECTRUM ACCESS AND SPECTRUM AWARENESS

- A CR with spectrum sensing capability and cooperative opportunistic frequency selection is an enabling technology for faster deployment and increased spatial reuse.
- Spectrum access is primarily limited by regulatory constraints.
- CRs may sense the local spectrum utilization through a dedicated sensor.
- If the regulatory body is allowing CRs to utilize the unoccupied “white space,” increased spectral access can be achieved.
- The CR can examine the signals and may extract detailed information regarding use.

NeXt Generation (XG)

- Funding for contractors involved in the DARPA NeXt Generation (XG) radio communications program has been a very significant.
- The FCC now has complementary projects to define policies for frequency-agile radios.
- XG is now focused on system concepts and enabling technology to dynamically redistribute allocated spectrum in operating radio networks in order to address rapidly growing requirements for communications bandwidth.
- The program goals are to enable radios to automatically select spectrum and operating modes in a manner that increases the survivability of communication networks and minimizes disruption to existing users.

Main Issues in Cognitive Radio Networks

1) Self-coexistence - One of the most important and specific issue of CR is to avoid secondary users to harmfully interfere with primary users. Overlay and underlay are two possible spectrum access techniques.

2) Accurate Sensing - Sensing aims to determine if a channel is idle or busy in terms of primary user activity.

3) Signalling - CR scenarios require the exchange of control information between CR devices for spectrum sensing and sharing. Most CR MAC protocols use a common control channel (CCC), which facilitates signalling and also neighbour discovery in CR adhoc networks.

4) Optimized spectrum decision - secondary users are expected to dynamically choose the best available channels and transmission parameters.

5) Seamless spectrum handover - Seamless transition with minimum quality degradation is a fundamental goal for any spectrum handover scheme.

6) Cross layer design - to get better performance, the strict layer-based approach is often violated in wireless networks, namely through cross-layer interactions.

7) Energy efficiency - The number of sensed channels must also be minimized through appropriate prioritization mechanisms as sensing is one of the main sources of energy and time consumption.

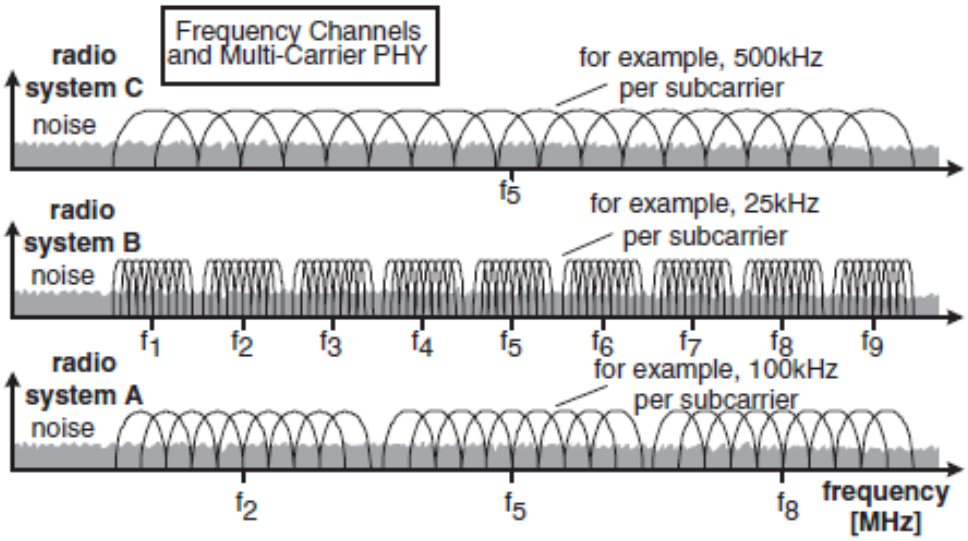
8) Spectrum underutilization- Cognitive radio offers a novel way of solving spectrum underutilization problems. It does so by sensing the radio environment with a twofold objective: identifying those subbands of the radio spectrum that are underutilized by the primary (i.e., legacy) users and providing the means for making those bands available for employment by unserviced secondary users.

RELATION WITH OTHER RADIOS

- Radios that have learned or adapted to local spectrum, channel, waveform, or protocol conditions can share their learning with other radios that have not yet learned these local optimizations.
- This learning can be infused to other radios via a network database which provides local optimization, or it can be shared directly from radio to radio.
- Network operators correctly worry that the network behavior be stable, and predictable, and within FCC guidelines.

- It is most appropriate that learned behaviors be shared from a database, where they can be checked, and validated as producing a net benefit to the network before being used.
- It seems that the Radio Environment Map is an example of a method for providing such services.
- Market studies have not yet characterized the value of cognitive radio learning technology.
- However, if learning to use spectrum wisely is an example, it will be very valuable.
- Cognitive Radio technology is a way in which one radio or even a network of radios are able to learn a useful degree of adaptivity, that aids the user, the network, and/or the spectrum owner.
- There are powerful economic incentives to provide new capabilities, through existing telecommunications infrastructure, and cognitive radios will provide those capabilities.

Frequency channel and multicarrier



(Image Source: Ref. Book)

- Three different types of radio systems are assumed to operate in the band, each operating with different frequencies and channel bandwidths.
- Type A operate on three frequency channels [compared to wireless LANs operating in the 5 GHz band (using OFDM)]

- Type B operate on nine frequency channels [represents narrow-band radio systems supporting for example a limited number of voice calls or blue tooth systems]
- Type C operates on one frequency channel [broadband CDMA system]
- Type A radio system requires the respective three frequency channels to be idle before allocating radio resources.
- Collisions of allocation attempts occur when more than one radio system detects the channel as idle at the same time.
- Two of the most representative etiquette rules are as follows:
- *rule : a radio system of type A, type B, or type C should apply LBT [*Listen Before Talk*]* when operating;
- *rule : in order to protect other radio systems most efficiently, a radio system* that follows rule 4 should synchronize its LBT process in time across neighboring frequency channels that overlap with the same channels.
- Describing the "packing" behavior as follows. If one radio system releases the spectrum, the other radio systems will switch their operating frequency band so that the vacant band is occupied (if it meets the demands of at least one of the active radio systems).

Example

- WLAN station reports a list of channels that it can support to an access point. When it's necessary to switch to a new channel, the access point uses this data to determine the best channel.

CR Applications (Image Source: Online)