Cognitive Radio, Software Defined Radio, and Adaptive Wireless Communication Systems

Hüseyin Arslan

arslan@usf.edu

USF UNIVERSITY OF SOUTH FLORIDA

WCSP Group

Outline

Future Trends in wireless	•Requirements •Applications •Core technologies
Introduction to Cognitive Radio, Adaptive Radio, and SDR	•Definitions •Relations with the evolution of wireless systems •Applications •Challenges •Standards
Details on Some Critical Applications	•White Space Radio •ISM band •Public Safety •4G and Beyond •Femtocells •Smart Grid

Details on Some Challenges and Research Problems	•Awareness
	    •Spectrum awareness
	    •Multi-dimensional signal awareness
	    •Signal intelligence (SigINT)
	    •Interference awareness
	    •Cognitive positioning and location awareness
	•CR & SDR measurements
	•Spectrum fragmentation and carrier aggregation
	•Security issues

OFDM(A) and OFDM based waveforms for CR	•Benefits of OFDM for CR •Challenges of OFDM in CR

Future Trends in wireless Communications ?

UNIVERSITY OF SOUTH FLORIDA

WCSP Group

Expectations from future

- Better spectral efficiency, more BW, better reuse
- Interoperability & co-existence (multiple networks)
- Higher capacity and data rates -100 Mbps to 1GBps
- Wide variety of services
- Collaboration and cooperation of nodes
- Robust networks
- IP core, end-to-end IP
- Person centric rather than network centric (short range when possible) – gradual transition from large to small scale networks
- Security
- Improved QoS and better coverage

Potential Future Applications

- Machine2machine communications
  - Smart homes/offices
  - Sensor networks
  - Chip2Chip communications (reconfigurable electronic devices through wireless buses)
  - Smart highways/cars (V2V, V2I communications)
  - Smart Grid & AMI
- Positioning & Location based services
- Environment monitoring
- Disaster management and military
- Medical (patient monitoring, noninvasive surgery)
- Underwater, Over the air, Underground, in Vivo

Fundamental enablers/techniques

- CR and cognitive networks
- SDR
- OFDM(A), SC-FDMA, and beyond ??
- Multi antenna systems and MIMO
- UWB
- Advanced routing and relaying techniques
- Higher order modulations ??
- Femto-cells
- Interference awareness and cancellation
- Cross layer optimization/adaptation

- Race between apps and core techs: Apps are moving ahead. There is a need for new core technologies.

Trend: Convergence of different worlds

- Terminal convergence (smart phones)
  - Communication devices compute - Computing devices communicate (computer phone, tablets, smart phones)
  - Entertainment devices communicate – Communication devices entertain (game phone, TV phone, multi-media phones, etc.)
- Network convergence (IP)
- Service convergence (Multi-media)
  - Voice, data, video
  - Camera, GPS and location, TV, radio, music, game, travel guide, etc.

Interesting Stat

- In 2001, number of mobiles exceeded landlines globally
- WWRF: by year 2017 seven trillion wireless devices will serve seven billion people. The overwhelming majority of these devices will be for short–range communications. ➔*Internet of Things*
- *"Wireless data traffic on the AT&T network has grown more than 5,000 percent over the past three years...We see this usage trend continuing in the years to come." John Donovan, AT&T CTO, 14 Feb 2010*
  - *Mainly due to penetration of smart phones (like Iphone)*
  - *Such data explosion threatens to overwhelm mobile networks*
  - *AT&T putting an end to its all-you-can-eat internet plans – Washington post, June 2 2010*
- Cisco report: IP traffic from wireless devices will exceed traffic from wired devices by 2015

Capacity and data rates

- Need more capacity from the spectrum
  - Historically major capacity gains obtained through frequency reuse
  - This trend will continue
    - Smaller cells (femtocells) and better reuse
  - Remove the guards in multiple domains
  - Reduce the overprotection (better radios allowing less protection)
  - Better channel awareness, better channel assignments
  - Better interference awareness
  - More interference allowance (partial overlapping)
  - DSA
- Need wider bands for higher data rates
  - Carrier and resource aggregation (adjacent or scattered)
- Better modulation/coding, MIMO, collaboration, cooperation, etc. for increasing spectrum efficiency

Impact of cloud in wireless communication

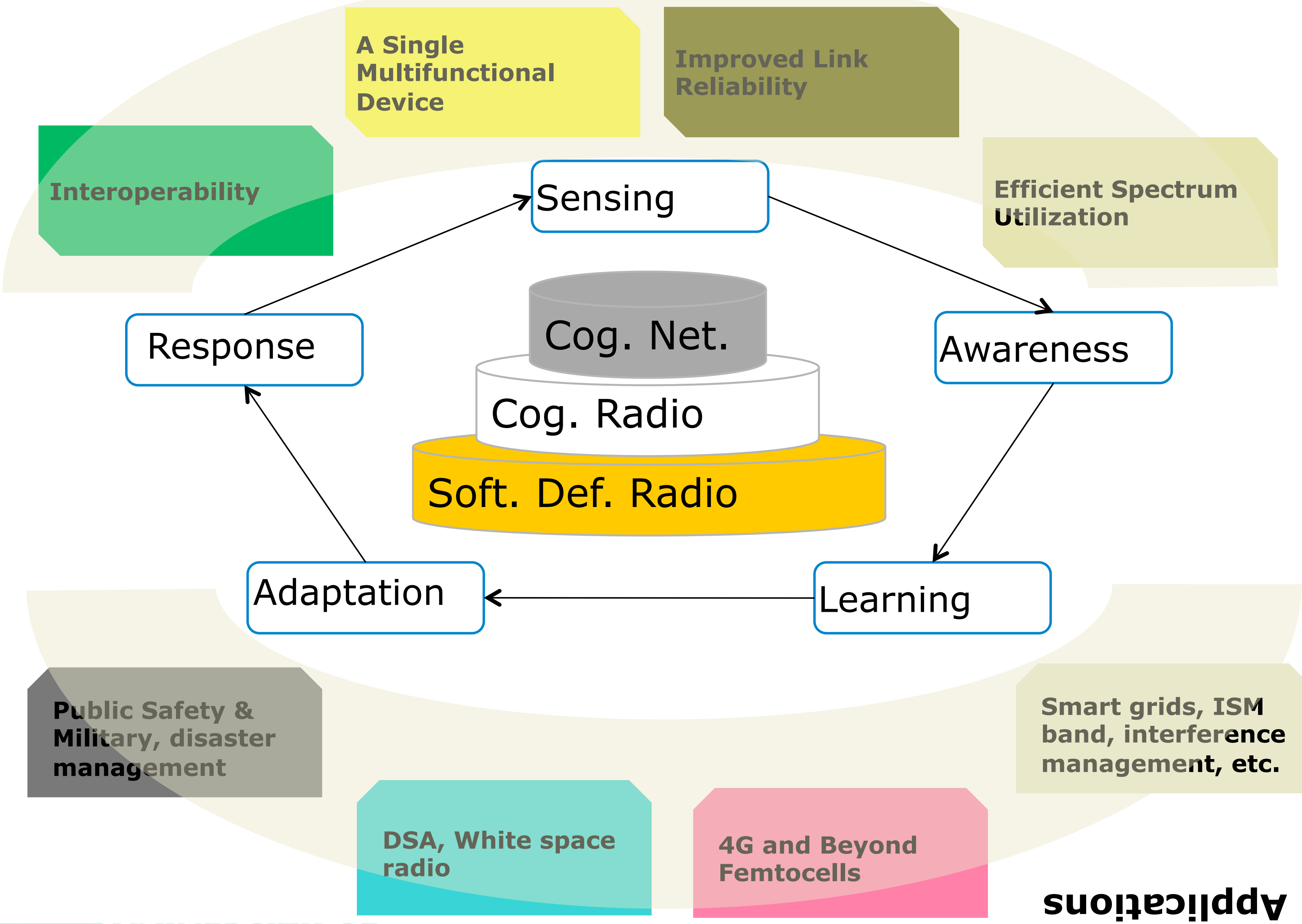
User trying to download/upload large files
from/to the cloud to/from their iPad

Cognitive Radio and Networks

UNIVERSITY OF SOUTH FLORIDA

WCSP Group

Capabilities



Applications

USF UNIVERSITY OF SOUTH FLORIDA

WCSP Group

Cognitive & Software Defined Radio

Introduction

USF UNIVERSITY OF SOUTH FLORIDA

WCSP Group

- CRs and CRNs are very complex systems
- Require multi-disciplinary research
- An individual or a small focused group can only handle a small piece of it
- Research to date has focused on developing components of CRs/CRNs, rather than complete ideal CRs/CRNs

• Statistical signal processing	• Neuroscience
• Stochastic control	• Artificial Intelligence
• Information theory	• Statistical learning theory
• Communication theory	• Game theory
• RF and microwave theories	• Biology, Sociology

WHAT IS COGNITIVE RADIO?

Cognitive Radio Definition

- Many different (and some conflicting) definitions exist
  - Most people focused around spectrum dimension and DSA

- Need a unified view of what a CR *is* and what it *can* and *must be capable of* achieving

- *The term "**Cognitive Radio**"* evolved over time and now has several meanings in a variety of contexts
  - Can autonomously exploit locally unused spectrum to provide new paths to spectrum access (spectrum aware)
  - Can roam across borders and adjust themselves to stay in compliance with local regulations (policy aware)
  - Can negotiate with several service providers (networks) to connect a user at the lowest cost (or optimal performance)- (network aware)
  - Can adapt themselves and their emissions without user intervention (context and channel aware)
  - Can understand and follow actions and choices taken by their users and over time learn to become more responsive and to anticipate their needs (user aware)

Some of the previous definitions

- ***ITU:* A radio or system that senses, and is aware of, its operational environment and can dynamically and autonomously adjust its radio operating parameters accordingly**

- **FCC**: CR is a radio that can change its transmitter parameters based on interaction with the environment in which it operates

- **NTIA:** A radio or system that senses its operational electromagnetic environment and can dynamically and autonomously adjust its radio operating parameters to modify system operation, such as maximize throughput, mitigate interference, facilitate interoperability, access secondary markets

- **WWRF**: **Cognitive** Radio employs a dynamic time-frequency-power based radio measurement and analysis of the RF environment, to make an optimum choice of carrier frequency and channel bandwidth to guide the transceiver in its end-to-end communication, with quality of service being an important design requirement

- **ATIS**: A radio that (a) monitors its own performance, (b) monitors the path quality through sounding or polling, (c) varies operating characteristics, such as frequency, power, or data rate, and (d) uses closed loop action to optimize performance by automatically selecting frequencies or channels.

SDR Forum CR working group definition

- Adaptive, multi-dimensionally aware, autonomous radio (system) that learns from its experiences to reason, plan, and decide future actions to meet user needs"
  - Adaptive—Capability to alter operational characteristics (to environment)
  - Aware—interpreted understanding of input data
  - Autonomous—not requiring user intervention

Minimum set of behaviors that a cognitive radio must include are:

- Adapts autonomously to situational or environmental changes
- Always in regulatory compliance

Awareness

The *perception* and retention of radio-related information

Perception

The process of acquiring, classifying, and organizing information.

Reason

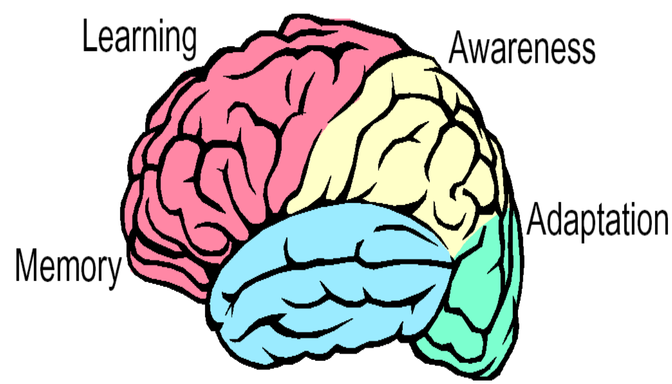
The application of logic and analysis to information.

Knowledge (Oxford English Dictionary)

Expertise and skills acquired through experience or education. Awareness

Learning

Process of acquiring skills or knowledge



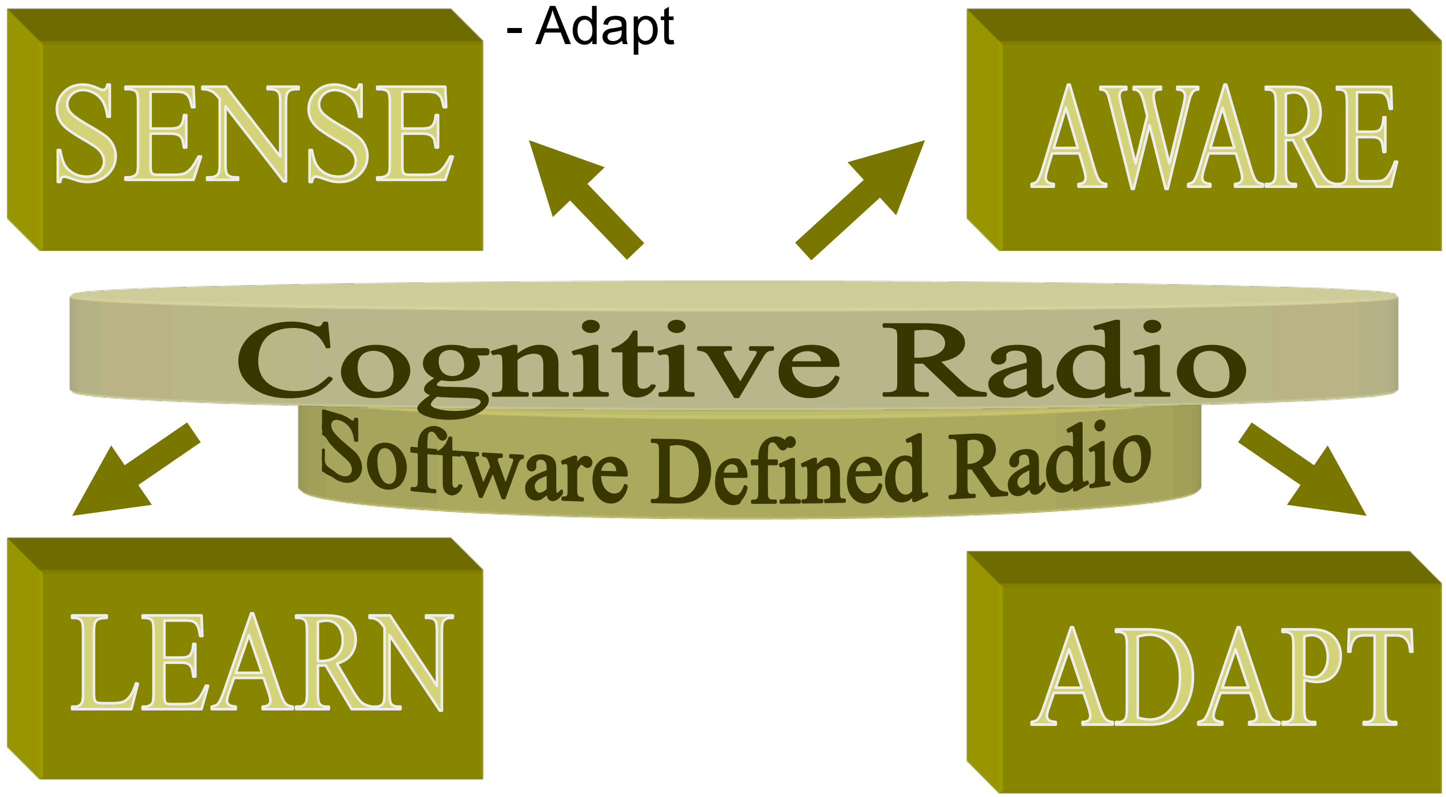
UNIVERSITY OF SOUTH FLORIDA

Cognitive and Software Defined Radio

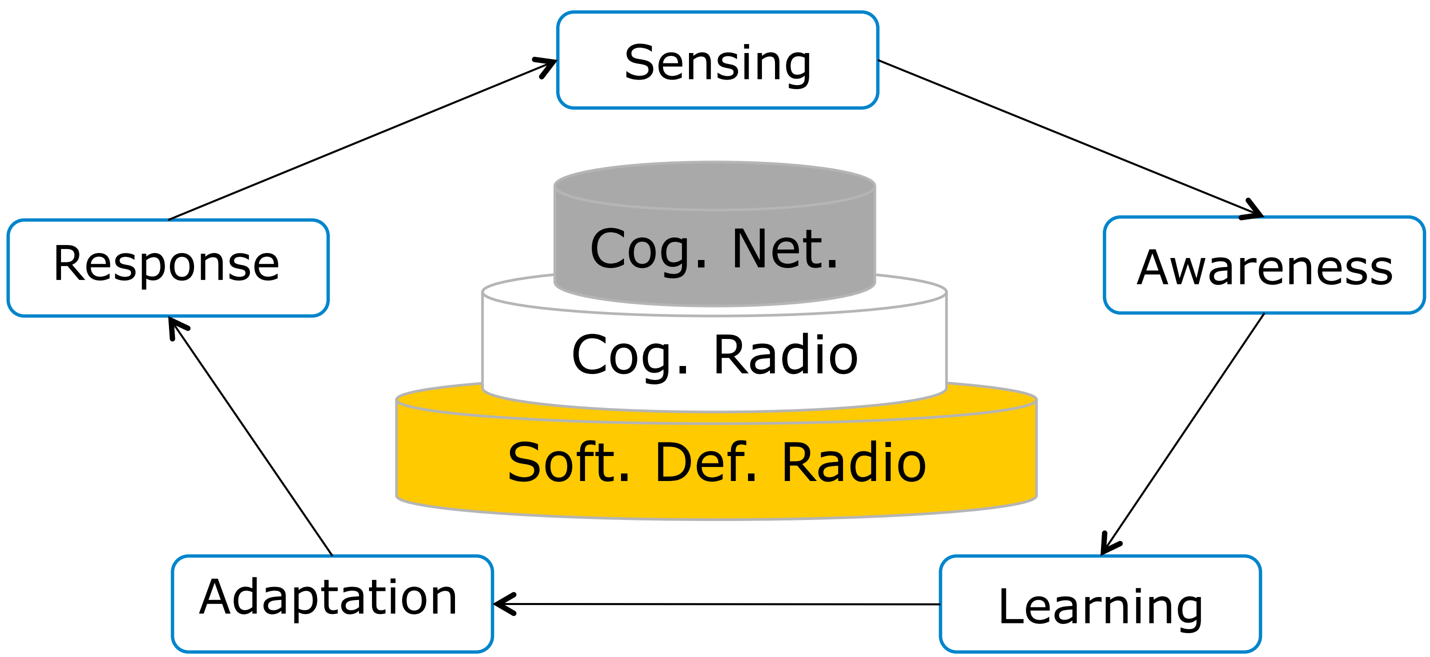
Cognitive radio (highly intelligent radio systems)

- To have awareness
- Create Knowledge
- Make decisions
- Adapt

Requiring a flexible platform: Flexibility



COGNITIVE CYCLE



Input (sensing, awareness)
Decision making (reasoning, interpretation, learning)
Action (implementation of decision, adaptation, parameter change)

2 Major Themes of CR

- Opportunistic radio (to exploit spectrum)
  - Secondary usage of the spectrum
  - Co-existence with other systems
  - Spectrum aware, spectrum adaptable
- Smart and reconfigurable radio that enables:
  - Better spectral efficiency
  - Flexible radio functionalities
  - Interoperable (seamless roaming on different networks, countries, frequencies, etc.)
  - Self organizing
  - All dimensions (not only spectrum, but also other dimensions) are considered

Also, based on the frequency spectrum, CR has different interpretation on different applications

- Licensed bands (like cellular radio)
  - More like smart and adaptive radio interpretation with efficient usage of the resources and strong interoperability capabilities
- Unlicensed bands (ISM)
  - More like an interference aware radio interpretation that can coexist with other unlicensed radios (sharing of equals)
- Opportunistic Unlicensed (like TV white spaces)
  - More like spectrum aware secondary usage (primary secondary sharing)

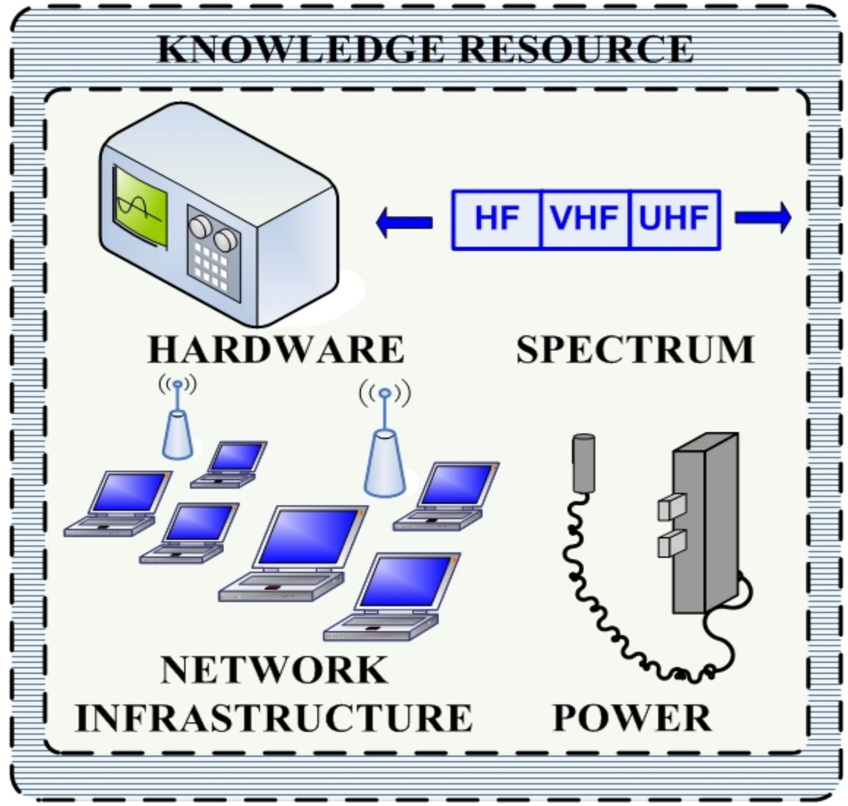
In a Nutshell:

Basic function of a cognitive radio could be thought of as *matching* requirements of a higher layer application or user with the available resources

What are resources?

Resources

- Available spectrum
- Infrastructure (network)
- Power/battery
- Radio hardware and software
- Other nodes (around)
- Memory
- Knowledge (about user preferences, radio capabilities, channel, geolocation, etc.)
- etc

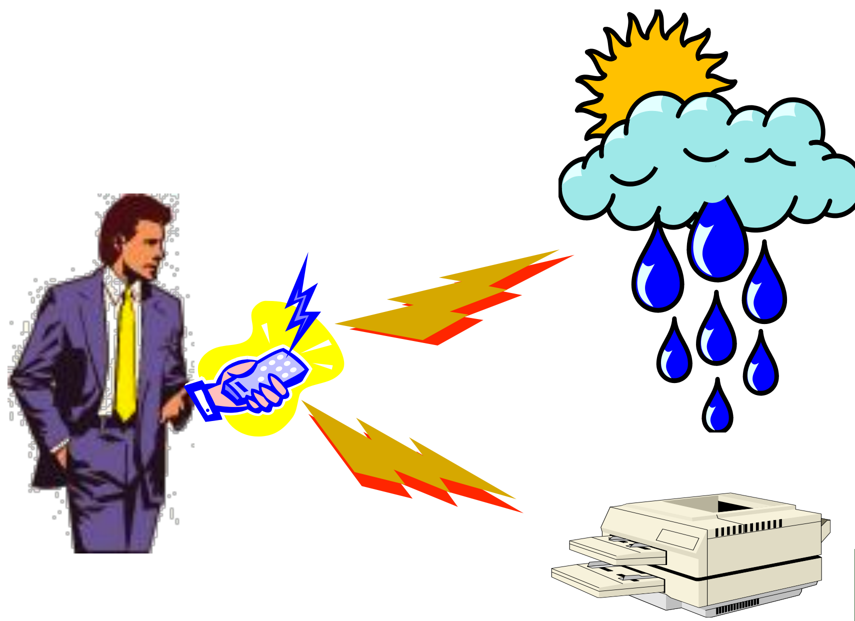


Cognitive layer would be *aware* of …

- Radio’s hardware resources
- Spectrum availability
- Available software modulations / signal waveforms, and capabilities/characteristics of these
- Data rates, quality service requirements of applications
- Network and nearby nodes and capabilities
- Local Policies, regulatory and other operating restrictions
  - The cognitive layer decision-making would be constrained by a "policy engine" that would prevent the radio from violating regulatory and other operating restrictions.

CR should (would ?) *sense (monitor) and learn* …

- RF environment
- User behaviors
- Available nodes (or infrastructures)
- Available power, spectrum and other resources
- From previous decisions and mistakes



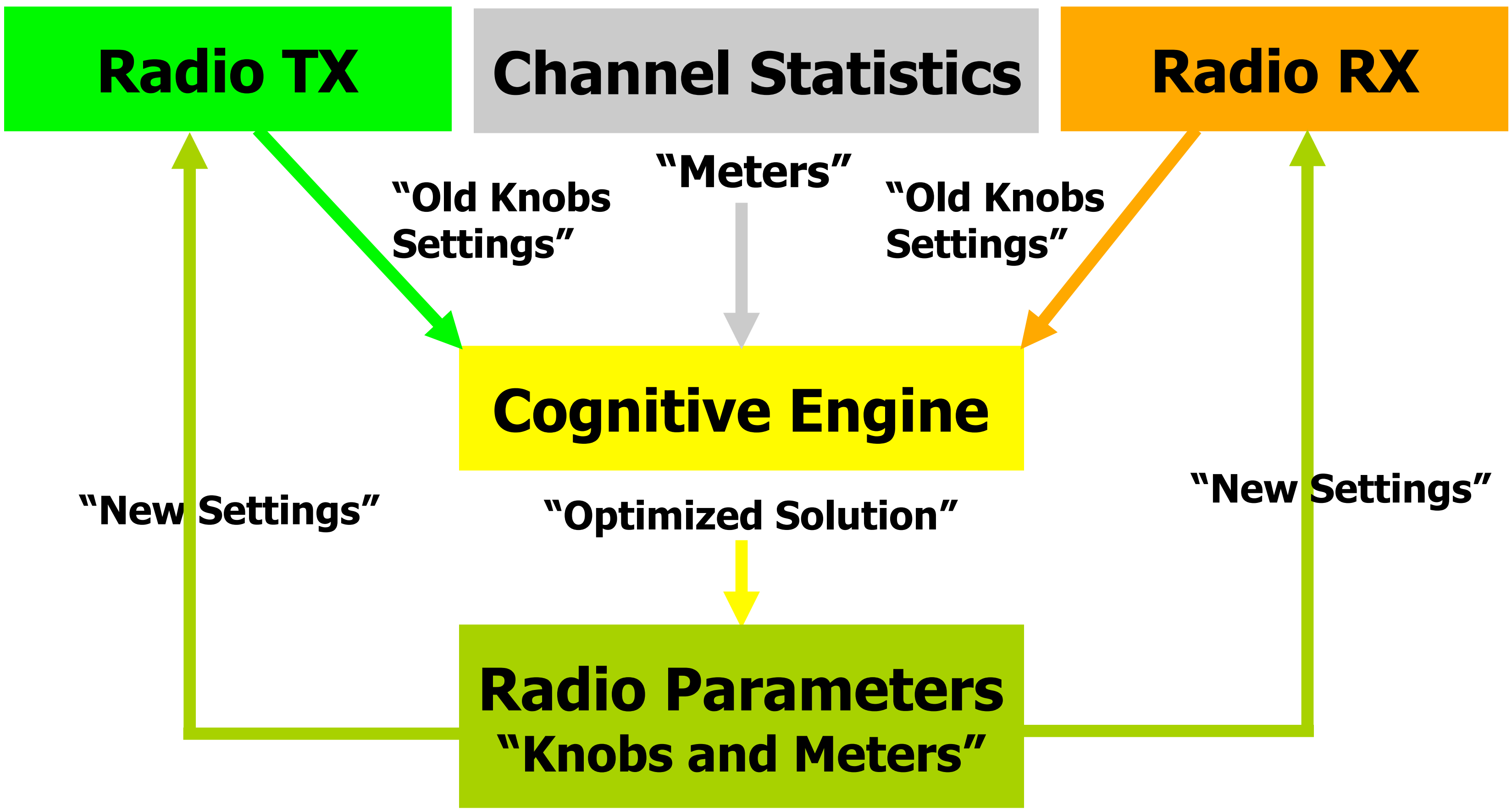
UNIVERSITY OF SOUTH FLORIDA

WCSP Group

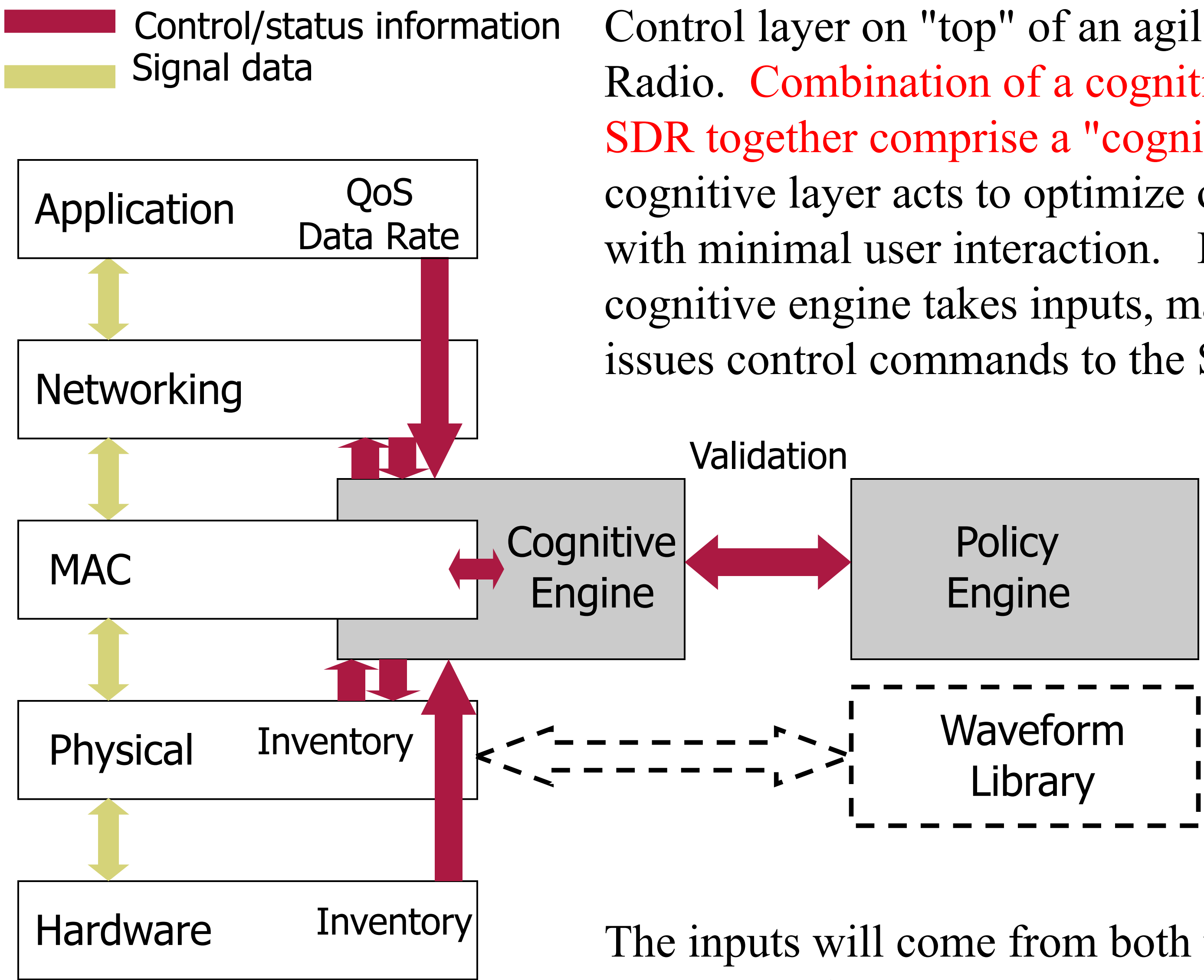
Having said these .....

What would be an appropriate conceptual model for CR?

A simple concept (from Virginia Tech.)



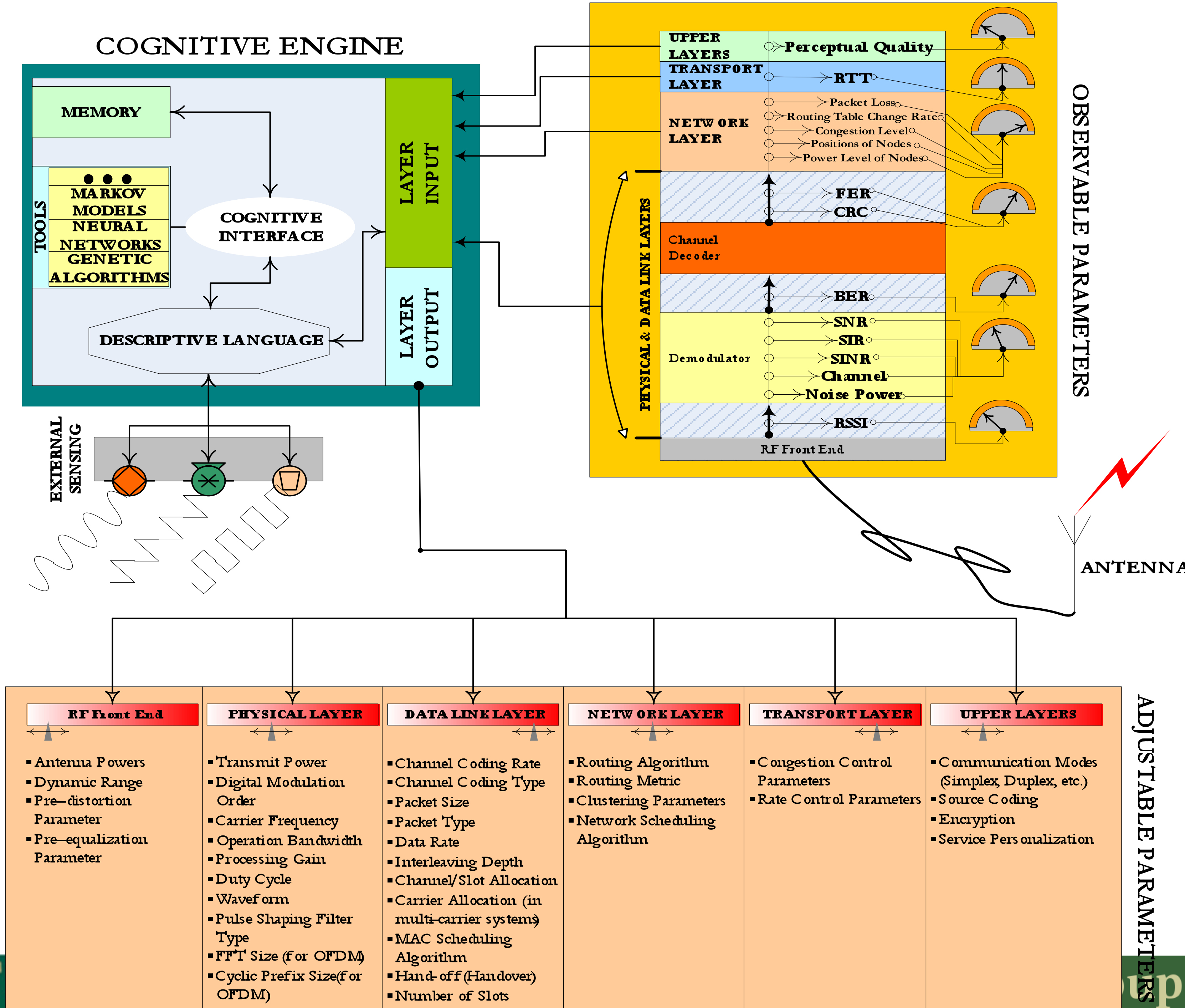
A possible Conceptual Model (from SDR-CR working group)



Control layer on "top" of an agile, Software Defined Radio. Combination of a cognitive "engine" and the SDR together comprise a "cognitive radio". The cognitive layer acts to optimize or control the SDR with minimal user interaction. In this model the cognitive engine takes inputs, makes decisions and issues control commands to the SDR.

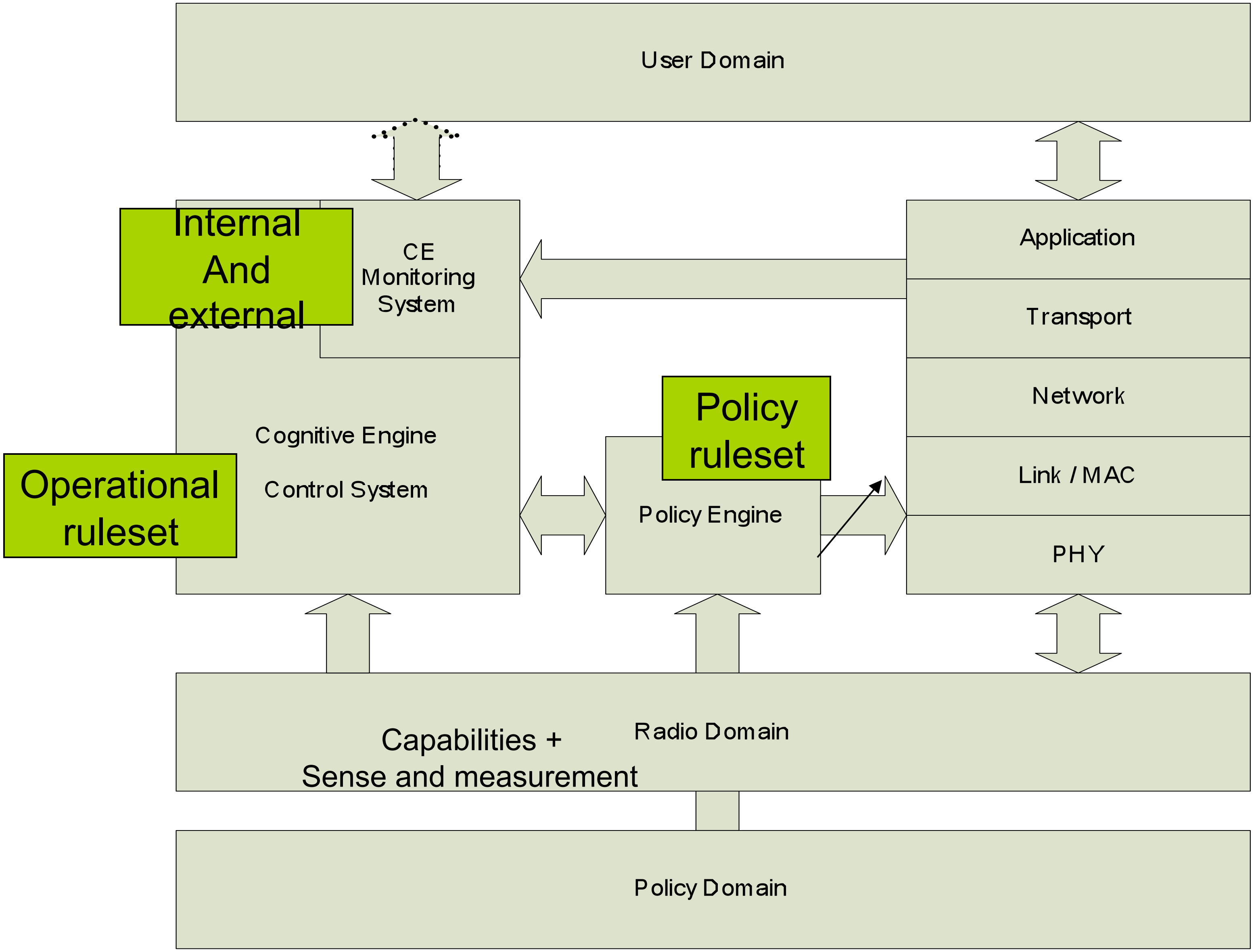
The inputs will come from both the SDR and from upper layers.

Conceptual Model of Channel Aware Radios



USF SOUTH FLORIDA ... up

Conceptual Model, alternate view (from SDR-CR working group)



WHAT IS THE RELATION BETWEEN ADAPTIVE RADIO and COGNITIVE RADIO ?

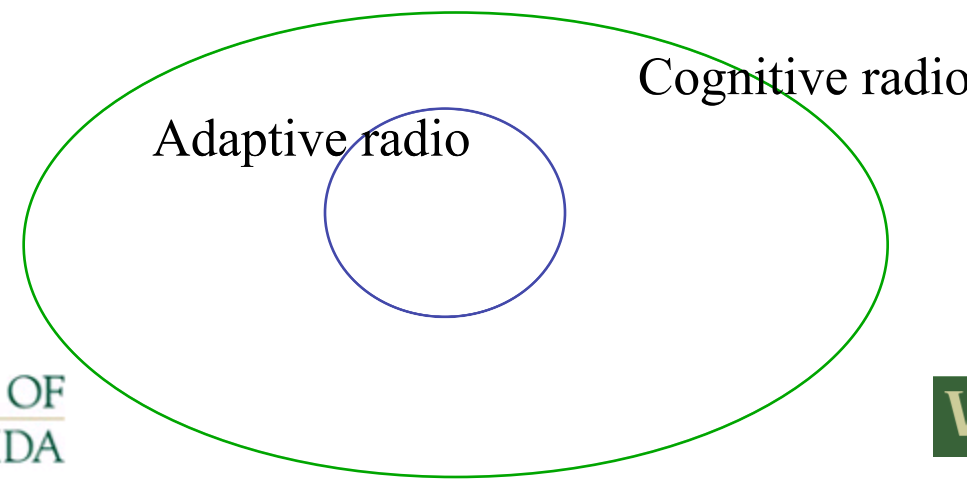
Adaptation

- Adaptation is one of the fundamental attributes for intelligent wireless systems
- Can be defined as: Systems demonstrating an awareness of its environment and an ability to automatically react.

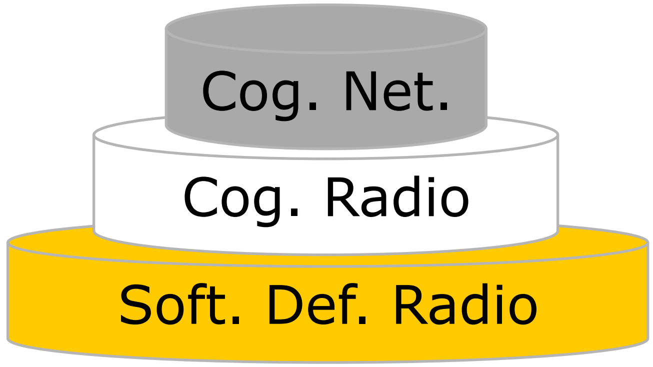
SDR Working group definition

Radio in which communications systems have a means of monitoring their own performance and a means of varying their own parameters by closed-loop action to improve their performance.

- Cognitive radio and adaptive wireless in essence mean the same thing
- Cognitive radio (depending on definition) might include additional features beyond adaptation
- Therefore, within the context of this presentation, we will assume Cognitive radio includes adaptation, but, might not be true in the other way around



What is the relation between SDR and Cognitive radio ?



•CR requires a flexible radio device. SDRs are ideal platform for CRs.

•SDR might not be necessary for CR, but, highly desirable
•SCR might possibly do the job for most interpretation of CR
•Even multiband and multimode radio devices can do the job for some CR interpretations

Software Defined Radio (SDR)

SDR Concept: Rather than determining a wireless device's function with dedicated hardware, keep the electronics to a bare minimum of generic hardware and implement them with software

Use software to control/implement how radio works.

Software Controlled

Software controlled refers to the use of *software processing* within the radio system or device *to select the parameters of operation.*

Software Defined

Software defined refers to the use of *software processing* within the radio system or device *to implement operating (but not control) functions*.

WHY SDR?

- Hardware limitation
- Difference in link-layer protocols and modulation/demodulation techniques.
- Constant evolution of link-layer protocol standards
- Existence of incompatible wireless network technologies in different countries

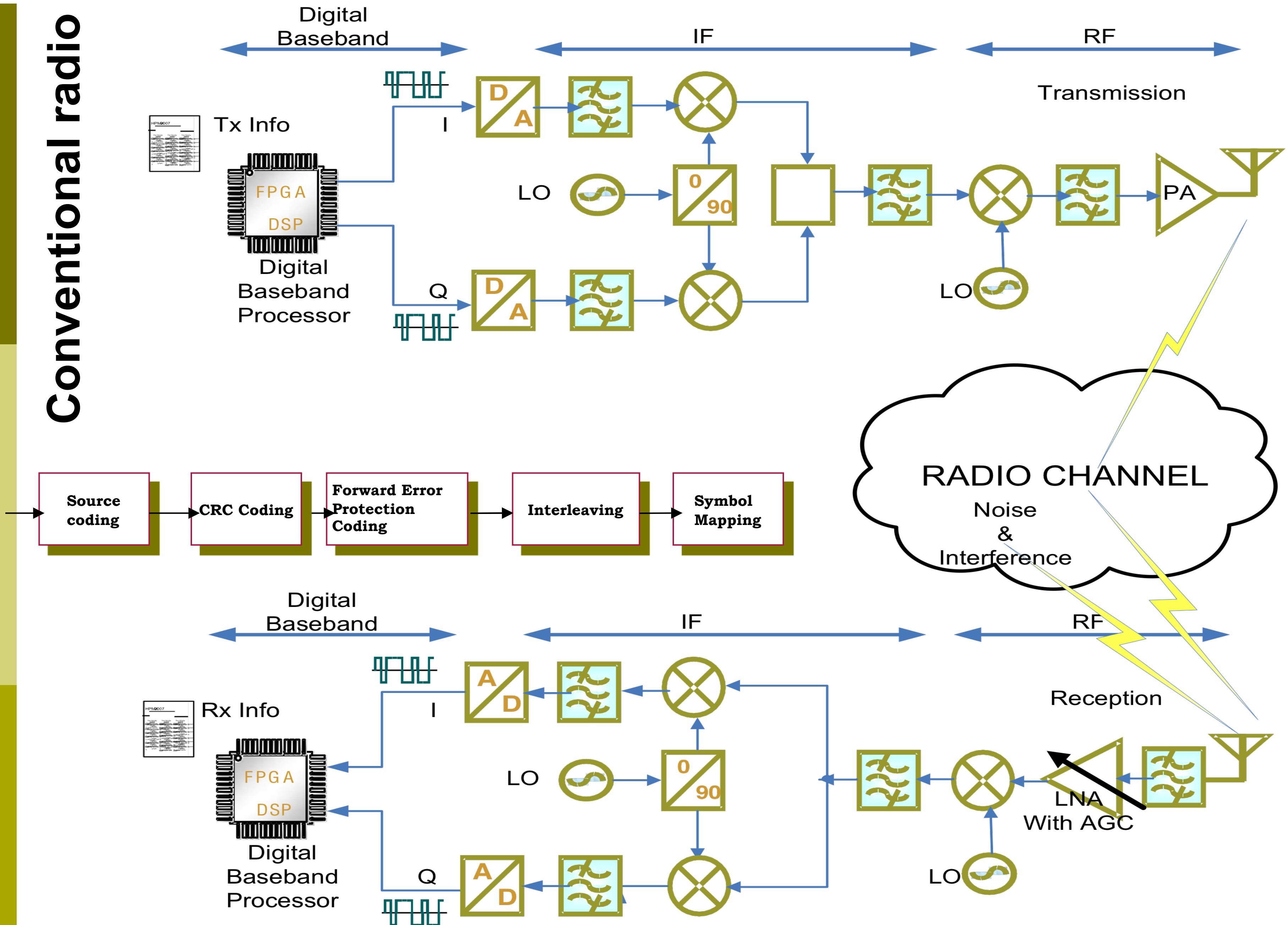
- SDR offers radio functionality as software modules running on a generic hardware platform.
- Multiple software modules for different standards can be present
- Also, software modules that implement new services/features can be downloaded over-the-air onto the handsets

- This flexibility of SDR helps in dealing with differences in standards and issues related to deployment of new services/ features

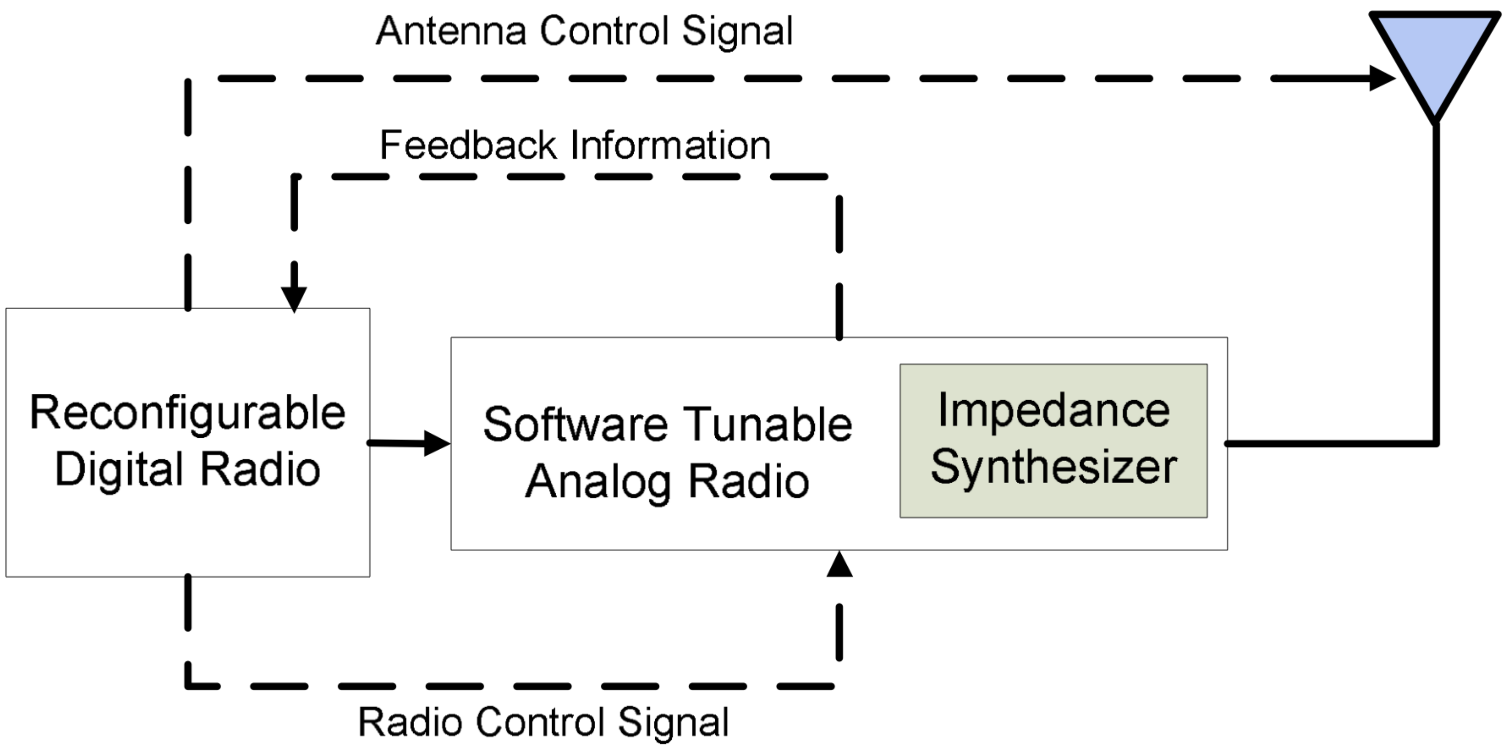
FEATURES

- Reconfigurability
- Ubiquitous Connectivity
- Interoperability
- Degrees of freedom in radio domain
  - Wide variety of waveforms, modulation techniques
  - Highly dynamic TRX
  - Lot's of standards and transmission formats
  - Wide-band or narrow-band operation
  - Operation in different frequency bands, with several bands
  - Band aggregation
  - Better spectral shaping and control
  - Communications security functions (such as hopping)

Conventional radio



Current SDR example



Having said that ....

- Cognitive Radio is comprised of a control layer on "top" of an agile Software Defined Radio.
- Combination of a cognitive "engine" and the SDR together comprise a "cognitive radio".

What is the relation between XG and Cognitive radio ?

- Radio spectrum is traditionally licensed through spectrum policy in a non-flexible way.
- Spectrum policy in the US is undergoing radical rethinking; new approaches for opening the radio spectrum by allowing opportunistic usage of licensed but unused radio resources.

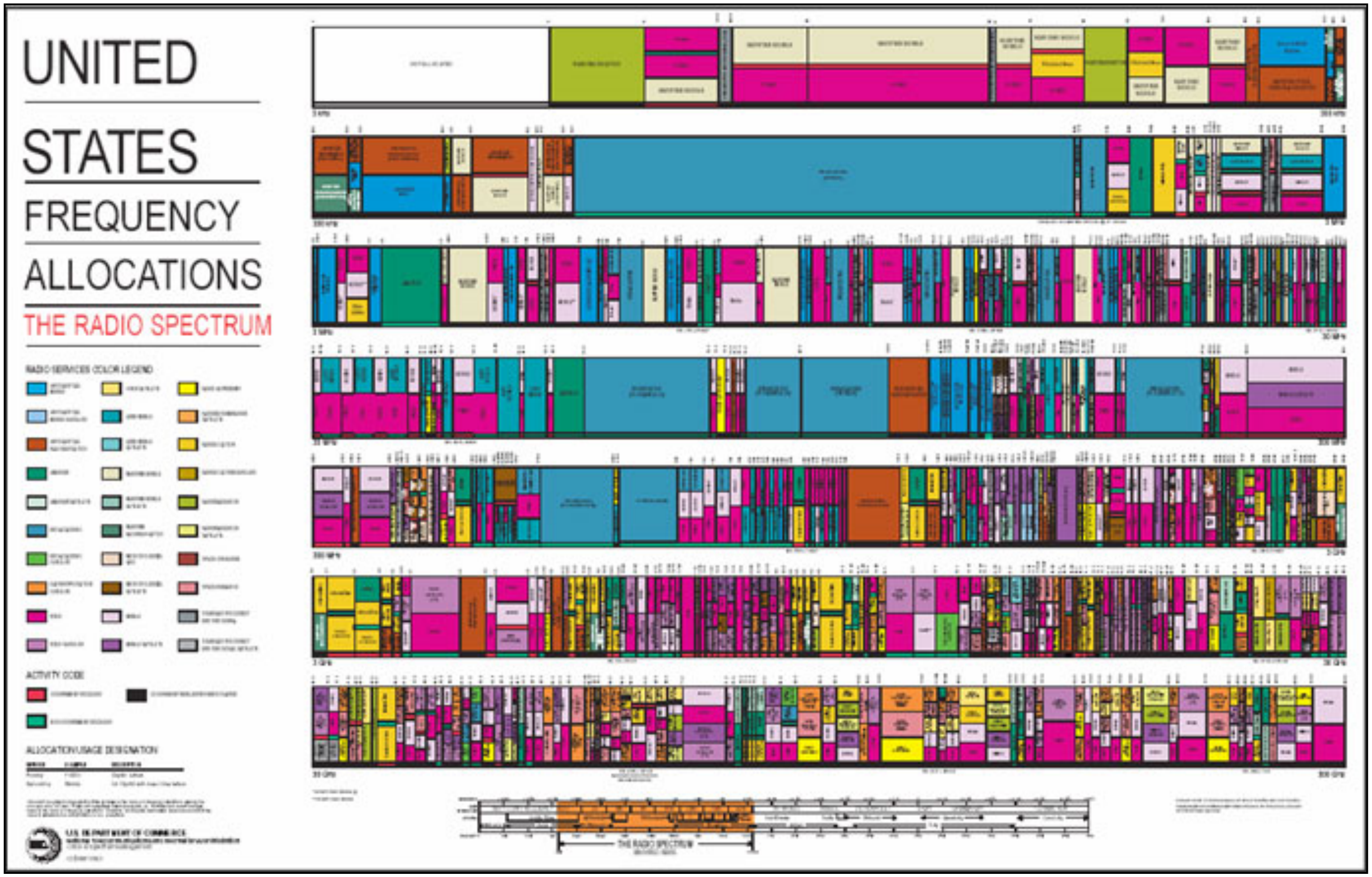
- A radio resource is defined as : frequency bands that can be used/occupied for certain duration, in a certain area.
- Spectrum that is not being used efficiently, at any frequency, geographical area, and time, is wasted.

XG (neXt Generation) concept includes:

- Dynamic spectrum utilization
- Improved bits/Hz/sec/km^2
- Co-existence in licensed spectrum?
- The technical means to dynamically assign or utilize spectrum involves
  - Highly adaptive modulation and coding techniques, Antenna technology and MIMO
  - Refined Multiple Access: Multidimensional/hybrid multiple access techniques
  - A spectrum- and resource-aware MAC/linklayer
  - Flexible networking
  - Multilayer resource management

Dynamically adapts to seize spectrum opportunities more efficiently than existing waveforms

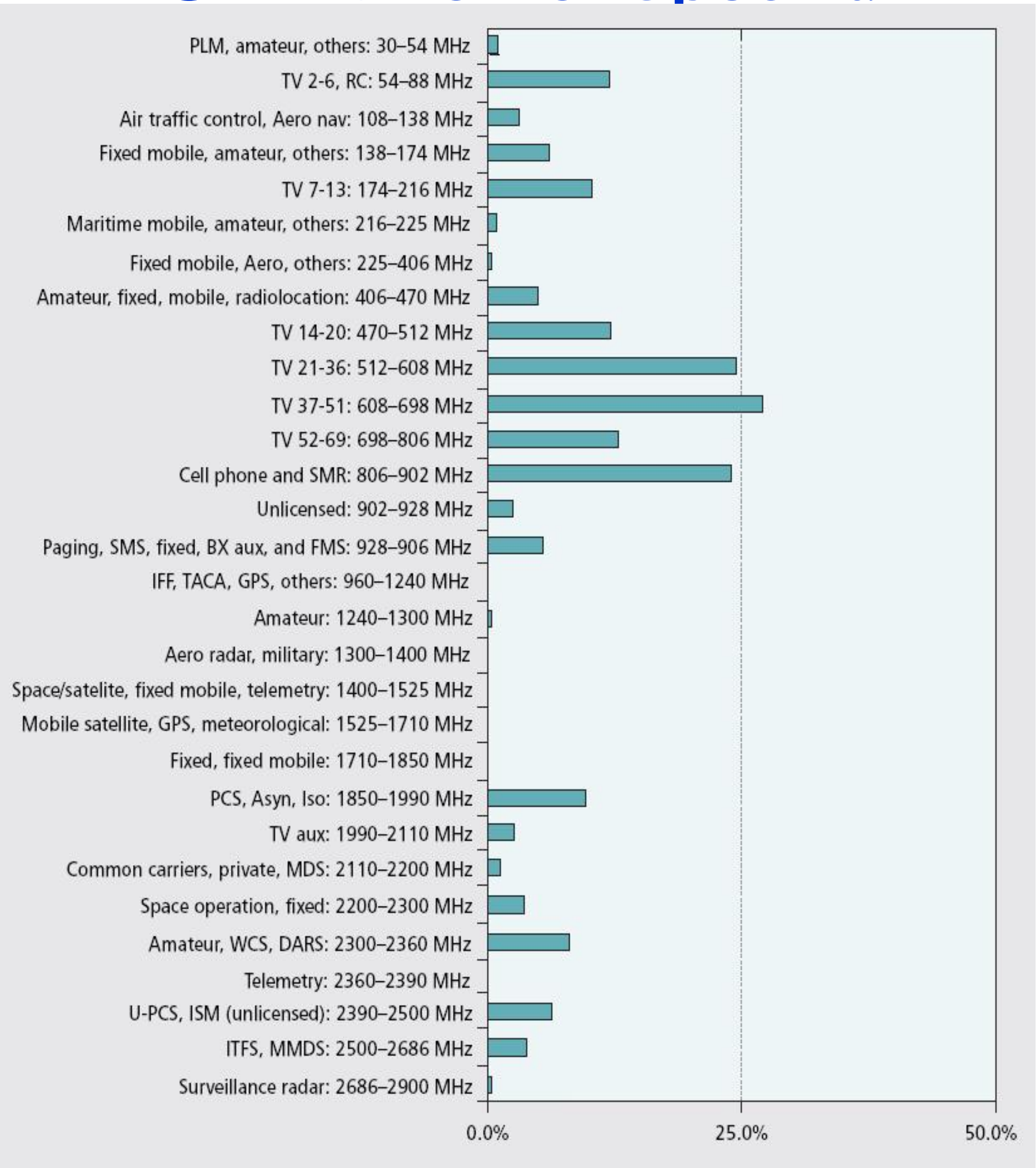
- Adapt parameters to increase capacity density when opportunities are available and channel conditions permit
  - Flexible Air Interface
  - Adaptation to Link, Network and User
  - Dynamic Adaptation in Many Parameters (Band, Freq, Data Rate, Time, Power, Bandwidth, Modulation Level, Code, Spatial)
- Adaptive spectrum usage not only improves the ability of systems to use the spectrum but can also reduce interference and the adverse impact to system performance.



Some frequencies are allocated but not used.

A spectrum hole is defined as 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

Utilization of Spectrum



- **Frequency range**
  - **30 MHz – 2.9 GHz**
- **Based on report by M.A. McHenry**
- **Max. utilization ~ 25%**
- **Average usage ~ 5.2 %**
- **New York City average ~ 13.1%**
- **Significant # white spaces**
  - **Even in cellular bands**

Ref: M.A.McHenry, "NSF Spectrum Occupancy Measurements Project Summary," August 2005

The occupancy was defined as the fraction measured in time and frequency dimensions where the received signal strength exceeds a threshold.

USF UNIVERSITY OF SOUTH FLORIDA

WCSP Group

Spectrum access

- licensed
- unlicensed (does not mean unregulated)
  - power limits and other technical requirements
  - new equipments must receive FCC approval
  - no *formal* protection from interference of others
- shared Unlicensed – underlay (e.g. UWB, Part 15 rules)
  - operate below the noise threshold of the high power licensed devices in the band
  - severe power limits allow for only very short-range device
- opportunistic Unlicensed
  - could detect such holes in the spectrum, switch communications there, and then move away as soon as the licensee began transmitting

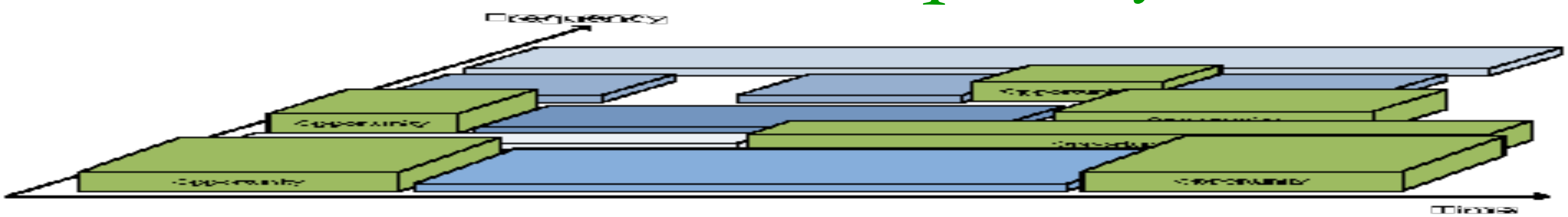
Possible Dimensions of Spectrum

UNIVERSITY OF SOUTH FLORIDA

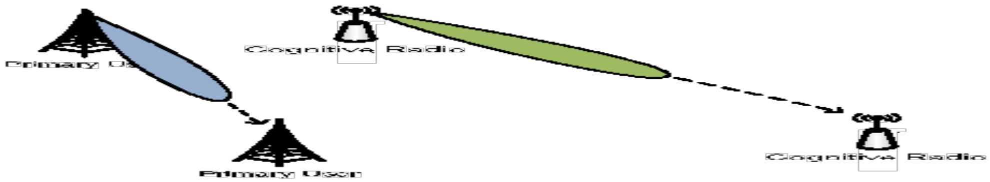
WCSP Group

- Typically, when defining an n-space, the dimensions are orthogonal, that is, the values uniquely define a point in the electrospace.
- However, several of the possible parameters (e.g., coding/modulation), do not necessarily define an orthogonal parameter but they can still be used to distinguish signals.
- The FCC has recognized and licensed spectrum primarily by defining spectrum rights in terms of three dimensions (frequency space, power, and time).
- The Task Force found that new technological developments are changing the way in which each of these spectrum dimensions is used.

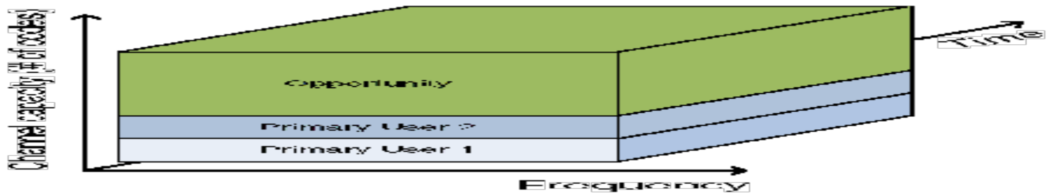
Possible Dimensions of the Spectrum Space: Time-frequency



ANGLE DIMENSION



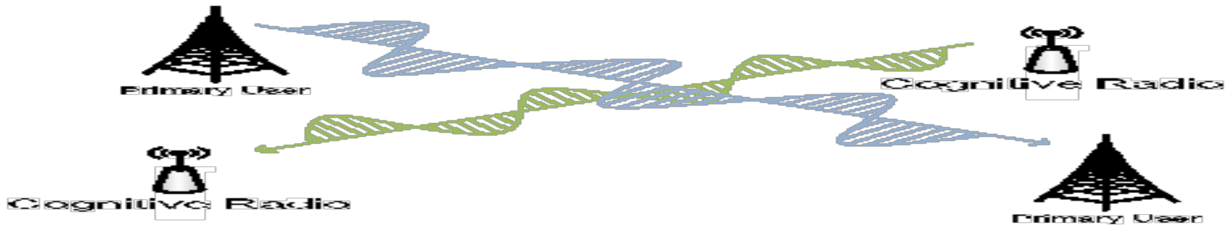
CODE DIMENSION



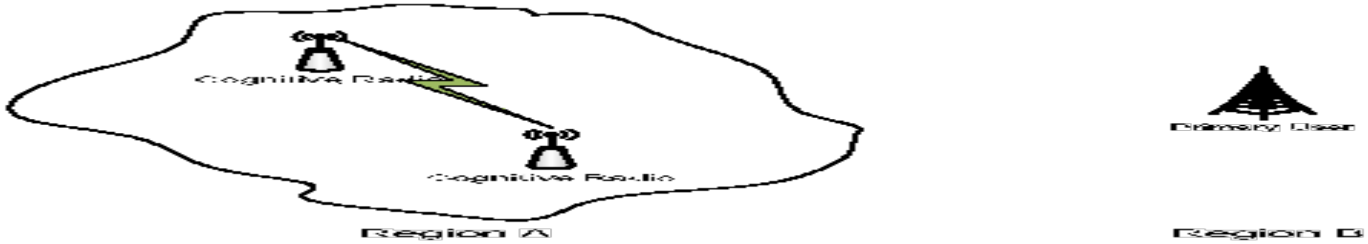
UNIVERSITY OF SOUTH FLORIDA

WCSP Group

MODULATION/WAVEFORM DIMENSION



SPACE DIMENSION



MIXED DIMENSIONS

- PARTIAL OVERLAPPING IN SPECTRUM AND SPACE (when combined properly and using advanced channel allocation techniques, opportunities can be created). Example, WiFi.
- PARTIAL OVERLAPPING IN CODE AND SPECTRUM
- PARTIAL OVERLAPPING IN SPACE (tight reuse, overlaid cells, …)
- ETC

Two ways of employing adaptive spectrum usage: Uncoordinated and Coordinated

Coordinated

- Spectrum access utilization by coordinating access across the various spectrum dimensions
- Example, cellular trunked radio
- Cellular systems that assign channels to users (either time slots or CDMA codes, or OFDMA carriers)
- Several methods may be employed to distribute the spectrum knowledge and control whether through beacons or control channels or by sharing databases of existing users.

Uncoordinated

- Often referred to as opportunistic; responds to a changing radiofrequency environment by automatically adapting its transmissions.
- First senses the spectrum to determine where other systems are operating and where idle spectrum ("white space") exists and then synthesizes a waveform to exploit the "white space.
- Thus, an adaptive system enables operation with other radio systems in non-cooperative fashion and potentially increases the utilization of the spectrum.
- Such a system can also share knowledge of the spectrum environment with other similar devices to ensure other users are not affected by the adaptive system.

Relation of CR with policy based radio

Policy-based Radio

- A radio that is governed by a predetermined set of rules for choosing between different predefined waveforms
- The definition and implementation of these rules can be:
  - during the manufacturing process
  - during configuration of a device by the user;
  - during over-the-air provisioning; and/or
  - by over-the-air control

COGNITIVE RADIO BENEFITS AND APPLICATIONS

USF UNIVERSITY OF SOUTH FLORIDA

WCSP Group

Benefits of CR

1. **New business opportunities**
2. **New applications**
3. **Dynamic Spectrum Access - Improved spectrum efficiency/utilization**
   - Fill in unused spectrum
   - Move away from over occupied spectrum
4. **Interoperability and improved vertical hand-off (public safety, military, etc.)**
   - Multi-network selection
   - Select “best” network access
5. **Link optimization (modulation, power, topology)**
   - Adapt away from bad channels
   - Increase data rate on good channels
6. **Better usage of other resources**
7. **Increased capacity and higher data rates**
8. **Improved coverage and improved link reliability**
9. **Improved service qualities**
10. **Low cost services and potentially low cost devices**
11. **Better time to market (from research to products)**
12. **Advanced networking**
13. **Etc.**

Some applications of CR

- Cellular
  - Improved spectrum efficiency
  - Improved capacity
  - Femtocells
- Public safety
  - Interoperability
  - Co-existence
- DSA
  - TV white space Radio
    - Secondary usage of the spectrum
  - Interference control in ISM bands
    - Automatic frequency coordination
    - Interoperability

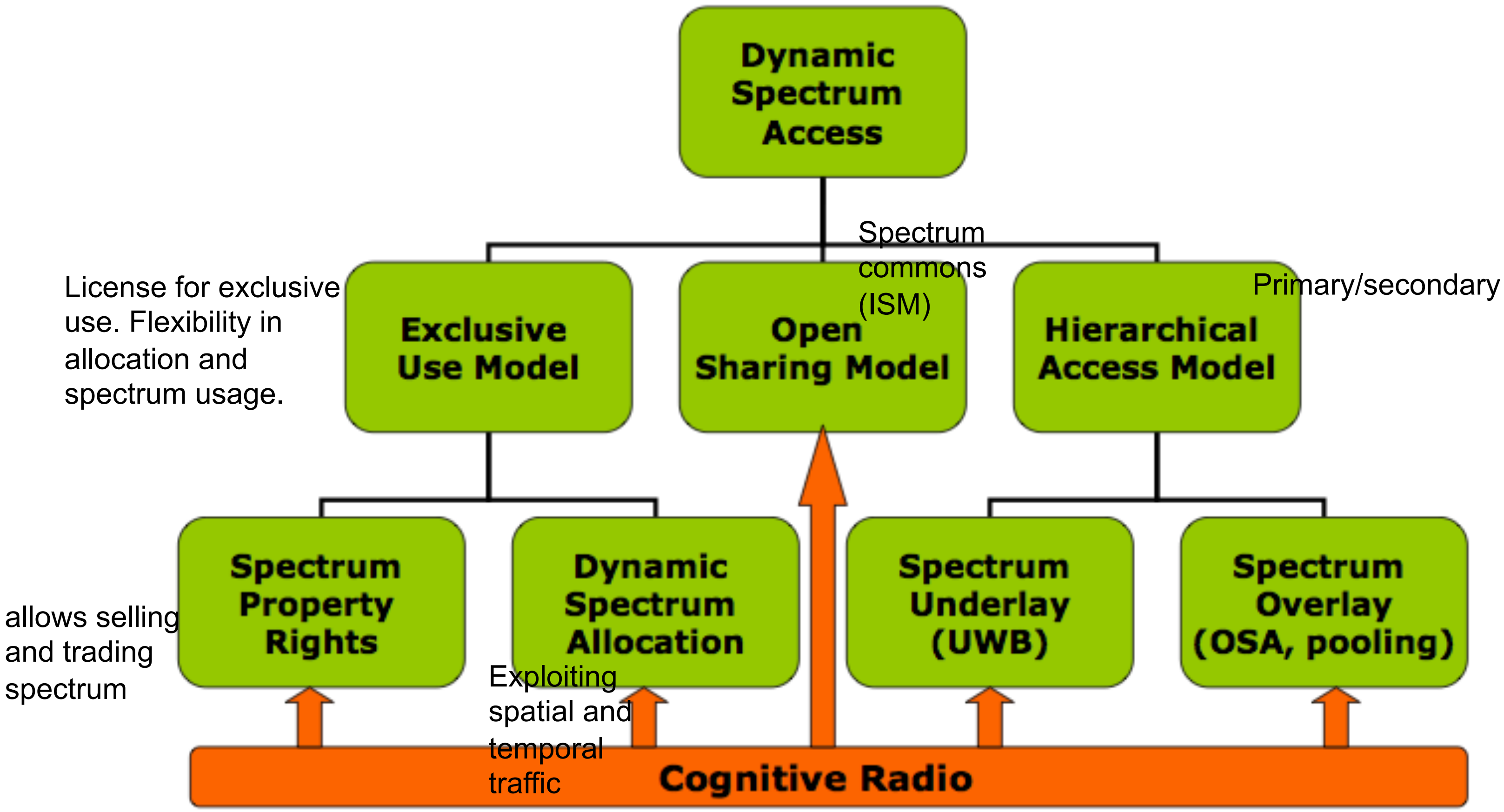
- Note that CR is not just about White Space
- Also, CR is not just about spectrum
- CR has applications beyond dynamic spectrum allocation
- DSA is just one application of the ultimate CR
- Within the DSA, CR can be used:
  - With exclusive models (like cellular bands)
  - With open sharing models (like in ISM bands)
  - With hierarchical access models
    - Underlay (like UWB)
    - Overlay (like secondary/opportunistic usage)

DSA Classifications

- (a) Co-existence (like ISM) or (b) cooperation
- (a) Sharing among equals (ISM band) or (b) primary/ secondary (TVWS)
- (a) Sharing in unlicensed band (ISM) or (b) licensed band (cellular, TVWS)
- Sharing between primary/secondary can be:
  - (a) Underlay or (b) overlay
- Sharing among secondaries can be with
  - (a) coexistence or (b) coordination
- Sharing within primary can be
  - micro-macro sharing of licensed spectrum – like femtocells
  - real time leasing and trading of spectrum between two cellular operators

Application of CR to DSA

DSA: Share spectrum dynamically across multiple systems and services



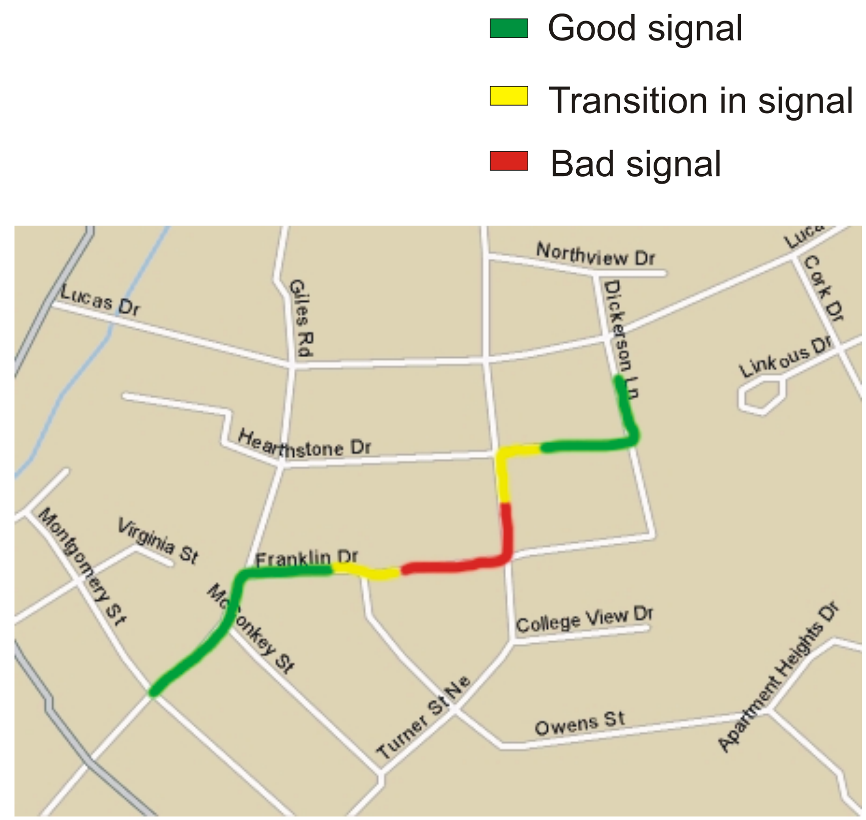
From *Qing Zhao's presentation in ISART*

USF UNIVERSITY OF SOUTH FLORIDA

WCSP Group

Example of Cognitive Radio in Cellular

- Cognitive radio is aware of areas with a bad signal
- Can learn the location of the bad signal
- Can take actions to compensate for loss of signal



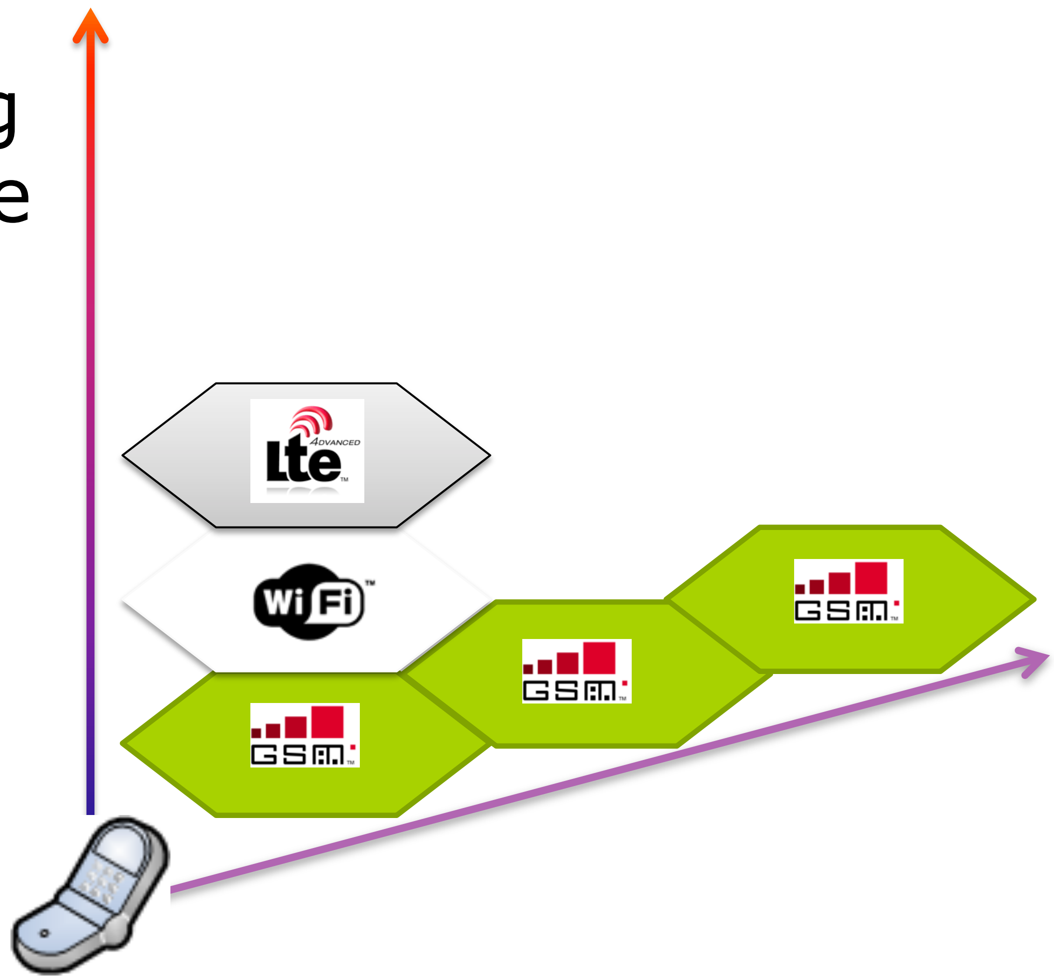
Example: Application of CR to interoperability

Coexistence of Multiple Networks

- There will be many more wireless networks coexisting in the near future
- Therefore mobile devices are desired to
  - Be aware of the networks around
  - Manage seamless transitions between the existing networks

Vertical and Horizontal Handoff

- Handoff: To transfer an ongoing session from a base station (BS) to another BS
  - Horizontal handoff: Transferring to the same network type
  - Vertical handoff: Transferring to another network type



CHALLENGES
&
OPPORTUNITIES

- Physical Layer Challenges/Opportunities
  - How to Use Any Piece of Available Spectrum (operation with various BWs – scalable BW)
  - How to Use a Collection of Pieces of Spectrum (aggregation)
  - How to “Squeeze” onto Spectrum Without Causing Interference (waveform design, shaping)
  - How to decide which band(s) to use (spectrum sensing and decision)
  - How to configure the radio and network adaptively (cross-layer optimization)
  - SDR challenges (ADC/DAC, processing, power constraints)
- Significant research to realize
  - Information collection and modeling
  - Decision processes
  - Learning processes
  - Hardware support
- Regulatory concerns
- Fear of undesirable adaptations, Loss of control
  - Need some way to ensure adaptations yield desirable networks
- CR and SDR test/verification/measurements
- Security Issues

Concerns

- Complex and unproven technology
- Characteristics of the systems are unknown and often must assume worst case interference analysis
- Inadequate enforcement, how to monitor
- Lack of trust that users will yield back the spectrum
- Security concerns

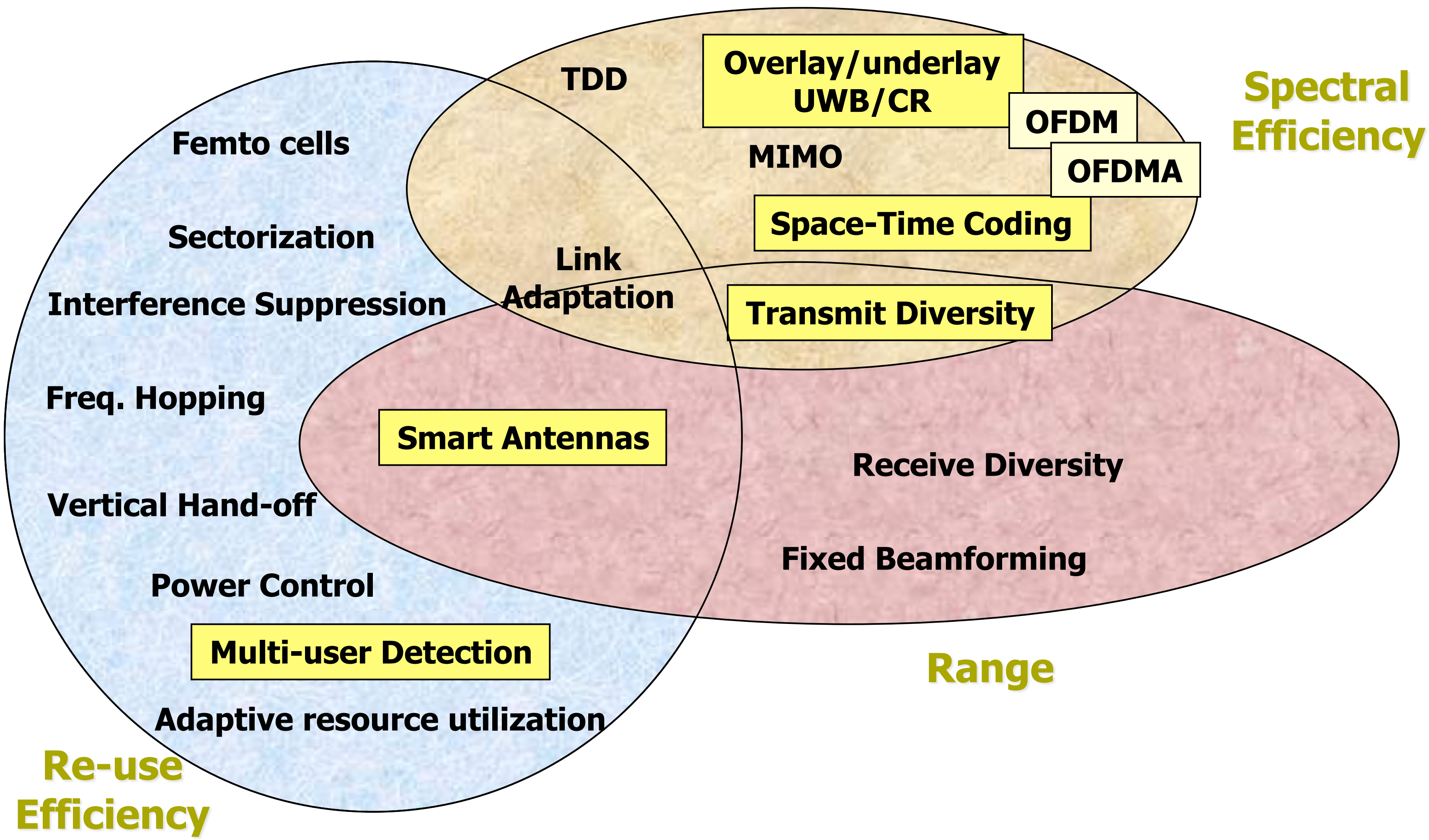
Opportunities in Digital Signal Processing

USF UNIVERSITY OF SOUTH FLORIDA

WCSP Group

- Hardware
  - New computing platforms
  - Fast, power efficient, small form factor, cheap
  - Signal Processing Power (DSP/FPGA)
  - ADC/DAC
    - **Sampling rate:** Nyquist rate.
    - **Resolution(Precision):** The resolution of each sample depends on the number of bits used.
- Software
  - New algorithms for emerging applications like:
    - Sensing
    - Adaptation
    - Awareness
    - Multi-mode, multi-functioning
    - Low complex designs

Some current technologies/concepts that help to the success of CR



Industry standards

(PHY/MAC Protocols)

- TVWS
  - IEEE 802.22- PHY and MAC for Rural broadband in TVWS (WRAN)
  - IEEE 802.11af- PHY and MAC for WiFi operation in TVWS (WhiteFI)
  - CogNeA/ECMA392 - PHY and MAC , mainly for home network applications in TVWS (HDTV streaming), 1st draft published in 2009
  - 802.16h – CR based WiMAX (WMAN)
- Other Bands
  - 802.11h (Dynamic Frequency Selection – DFS)
  - 802.11y (Ports 802.11a to 3650-3700 MHz (US only) Incumbent: radar)

Related Activities and standards

- 802.19.1 (Coexistence in TVWS)
- WiFi Alliance- TV White Space Marketing task force formed (July 2010). Focus is on creating a certification program for enhanced WiFi services TVWS
- Self-organizing networks (SONs)
- 1900
- 802.21 (**Beacon for Protection of Wireless**)
- IEEE 802.22.2 **(WRAN Installation & Deployment)**
- ETSI RRS (Reconfigurable Radio Systems)

WRAN – 802.22

UNIVERSITY OF SOUTH FLORIDA

WCSP Group

- Operates in TV bands
  - 54 to 862 MHz
  - 6 MHz, 7 MHz and 8 MHz channel bandwidth
  - Incumbents: TV broadcast, low power auxiliary (including wireless microphones and wireless assist video devices), Broadcast Auxiliary Service stations, Cable TV headends,
- Entities
  - Base Station (BS)
  - Consumer Premise Equipment (CPE)
- Fixed point-to-multi-point access only.
- Base station controls all transmit parameters and characteristics in the network.

- OFDMA both in uplink and downlink
- QPSK, 16-QAM, and 64-QAM,
- Contiguous channel bonding up to 3 TV channels
- Data rate range from 5Mbps to 70Mbps
- TDD, FDD
- Adaptive OFDMA, scalable bandwidth
- Some similarities with mobile WiMAX PHY
- MIMO capabilities

Comparison of some known standards with WRAN

Standard	Fixed/Mobile WiMAX 802-16-2004 802-16e-2005	LTE	WRAN (Cognitive Radio) 802.22	WiFi (802.11a/g) And extension to 802.11n	DVB-T
Bandwidth (MHz)	1.25 to 20 (flexible)	1.25, 1.6, 2.5, 5, 10, 15, 20 (flexible)	**6 (USA) ,7,8 (fixed) Depending on the country / region**	20 (fixed) 40 with .n	8 (fixed)
FFT size	128,256,512,1024,2048 (flexible)	128,256, 512, 1024, 2048 (flexible) ------- 4096 (broadcasting)	**2048 (mandatory) 1K / 4K optional, 2K / 4K / 6K for channel bonding . Optional fractional use and channel bonding up to 3 contiguous TV channels**	64 (fixed)	2048,8192
Subcarrier spacing and OFDM Symbol Duration	10.94 KHz 91.4 us	15 KHz (7.5 kHz for Broadcasting) 66.67 us	**3.34 kHz (3.90625 and 4.46 for 7 and 8 MHz) 298 us (256, 224)**	312.5 KHz 3.2 us	
CP size	1/4 (22.8 us), 1/8,1/16,1/32	Normal (4.69 us) Extended (16.67 us) Extended B. (33.3 us)	**1/4 (74.5 us), 1/8,1/16,1/32**	1/4 (800 ns) .n allows short 400 ns	1/4,1/8,1/16, 1/32
Range	Typical 5-10 miles	From femtocells up to 30 miles of macrocells	**Up to 100 km (typical 30 km radius)**	100 ft (30 meters) More with .n	
Main Application	Wireless Broadband, Last mile, Backhaul Cellular like mobile broadband	Cellular broadband	**Broadband for rural areas using opportunistic spectrum usage over unused TV bands (between 54 to 862 MHz)**	Broadband for homes and offices	Digital and Synchronous broadcasting
Modulation	BPSK, QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM	**QPSK, 16QAM, 64QAM**	BPSK, QPSK, 16QAM, 64QAM	QPSK, 16QAM, 64QAM
Data rates Mbps	70	SISO: 100 DL, 50 UL	**• Maximum: 72.6 Mbps • Minimum: 4.8 Mbps**	54 .a/g 600 .n	
Multiple Accessing and Duplexing	OFDMA/TDMA (synchronous) TDD, FDD, HFDD	OFDMA (DL) SC-FDMA (UL) (synchronous) TDD, FDD, HFDD	**OFDMA/TDMA (synchronous) TDD (mandatory), FDD (opt.)**	CSMA (listen-before-talk)	N/A Broadcasting

Scalable Bandwidth Concept

How can we adapt the BW of the waveform with a minimal change in the waveform parameters?

One radio to support a variety of bandwidth options.

Scalable BW (WiMAX & LTE)

- Main parameters are the same (carrier spacing, OFDM symbol duration, CP sizes, frame formats)
- Only, used BW, FFT size, and sampling rates change accordingly
  - More BW, higher sampling rate
  - For fixed carrier spacing, more BW means increased FFT size
- Mobile WiMAX and LTE are using variable sampling rate and FFT size to scale the BW
- Fixed WiMAX uses a fixed 256 FFT, hence, when the BW is scaled carrier spacing changes

WiMAX Scalability

Parameters	Values			
System Channel Bandwidth (MHz)	1.25	5	10	20
Sampling Frequency (F_p in MHz)	1.4	5.6	11.2	22.4
FFT Size (N_{FFT})	128	512	1024	2048
Number of Sub-Channels	2	8	16	32
Sub-Carrier Frequency Spacing	10.94 kHz			
Useful Symbol Time ($T_b = 1/f$)	91.4 microseconds			
Guard Time ($T_g = T_b/8$)	11.4 microseconds			
OFDMA Symbol Duration ($T_s = T_b + T_g$)	102.9 microseconds			
Number of OFDMA Symbols (5 ms Frame)	48			

LTE scalability

Transmission BW		1.25 MHz	2.5 MHz	5 MHz	10 MHz	15 MHz	20 MHz
Sub-frame duration		0.5 ms					
Sub-carrier spacing		15 kHz					
Sampling frequency		192 MHz (1/2 x 3.84 MHz)	3.84 MHz	7.68 MHz (2 x 3.84 MHz)	15.36 MHz (4 x 3.84 MHz)	23.04 MHz (6 x 3.84 MHz)	30.72 MHz (8 x 3.84 MHz)
FFT size		128	256	512	1024	1536	2048
OFDM sym per slot (short/long CP)		7/6					
CP length (usec/ samples)	Short	(4.69/9) x 6, (5.21/10) x 1	(4.69/18) x 6, (5.21/20) x 1	(4.69/36) x 6, (5.21/40) x 1	(4.69/72) x 6, (5.21/80) x 1	(4.69/108) x 6, (5.21/120) x 1	(4.69/144) x 6, (5.21/160) x 1
	Long	(16.67/32)	(16.67/64)	(16.67/128)	(16.67/256)	(16.67/384)	(16.67/512)

Scalable BW (WRAN-Cognitive Radio)

- WRAN scalable BW concept is different
- Fixed sampling frequency (corresponding to the highest BW) and constant carrier spacing
  - With the largest FFT size: decreasing or increasing the BW can simply be achieved by changing the guard frequency lengths (we are not transmitting anything on the guard carriers). By changing the length of guard carriers the BW can be adjusted. THINK OF THIS AS THE SPECIAL CASE OF THE FRACTIONAL BW CONCEPT. Occupied subcarriers is adjusted to scale the BW.
- *Note, in WRAN, the FFT size is also adaptive, but, FFT size is only changed to adapt the carrier spacing (adaptive carrier spacing), not for scaling the BW.*

Scalability in WRAN (6MHz)

Mode	1K	2K	4K	6K
FFT Size	1024	2048	4096	6144
Bandwidth (k = 1, 2, …, 6)	k MHz			
Sampling Factor	8/7			
No. of Used Subcarriers (including pilot, but not DC)	140 * k	280 * k	560 * k	840 * k
Sampling Frequency	48/7 MHz			
Subcarrier Spacing	*6.696 kHz*	*3.348 kHz*	*1.674 kHz*	*1.116 kHz*
Occupied Bandwidth	*6.696* kHz*140*k	*3.348* kHz*280*k	*1.674* kHz*560*k	*1.116* kHz*840*k
Bandwidth Efficiency(*)	*93~94 %*			
FFT Time	*149.33 us*	*298.66 us*	*597.33 us*	896 us
Cyclic Prefix Time(**)	*37.33 us*	*74.66 us*	*149.33 us*	224 us
OFDMA Symbol Time	*186.66 us*	*373.33 us*	*746.66 us*	1120 us

For example, for 1K FFT, which is used for carrier spacing of 6.696KHz, we can have bandwidth of 1,2,3,4,5,6 MHz. 1 MHz BW is obtained if we only use 140 (out of 1024) carriers. By occupying more carriers we can increase the BW usage. As can be seen above, for scalability, fixed FFT size, fixed sampling rate, fixed carrier spacing is assumed. Only the used number of carriers is changed.

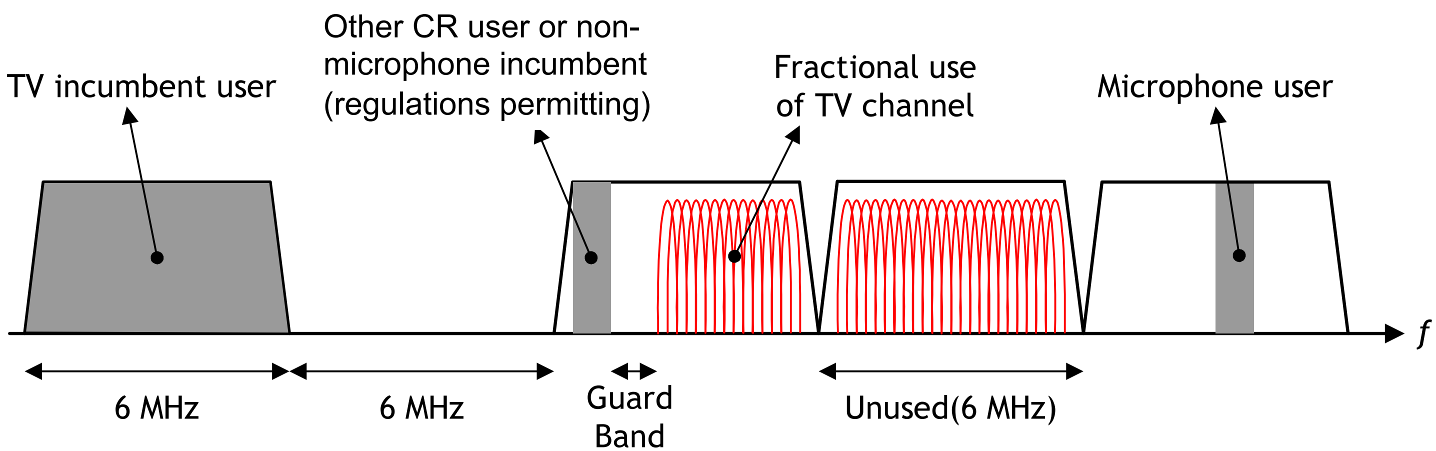
Carrier Aggregation (channel bonding)

- Considered in future standards
  - LTE advanced and 802.16m (up to 100 MHz)
    - Continuous or Non-continuous
- Adjacent or non-adjacent radio-frequency (RF) carriers
- If the MS supports multi-carrier operation, it can receive control and signaling, broadcast, and synchronization channels through a primary carrier, and traffic assignments can be made on the secondary carriers.
  - WRAN (up to 3 TV bands, 3*6MHz=18MHz)
    - Continuous
    - In WRAN, the official name is channel bonding
  - WiFi (802.11n)
    - 2 non-overlapping and adjacent 20 MHz channels are bonded to increase data rates (note that in 2.4 GHz, only 3 non-overlapping bands are available)

- Backward compatibility is critical, since the same physical layer and MAC layer configuration parameters and schemes can be used.
- Use of single carrier frequency, one radio, one FTT, and minimal change to the signaling format is desirable. Easier in continuous but not easy in non-continuous

Fractional Bandwidth Usage in WRAN

- Considering the frequency, bandwidth and type of the narrowband incumbent users, we can use the fractional bandwidth
- The number of used sub-carriers is proportional to the fractional bandwidth
- If the wireless microphones are operating co-channel, the WRAN systems shall clear the entire channel
- The fractional BW mode is identified by using a Preamble
- Example:



Adaptive sub-carrier spacing

- Subcarrier spacing adaptation is ***not*** employed in mobile WiMAX and LTE
- Fixed WiMAX uses 256 FFT with various BW options. Hence, the carrier spacing is adaptive. But, requires sampling rate, OFDM symbol duration and CP changes
- WRAN employs this feature
- WRAN has 4 different subcarrier spacing option
- Adaptive subcarrier spacing can allow:
  - Robustness to ICI (and Doppler spread)
  - Can be used to increase data rate
  - For the same BW, by reducing the subcarrier spacing, we can increase the data rate, but, this comes with less robustness to ICI.