Cognitive Networks/Dynamic Spectrum Access in Wireless Networks: Overview

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11/3/2010

Outline

- Introduction/ Motivations
- Related Standards Activities
- Characteristics of the available bandwidth
- Sensing Techniques and Algorithms for Sensing Intervals
- Spectrum Allocation--Problem formulation
  - Graph coloring
  - Game theory
  - Linear programming
  - Machine learning
- Security
- Implementations

2

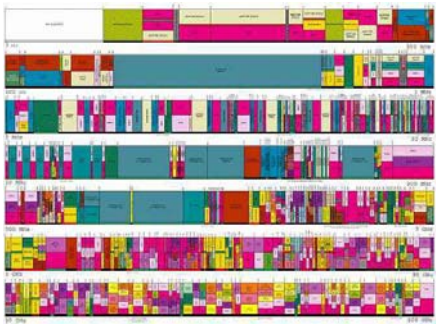
Cognitive Radio/DSA Covers Many Areas –Inter-disciplines

- Signal Processing
- Radar Systems
- Communication Theory
- Control Theory
- Optimization (liner, non-liner or dynamic programming)
- Security
- Neural Networks
- Game theory
- Learning Machines
  - Kalman filter
- Thousands of papers, a lot of conferences, forums, etc
- 15 survey papers (so far, may still miss some)

Motivation

Increasing in demand

Everything is going to be wireless!



- Current radio spectrum allocation is not efficient due to **rigid regulation:**
  - **access-limited** (i.e., big player syndrome)
  - **peak traffic planning** causes temporal underutilization since spectrum demands vary in time
  - **spatial and spectral restrictions** on frequency re-usage

4

Spectrum is Underutilized

- The FCC Spectrum Policy Task Force reported in Nov. 2002 [1] vast temporal and geographical variations in the usage of allocated spectrum : utilization from 15% to 85% under 3 GHz.
- Spectrum measurements were also taken in downtown Berkeley [2]
  - utilization of 30% below 3GHz utilization of 0.5% between 3 and 6 GHz

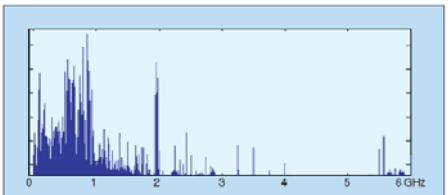


Figure 2. Spectrum utilization measurement in 0-6 GHz band.

5

How to Fully Utilize the Spectrum

Need new generation radios and new radio interfaces support flexible transmission frequencies

- Cognitive Radio, or dynamic spectrum access (DSA)

Cognitive Radio/DSA

The concept of CR was proposed by Mitola in 1998 (see e.g. [3])

Cognitive radio is a context-aware intelligent radio potentially capable of autonomous reconfiguration by

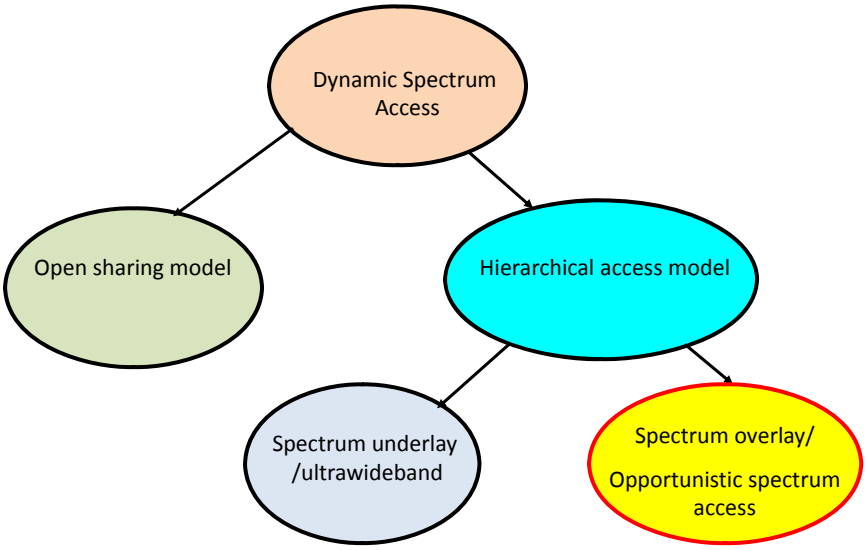
- learning from its environment (sensing whitespace, etc)
- and adapting to it (e.g. adapting transmit power, carrier frequency, modulation,…)== DSA

7

DSA Benefits

- Previous view is that DSA does not benefit Primary Users (Pus)
  - Of Benefit to Unlicensed, Secondary Users of Spectrum
  - Not Particularly Beneficial to Primary Users Already Provisioned with Spectrum
- Current view
  - DSA is Highly Beneficial to Environmentally Stressed Devices
  - Existing "Mission Critical" Primary Users Could Most Benefit from DSA, Even if they Have Adequate Spectrum Access

Classifications of DSA



9

Open Sharing Access model

- In some frequency bands (e.g. ISM band), it is was proposed that "unlicensed" devices can coexist in a largely unregulated way.
- No hierarchical access between the users.
- Baselines rules of user coordination are necessary to avoid interference-producing collision and network congestion.
- Examples: ISM band (2.4 Ghz), UNII band (5-6 GHz) and microwave band (57-64 Ghz)*

*D. Cabric et al.,"Spectrum sharing radios", IEEE Circuits and Systems Magazine, 2006.

10

Hierarchical Access Underlay Model

- SUs are allowed (by spectrum regulator, not by PUs) to use spectrum all the time but severe limits are imposed on their transmitted power.
- Spectrum holes do not need to be detected.
- This limits this approach to short range links (WPAN, sensor networks,…)
- However, by spreading transmitted signals over a wide frequency band, secondary users can potentially achieve high data rate with extremely low power within this short range.
- What happens if there are too many underlay users?

11

Spectrum Underlay and Spectrum Overlay

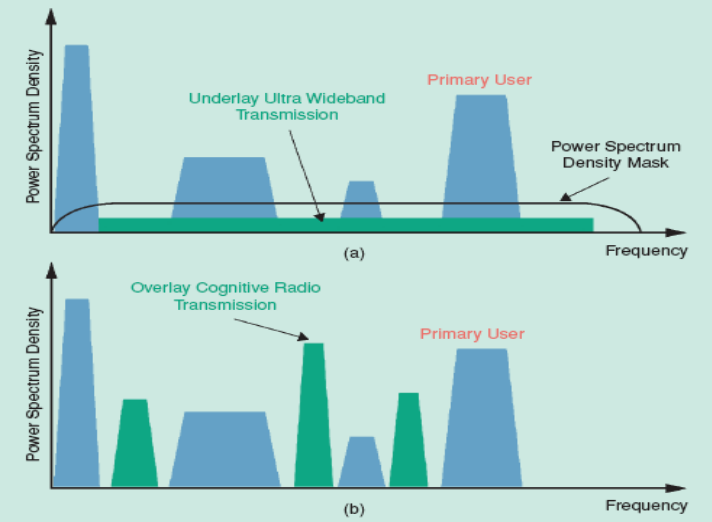


Figure 3. (a) Underlay and (b) Overlay approach for sharing spectrum with primary users.

12

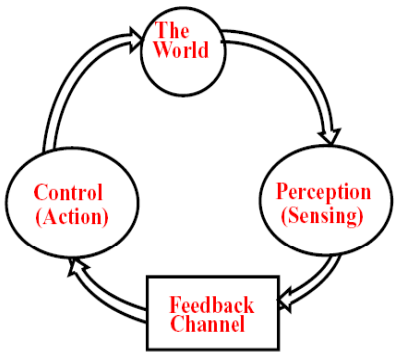
Hierarchical Access Overlay Model

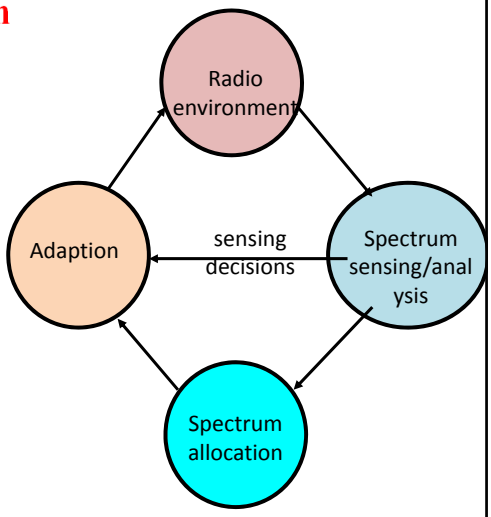
- Hierarchical access between the users : secondary users (SUs) (unlicensed) can opportunistically access the spectrum if limiting the interference perceived by primary users (PUs) (licensees).
- SUs are given implicit permission to use the spectrum if they can transmit without interfering with PUs. When they produce an unacceptable level of interference, PUs issue a "shut up" order that must be obeyed.
- SUs seek out spectrum holes and exploit them. They may thus access the spectrum only when the PU is not transmitting.
- SUs == cognitive radios. This is the focus of the talk.

13

Human Cognition and Cognitive networks

The Essence of Human Cognition in the Simplest Terms Possible





Standards Bodies

- IEEE 1900 Standard Committee, [Now IEEE SCC 41 Group, standard coordinating committee]
- IEEE 802.22 Working Group, Wikipedia on IEEE 802.22
- Software Defined Radio (SDR) Forum
- Object Management Group
- http://www.scc41.org/crinfo
- *IEEE COMSOC Technical Sub-Committee on Cognitive Networks*

IEEE SCC 41

- IEEE 1900.1 Working Group on Terminology and Concepts for Next Generation Radio Systems and Spectrum Management
- IEEE 1900.2 Working Group on Recommended Practice for Interference and Coexistence Analysis
- IEEE 1900.3 Working Group on Recommended Practice for Conformance Evaluation of Software Defined Radio (SDR) Software Modules
- IEEE 1900.4 Working Group on Architectural Building Blocks Enabling Network-Device Distributed Decision Making for Optimized Radio Resource Usage in Heterogeneous Wireless Access Networks
- IEEE 1900.5 Working Group on Policy Language and Policy Architectures for Managing Cognitive Radio for Dynamic Spectrum Access Applications
- IEEE 1900.6 Working Group on Spectrum Sensing Interfaces and Data Structures for Dynamic Spectrum Access and other Advanced Radio Communication Systems

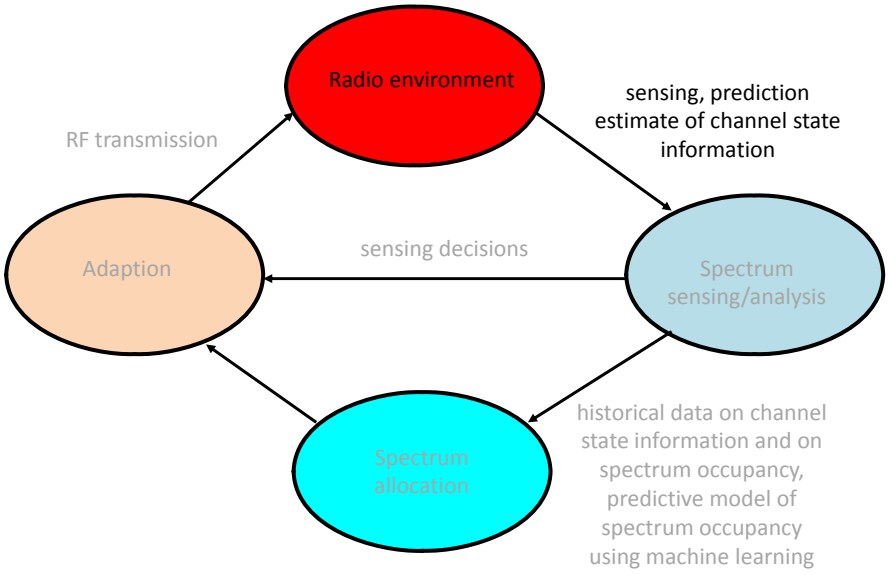
Cognitive radio—IEEE 802.22

In Nov. 2004, the IEEE 802.22 Working Group was established to formalize PHY/MAC layers wireless air interfaces standards for Cognitve Radio-based wireless regional area networks (WRAN) over the spectrum assigned to digital TV service.

The elaboration of this wireless standard is being finalized.

17

Cognitive Radio/DSA Cycle



18

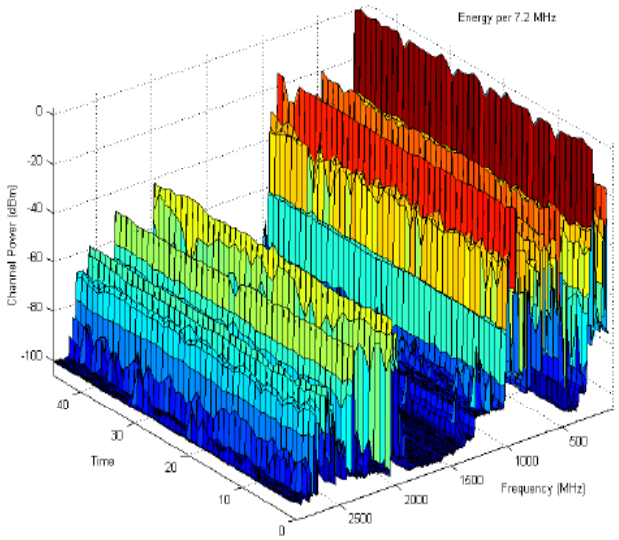
Characteristics of the available bandwidth (Three different studies)

- Simple on-off process, either exponential or fixed pattern, independent
- Empirical studies: 6 cities in USA
  - Three key parameters
    - Threshold level at which spectrum is declared occupied
    - Contiguous spectrum available
    - Contiguous time available
  - Two cases: narrowband, and wideband
- Empirical studies: 4 cities in China
  - Channel vacancy durations follow an exponential-like distribution, but not independent , with strong spectral and spatial correlations

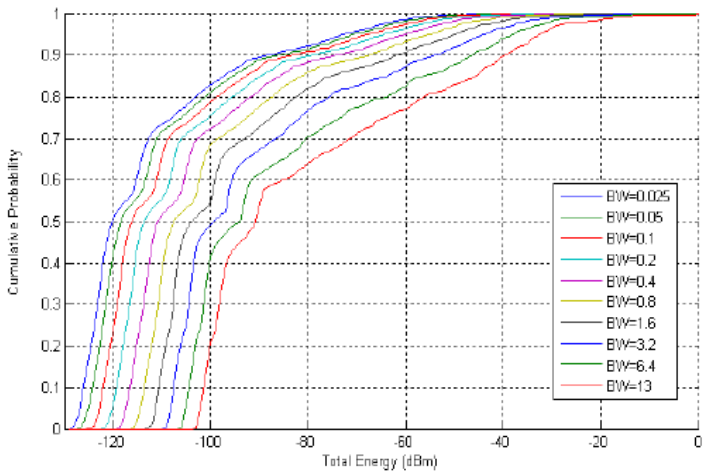
US 6 cities study

Sample	Location	Date(s)
Chicago	Illinois Institute of Technology, Chicago, IL	November 16 to 18, 2005
Riverbend	Riverbend Park, Great Falls, Virginia	April 7, 2004
Tysons	Tysons Square Center, Vienna, Virginia	April 9, 2004
New York	Republican National Convention, New York City, New York (Day 1 and Day 2)	August 30, 2004 - September 2, 2004
NRAO	National Radio Astronomy Observatory (NRAO), Green Bank, West Virginia	October 10 -11, 2004
Vienna	Shared Spectrum Building Roof, Vienna, Virginia	Dec. 15-16, 2004

A Total of 52,436 MATLAB Files and 1,073 MB of Data



24 Hours of Chicago Spectrum Dynamics

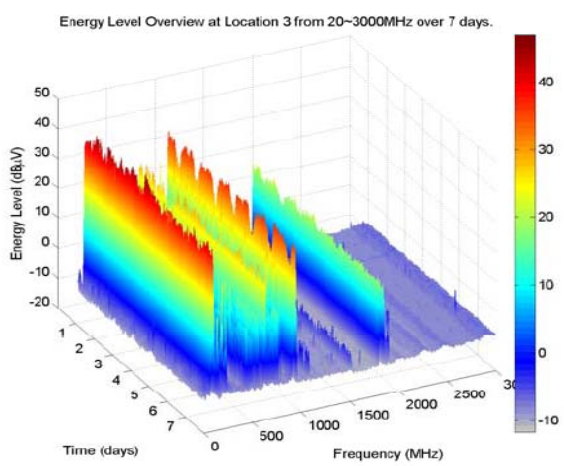


SpectrumOpportunity Measurements for Chicago Spectrum as a Function of Bandwidth in MHz

China 4 cities study

Table 1: Location Overview

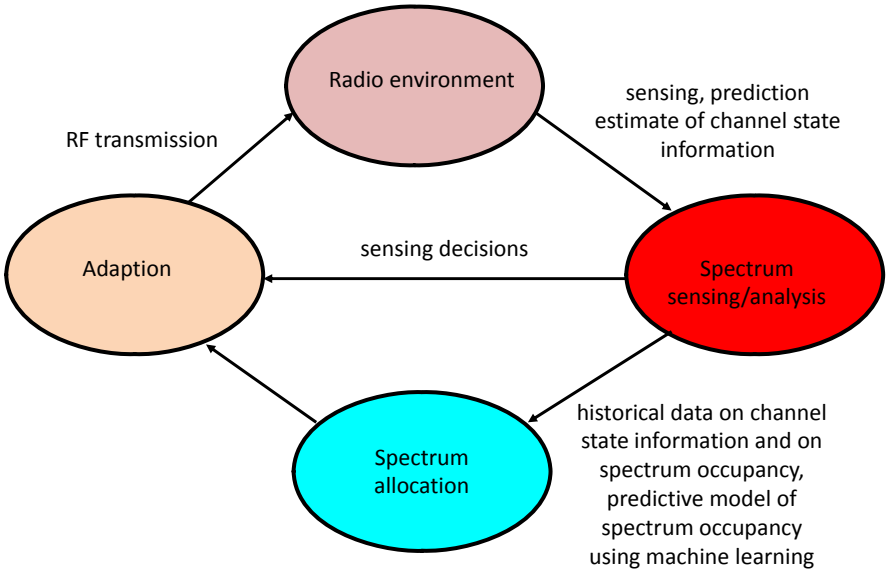
Location	Type	Coordinate
1.Trade Center, Guangzhou	Downtown	E 113°15′25″ N 23°08′01”
2.Canadian Garden, Guangzhou	Downtown	E 113°21′45″ N 23°08′20”
3.Jiangmen	Suburban	E 113°7′59.9″ N 22°22′46.9”
4.Zhongshan	Suburban	E 113°27′24.8″ N 22°25′32.5”



3-D view of the energy level over all bands.

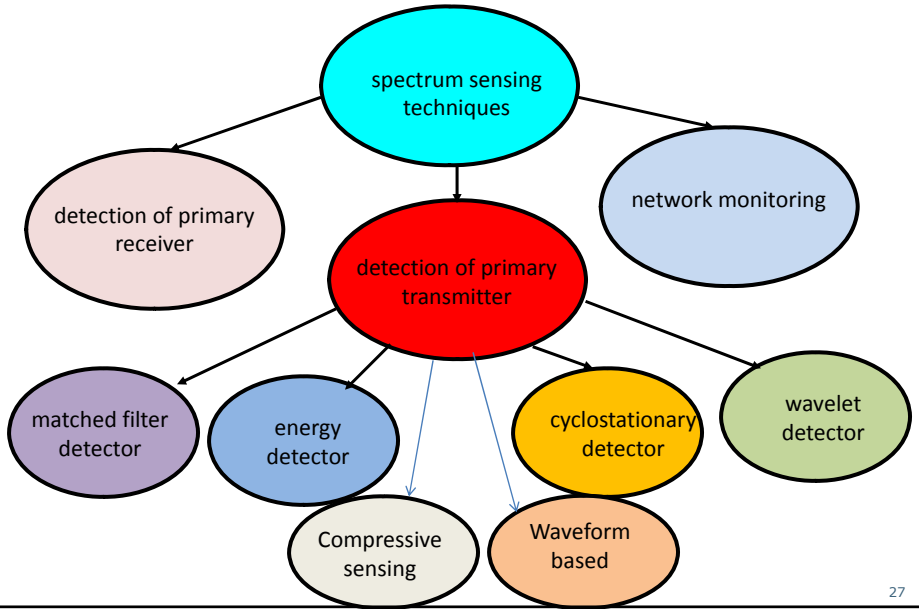
Sensing technolgies

Cognitive Radio/DSA Cycle



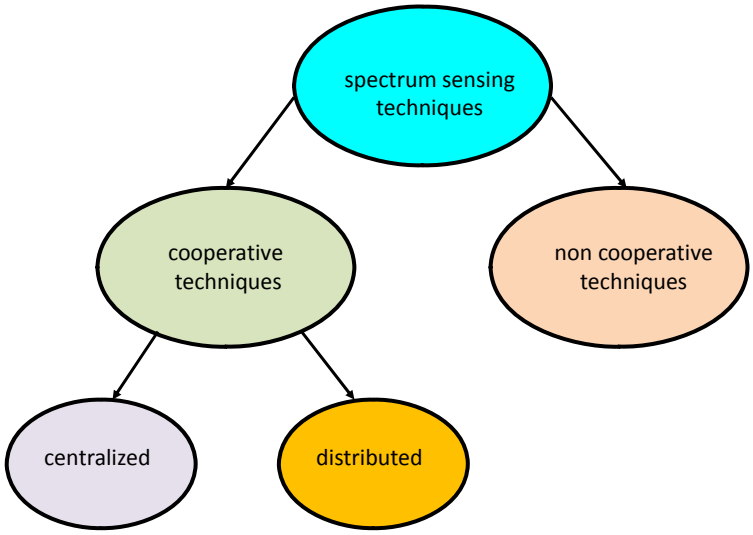
26

Classification of sensing techniques



27

Classification of sensing techniques:



28

Principle of Spectrum Sensing

The spectrum opportunity detector discovers the presence of PUs in a given channel.

It can be considered as performing a binary hypothesis test:

$$\begin{cases} H_0 : \text{absence of PUs (spectrum opportunity)} \\ H_1 : \text{presence of PUs} \end{cases}$$

29

Primary Tx detection: problem formulation

Let us assume the binary hypothesis testing:

$$\begin{aligned} \mathcal{H}_0 : Y[n] &= W[n] & n = 1, \ldots, N \\ \mathcal{H}_1 : Y[n] &= X[n] + W[n] & n = 1, \ldots, N \end{aligned} \qquad W[n] \sim N(0, \sigma^2)$$

and that X[n] and W[n] are i.i.d. real samples, independent of each other.

Neyman-Pearson criterion

$$=> \quad L(Y) = \frac{PDF(Y \mid H_1)}{PDF(Y \mid H_0)}$$

$$L(Y) > \gamma \Rightarrow decide\ H_1$$

$$L(Y) < \gamma \Rightarrow decide\ H_0$$

Y is the vector with all samples Y[n]

30

Matched filter detector

Here, we assume that the samples X[n] are completely known to the Rx (strong assumpt.)

Then, L(**Y**) $\underset{H0}{\overset{H1}{\gtrless}} \gamma$ => $T(\mathbf{Y}) = \sum_{n=0}^{N-1} Y[n]X[n] \underset{H_0}{\overset{H_1}{\gtrless}} \gamma$

"Correlator" or "matched filter" : it correlates the signal received by CR with potential signal emitted by PU.

Threshold γ is fixed by setting P_{FA} to a desired value.

$$\begin{aligned} N &= [Q^{-1}(P_D) - Q^{-1}(P_{FA})]^2 (snr)^{-1} \\ &= O(snr^{-1}) \end{aligned}$$

31

Energy detector

Here, we assume that X[n] are i.i.d. Gaussian samples of known variance

Then, L(**Y**) $\underset{H0}{\overset{H1}{\gtrless}} \gamma$ => $T(\mathbf{Y}) = \sum_{n=0}^{N-1} Y^2[n] \underset{H_0}{\overset{H_1}{\gtrless}} \gamma$

"Energy detector" : it measures the energy of the received signal (in a given bandwidth) over an observation time window.

Threshold γ is fixed by setting P_{FA} to a desired value.

$$\begin{aligned} N &= 2\left[(Q^{-1}(P_{FA}) - Q^{-1}(P_D))snr^{-1} - Q^{-1}(P_D)\right]^2 \\ &= O(snr^{-2}) \end{aligned}$$

32

Cyclostationary Detector

It exploits the cyclostationary property of the PU signal.

A signal is cyclostationary if its mean and auto-correlation are periodic functions.

Many of the signals in wireless comm. possess this property.

Cyclostationarity may be caused by:
- modulation, pulse shaping or coding
- or "intentionally" produced by cyclic prefixes, repeating preambles or synchronization patterns

33

Other Sensing Techniques

- Radio identification based sensing
  - Received signals first classified, other property can be derived from the particular class, such as Zigbee, bluetooth, etc
- Waveform based approaches
  - Utilize known pattern, such as preamble or mid-amble, correlate the received signal with the known pattern
- Cooperative sensing
  - Users share sensed information and collectively determine whether a signal is detected, potential increasing detection probability, at the expense of extra overhead
- Distributed sensing
  - Users share sensed information distributedly and make their own decision whether a signal is detected.
- Compressive sensing

Sensing Algorithms

- Schedule when to start and stop sensing the channels and which set of channels to sense
  - Proactive sensing
  - Reactive sensing
- Trade-off: sense more frequently will increase the chance to detect the PUs, and reduce the interference from SUs, but more time spent on sensing results in more overhead
- Need to select the appropriate sensing schedule so that the overall performance is optimized.

Sensing Algorithms

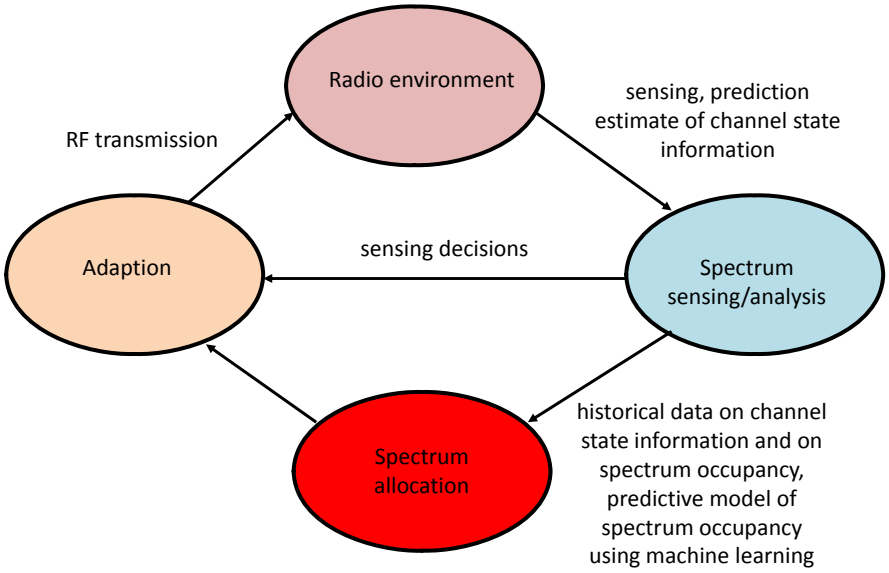
- Proactive approach (Zheng 2008)
  - predict the PUs' behavior assuming exponential and periodic traffic models
  - to minimize disruption to primary users, secondary users proactively switch channel before any primary user appears (based on the assumption about the PU's behavior)
  - To quickly resume communication, secondary users intelligently select another available (and reliable) channel based on the prediction.
  - 30% improvement over a reactive approach

Sensing algorithms (Zhang 2008)

- Sensing start time
  - After transmitting T units of time or no more packets to transmit
- Sensing stop time
  - An optimal stop decision problem
  - At any decision point, the decision is either making a decision and accepting the given reward (depending on the states up to the current) or
  - To continue observing the next state and make a decision then
    - Based on the assumption that the probability of the channel availability is known

Spectrum Management/Allocation

Cognitive Radio/DSA Cycle



39

Spectrum decision/access: 3 main decisions

- Whether to access spectrum
- How to access spectrum
- How to share spectrum opportunities among CRs (spectrum allocation)

40

Whether to access spectrum

- Is the decision of detector reliable enough ? How much should trust we it ?

- Is the price charged by the PU acceptable ? (if relevant)

- Is *this* frequency band a good opportunity ? Or should wait for another one (elsewhere in the spectrum or later on in the future) ?
  => a statistical model of spectrum occupancy might help

41

How to access spectrum

- Select the number of spectrum bands to access and the set of appropriate bands (e.g. subcarriers in OFDM systems)

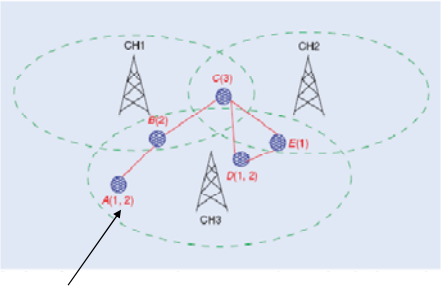
- Which modulation ? Which bit loading on OFDM subcarriers (if OFDM) ?

- Which pulse shaping ?

- Which power level to use (transmission power control) ?

42

How to share spectrum opportunities among CRs?



A(1,2) means that channels available to A are 1 and 2

Assume 3 PUs, each occupying one of the three channels.

A SU within the coverage area of a PU cannot use the channel occupied by that PU.

Furthemore, neighboring SUs interfere with each other if they access the same channel.

How to allocate available channels to SUs to optimize certain network utility such as capacity under fairness constraints ?

43

Spectrum management

- There are several major approaches
  - Converting the spectrum assignment as a graph coloring problem or a linear/mathematical programming
  - Formulating the problem as a game
  - Machine Learning
  - Cross Layer (spectrum allocation + routing)

Graph coloring approach

- Typically for static spectra allocation, assuming a given set of available spectra
  - Or slow interactive
- Same price for all the spectra
- Reduce the spectra allocation problem to a conventional graph coloring problem
  - Solving the graph coloring problem is NP-hard, many heuristic algorithms have being proposed
  - Existing solutions for graph coloring can be used
- When available spectrum changes, (or network topology or demand changes), the spectrum allocation must be done again

Graph coloring problem formation

Original graph F	New graph G
Link	vertex
If two links cannot be active concurrently	An edge exists between the two vertices
If two links share one common node	An edge exists between the two vertices
If links within a close proximity (interfere with each other) using the same frequency	Edges exist between those vertices

A set of candidate colors is given based on the available spectra sensed and policies
Vertices having a common edge cannot have the same colors
Coloring the graph in such a way that a pre-defined objective is optimized.

Goals: spectrum utilization and fairness

Once Graph G is colored, we will have a corresponding conflict-free spectrum allocation scheme

Linear program formulation [Zheng 08]

- Maximizing a given objective function subject to some constraints
- Objective function
  - Node dependent channel throughput
- Constraints
  - Spectrum or channel availability
  - Interference constraint
  - Conflict avoidance
- Output: spectrum allocation

Game Theory Approach

- Initially used in the microeconomics
- A game consists of players, strategy /decision and rewards /utility
- Suitable for interactive,
  - players make decision independently
  - some time, players make decision based on other players' decisions
- Different rewards or utility functions
  - Each user has a common interest
  - However, users have a competing interest to maximize their own share of the spectrum resources (their decision impacts each other)
  - Their rational decision must be undertaken while anticipating the response of its rivals
  - Most case, the approach achieves Nash equilibrium, cannot guarantee the Pareto optimum, leading to lower network capacity

Game Theory Approach: example[5]

- Channel allocation problem
- Mathematically defined as

$$\Gamma = \{N, \{S_i\}_{i \in N,} \{U_i\}_{i \in N}\}$$

- N a finite set of players (decision makers)
- S_i the set of strategies associate with player *i*
- U_i the set of utility functions that the players associate with their strategies. U_i is a function of s_i and the strategies of the rest players, s_{-i}

Utility Function U1

- U1 –selfish user, which values a channel based on the level of interference perceived on that particular channel:

$$U1_i(s_i, s_{-i}) = -\sum_{j \neq i, j=1}^{N} p_j G_{ij} f(s_j, s_i), \forall i = 1, 2, \ldots, N$$

p_j the transmission power, $S=[s_1,s_2,\ldots,s_N]$, $f(s_i,s_j)$ an interference function, G_{ij} is the channel gain

Utility function U2

- U2 –which values a channel based on the level of interference perceived on that particular channel and the interference to neighbors:

$$U1_i(s_i, s_{-i}) = -\sum_{j \neq i, j=1}^{N} p_j G_{ij} f(s_j, s_i) - \sum_{j \neq i, j=1}^{N} p_i G_{ji} f(s_i, s_j),$$
$$\forall i = 1, 2, \ldots, N$$

p_j the transmission power, $S=[s_1,s_2,\ldots,s_N]$, $f(s_i,s_j)$ an interference function, G_{ij} is the channel gain

Key steps using game theory

- Random access for decision making
- At the start of each slot, each user selects to make a decision based on probability P_a. If successful, makes a new decision, otherwise, no action
- Transmitter sends interference information (estimated) on neighbors
- Receiver computes the current interference for the user, determine U2(f) and decides one channel having the highest U2, and send this info to transmitter
- Transmitter ACK the decision, and starts to transmit
- All other users update their channel status table

Machine Learning for non exact potential games

- U1 lacks necessary symmetry, cannot use the above approach
- Need machine learning

Types of machine learning

- Supervised learning
  - We know the values of the function, ***f***, for ***m*** samples in the training set
  - Curve fitting is a simple example of supervised learning of a function.
- Unsupervised learning
  - Simply have a training set of vectors without knowing the function values for them
  - Have application in taxonomic problems in which it is desired to invent ways to classify data into meaningful categories
- Some learning in between
- Reinforcement learning

Learning algorithms

- Definition: a state space, S, an action set, A, an objective function, has a value for each state s in S.
- The learning algorithm will try to characterize the function in an effort to find an optimal state.

- Markov Decision Process (MDP)/reinforcement learning (RL)
- Neural networks
- Genetic algorithm
- Hidden Markov chain

Machine Learning in DSA

- For radio
  - Decide transmit power, select waveform (FM, AM, SS, OFDM), etc
- For spectrum allocation
  - Select an optimal spectrum allocation so that some objectives are optimized (maximum throughput, minimum delay, etc)

Q-learn or Reinforcement learning

- Markov decision process or Q-learning
- Q-learning is an on-line algorithm in Reinforcement Learning (RL) that determines an optimal policy without detailed modeling of the operating environment.

$$Q_{t+1}(s_t, a_t) = (1-\alpha)Q_t(s_t, a_t) + \alpha\{r_{t+1}(s_{t+1}) + \gamma \max_{a \in A} Q_t(s_t, a)\}$$

where α is the learning factor and γ an aging/ discount factor, $r_{t+1}(s_{t+1})$ is the delayed reward

- An optimal policy is being searched for in RL that maximizes the value function *V*(s,t)* as shown in equation

$$V^*(s_t) = \max_{a \in A} \{Q_t(s_t, a)\}$$

- Hoe to select *Q(s,t)*? See [7] for more details

Price of Anarchy

- Non-cooperative game
  - Each user chooses its strategy to optimize its own performance metric
- Cooperative game
  - each player aims at maximizing a common benefit for the set of players
  - require information regarding all the players' local information
- Price of Anarchy is defined as a measure of the loss of performance observed in a non-cooperative game due to the lack of cooperation

Security

Dynamic spectrum Access (DSA) Attacks (1/4)

- Primary user emulation attack
  - By temporarily manipulating their signals, attackers can cause other secondary users to permanently misclassify them as primary users, giving adversaries complete access to the spectrum
  - Example: the attacker could easily transmit a TV signal by using a TV Ultra High Frequency (UHF) transmitter or just replay a real TV si
- To overcome this attack, better-developed detection algorithm may be able to distinguish the legitimate primary user from the adversary.
  - radios might compare their perception of their environment with characteristics know a priori. For example, one can geolocate primary transmitters, and compare their measured location to the locations of known primary users.
  - use feature-based signal classification and a machine learning approach to identify whether it is indeed a primary user

Dynamic spectrum Access (DSA) Attacks (2/4)

- Spectrum sensing data falsification attacks
  - An adversary sends false local spectrum sensing results causing degraded system performance
- To overcome this attack, efficient filtering scheme which uses information (spatial and temporal) from multiple sources to filter out false reports by applying majority or voting rules

Dynamic spectrum Access (DSA) Attacks (3/4)

- Attacks against learning engine
  - An adversary persistently feeds the learning engine with false results, which later become "known" historical data, achieving long lasting DoS attack
- To overcome this attack,
  - Be more critical of the accepted information,
  - Decrease the persistence of beliefs
  - Define trust metrics and let the learning engine reason about the trustworthiness of their neighbors

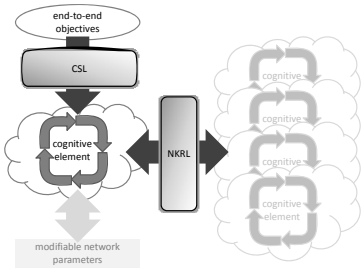
Dynamic spectrum Access (DSA) Attacks (4/4)

- Common control channel attack
  - An adversary can take control f the common control channel that some DSA networks use and can change the key parameters of the available band or interfere with primary users
  - Or jamming the channel or eavesdropping on the control data
- To overcome this attack, one approach is to secure the control channel using the authentication, authorization and auditing (AAA) techniques

Implementations

Interface Languages

- CNs require the ability to share knowledge and interpret end-to-end objectives
- This is requires two languages for two interfaces:
  - an interface to the other cognitive elements in the network
  - an interface to the sources of the network's end-to-end objectives



NKRL and CSL

- The development of a Network Knowledge Representation Language (NKRL) is needed to store and communicate knowledge between cognitive elements
- The development of a Cognitive Specification Language (CSL) is needed to bridge the interface between the end-to-end goals and the cognitive elements

Interface Language Requirements

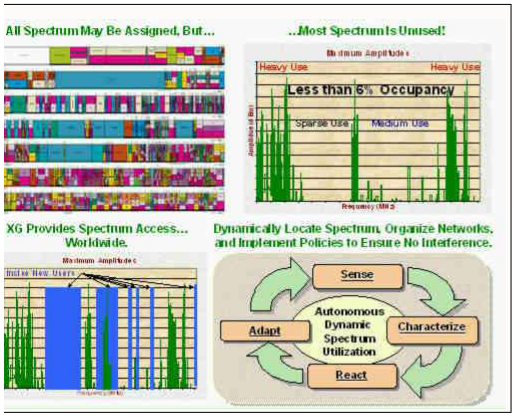
- Expressiveness: ability to express constraints, goals, priorities and behaviors to the cognitive elements that make up the process
- Cognitive process independence: reusability of cognitive engines
- Interface independence: works with different sets of dials, knobs, objective functions and policy engines
- Extensibility: adapt to new network elements, applications and goals

Projects Related to Next Generation Radio

- DARPA's Wireless Network after Next (WNaN) Program
- DARPA's XG Program
- DARPA's Situation Aware Protocols in Edge Network Technologies (SAPIENT)
- DARPA's Architectures for Cognitive Information Processing
- DARPA's Real World Reasoning
- SRI's International XG Policy Control
- US Army Joint Tactical Radio Systems (JTRS)
- Software Communications Architecture
- OSSIE
- Software Communications Architecture - Reference Implementation
- European Commission FP6 E2R Programme (E2R I & II Projects)
- European Commission FP7 E3 Project

DARPA XG DSA

GOAL: 10x Increase in Available Spectrum



Technical Achievements:

- Sensing: **High-Speed, Wideband, High-Sensitivity at Reasonable Cost**
- Adaptation: **Protocols for Rendezvous and Network Adaptation**
- System Integration: **End-to-End Performance and Scalability**
- Interference Protection: **Algorithms for Protection of Other Radios via Automated Reasoning**
- Performance & Scalability: **Increased Spectrum Access and Large-Scale Operation of Non-Cooperative XG Networks**

DSA Rapid-Fielding Efforts

- **DARPA, Army G-6, USMC, and OSD NII Leadership Jointly Accelerated XG Integration into Existing Radio(s) for Rapid Fielding**
  - –DARPA-Funded Initiative for Near-Term Exploitation of Technologies
  - –Goal 1: Evaluate DSA Technologies in Existing Software-Based DoD Radios
  - –Goal 2: Accelerate DSA Transition to Overcome Hurdles in Current Operations
- **PRC-148 and PRC-152**
  - –Digital Narrowband Voice Communications
  - –Software Upgrade – No Hardware Modifications
  - –11 Months from Selection to Demonstration
  - –Demonstrated Capability in May-June 2008
  - –Met Goal of Removing Engineering Risk and Demonstrating Ability to Apply DSA to Existing DoD Inventory
- **EPLRS-XF** enhanced position locations reporting system
  - –Working with US Army PEO-C3T (PM CP) to Demonstrate DSA in the EPLRS-XF Radio
  - –Provides DSA in Packetized Networking Tactical Radio

Recent DARPA Programs

- BLADE
  - Apply cognitive techniques to develop smart jammers
  - Behavioral Learning for Adaptive Electronic Warfare
- CommEx
  - Apply cognitive techniques to build robust communications under different types of interferences (High J/S, conventional Jammers, common interference)
- CLASIC
  - Cognitive radio Low-energy signal Analysis Sensor ICs

White Space Device (WSD)

- Motorola WSD
  - operates on channels 21–51 (512 MHz–698 MHz) and includes capabilities for geo-location and sensing of digital TV signals
- Adaptrum WSD
  - an integrated hardware and software development system that has been designed for TV white space operation on UHF television channels 21–51 (512 MHz–698 MHz).
  - http://www.adaptrum.com/

Conclusions

- Discussed why we use DSA
- Main components of DSA
  - Characteristics of the available bandwidth
  - Sensing technologies and sensing algorithms
  - Spectrum management
  - Other applications
- Open issues--Many
  - Security, policy, more accurate measurements/studies on users behave, realistic trade-off studies on the overhead versus performance gain

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