Cognitive Networks/Dynamic Spectrum Access in Wireless Networks: Overview

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Outline

- Introduction/ Motivations
- Characteristics of the available bandwidth
- Sensing Techniques
  - Algorithms for Sensing Intervals
- Spectrum Allocation--Problem formulation
  - Graph coloring
  - Game theory
  - Linear programming
  - Machine learning
- Related Standards Activities
- 5G and Cognitive Radio

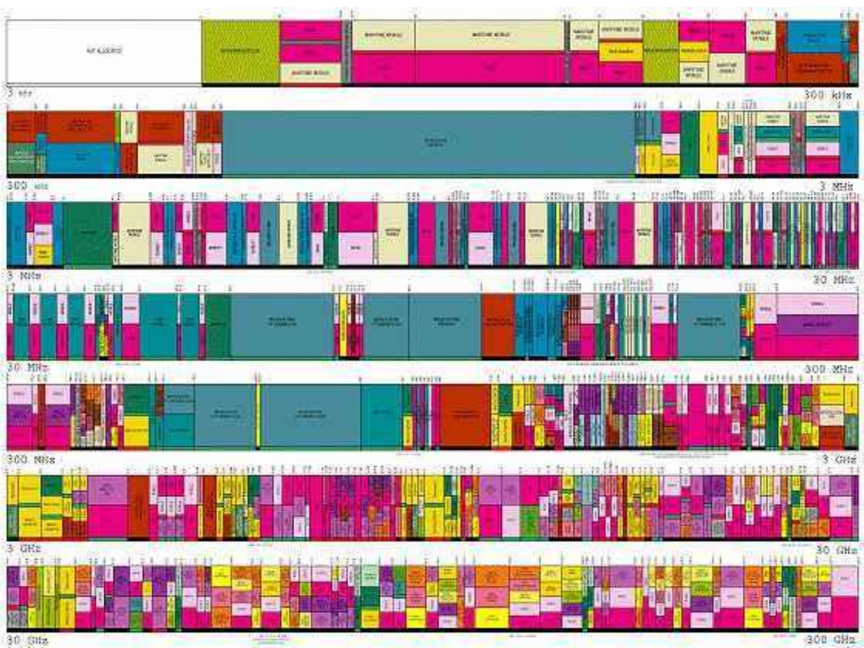
Cognitive Radio/DSA Covers Many Areas –Inter-disciplines

- Policy/Regulation/Legal Issues/Business
- Signal Processing
- Radar Systems
- Communication Theory
- Control Theory
- Optimization (liner, non-liner or dynamic programming)
- Security
- Neural Networks
- Game theory
- Learning Machines, artificial intelligent (AI)
  - Kalman filter
- Thousands of papers, a lot of conferences, forums, etc

DSA - 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

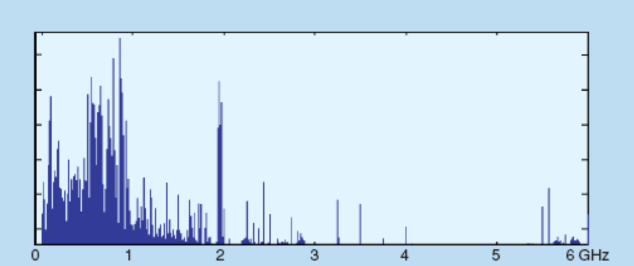


Figure 2. Spectrum utilization measurement in 0-6 GHz band.

- utilization of 30% below 3GHz
- utilization of 0.5% between 3 and 6 GHz

Future networks

- Future 5G networks will have (comparing 4G)
  - 1000 times the system capacity,
  - 10 times the spectral efficiency, energy efficiency, and data rate, and
- IoT, D2D, M2M, all require spectrum
- To this end, it is envisioned that cognitive radio networks would contribute to enormous increases in data rate in 5G

Cognitive Radio/DSA

The concept of CR was proposed by Mitola in 1998

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,…)

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A Multidimensional Spaces/Domains

- Spectrum Policy
  - Economics
  - Regulation
  - Legal
  - Business

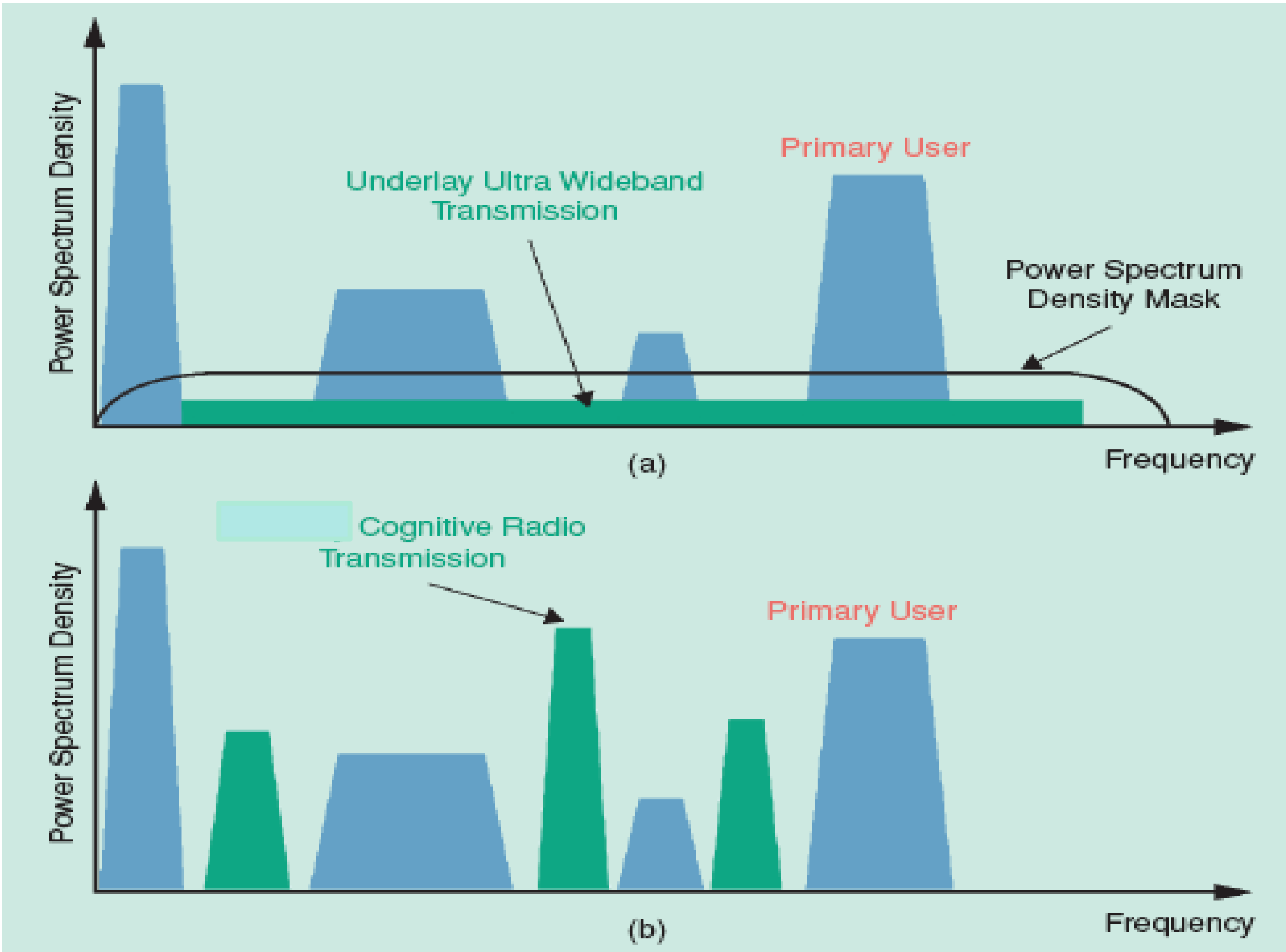
- Theory, Protocols and Algorithms
  - Cooperative Communications
  - Information & Coding Theory
  - Statistical Signal Processing
  - Game Theory & Microeconomics

- Hardware/Software Platforms & Prototyping
  - Programmable agile radios
  - GNU platforms
  - Cognitive Radio Network Testbeds

Three DSA Models

- Underlay
- Interweave
- Overlay

Spectrum Underlay and Spectrum Interleave



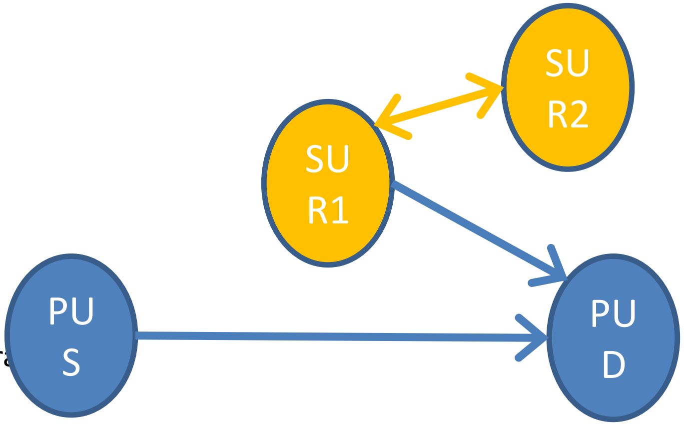
a) Underlay b) Interweave

Interweave 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.

Spectrum Overlay Model

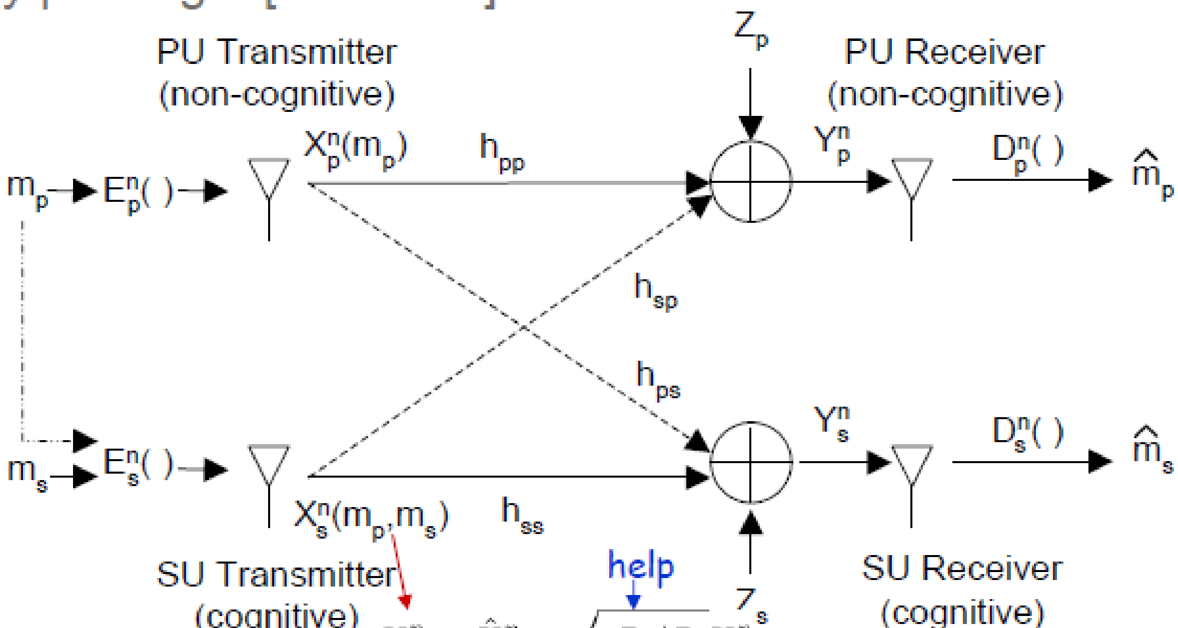
- PU and SU can transmit simultaneously
- SUs may use a part of their energy to assist the communications of PUs through cooperative communications techniques and the rest of the energy to transmit their own signals.
- The interference from the SUs' signals can be compensated with the gain for the PUs' signal quality through the cooperation of the SUs.
- It requires the SUs to know the PUs' packets before the PUs begin their transmissions



Jafar, Srinivasa, Maric, Goldsmith, “Breaking spectrum gridlock with cognitive ra
an information theoretic perspective”, Proc. IEEE, 2009

Spectrum Overlay Model

- Overlay paradigm [Jovicic06]



$$X_s^n = \hat{X}_s^n + \sqrt{\rho P_s / P_p} X_p^n$$

interference

1. PU and SU transmit simultaneously
2. Performance of PU does not degrade
3. SU gets some rate optimally via dirty paper coding

PU capacity with SU TX

$$\frac{1}{2}\log\left(1 + \frac{(h_{pp}\sqrt{P_p} + h_{sp}\sqrt{P_s\rho})^2}{N_p + h_{sp}^2(1-\rho)P_s}\right)$$

=

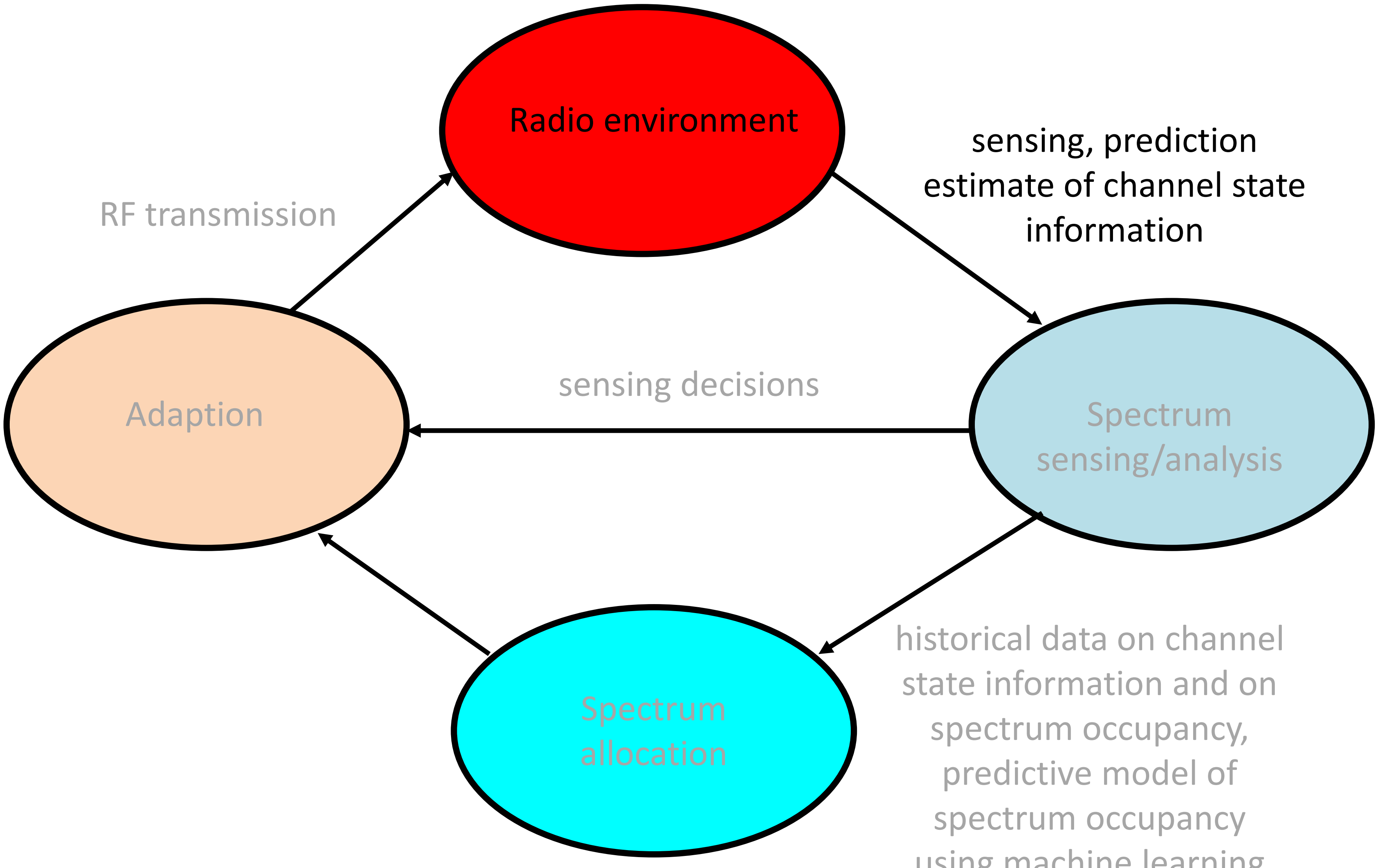
PU capacity without SU TX

$$\frac{1}{2}\log\left(1 + \frac{h_{pp}^2 P_p}{N_p}\right)$$

$$\rho^* = \frac{h_{pp}^2\left(\sqrt{h_{sp}^2 P_s (h_{pp}^2 P_p + N_p) + N_p^2} - N_p\right)^2 P_p}{h_{sp}^2 (h_{pp}^2 P_p + N_p)^2 P_s}$$

Fraction of SU power used for PU signal

Cognitive Radio/DSA Cycle



Characteristics of the available bandwidth (Three different studies)

- Assume Simple on-off process, either exponential or fixed pattern, independent, finding the most suitable parameters
- 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

Traffic – Packet --Pattern

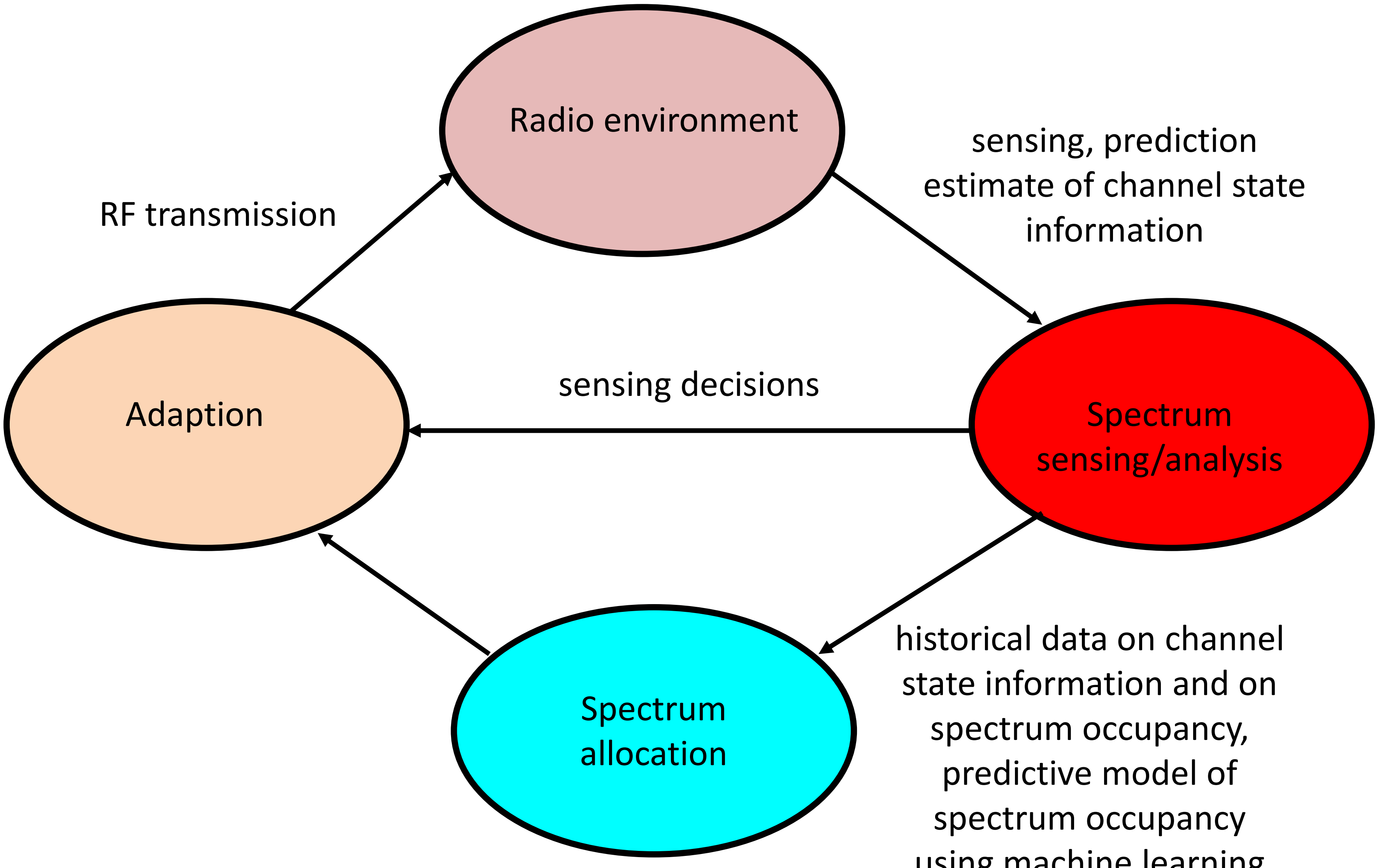
- Traffic characteristics
  - Packet length, packet inter-arrival time, variance of packet lengths
- SU observes the PU traffic by looking at PU packet headers
- Given the PU observation Y, to find 1) how many patterns generated Y, and 2) which data point yi belongs to which traffic pattern
- Use the Bayesian non-parametric clustering method

Dataset					
Game		VoIP		UDP	
Feature	Mean	Feature	Mean	Feature	Mean
Packet length (bytes)	69.33	Packet length	1,512	Packet length	210
Packet inter-arrival time (usec)	55,644.58	Packet inter-arrival time	2,655.304	Packet inter-arrival time	73
Variance(Packet length)	352	Variance(Packet length)	0	Variance(Packet length)	0
Uplink/Downlink ratio	0.94	Uplink/Downlink ratio	0.000242	Uplink/Downlink ratio	1

Utilization

- Knowing the characteristics of the available bandwidth or packet inter-arrival time, it helps
  - Design sensing algorithms, when to start/stop sensing and which channels to sense
  - Routing: select the path which fits the secondary user's packet pattern (may not be the shortest path)
- New research: how to accurately estimate the PU's available bandwidth and packet pattern.
  - Using Machine learning to identify the traffic pattern
  - Exemplary approaches: Bayesian nonparametric machine learning algorithms, Dirichlet process, infinite Gaussian mixture model and Gibbs sampling.

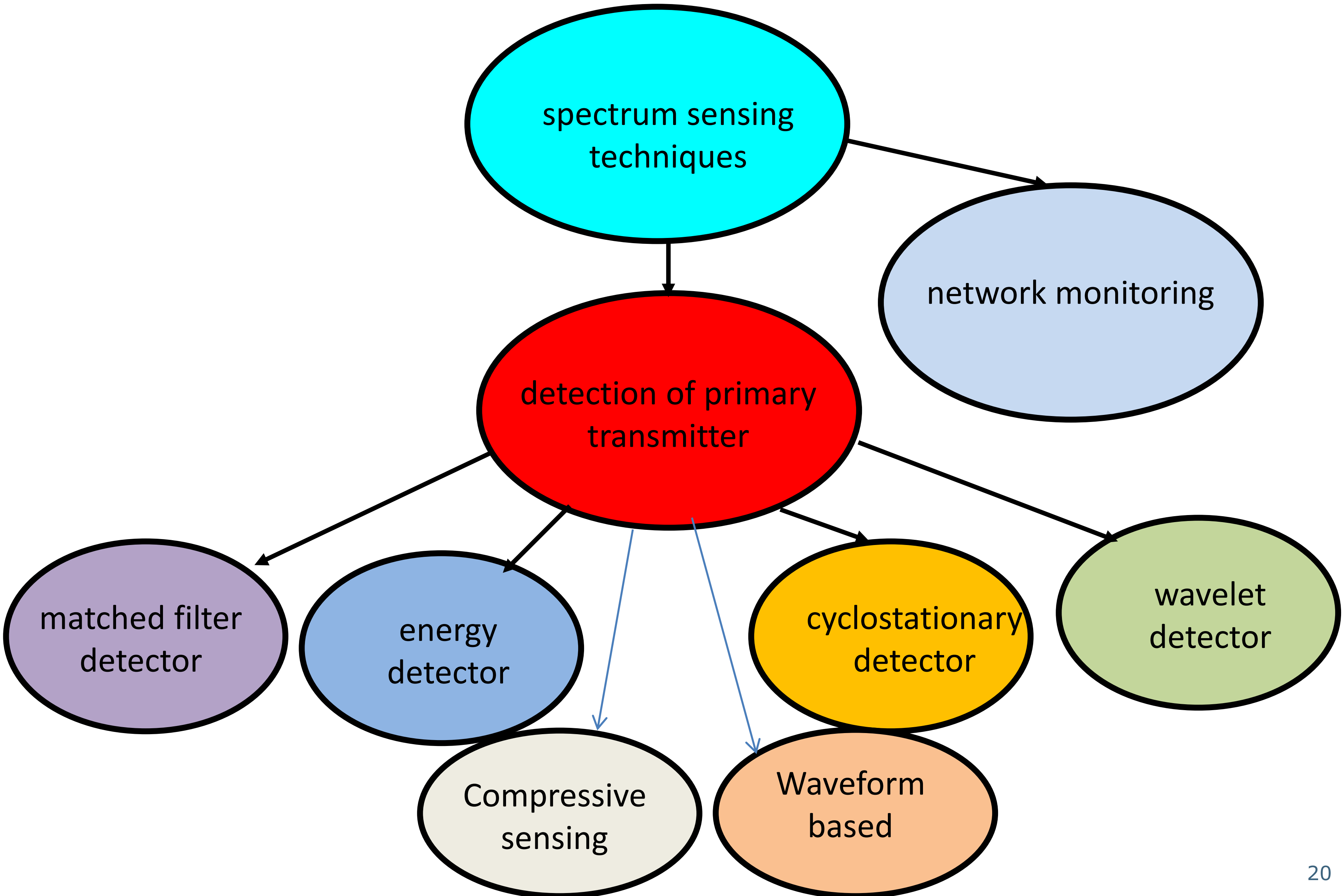
Cognitive Radio/DSA Cycle



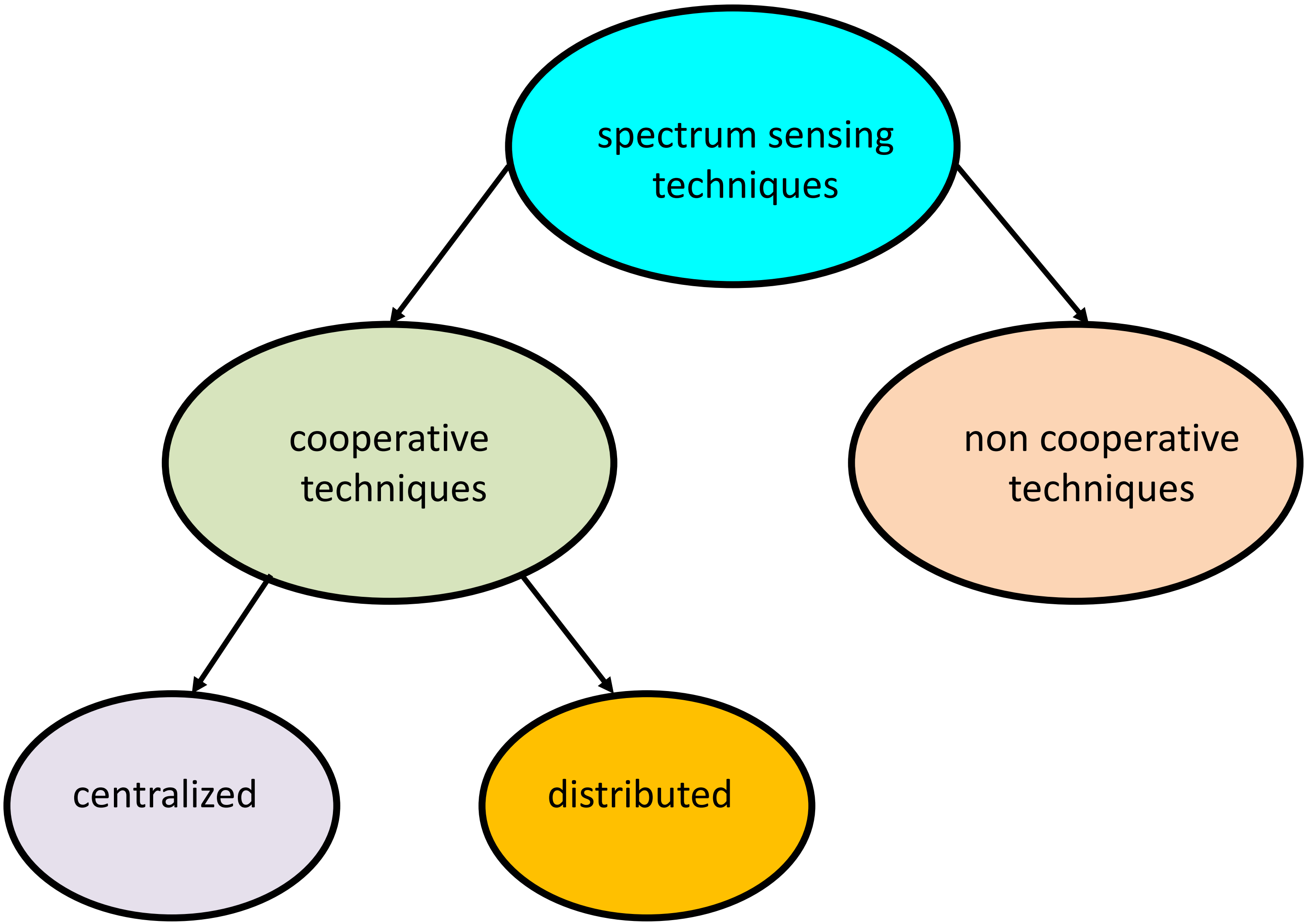
Issues in Sensing

- What sensing technologies to use
- What time to start and stop sensing
- Which channels to sense

Classification of sensing techniques



Classification of sensing techniques:



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:

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

Primary Tx detection: problem formulation

Let us assume the binary hypothesis testing:

$$\mathcal{H}_0 : Y[n] = W[n] \qquad n = 1, \ldots, N$$
$$\mathcal{H}_1 : Y[n] = X[n] + W[n] \qquad n = 1, \ldots, N$$

$$W[n] \sim N(0, \sigma^2)$$

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

Neyman-Pearson criterion

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

$$L(Y) > \gamma \Rightarrow decide\ H_1$$
$$L(Y) < \gamma \Rightarrow decide\ H_0$$

Y is the vector with all samples Y[n]

Matched filter detector

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

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

"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.

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

Energy detector

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

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

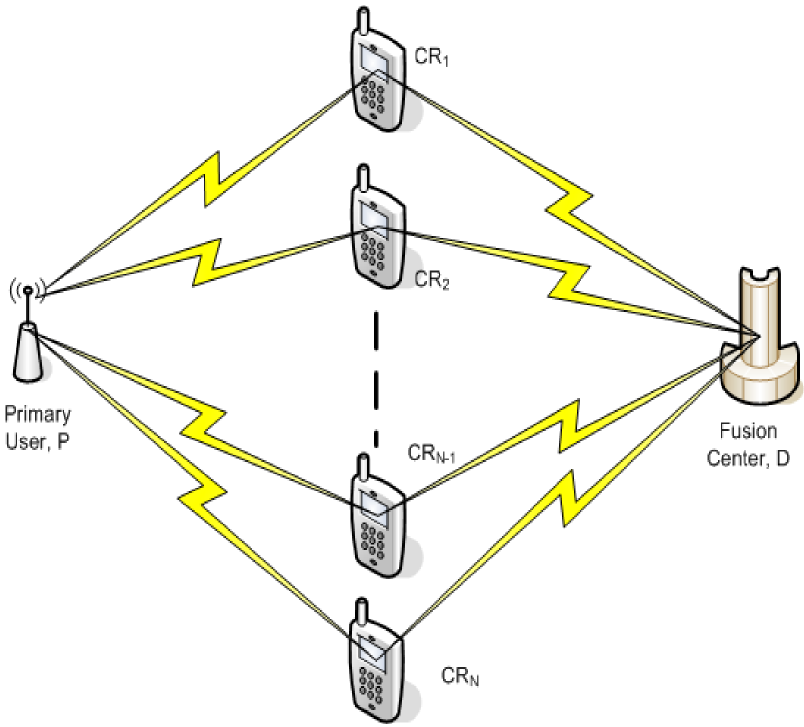
"Energy detector" : it measures the energy of the received signal (in a given bandwidth) over an observation time window.

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

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

Decision Fusion versus Data Fusion

- Decision Fusion
  - Each CR senses the PU signal and make local binary detection decision
  - Each CR forwards the binary decision to the fusion center over wireless channel (possible reporting error)
  - Fusion center combines the received binary signals and fuse them based on pre-determined decision fusion rule to make the global detection decision
- Data Fusion
  - Each CR based on the knowledge of channel state information amplifies the PU signal
  - CR does not make any local detection decision
  - Each CR forwards the amplified PU signal to the fusion center over the wireless channel (no reporting error)
  - Fusion center combines the received signal coherently or non-coherently and make global detection decision



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

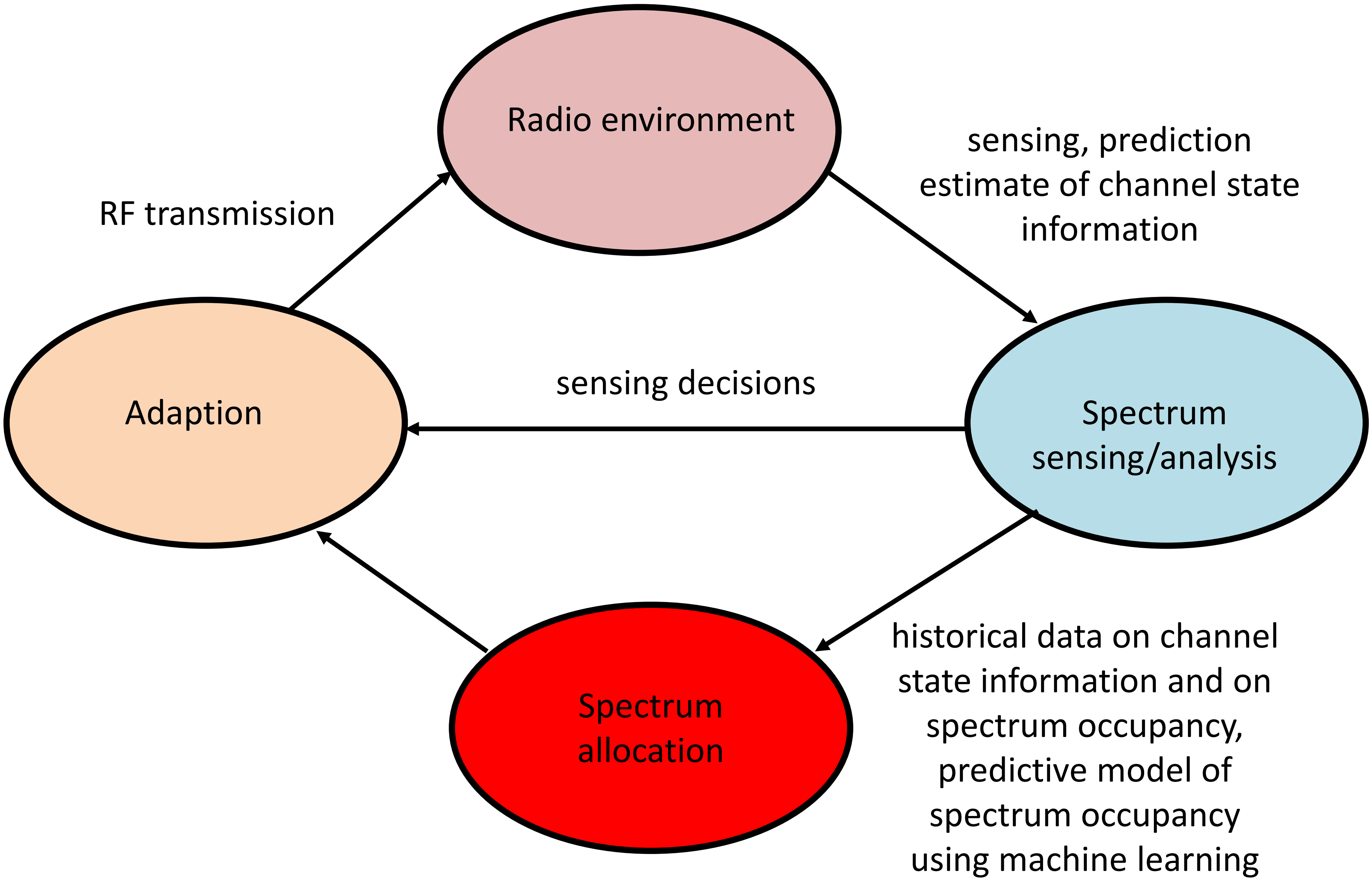
- Proactive approach (Zheng 2008)
  - predict the PUs' behavior assuming exponential and periodic traffic models
  - to minimize disruption to primary users, secondary users proactively switch channel before any primary user appears (based on the assumption about the PU's behavior)
  - To quickly resume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

REM

- A Radio Environment Map (REM) is an advanced framework for collecting, storing and processing data that characterizes the radio environment.
- Such data can be gathered from geolocation tagged spectrum measurements taken by Measurement Capable Devices (MCDs), which could be mobile devices/handsets.

Spectrum Management/Allocation

Cognitive Radio/DSA Cycle



Spectrum decision/access: 3 main decisions

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

Whether to access spectrum

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

- 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

How to access spectrum

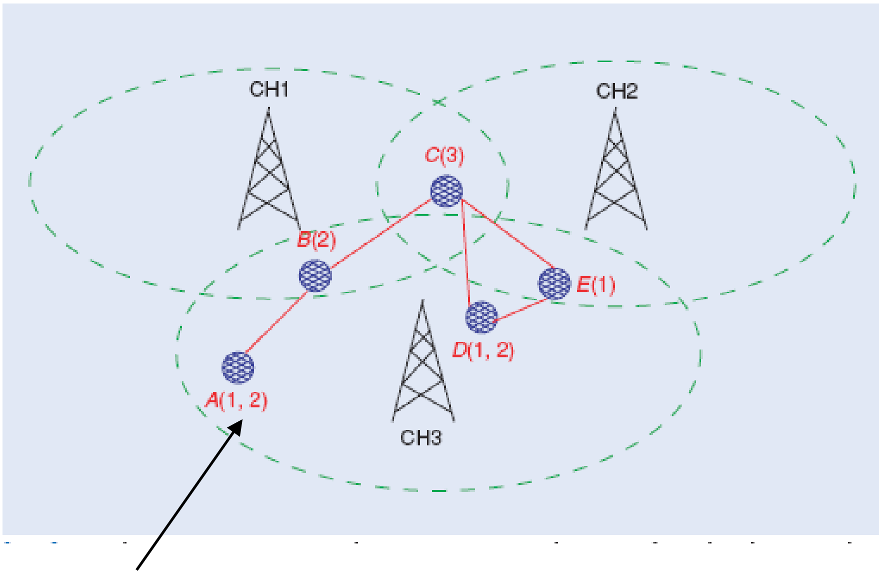
- Select the number of spectrum bands to access and the set of appropriate bands (e.g. subcarriers in OFDM systems)

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

- Which pulse shaping ?

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

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.

Furthermore, 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 ?

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
  - 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

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

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)

CR and 5G network

- 5G is expected to be deployed in 2020, one of the fundamental issues is the increasing challenge of acquiring adequate spectral resources in radio frequency bands to operate 5G cellular systems
- CR offers the possibility to significantly increase the spectrum efficiency, by smart secondary users (CR users) using the free licensed users spectrum holes
- Both the cognitive radio (CR) and the 5G cellular wireless standards are considered to be the future technologies:

Standards Bodies

- IEEE 1900 Standard Committee,
  - Now IEEE DySPAN
- IEEE 802.22 Working Group,
  - Wikipedia on IEEE 802.22
- *IEEE COMSOC Technical Sub-Committee on Cognitive Networks*
  - *SIG: Cognitive Radio in 5G*

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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