A Cognitive PHY/MAC Paradigm for Spectrum Sensing, Allocation, and Control

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Outline

- Our Vision
- Proposed Cognitive OSI Model:
  - Physical Layer Functions
  - Link Layer Functions
- Spectrum Sensing
- Channel Allocation
- Control Channel
- Open Questions

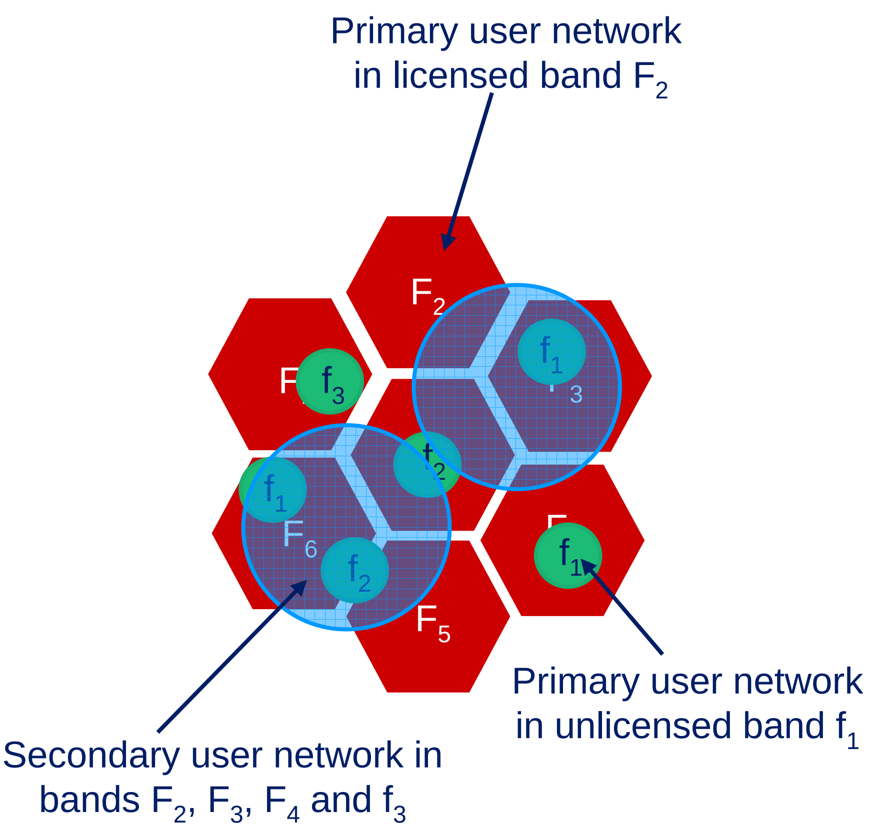
Towards Virtually Unlicensed Spectrum

- Spectrum is divided into:
  - Licensed bands
  - Unlicensed bands

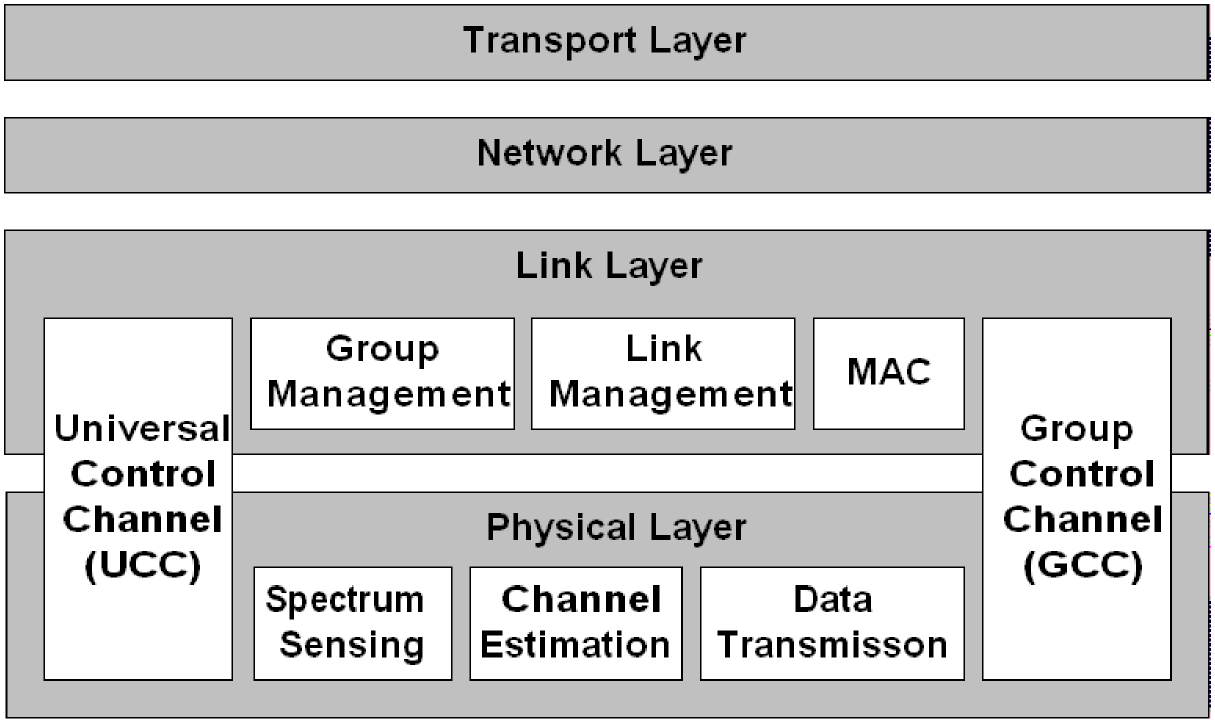
- Our vision is that:

  Cognitive users can create
  virtually unlicensed bands

- Cognitive users are secondary users in primary users' networks:
  - Use primary user's unused spectrum resources on a non-interfering basis



General OSI Stack for a Cognitive Radio



Spectrum Sensing

- Goal: Reliably detect presence of a Primary User
- Different Primary Users have different sensitivity thresholds
- Three possible approaches:

  1. Matched Filter

  2. Energy detector

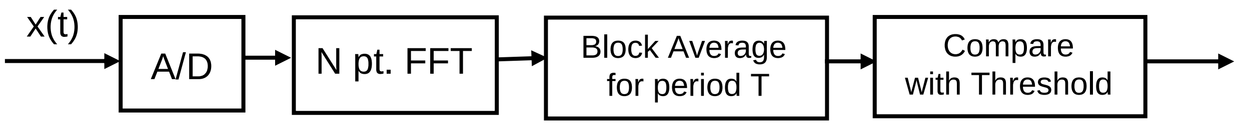
  3. Feature detector
- Local Spectrum Sensing
  - Each user makes decision on a Primary User presence based on its local sensing measurements
- Cooperative Spectrum Sensing
  - Users within a group share their local spectrum sensing measurements and jointly decide on the presence of a Primary Users

Matched Filter

- This is the optimal way for signal detection, even demodulation
- Maximizes signal to noise ratio
- Requires coherency with primary user signal:
  - signal structure: modulation type, order, packet format
  - carrier and timing synchronization
  - channel knowledge
- Pilots, preambles, synchronization words, training sequences, spreading codes can be used for coherent detection
- Examples:
  - TV signals have narrowband pilot for audio, video carriers
  - CDMA systems have pilot channels, paging channels, etc.
  - OFDM systems have fixed preamble for packet acquisition
- Drawback: CR would need special receiver for each Primary User

Energy Detector

- Energy detector is sub-optimal non-coherent receiver
- Simple technique similar to Spectrum Analyzer approach



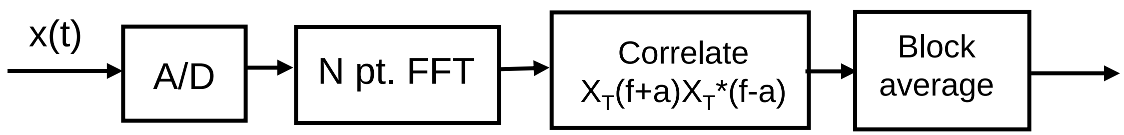
$$Y = \begin{cases} 0 & \text{absent} \\ 1 & \text{present} \end{cases}$$

- Processing gain is proportional to N and T
- Drawbacks:
  - Threshold is highly susceptible to unknown or changing noise levels and interference
  - Does not differentiate between modulated signals, noise, and interference
  - Does not work if the signal is direct-sequence or frequency hopping signal, or any time varying signal
  - Good for narrowband signals, but wide band signals in the frequency selective fading might not be detected

Feature Detection

- <u>Modulated signals</u> are coupled with sine-wave carriers, pulse trains, repeating spreading, hoping rates, cyclic prefixes resulting in <u>built-in periodicity</u>
- Cyclostationary processes have <u>spectral correlation</u> that can be used for <u>feature detection</u>

<u>Spectral correlation fcn:</u> $$S_x^{\alpha}(f) = \lim_{T \to \infty} \lim_{\Delta t \to \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{-\Delta t/2} \frac{1}{T} X_T\left(t, f + \alpha/2\right) X_T^*\left(t, f - \alpha/2\right) dt$$

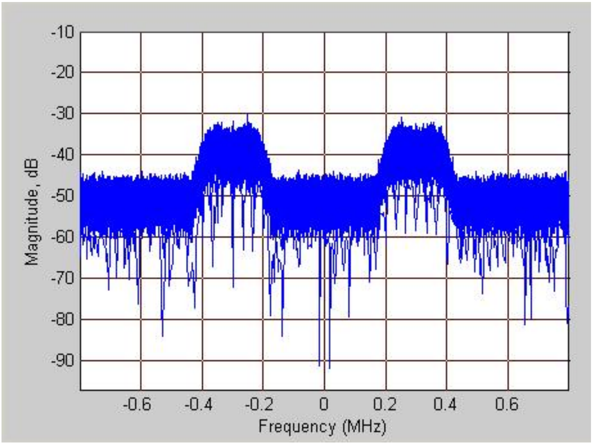


Features:
1. number of signals
2. modulation types
3. symbol rates
4. Interference

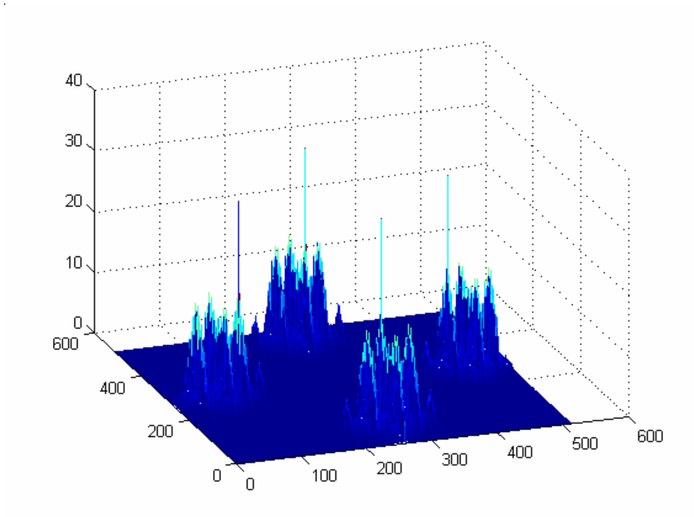
- Different types of modulated signals can have:
  - identical power spectral density
  - highly distinct spectral correlation functions
- Stationary noise and interference exhibit no spectral correlation
- Spectral components can be estimated using other spectral components of the signal if there is a spectral correlation

Example 1

- QAM modulated signal with –10dB CW pilot in 10 dB SNR



Power Spectrum Density 1024 pt FFT averaged 8 times



Spectrum Correlation Function (512x512) pt averaged 8 times

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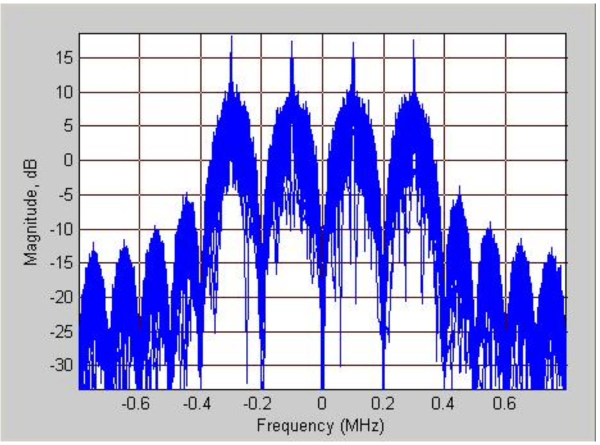
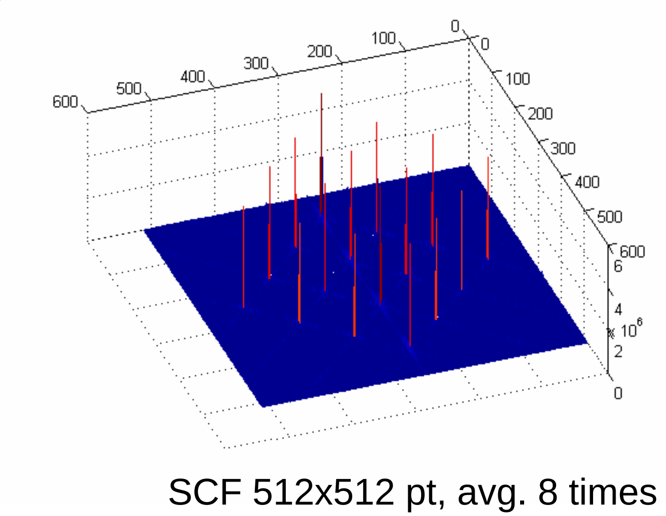
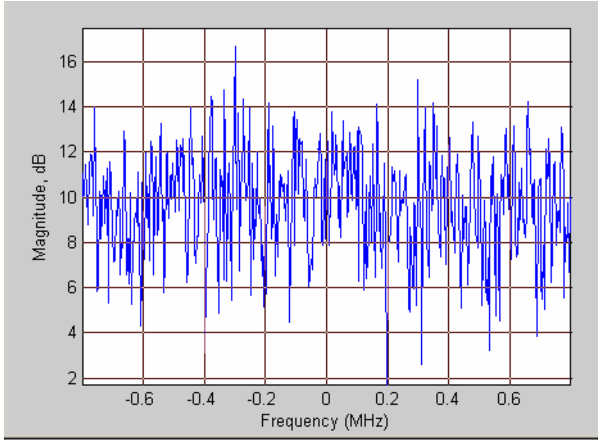
Example 2



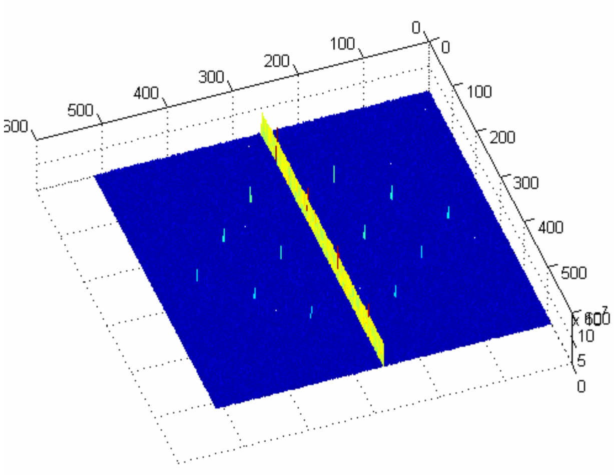
PSD 4 FSK, SNR=10 dB



SCF 512x512 pt, avg. 8 times



PSD 4 FSK, SNR=-20 dB



SCF 512x512 pt, avg. 32 times

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Spectrum Map

- Local Spectrum Map created by each Cognitive User

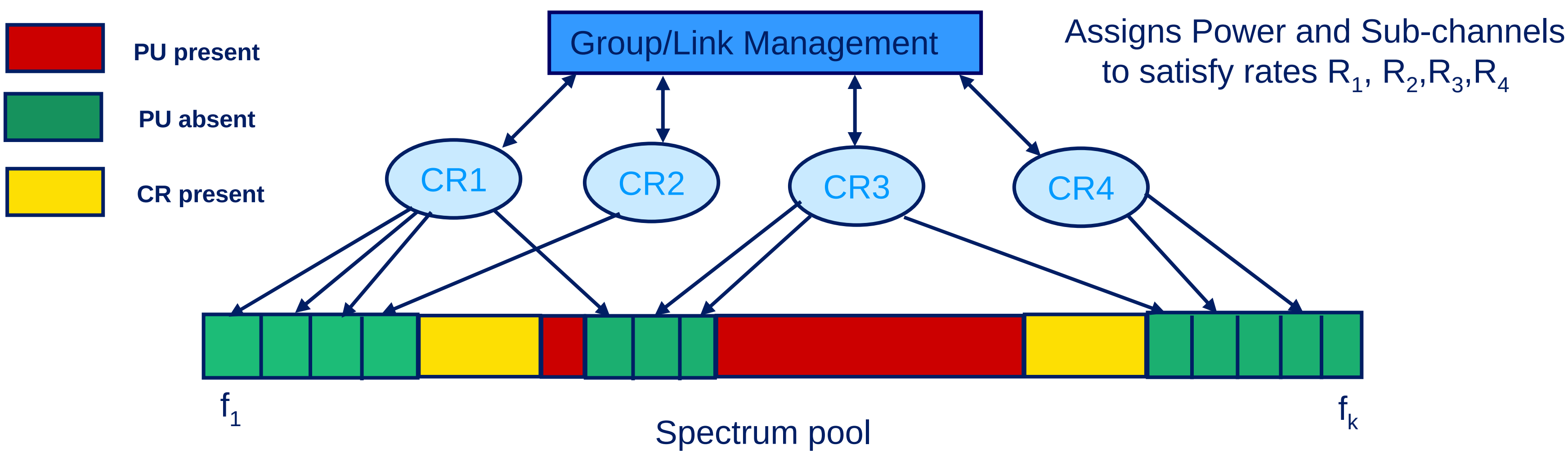
Frequency	Bandwidth	Power level	Signal type	Time stamp
550.4 MHz	200 kHz	-100dBm	FM mod	$[t_1\ \Delta T_1]$
904 MHz	10 MHz	- 65 dBm	FH, rate 1khop/s, BW=1MHz	$[t_k\ \Delta T_k]$
2.45 GHz	20 MHz	-80 dBm	OFDM packet, t=500usec	$[t_m\ \Delta T_m]$

- Detect empty channels and estimate their quality through sounding
- Combined Group Spectrum Map after Channel Sounding

	$SubChannel_1$	$SubChannel_2$	…..	$SubChannel_N$
CR 1	$0/\ \lvert h_{11}\rvert^2$	1	…..	1
……	1	1	…..	0
CR K	$0/\ \lvert h_{1K}\rvert^2$	1	…..	$0\ /\lvert h_{NK}\rvert^2$

Channel Allocation

- Goal: Satisfy users' requested rates (QoS, Latency, ….)
- Policy for each Primary user band:
  - E.g. time limit on use, power level, guard bands
- Rules of sharing the available resources (time, frequency, space)
  - One user per degree of freedom for simplified decoding
- Redundant channels reservation if primary user reappears



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Control Channels

- CR system decomposition into groups:
  - Introduces hierarchy
  - Short tables and limited change announcements
  - Reduces control messages
  - Spectrum availability
- Universal Control Channel
  - Group Announcements
  - New User Joining
- Group Control Channel
  - Exchange of Spectrum Maps
  - Channel Allocation
- Suitable for Centralized and Ad-Hoc mode

Issues with Control Channels

- Possible candidates for control channel:
  - Licensed Band
  - Unlicensed Band
  - Ultra Wide Band (if allowed in operating band)
  - In-band signaling
- Universal Control Channel should be self-organizing
- Limited throughput
- Strict timing and synchronization requirements
- Security

Open Questions

- Spectrum Sensing:
  1. Is the energy detection still sufficient for PU detection?
  2. Is it necessary to detect other features?
  3. How can we use that information?
  4. Should we differentiate cognitive users from primary users?
- Channel Allocation:
  1. What if multiple CR networks compete for the same spectrum?
  2. How much redundancy do we need?
  3. Sub-optimal vs. optimal allocation algorithms?
- Control Channels:
  1. Is it necessary or what is the alternative way of control?
  2. What is the preferred candidate?