Lecture 3: Spectrum Sensing in Cognitive Radio

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Spectrum Management Operations

- SUs perform four main operations to manage the spectrum:
  - Spectrum sensing & monitoring,
  - Spectrum analysis,
  - Spectrum decision,
  - Spectrum mobility.
- **Terminology**: Spectrum sensing & monitoring is classified based on the size of the band of interest into **Narrowband** and **Wideband** sensing.
- Initially, wideband sensing detects the available spectrum chunks. After detecting and analyzing such spectrum holes, the best available band (out of the chunk) is selected by narrowband sensing.

Spectrum Sensing & Monitoring

- A requirement for CRN is that the cognitive user must **sense** the available spectrum, detect spectrum holes, and capture spectrum information.
- Spectrum sensing captures proper observations about the spectrum white space (bandwidth, SNR, etc) in order to assist the next stage (spectrum analysis).
- Once the SU starts utilizing a spectrum slice for communication, then the occupied narrowband is continuously **monitored** to determine whether the original PU reappears or not (to decide if the SU can continue its communication on the same band).

Spectrum Analysis

- The characteristics of the spectrum holes that are detected through spectrum sensing are estimated.
- The PU activity and the spectrum band information (carrier frequency, bandwidth, interference level, SNR, channel error rate, path-loss, link layer delay, holding time, etc) are considered for individual holes.
- Such characteristics are used to represent the quality of a particular spectrum band.

Spectrum Decision

- A cognitive device determines the data rate, transmission mode, and the bandwidth of the transmission it needs based on user requirements.
- Then, the appropriate spectrum band (or bands) are chosen according to the spectrum characteristics once available spectrum holes are found.
- Spectrum decision is the step of selecting the best available spectrum suitable for the user's specific Quality-of-Service (QoS) requirements.
- Due to dynamically changing topologies and varying propagation characteristics, spectrum selection techniques can be closely coupled with routing protocols.
- Spectrum *prediction* based on artificial learning, game theory, and graph theory can provide details for the spectrum selection stage (very complex math).

Spectrum Mobility

- Spectrum mobility refers to the ability of the SU to vacate the channel it is using when a PU is detected in that channel.
- Spectrum mobility suspends the SU transmission, vacates the channel, and resumes ongoing communication using another vacant channel.
- The handoff strategies are the key element in this process, where reactive and proactive approaches are possible.
- **Reactive** approach: SU applies another round of spectrum sensing to find new target channels after it leaves its current channel
- **Proactive** approach: SU collects sufficient knowledge of PU traffic model so that SU is able to predict PU arrival, and the SU evacuates the channel beforehand (might even find backup target channels before leaving its current channel).

Sensing Techniques

- Sensing is very important in cognitive radio networks (CRNs). It enables the interweave method.
- Allows SUs to detect the state of channel occupancy (presence of PUs temporally and geographically).
- Also, provides knowledge of channel characteristics (wireless channel noise, attenuation, fading, channel correlation, etc).
- Sensing can be hampered by SU transceiver imperfections (non-linearities, practical issues, etc).
- That is why there is extensive research activity on spectrum sensing in CRNs.

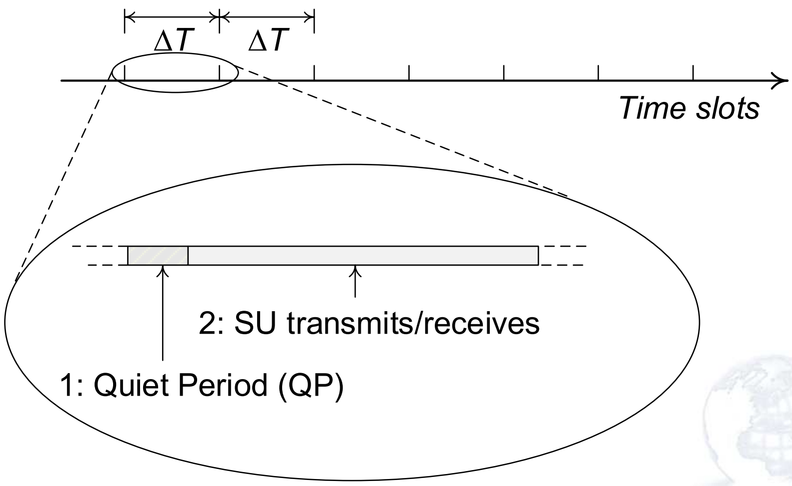
Sensing: Central Database

- Centrally-controlled database is an alternative spectrum awareness.
- Centralized database to which PU activity and spectrum usage (place, time, frequency, etc) is continuously uploaded.
- SUs request a channel from the database system. Based on availability of unoccupied channels, the system can grant access to one of the channels.
- SUs can also use the database along with history information and prediction methods to make the operation more efficient.
- Requires building an expensive infrastructure. Also need to frequently maintain and update the database (expensive).
- Can result in low spectrum utilization (missed opportunities) or extra PU interference if PU information is not updated fast enough in the database.
- Adopted by the early version of the IEEE 802.22 standard.

Sensing: Single-Radio Architecture

- Dynamic spectrum sensing is more interesting. Can be single-radio or dual-radio architecture.
- **Single-Radio** Architecture: A single RF device at the SU is utilized to perform both sensing and data transmission.
- A specific part of the time slot (called quiet period (QP)) is allocated for spectrum sensing.
- SUs do not transmit during the sensing period (QP).
- **Disadvantages**: Limited sensing duration means limited sensing accuracy (due to limited number of samples).
- Spectrum efficiency is decreased as some portion of the time slot is used for sensing instead of data transmission.
- **Advantages** of single-radio architecture: simple solution, low cost hardware, low power consumption.

Single-Radio Architecture



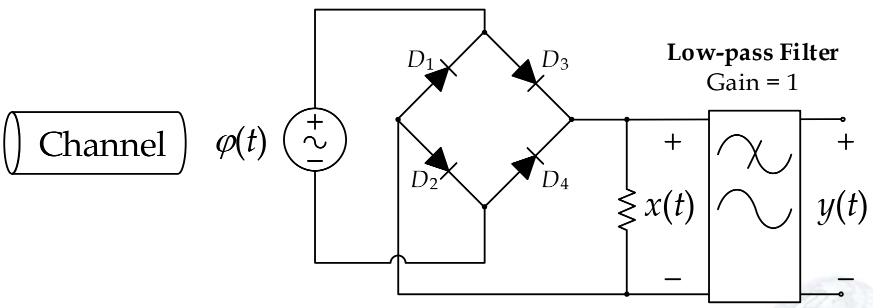
Sensing: Dual-Radio Architecture

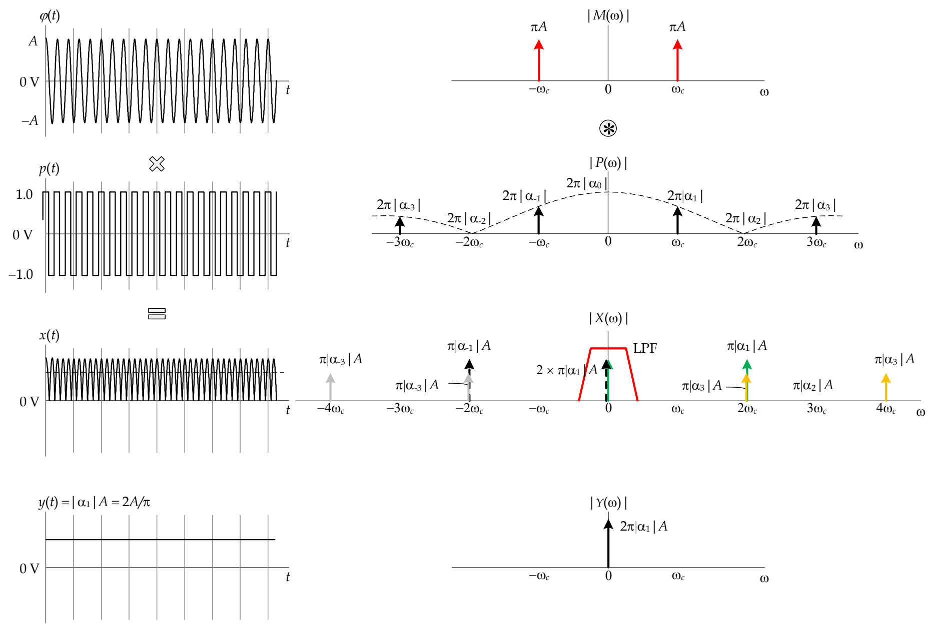
- One radio chain is dedicated for data transmission/reception while another radio chain is dedicated to spectrum monitoring.
- Disadvantages: increased power consumption, higher hardware cost.
- Since SUs do not stop transmission, dual-radio sensors might not be able to differentiate between PUs and SUs during the monitoring stage.
- Advantages: longer sensing period (more accurate results), and higher channel utilization.

Sensing: Energy Detector (ED)

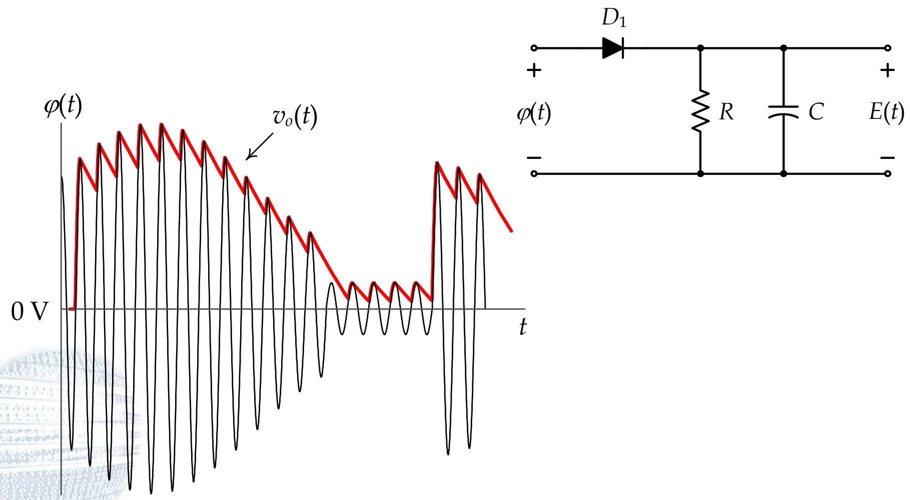
- A popular non-coherent detection method (widely employed in literature).
- Sensing measures PU signal power (compares measured power to noise floor).
- **Advantages**: Intuitive and simple to design (relatively low computational complexity to implement) – see below.
- Works for various environments and channel conditions.
- Does **not** require prior information about PU signals.
- **Drawback** for ED is that it has poor detection performance under low SNR scenarios & under noise uncertainty.
- Also cannot differentiate between the signals from PUs and the interference from other SUs.

Example 1: Full-Wave Rectifier

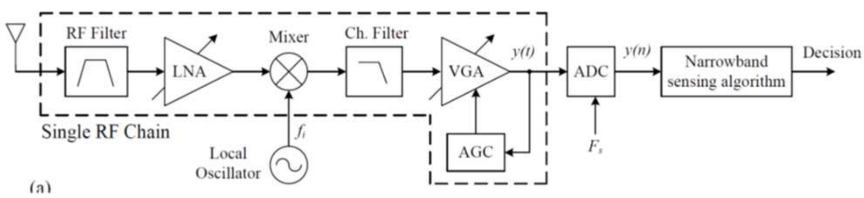




Example 2: Envelope Detector



Modern Hardware: DSP



Energy Detector (ED) Hardware

- In energy detection (ED) sensing, the absolute square of the received signal $y(n)$ is computed and averaged over a period of time, say N samples:

$$\Gamma = \frac{1}{\mathrm{N}}\sum_{n=1}^{N} y^2(n)$$

- Using a higher number of samples N allows more reliable decision statistic.
- Many in the literature assume the channel is affected by the typical AWGN with a known noise power.
- Many assume the SU receiver is a perfect one.
- But some studies looked at noise uncertainty, fading channels, imperfect receivers where there is distortion introduced due to non-linear frequency mixing, amplification, and IQ imbalance.
- Practical fading severely affects energy detectors.

Fading Effects

- Multipath fading and shadowing result in power fluctuations of the received PU signals.
- Hence, the need to operate under very low PU SNR is unavoidable.
- To achieve sustainable performance in these scenarios, the noise uncertainty and the channel effect have to be carefully studied.
- Remember that ED performance relies on a well-known noise power and SNR.
- It has been shown that noise uncertainty will result in the **SNR-wall** problem: in which an infinite number of samples is not enough to guarantee the required false alarm and detection rates when there is uncertainty about the noise level.
- In recent approaches many SUs cooperatively estimate the noise level to overcome the noise uncertainty problem.