Cognitive Radio Networks

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Integrated Communication Systems Group
Ilmenau University of Technology

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  - Spectrum Sensing
  - Spectrum Management
  - Spectrum Mobility
  - Spectrum Sharing
- Cognitive MAC Protocols
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- Control Questions
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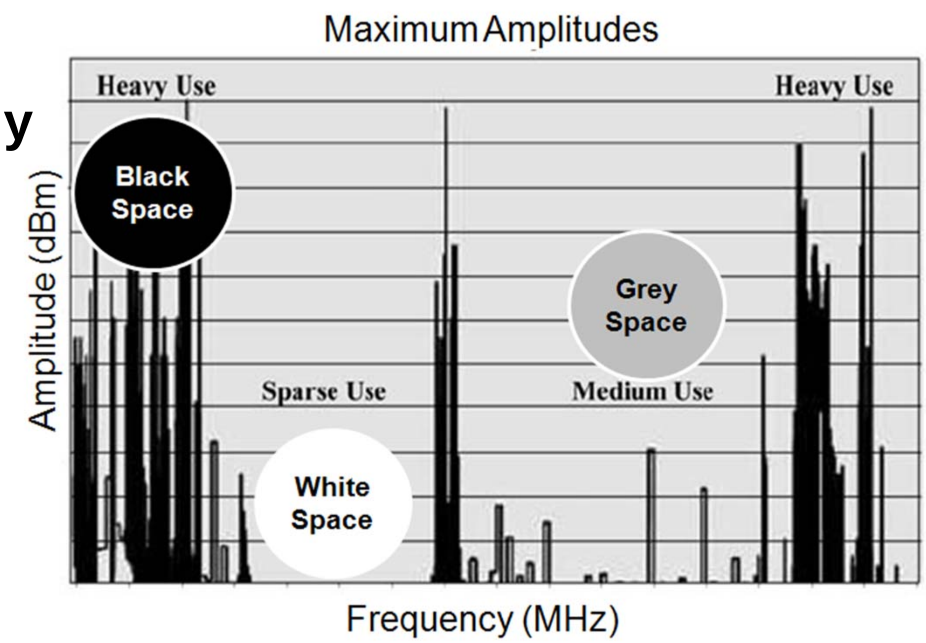
Introduction

Introduction

- Limited spectrum
- Inefficiency in spectrum usage
  - Utilization of the assigned licensed spectrum varies between15% and 85%
- A new technology is required to enable better utilization of unused licensed spectrum

→ **Cognitive radio technology**



Cognitive Radio Technology

What is a Cognitive Radio

- Definitions
  - **Federal Communications Commission Definition**: a cognitive radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates
  - **Mitola Definition**: the cognitive radio identifies the point at which wireless PDAs and the related networks are sufficiently computationally intelligent on the subject of radio resources and related computer-to-computer communications
    - to detect user communications needs as a function of use context, and
    - to provide radio resources and wireless services most appropriate to those needs

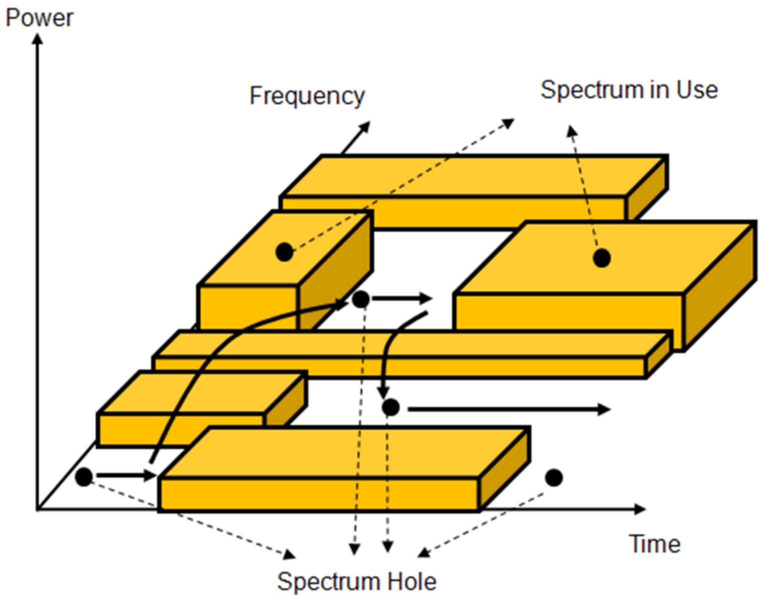
What is a Cognitive Radio

- Characteristics
  - **Cognitive capability**: the capability of the radio technology of capturing or sensing information from its radio environment (monitoring the power in some frequency band)

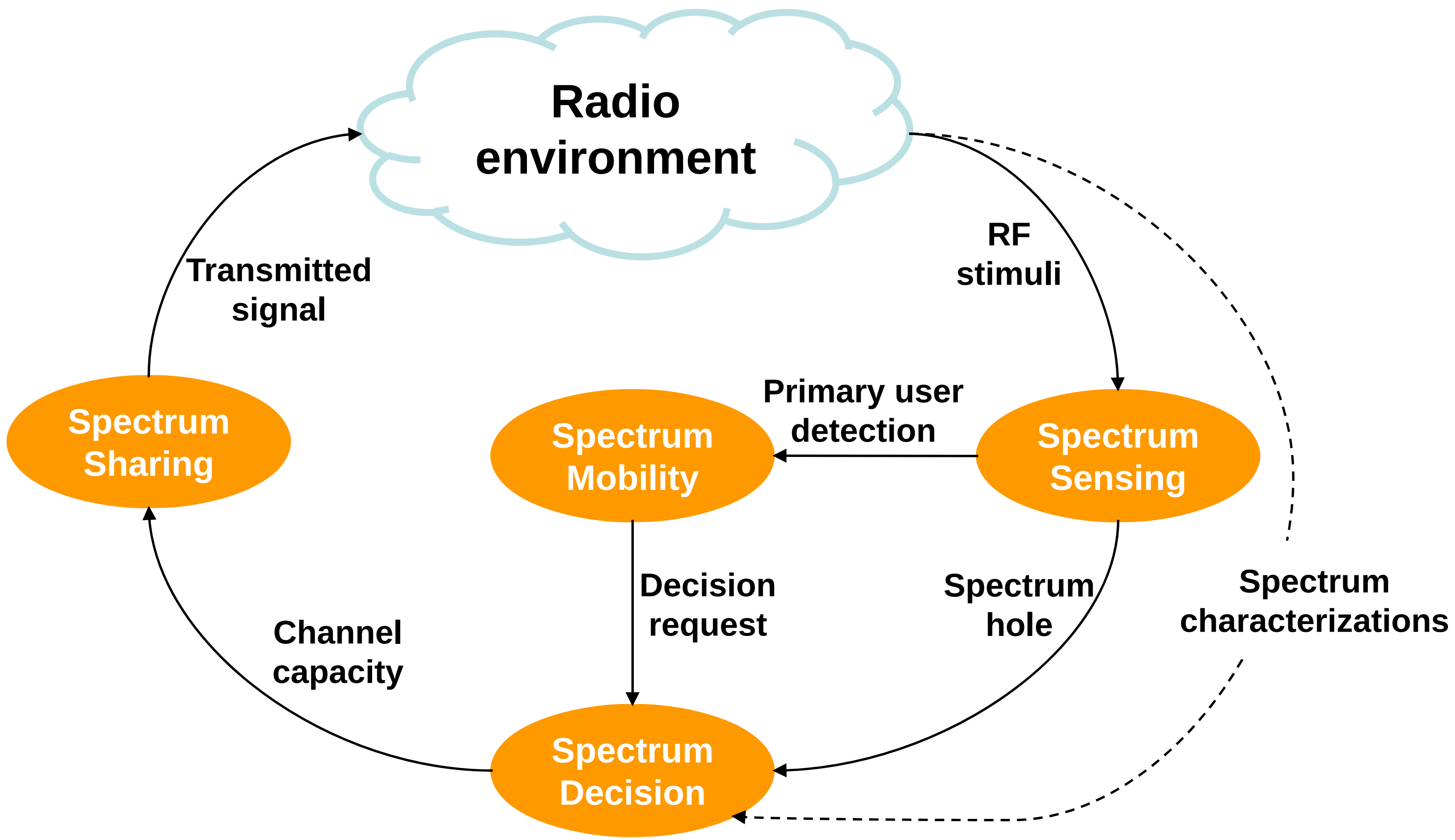
  - **Reconfigurability**: the ability of the radio to be dynamically programmable according to the radio environment (transmission and receipt of data on a variety of frequencies and using various radio access technologies)

What Should Cognitive Radio Enable to Do?

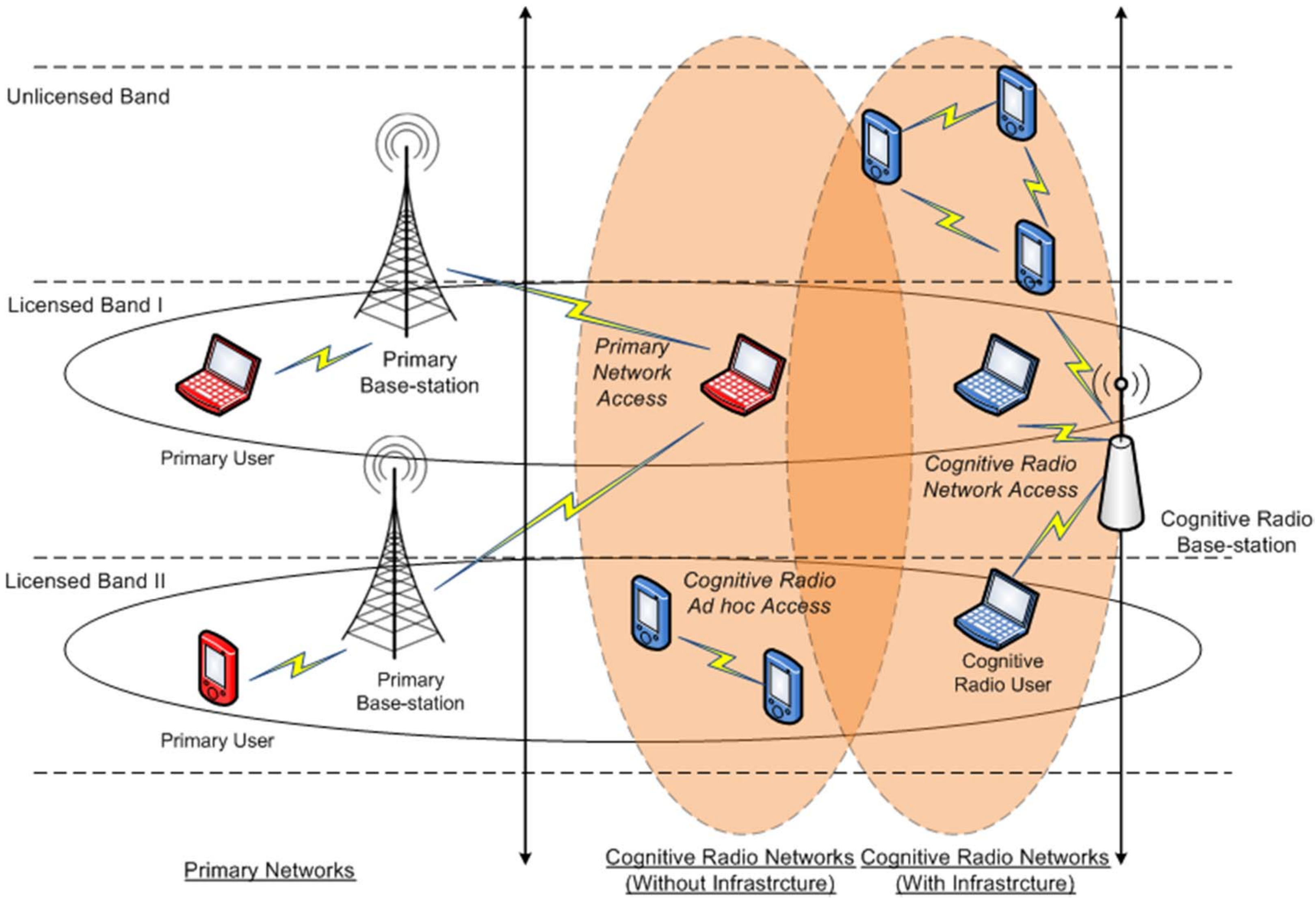
- Determination of unused portion of spectrum (spectrum holes or white space)
- Selection of the best available channel
- Coordination of the access with other users
- Detection of the appearance of licensed users → vacate the channel



Cognitive Radio Cycle



Cognitive Radio Network Architecture



Cognitive Radio Network Architecture

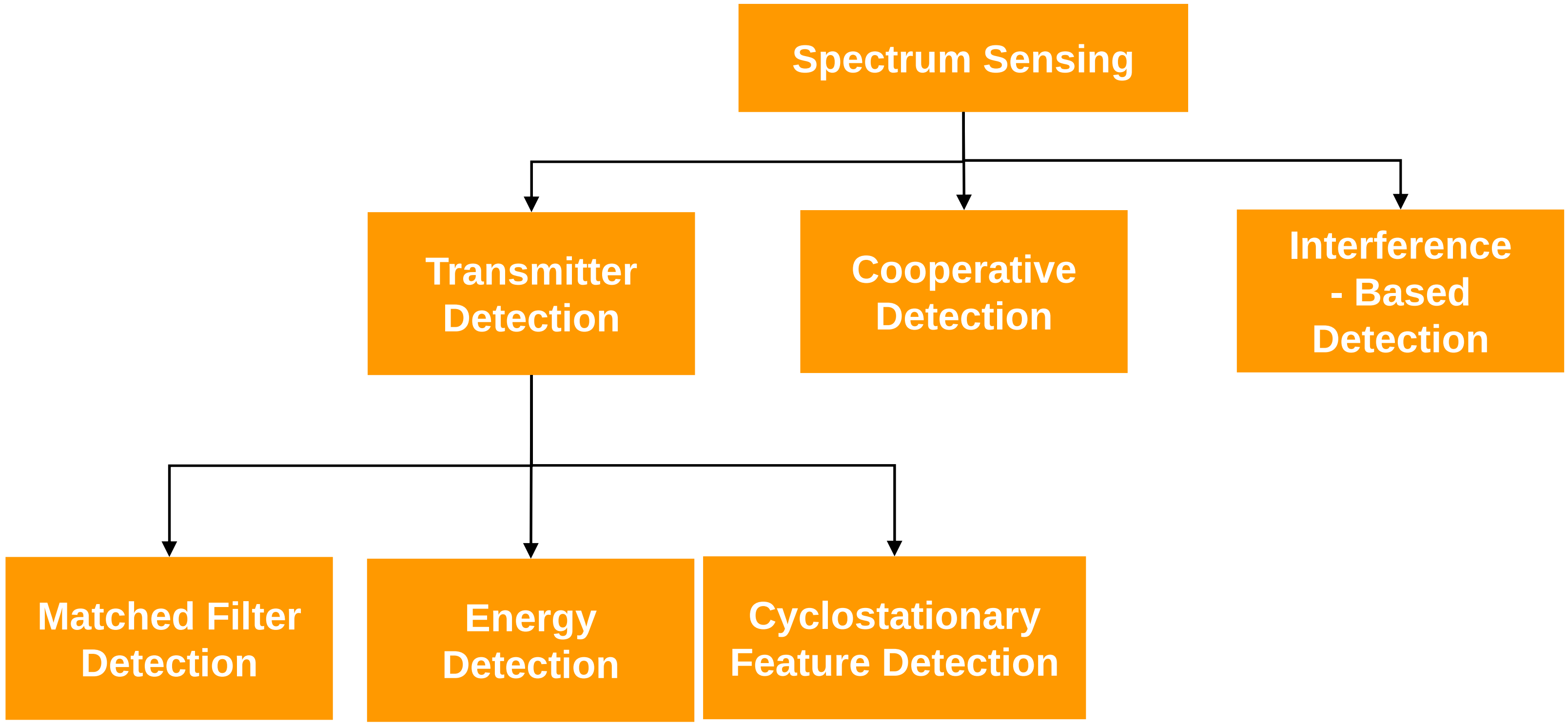
- **Primary networks**
  - Networks with access right to certain spectrum bands, e.g. common cellular systems and TV broadcast networks
  - Users of these networks are referred to as **primary users**. They have the right to operate in licensed spectrum
  - Users of certain primary network do not care of other primary or secondary networks users

- **Secondary networks**
  - Do not have license to operate in the spectrum band they currently use or aim at using
  - Opportunistic spectrum access
  - Users of these networks are referred to as **secondary users**. They have no right to access licensed bands currently used
  - Additional functionalities are required to share licensed spectrum bands with other secondary or primary networks

Spectrum Sensing

Spectrum Sensing

- Spectrum sensing is determined as the capability of detection of spectrum holes



Transmitter Detection

- Location of primary receiver is not known (no signaling between primary and secondary users) → detection of the weak signal from a primary transmitter through local observations of secondary users

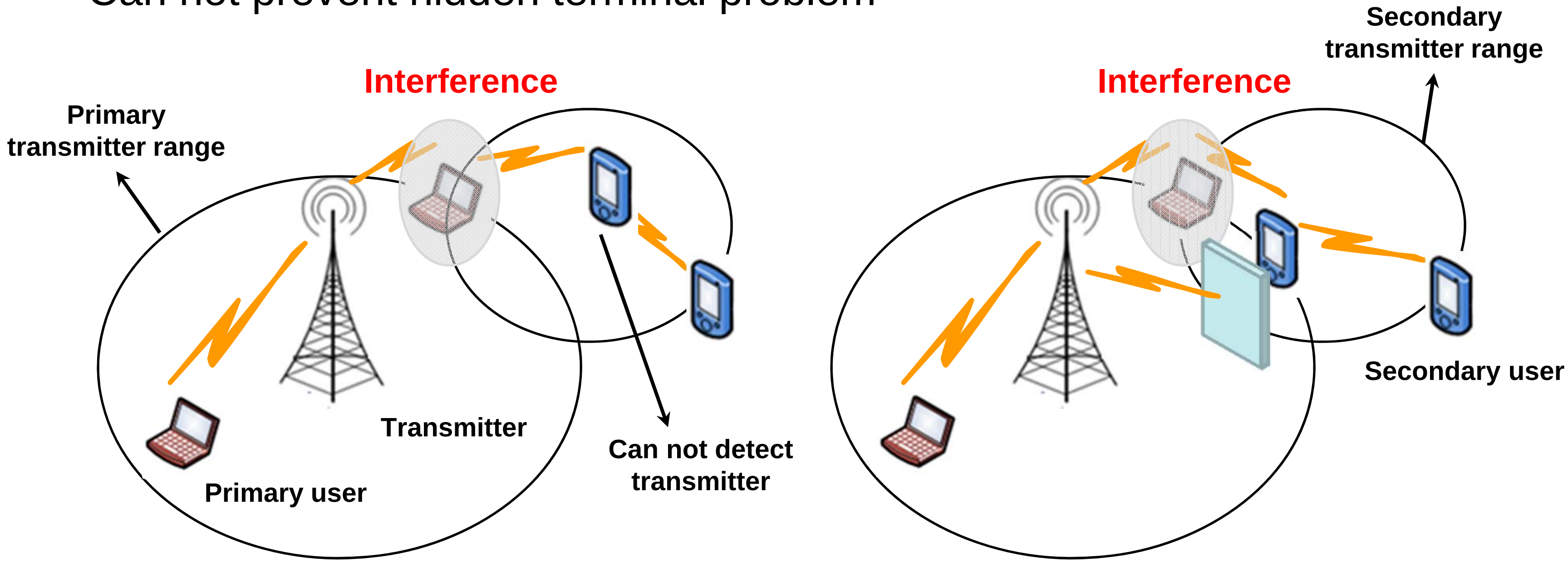
- Mechanisms
  - Matched filter detection
  - Energy detection
  - Cyclostationary feature detection

Transmitter Detection

- Matched filter detection
  - Optimal detector when all information of the primary user signal is known (it maximizes the received signal-to-noise ratio)
  - Produces poor performance if primary users information not known
- Energy detection
  - Used if primary users information not known
- Cyclostationary feature detection
  - Mean and autocorrelation of modulated signals exhibit periodicity (modulated signals are coupled normally with sine wave carriers, pulse trains, repeating spreading, etc.)
  - Differentiates noise from modulated signal (noise is a wide-sense stationary signal with no correlation)
  - Computationally complex and requires long observation time

Transmitter Detection

- Primary and secondary networks are physically separated → transmitter detection can not avoid interference due to the lack of the primary receiver's information
- Even if the secondary user has a line of sight to the transmitter, the secondary user may not be able to detect the transmitter, e.g. due to shadowing, etc.
- Can not prevent hidden terminal problem



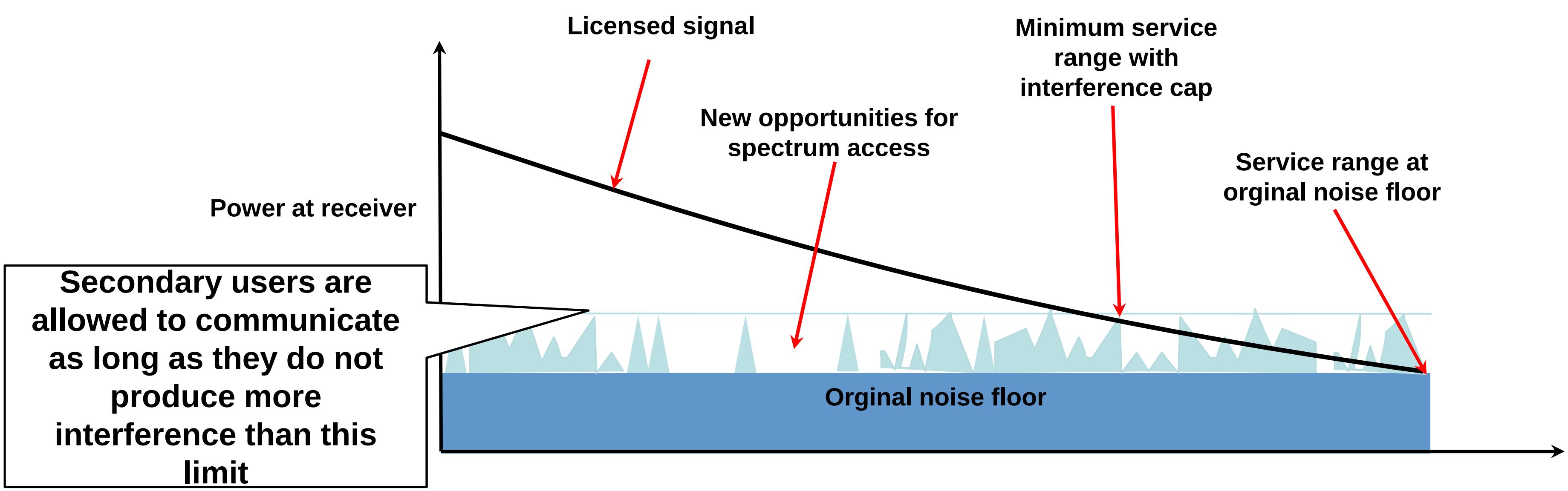
Cooperative Detection

- Incorporating information from multiple secondary users to detect primary users
- Classified into
  - Centralized cooperative detection
    - Controlled mostly by cognitive BSs
    - Cognitive BS collects sensing information from all secondary users it serves and detects spectrum holes
  - Distributed cooperative detection
    - No centralized infrastructure
    - Observations are exchanged among secondary users
- More accurate detection than that based on single secondary user observations, e.g. transmitter detection. Moreover, multi-path fading and shadowing effects are mitigated

Interference-Based Detection

- Interference takes place at the receiver side (i.e. the receiver is disrupted). However, it is controlled at the transmitter side, e.g. using power control, etc.

- Interference temperature is well-known example (receiver-detection model)



Challenges

- Interference temperature measurement
  - Secondary users are aware of their locations and transmission power. They are not a ware of primary users locations
  - Currently, no practical way for a cognitive radio to measure or estimate the interference temperature at neighbor primary users
- Spectrum sensing in multi-user networks
  - Multi-user environment makes it more difficult to sense primary users (secondary networks coexist with each other as well as with primary networks)
  - Cooperative detection can be considered as possible solution for such environments
- Detection capability
  - Detection of primary users in very short time is essential
  - OFDM-based secondary users are best adequate (multi-carrier sensing can be exploited)

Spectrum Management

Spectrum Management

- Spectrum bands are spread over wide frequency range including licensed and unlicensed bands

- Radio environment characteristics show fast and mostly not predictable variation over time

- Secondary users have to select the best spectrum band meeting their QoS requirements → **spectrum management functions are required**

- Spectrum management include following steps
  1. Spectrum sensing
  2. Spectrum analysis
  3. Spectrum decision

Spectrum Analysis

- Characterizes sensed spectrum holes to obtain the band appropriate for user’s requirements
- Characteristics of spectrum holes
  - Interference
    - Some spectrum bands are more crowded than others
    - Based on the interference at primary receivers, the allowed sending power of secondary user can be derived → channel capacity is estimated
  - Path loss
    - Path loss increases as frequency increases. To retain the capacity when switching to higher frequency, sending power should be increases → more interference produced
  - Wireless link errors
    - Modulation scheme and interference affect strongly the error rate
  - Link layer delay
    - Affected by the interference, path loss, etc.
  - Holding time
    - Expected time duration the secondary user can occupy the channel

Spectrum Decision

- Once spectrum bands are characterized, the band best meeting QoS requirements should be selected → spectrum decision function should be aware of QoS requirements of current ongoing applications
- Spectrum decision rules are required
- QoS requirements for secondary user
  - Data rate
  - Acceptable error rate
  - Delay
  - ...

Challenges

- Decision Model
  - Development of suitable decision rules that consider spectrum bands characters is until now an open issue
- Multiple spectrum band decision
  - In case secondary users are capable of using multiple channels for transmission simultaneously, it is important to determine the number of spectrum bands available and select the bands appropriate
- Spectrum decision over heterogeneous spectrum bands
  - Support spectrum decision operations on both licensed and unlicensed bands is challenging

Spectrum Mobility

Spectrum Mobility

- The process when a secondary user changes its frequency of operation, also called spectrum handoff as well

- Reasons
  - Operating channel becomes worse
  - Primary user wants to communicate on the channel
  - User movements (available spectrum bands change)

- Requirements
  - Low latency
  - Transparence to upper layers protocols if possible
  - No impairments on ongoing applications (ideal case)

- Multi-layer mobility management with which protocols of many layers cooperate to support mobility is required

Challenges

- Smooth spectrum mobility schemes
- Synchronization between protocols of many layers and possibly with applications to support smooth spectrum handoffs (e.g. applications or protocols switch from operation mode to another upon prediction of a spectrum handoff, etc.)
- Support of horizontal (changing channels while staying in the same secondary network) and vertical handoffs (between secondary networks)
- Performing spectrum handoffs to maintain QoS requirements satisfied

Spectrum Sharing

Spectrum Sharing

- Considered similar to Medium Access Control (MAC) issue in existing systems. However, different challenges arise due to
  - Coexistence with licensed users
  - Wide range of available spectrum

- Spectrum sharing steps
  - **Spectrum sensing**: detect unused spectrum holes
  - **Spectrum allocation**: allocation of possible target channels based on spectrum sensing results and allocation policies
  - **Spectrum access**: coordination of access to the allocated channel to avoid collisions
  - **Transmitter-receiver handshake**: negotiation of communication channel between sender and receiver
  - **Spectrum mobility**: enable continuous communication between sender and receiver in spite of primary user appearance on the used channel

Spectrum Sharing Techniques

Spectrum sharing techniques are classified according to

- Architecture
  - Centralized
    - Centralized entity controls the spectrum allocation and access
    - Secondary users do observations and report to the centralized entity, which creates **spectrum allocation map**
  - Distributed
    - Applied when construction of infrastructure is not possible or not preferable
    - Each node is responsible for the spectrum allocation

Spectrum Sharing Techniques

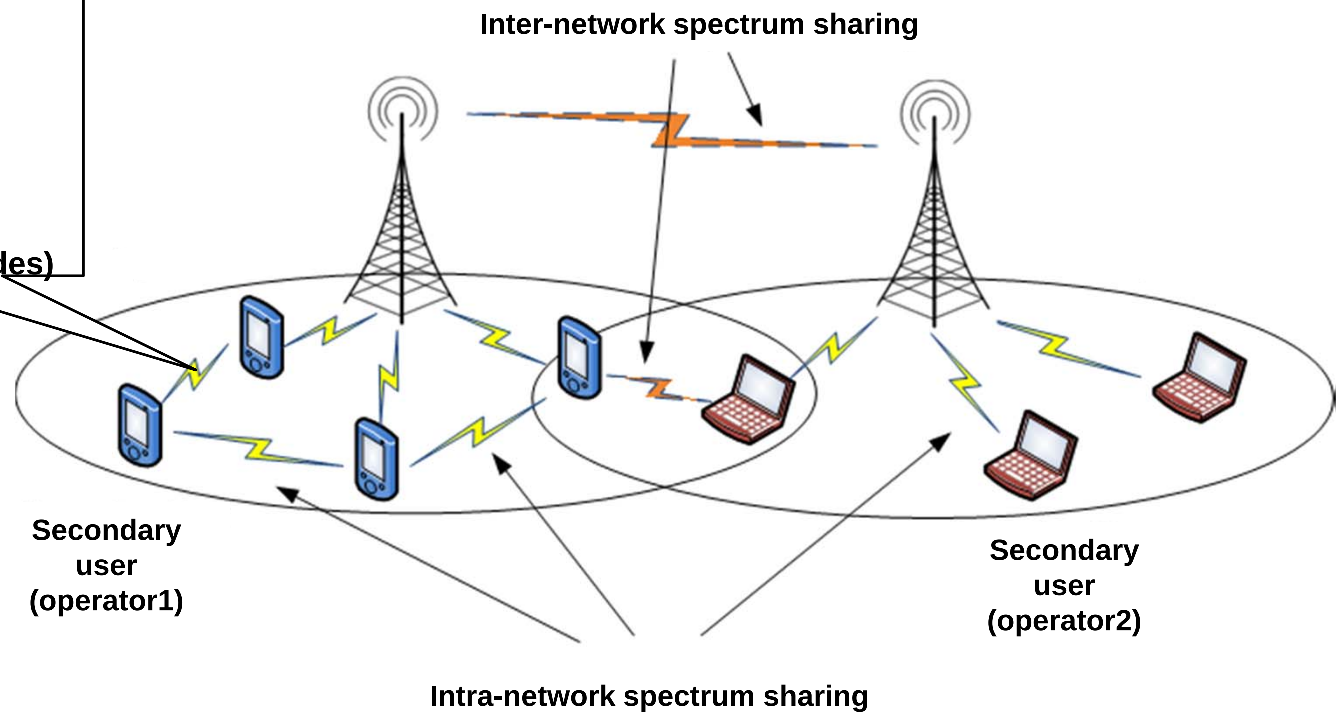
- Spectrum allocation behavior
  - Cooperative
    - Observations results of each node are shared with other nodes → spectrum allocation is done based on these measurements
    - These techniques result in better spectrum utilization at the cost of considerable signaling between nodes
  - Non-cooperative (selfish)
    - Each node does its observations and allocates its spectrum band
    - These techniques result in reduced spectrum utilization. However, they may be practical for certain applications or situations

- Spectrum access technology
  - Overlay spectrum sharing
    - Secondary nodes access spectrum holes not used by primary networks → Interference to primary users is minimized
  - Underlay spectrum sharing
    - Based on spread spectrum techniques developed for cellular networks
    - After acquiring spectrum allocation map, secondary users begin sending, so that their transmission power is regarded as noise by licensed users

Intra/Inter-Network Spectrum Sharing

Classified according to
- **Architecture**
- **Spectrum allocation behavior**
- **Spectrum access technology**

(see the previous two slides)



- **Inter-network spectrum sharing**
  - **Centralized inter-network spectrum sharing**: secondary networks organize cooperatively the spectrum allowed to be accessed by users of each secondary network, e.g. by means of central spectrum policy server, etc.
  - **Distributed inter-network spectrum sharing**: BSs of secondary networks compete to allocate spectrum holes

Challenges

- Common control channel (CCC)
  - Tasks
    - Transmitter-receiver handshake
    - Communication with a central entity organizing the spectrum allocation
    - Sensing information exchange
  - Problems
    - Fixed CCC is infeasible (CCC must be vacated when a primary user appears on it)
    - CCC for all users seems to be topology-dependent, thus CCC varies over time
    - If no CCC is allocated, transmitter-receiver handshake becomes a challenge

- Dynamic radio range
  - Radio range and characteristics change with operating frequency → CCC must be selected carefully (better to select CCC in lower spectrum bands and data channels in higher ones)

- Spectrum unit
  - Existing techniques consider channel as the basic spectrum unit. As known, channel may be time slot, frequency, code, etc.

Cognitive Radio MAC Protocols

Classification

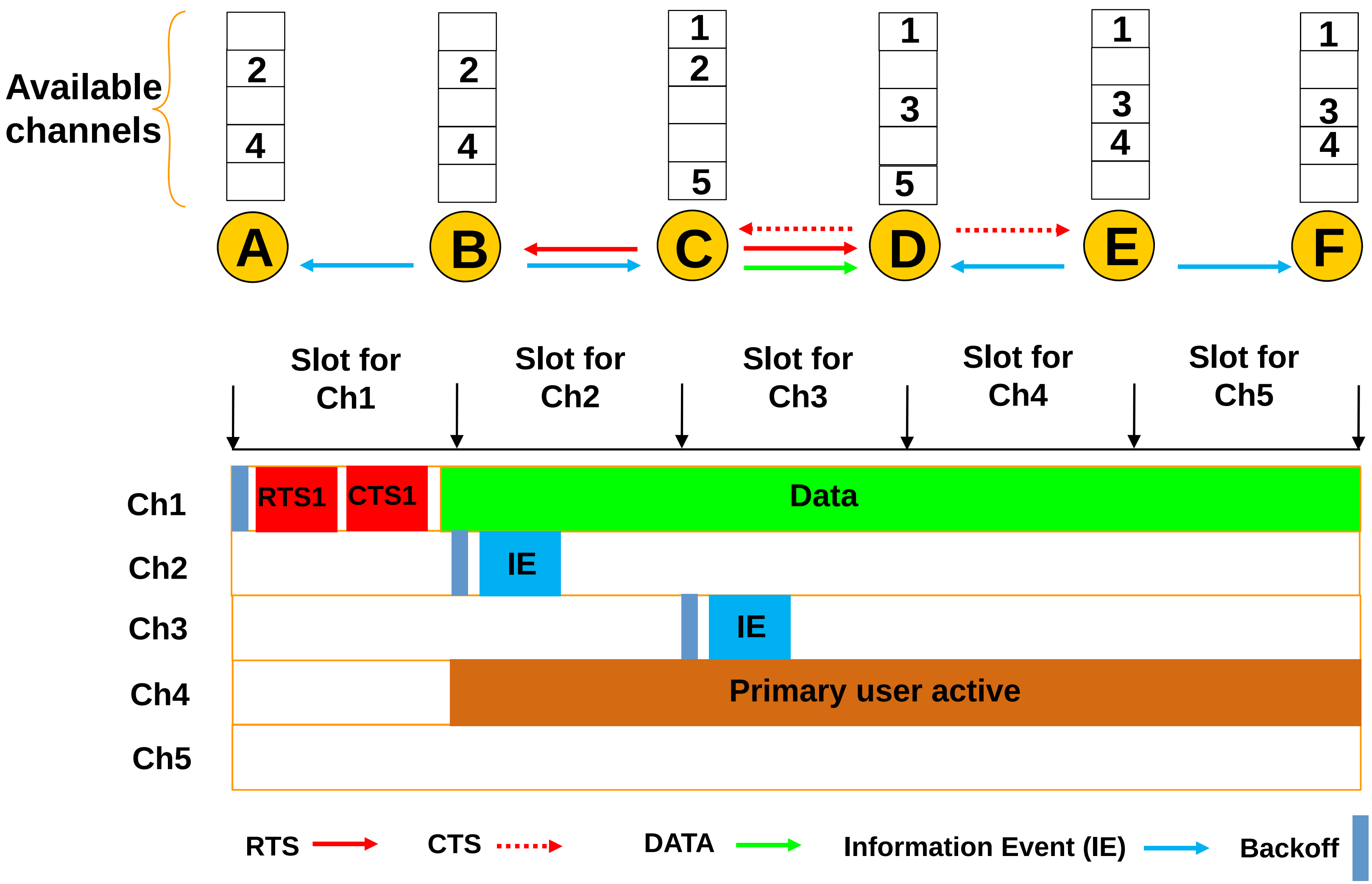
Cognitive Radio (CR) MAC Protocols

		Random Access MAC Protocols **(CSMA/CA-like random access for control packets and data)**	Time Slotted MAC Protocols **(Time synchronized control and data slots)**	Hybrid MAC Protocols **(Partially time slotted and partially random access)**
CR Centralized MAC	**Single Radio**	**CSMA-MAC**	**IEEE 802.22**	**DSA Driven MAC**
CR Ad Hoc MAC	**Single Radio**	**SCA-MAC** **HC-MAC**	**C-MAC**	**OS-MAC**
	Multi Radi	**DOSS** **DCA-MAC**		**SYN-MAC**

Classification

- Classified according to the access method into
  - Random access MAC protocols
    - No need for time synchronization
    - Based on Carrier Sense Multiple Access (CSMA)
  - Time slotted MAC protocols
    - Need for network-wide synchronization
    - Time is divided into slots for both control and data channels
  - Hybrid MAC protocols
    - Partially slotted transmission, in which
      - Signaling generally occurs over synchronized time slots
      - Data transmission may have random channel access schemes without time synchronization
- Classified according to the architecture into
  - CR centralized MAC
    - Central entity manages, synchronizes and coordinates operations among secondary users
  - CR Ad Hoc MAC
    - No central entity, neighbors cooperate to gain access to available channels

SYNchronized MAC (SYN-MAC) Protocol



SYN-MAC Protocol

- Time is divided into fixed-time intervals (slots)
- Each time slot is dedicated to one channel
- Each node has two radios, one for listening to control messages and one for sending data
- C wants to send data to D
  - Each node knows the available channel sets of their neighbors
  - Channels 1 and 5 are common
  - C chooses Ch1 for transmission and starts negotiation over it using RTS/CTS
  - Once negotiation is successful, data transmission takes place on Ch1
- B observes that primary user of Ch 4 has returned
  - B knows that it can reach its neighbors (A and C) through Ch2
  - B waits for the time slot which represents Ch2
  - B sends Information Events (IE) control message with its new channel list
  - Nodes A and C, on receiving this information learn that node B will not be available on Ch 4
- E applies the same procedure as B to notify D and F that Ch 4 is removed from its channels list

Conclusions

- Cognitive radio technology enables better utilization of unused licensed spectrum
  - Basic idea
    - Allocation of an unused spectrum band
    - Utilization of the allocated band for communication as long as no primary user appears on this band or no interference produced for primary users working around
  - Requirements
    - Fast and accurate spectrum sensing equipments as well as mechanisms
    - Adequate spectrum decision approaches
    - Seamless spectrum mobility techniques
    - Efficient spectrum sharing methods
  - However
    - Lots of new open issues and challenges to solve

- IEEE 802.22 is the standard for cognitive radio networks

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