Chapter 7: A Survey on MAC Protocols for Cognitive Radio Networks

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Outline

- Abstract
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- Spectrum sensing
- Spectrum access
- MAC Protocols for CR infrastructure-based networks
- MAC protocols for CR ad hoc networks
- Conclusion

Abstract

- In cognitive radio (CR) networks, identifying the available spectrum resource through spectrum sensing, deciding on the optimal sensing and transmission times, and coordinating with the other users for spectrum access are the important functions of the medium access control (MAC) protocols.
- In this survey, the characteristic features, advantages, and the limiting factors of the existing CR MAC protocols are thoroughly investigated for both infrastructure-based and ad hoc networks.

Abstract (Cont.)

- First, an overview of the spectrum sensing is given, as it ensures that the channel access does not result in interference to the licensed users of the spectrum.
- Next, a detailed classification of the MAC protocols is presented while considering the infrastructure support, integration of spectrum sensing functionalities, the need for time synchronization, and the number of radio transceivers.
- The main challenges and future research directions are presented, while highlighting the close coupling of the MAC protocol design with the other layers of the protocol stack.

Introduction

- Cognitive radio (CR) is a promising technology geared to solve the spectrum scarcity problem by opportunistically identifying the vacant portions of the spectrum and transmitting in them, while ensuring that the licensed or primary users (PUs) of the spectrum are not affected.
- This necessitates adapting to the dynamically changing spectrum resource, learning about the spectrum occupancy, making decisions on the quality of the available spectrum resource, including its expected duration of use, probability of disruption caused by the PUs, among others.

Introduction(Cont.)

- Thus, CR networks help to make efficient use of the available spectrum by using bands, such as television broadcast frequencies below 700MHz, that have been recently marked for CR operation [29].
- In addition, frequencies reserved for public service may experience intermittent use and the frequent quiet periods may also be used for CR transmission.
- However, in each of these cases, an important consideration is the prevention of performance degradation to the licensed users of the band used for CR transmission.

CR MAC protocols

- This motivates the research in CR MAC protocols, with an aim for providing efficient means of sensing the channel to determine its occupancy, and sharing the spectrum among the other CR users2 to maintain tolerable interference levels to the PUs that have a priority usage.
- The design of CR MAC protocols has followed two approaches –
  - (i) standardization efforts leading to the formation of the IEEE 802.22 working group
  - (ii) application/scenario specific protocols.

CR MAC protocols (Cont.)

- The former approach is mainly focused on infrastructure-based networks, in which a centralized coordinator or base station manages the spectrum allocation and sharing among the CR users.
- The CR users, however, may participate in the spectrum sensing function and provide channel information to the central controller. The standardization efforts lead to a uniformity in design and policy, thereby allowing multiple independent CR operators to coexist.

Used in distributed CR MAC protocols

- On the other hand, application or scenario specific protocols are optimized for a particular type of environment, or user specified application goal. This approach has been increasingly used in distributed CR MAC protocols, that operate without the support of a centralized controlling entity.
- As an example, nodes in an ad hoc network may exhibit high degrees of mobility with coarse time synchronization that makes sensing coordination difficult.

Used in distributed CR MAC protocols (Cont.)

- For such cases, the MAC protocol may leverage the mobility to determine which regions (covered by the node during its motion) exhibit high levels of PU activity.
- The spectrum availability in a region may be learnt by the node over time, such that the choice of the transmission spectrum can be improved.
- Moreover, as the information collected by a node is mostly based on its own observations, the dedicated sensing duration in the initial stage of the learning process may be higher than that compared to useful data transmission time.

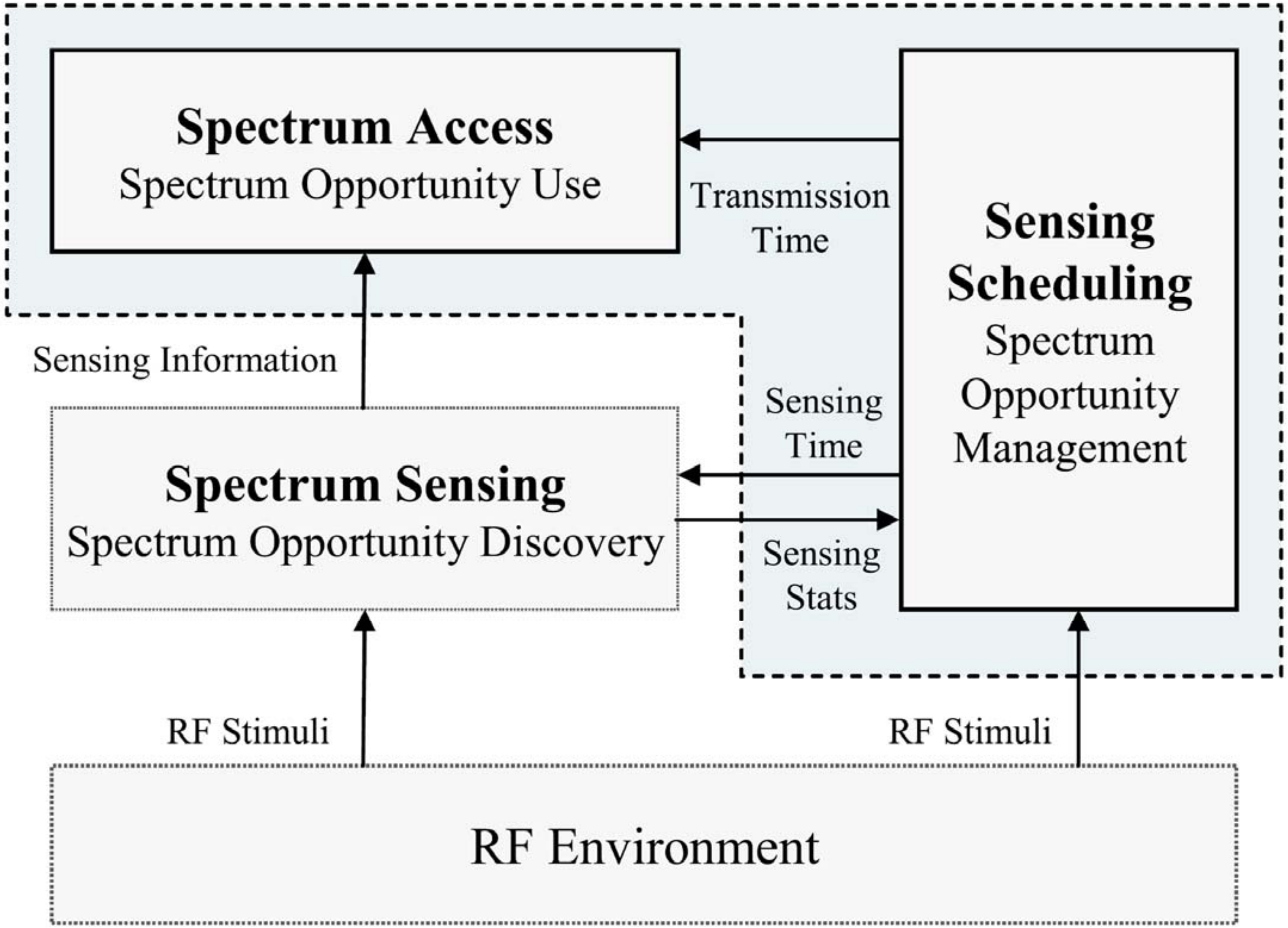
Quality of service (QoS)

- While this provides higher protection to the PUs in the long run, it results in reduced throughput that must still meet the quality of service (QoS) requirements set by the user.
- Thus, the MAC protocol operation must be adaptive to the environment and suited to the application needs, that makes standardization efforts particularly challenging.

Example for CR MAC protocol

- As an example, the carrier sense mechanism at the MAC layer may not reveal complete information regarding the channel owing to its inability to distinguish between the energy radiated by other CR users and the active PUs in the spectrum.
- In addition, packets may be simply retransmitted in the event of a collision with other CR users, while the transmission must cease immediately if the packet loss is due to PU activity.

Spectrum functions at the CR MAC



Spectrum functions at the CR MAC (Cont.)

- Based on the radio frequency (RF) stimuli from the physical layer RF environment, the sensing scheduler at the MAC layer can determine the sensing and transmission times.
- The availability of the spectrum, whenever a data packet needs to be sent, is coordinated by the spectrum access function.
- The spectrum sensing block plays a crucial role, both in terms of long term channel characterization and ensuring that the channel is available at the time of actual data transmission.

Spectrum functions at the CR MAC(Cont.)

- This helps in the other higher layer CR functions of joint spectrum and route decisions, congestion-free end-to-end reliability, spectrum and node mobility, among others.
- While many of these functions can be located at the central CR controller in infrastructure networks, distributed CR ad hoc networks need further interaction between the different layers of the protocol stack, as well as cooperation among the different users.

Spectrum sensing

- Spectrum sensing is one of the key enabling functions in CR networks that is used to explore vacant spectrum opportunities and to avoid interference with the PUs.
- The primary transmitter detection is based on the detection of the weak signal from a primary transmitter through the local observations of CR users.
- The primary receiver detection aims at finding the PUs that are receiving data within the communication range of a CR User.

Spectrum sensing(Cont.)

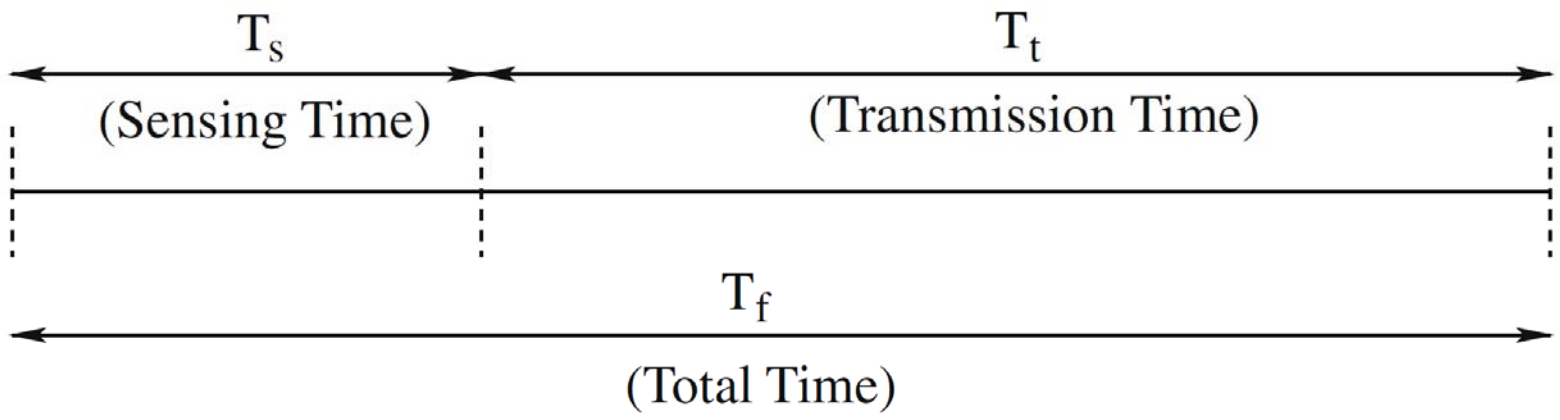
- Usually, the local oscillator (LO) leakage power emitted by the radio frequency (RF) front-end of the primary receiver is exploited, which is only feasible in the detection of the TV receivers.
- Thus, most of current research on spectrum sensing, described in this section, have mainly focused on primary transmitter detection.
- In addition to providing sensing coordination support at the MAC layer, the issues that are investigated are –
  - (i) how long the optimal sensing and transmission durations must be, and
  - (ii) the order in which the spectrum bangs must be searched to minimize the time for finding the available spectrum

Optimization of spectrum sensing and transmission duration

- The choice of the spectrum sensing time followed by the transmission time deals with two main parameters optimized by the MAC protocol, as shown in Fig. 2.
- While higher sensing times (T_s) ensure the correct detection of the spectrum, this may result in a comparatively smaller duration for actual data transmission (T_t) in the total time for which the spectrum may be used (T_f), thereby lowering the throughput.

Optimization of the sensing and transmission times.

- We discuss these functions further depending on whether they are undertaken independently of each other, or in a joint optimization framework.



Independent sensing duration optimization

- In this approach, the main objective is to find the sensing that minimizes the missed detection probability.
  - i.e. determining the spectrum to be unoccupied when there is an active PU, and conversely, the false alarm probability.
  - i.e. incorrectly inferring the presence of a PU in a vacant spectrum band.
- The sensing time (T_s in Fig. 2) optimization problem is studied, while keeping the transmission time (T_t) constant.
- Here, the channel efficiency is defined as the amount of the time that the idle channel can be utilized by the CR user for data transmission to the total time in a frame (T_f).

Independent sensing duration optimization(Cont.)

- The operation is as follows: After transmitting within a certain spectrum band for the duration (T_t) , the CR user will undertake spectrum sensing.
  - If there is no PU detected, it will continue to transmit in the same spectrum band.
  - If indeed the CR user infers the presence of a PU, it has to search for a new spectrum band.
  - If the spectrum is detected to be busy, the CR user needs to repeat this procedure on another band till a vacant spectrum band is identified.

Independent transmission duration optimization

- The optimal transmission duration (T_t) is derived while keeping the sensing duration (T_s) constant.
- The problem is formulated as a collision-throughput tradeoff problem, which finds the optimal value of the frame duration (T_f) for the CR operation.
- It integrates the minimum desired sensing time requirement and the traffic pattern of the PUs in its transmission time optimization function.

Independent transmission duration optimization(Cont.)

- The objective of the optimization is to maximize the throughput of the cognitive radio network while keeping the packet collision probability for the primary network under a certain threshold.
- For this, the authors assume exponential on-off traffic model for PUs but present a simplified treatment for the optimal frame duration.

Joint sensing and transmission duration optimization

- A theoretical framework is proposed for jointly optimizing the sensing and transmission parameters in order to maximize the spectrum efficiency subject to interference avoidance constraints.
- With the goal of exploiting multiple spectrum bands, a spectrum selection and scheduling method is proposed, where the best spectrum bands for sensing are selected to maximize the sensing capacity.

Joint sensing and transmission duration optimization(Cont.)

- In particular, sensing and transmission are performed in a periodic manner with separate observation and transmission periods. We believe that this approach is best suited for CR networks, as it best balances the tradeoff between sensing accuracy and the spectrum utilization efficiency.
- However, this approach is inherently more complex, and issues such as obtaining a solution to the optimization problem in real-time and the computationaloverhead must be considered.

Spectrum search sequence optimization

- The order in which the spectrum bands are chosen for sensing for the presence of PUs, called as the spectrum search sequence, determines the overall time used for searching the vacant spectrum.
- An interesting approach is the consideration of correlated spectrum band occupancy models, in which it is more likely to detect a PU transmission in the neighboring spectrum of a band that is already known to be occupied.
- Random and serial search schemes are investigated and a general n-step serial search scheme is proposed at the best solution.

Spectrum search sequence optimization(Cont.)

- Both sensing duration and spectrum search sequence optimization problems are jointly studied.
- The aim here is to discover as many spectrum opportunities as possible in advance, while minimizing the average time taken to detect a vacant spectrum band.
- The authors assume a semi-Markov traffic model for the PU spectrum usage and propose an estimation technique to learn the traffic pattern exhibited by the PUs.
- Moreover, the problem of deciding on an on-demand sensing schedule, as opposed to using periodic sensing, is investigated.

Research challenges

- The spectrum sensing involves several research challenges that are described as follows:
- Sensing coordination:
  - For accurate sensing, the measurements on the channel must be undertaken during quiet periods, when the other CR users in the neighborhood can be silenced.
  - This ensures correctly attributing the measured power to the radiation caused by the PUs alone.
  - However, in the absence of time synchronization, especially in distributed networks, this coordination is difficult to achieve at the MAC layer.

Research challenges(Cont.)

- Sensing information dissemination:
  - For accurate sensing, the measurements from several different CR users may be integrated.
  - However, the exchange of this information constitutes an overhead and may possibly interfere with the data packets sent by the other CR users.
- Optimal sensing duration:
  - Allocating the sensing and transmission time at the MAC layer is an important tradeoff between ensuring protection to the PUs, as opposed to maximizing the data throughput.
  - These durations must be carefully balanced to meet the user QoS requirements and prevent performance degradation to the PUs at the same time.

Research challenges(Cont.)

- Integration of sensing with other transmission parameters:
  - The sensing results must be closely associated with the choice of transmission parameters, leading to adaptive modulation and power control techniques.
  - A secondary transmitter adapting its transmit power according to the sensing metric is considered.
  - Here, the SNR or the resulting capacity of the CR user is maximized satisfying its peak transmit power constraint and average interference constraint at the primary receiver.
  - However, a more general class of sensing-dependent optimization techniques are needed that consider different possible transmission parameters.

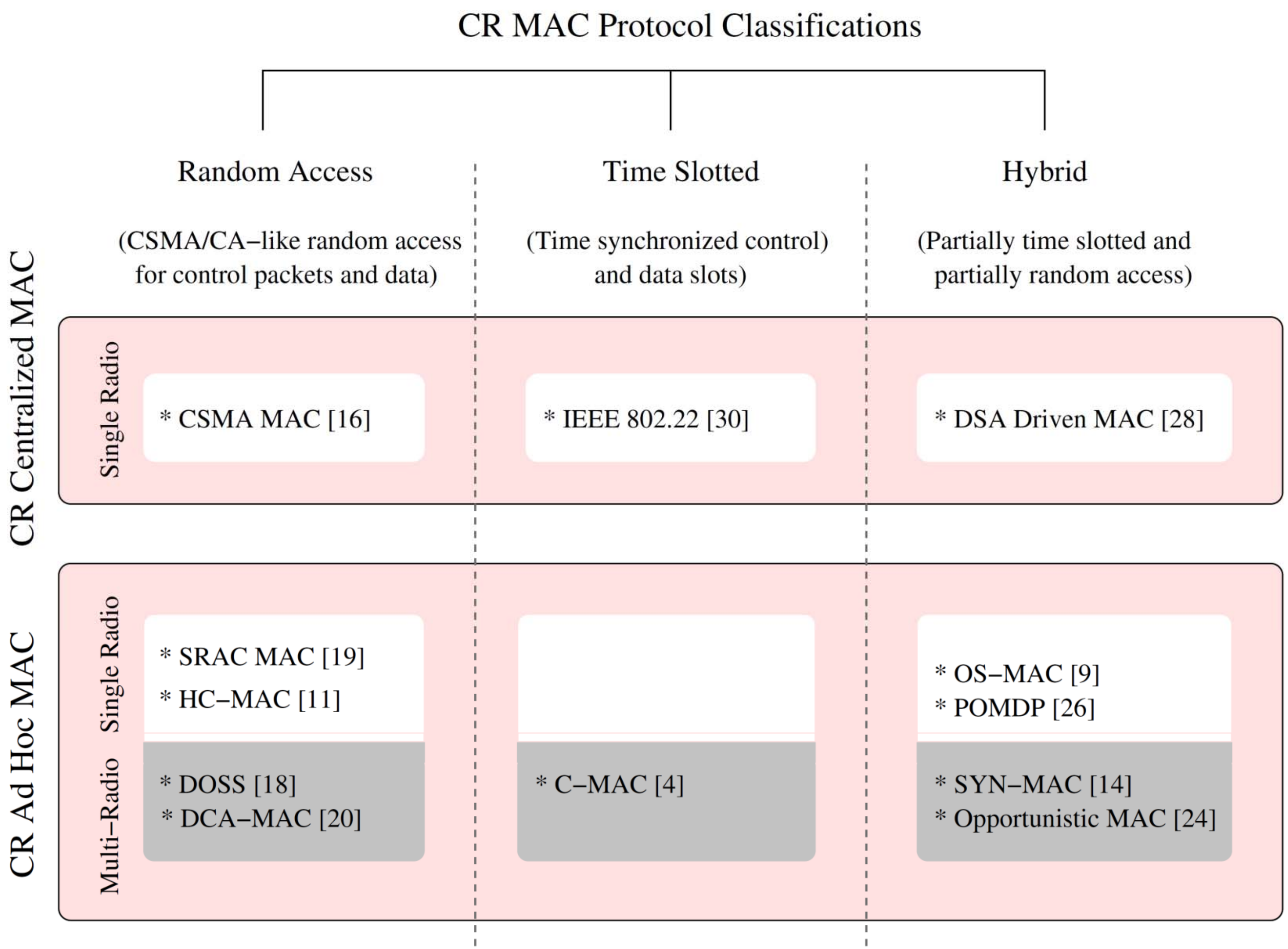
Spectrum access

- Spectrum access enables multiple CR users to share the spectrum resource by determining who will access the channel, or when a user accesses the channel.
- While both time slotted and random access schemes may be used in infrastructure-based networks, the difficulty in maintaining network-wide time synchronization in mobile ad hoc networks makes it infeasible to adopt completely slotted protocols.

Spectrum access(Cont.)

- In this paper, we provide a thorough description of MAC protocols for both CR infrastructure-based and ad hoc networks. We classify the existing approaches into
  - (i) random access protocols
  - (ii) time slotted protocols
  - (iii) hybrid protocols, as shown in Fig. 3.
- In addition, the number of radio transceivers also decides the working of the MAC protocol. We explain the classification as follows:

Classification of CR MAC protocols.



Classification of CR MAC protocols(Cont.)

- Random access protocols:
  - The MAC protocols in this class do not need time synchronization, and are generally based on the collision sense multiple access with collision avoidance (CSMA/CA) principle.
  - Here, the CR user monitors the spectrum band to detect when there is no transmission from the other CR users and transmits after a backoff duration to prevent simultaneous transmissions.
- Time slotted protocols:
  - These MAC protocols need network-wide synchronization, where time is divided into slots for both the control channel and the data transmission.

Classification of CR MAC protocols(Cont.)

- Hybrid protocols:
  - These protocols use a partially slotted transmission, in which the control signaling generally occurs over synchronized time slots.
  - However, the following data transmission may have random channel access schemes, without time synchronization.
  - In a different approach, the durations for control and data transfer may have predefined durations constituting a superframe that is common to all the users in the network.
  - Within each control or data duration, the access to the channel may be completely random.

Research challenges

- The challenges for efficient spectrum access are as follows:
- Control channel design:
  - The spectrum access involves control signaling between the two CR users on either ends of the link.
  - This messaging must be uninterrupted by the neighboring PU activity as it is used to exchange the sensing information, and coordinate the channel access.
  - For this, reliable and dynamically changing control channels must be devised.

Research challenges(Cont.)

- Adapting to PU transmission:
  - Some PUs have specific transmission patterns, such as pre-determined spectrum usage times and durations, such as television broadcast stations, or may have occasional random access to the channel, such as public service agencies.
  - At these times, the CR MAC protocol may infer the nature of the PU and adapt its own transmission to avoid both interference to itself and also prevent conflict with the PUs.
  - For this reason, dynamic power control and transmission scheduling schemes need to be devised.

MAC Protocols for CR infrastructure-based networks

- These protocols need a central entity, such as a base station, that manages network activities, synchronizes and coordinates operations among nodes.
- However, the central entity is static and generally forms a single hop link with the mobile CR users that are within its coverage area.
- This architecture helps in the coordination among the CR users for collecting the information about the network environment, and allows the spectrum decisions to be localized.

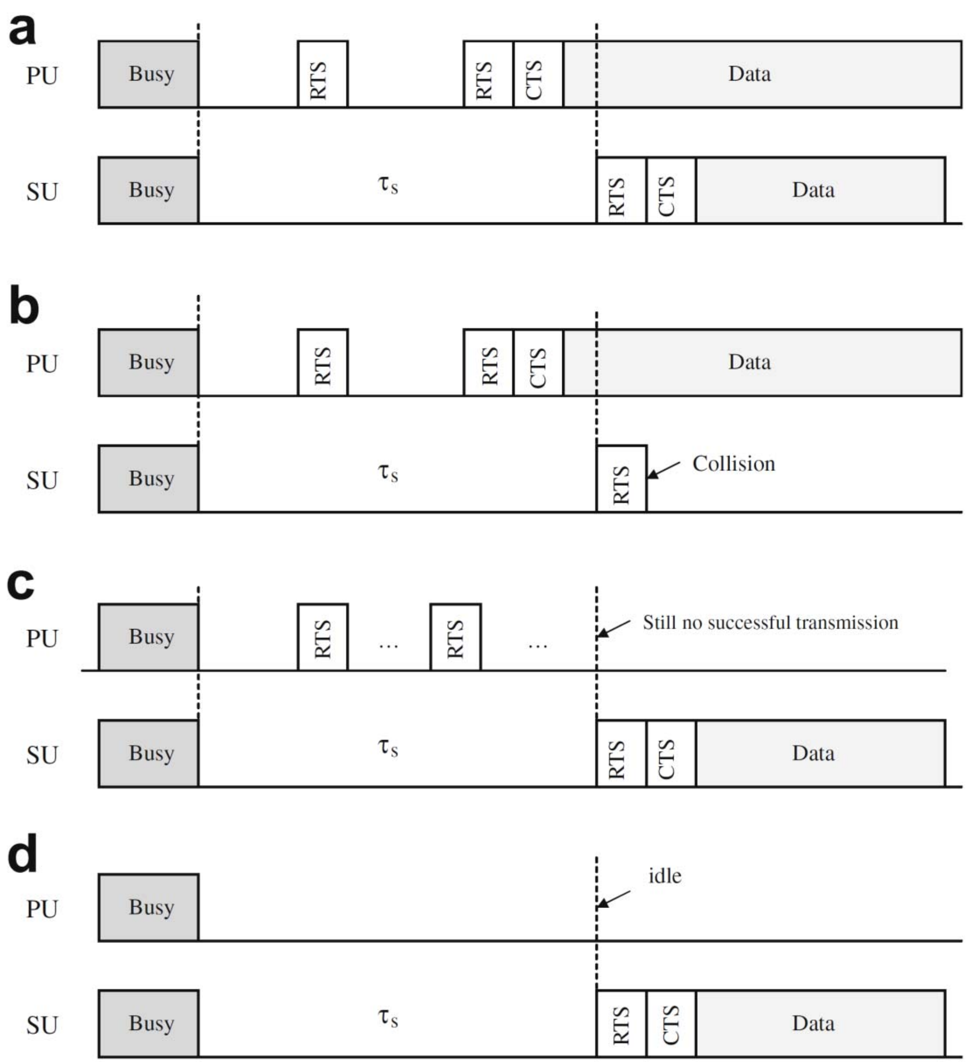
Random access protocols

- A CSMA based protocol is proposed that uses a single transceiver and in-band signaling.
- This protocol ensures coexistence among the CR users and the PUs by adapting the transmission power and rate of the CR network.
- Here, the CR and the PU base stations are separate, though they may have overlapping coverage areas.
- The CR users and the PUs establish direct single-hop connections with their respective base stations.

Random access protocols(Cont.)

- Based on the (i) distance of the CR users from the CR base station, and the (ii) noise power, the base station decides the transmission parameters, namely the transmit power and data rate, for the current transfer.
- The CR user is allowed to send just one packet in one round of this negotiation in order to minimize the risk of interference to the other PUs.
- Fig. 4 shows the detailed protocol behavior in four different cases (a-d) plotted against a horizontal time axis:

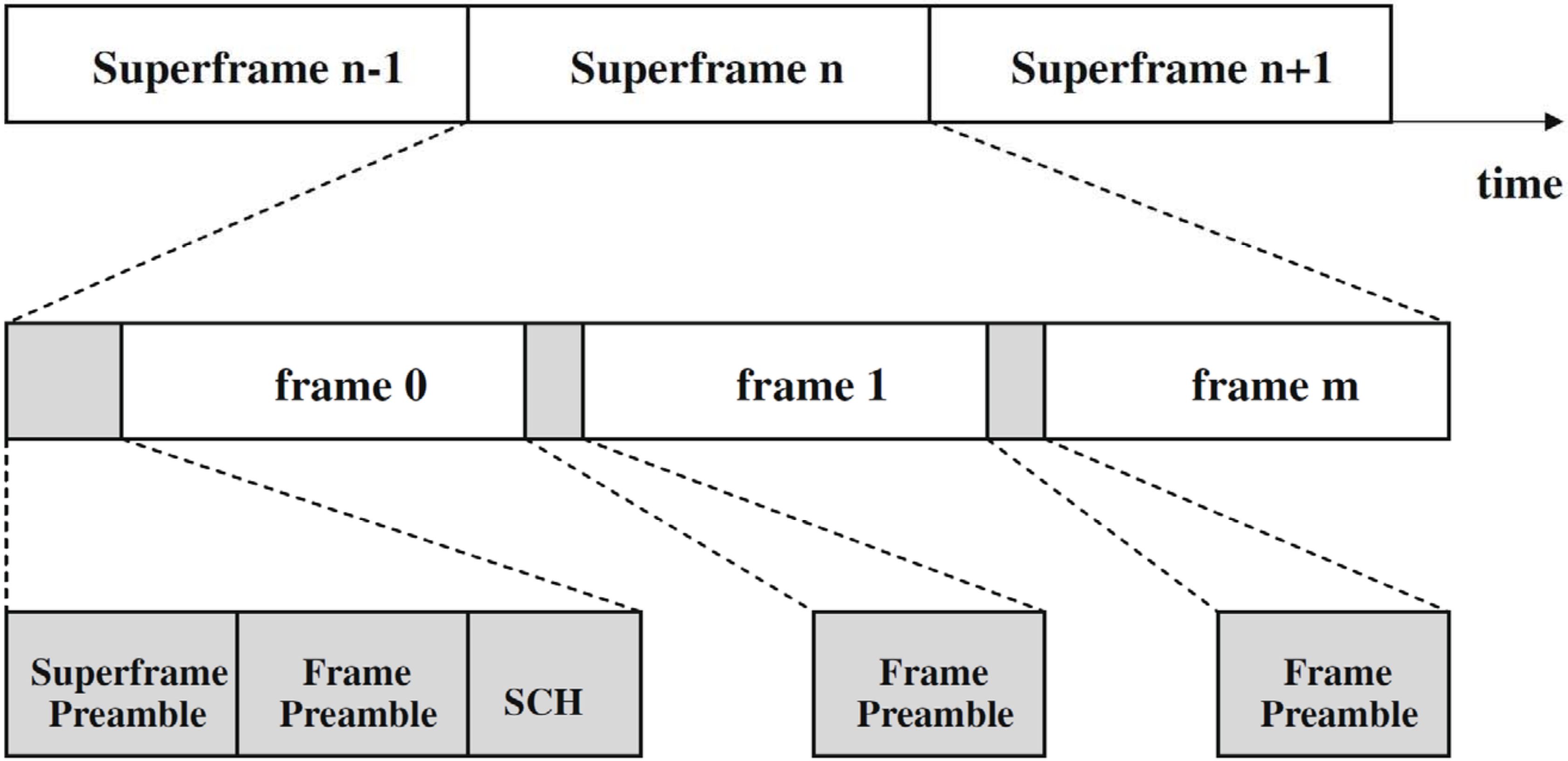
CSMA based protocol with four-way handshaking procedure.



Time slotted protocols

- The standard specifies time slotted operation, with the frame hierarchy as shown in Fig. 5.
- At the apex, a superframe is defined, each of which is composed of multiple MAC frames preceded by the frame preamble.
- At the start of each superframe, there is also a superframe control header (SCH) that is used to inform the CR users of the current available channels, different bandwidths supported, future spectrum access time, among others.

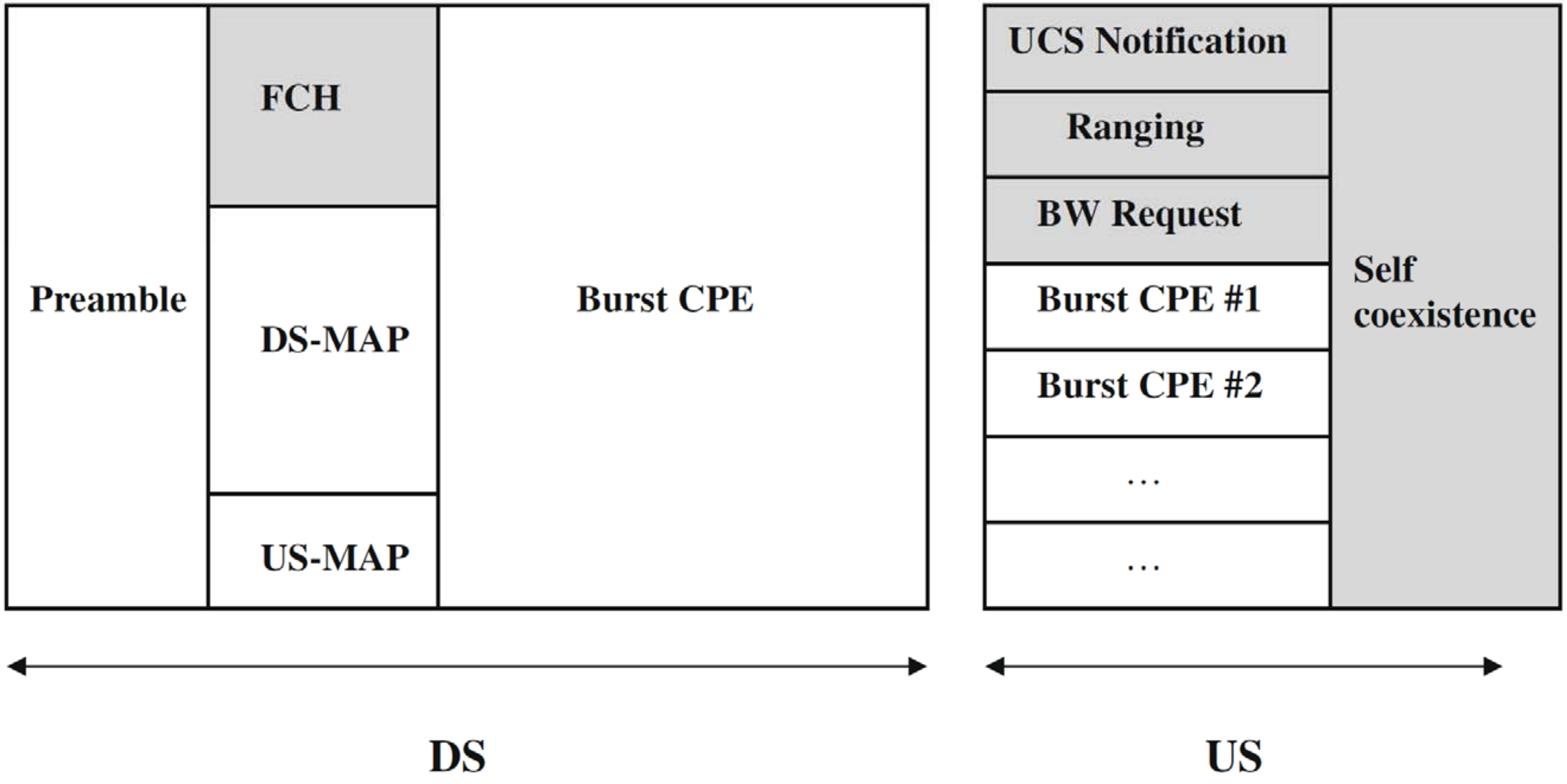
Superframe Structure in IEEE 802.22



Superframe Structure in IEEE 802.22(Cont.)

- The MAC frame is formed by two parts in the frame structure, as shown in Fig. 6 – DS subframe and US subframe.
- The DS subframe contains a single packet burst from a given CPE, while the US subframe has multiple packet bursts, each transmitted from different CPEs.
- The different fields in these two subframes are as follows: In the DS subframe, the preamble deals with synchronization and channel estimation, the frame control header (FCH) contains the size of the DS- and US-MAP fields together with channel descriptors, and the DS/US-MAPs give the scheduling information for user bursts.

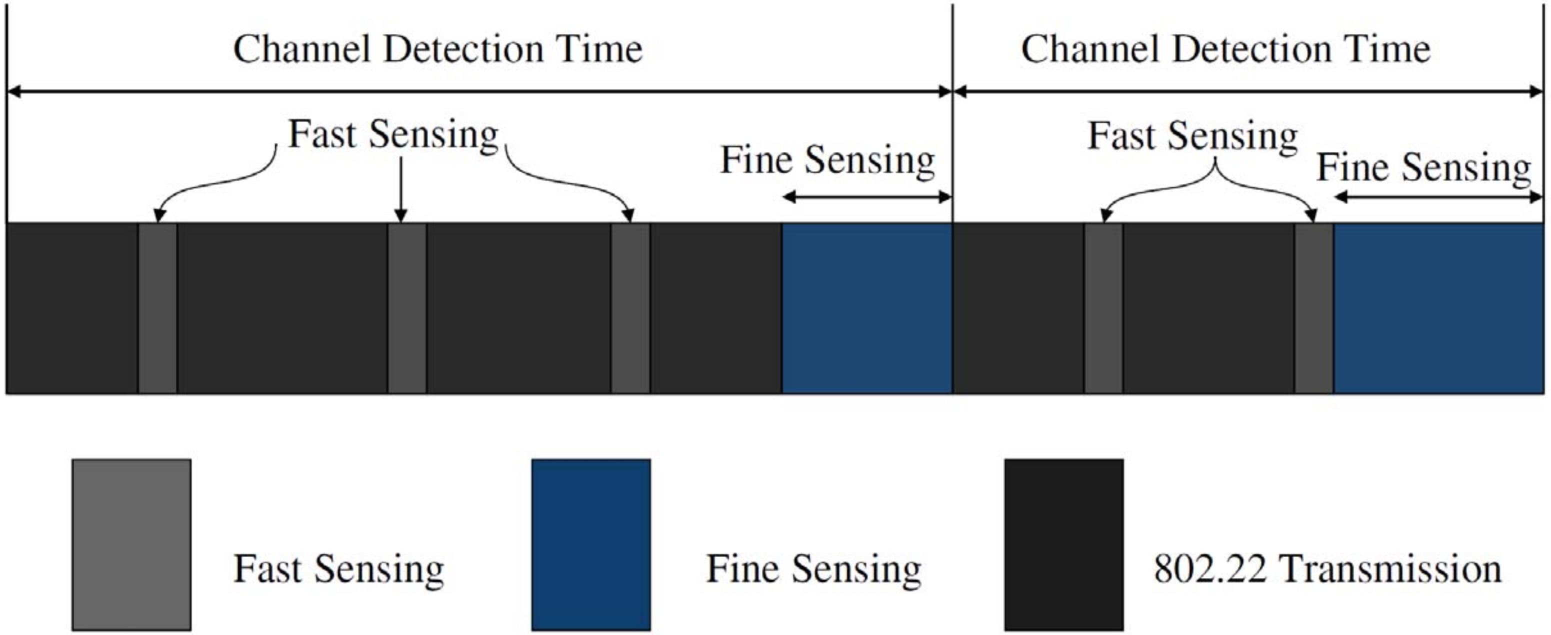
Frame Structure in IEEE 802.22



Spectrum sensing support

- The IEEE 802.22 protocol has a two-stage sensing (TSS) mechanism as shown in Fig. 7.
- Fast Sensing:
  - This is done at the rate of 1 ms/channel, and the sensing results are used to decide if a subsequent fine sensing stage is needed.
  - The sensing is completed quickly though the accuracy is low.
- Fine Sensing:
  - Fine sensing is performed on-demand, which allows CR networks to meet the strict quality of service (QoS) requirements by decreasing the rate of false alarms.
  - The duration for this is much larger than the fast sensing, and gives a tradeoff for improving the sensing accuracy at the cost of transmission time.

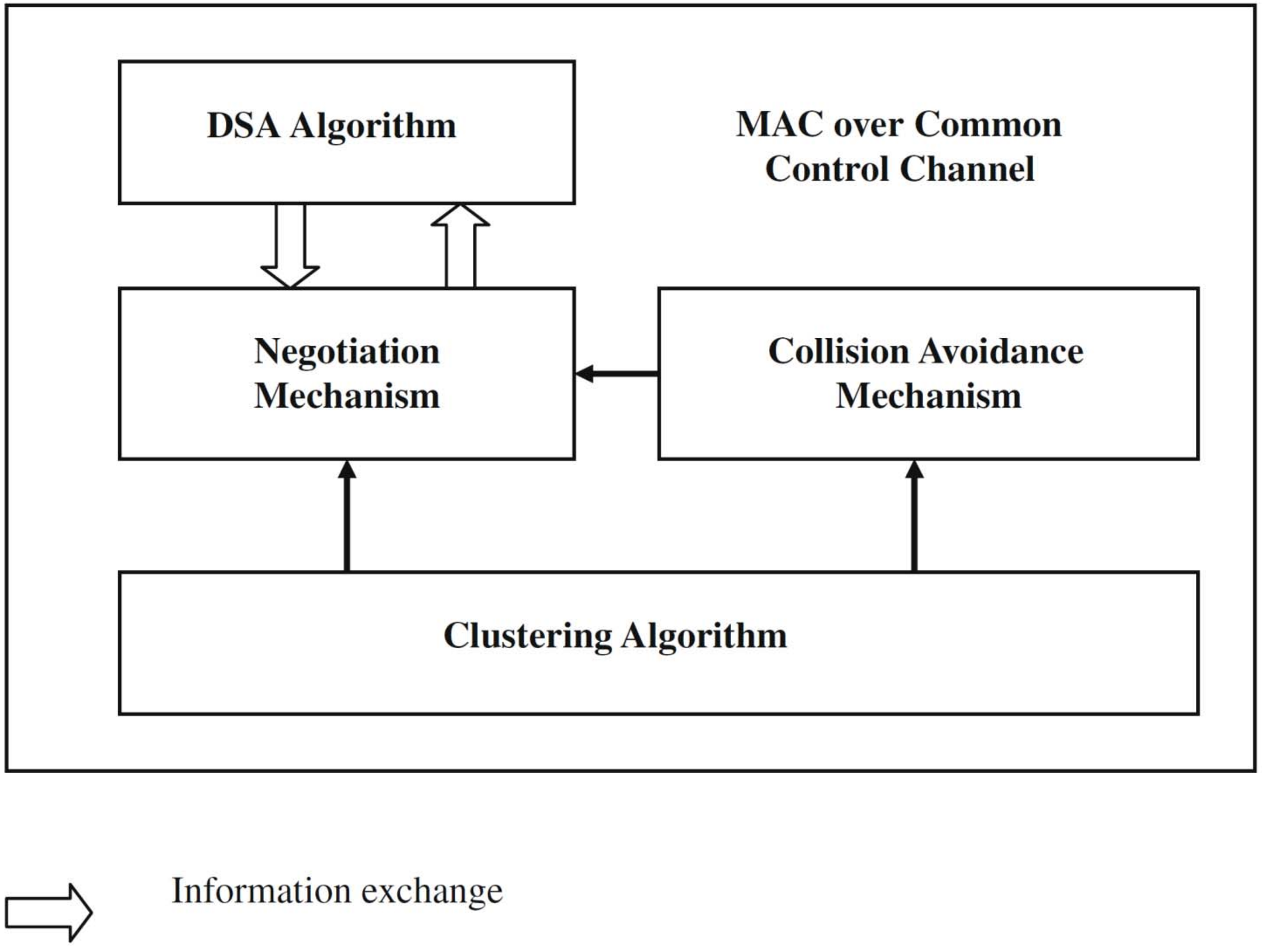
Two-stage sensing (TSS) mechanism in IEEE 802.22



Hybrid protocols

- A game theoretic dynamic spectrum access (DSA) is proposed .
- The proposed MAC protocol has high spectrum utilization, collision free spectrum access with QoS and fairness guarantees.
- Four integral components can be recognized in the DSA-driven MAC framework, as shown in Fig. 8:
  - (i) DSA algorithm
  - (ii) clustering algorithm
  - (iii) negotiation mechanism
  - (iv) collision avoidance mechanism.

DSA-driven MAC framework



DSA algorithm

- The game theoretic DSA algorithm aims at pursuing a global optimization solution by reaching the Nash Equilibrium.
- In particular, the CR user behavior can be modeled as a repeated game model.
- Therefore, each player keeps updating its strategy in order to maximize its own local utility function until the game converges to the Nash Equilibrium, after which a collision free channel access can be experienced.

DSA algorithm(Cont.)

- The utility function is composed of two components:
  - the payoff or the gain obtained from the choice of the strategy
  - the price the player should pay to the others for its strategy.
- The utility function may also take into account QoS and fairness requirement.
- From the networking viewpoint, the Nash equilibrium represents the assignment of spectrum access opportunities to all the CR users.

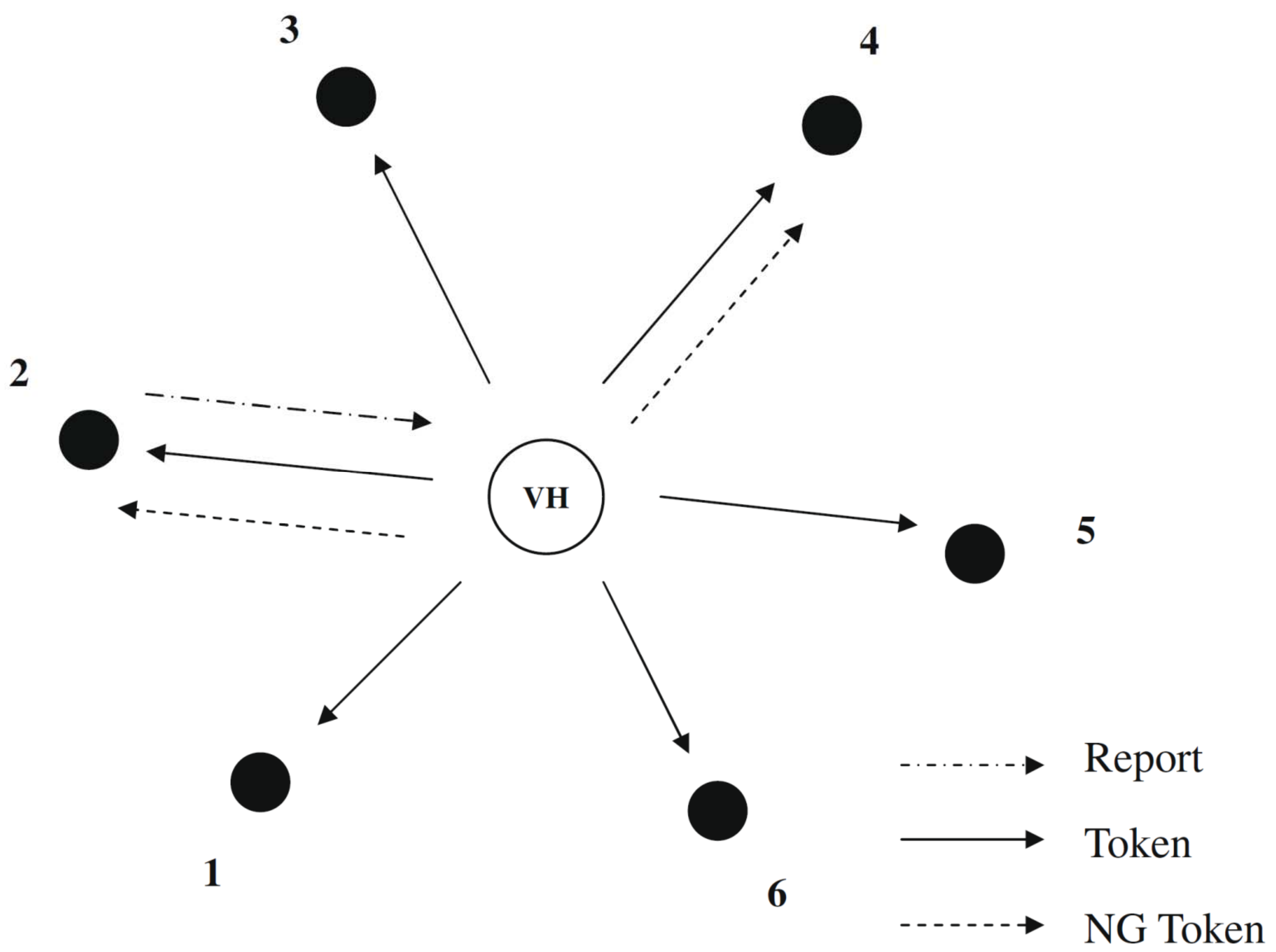
Clustering algorithm

- All the nodes within the hexagonal area are part of the cluster. The identity of each cluster is exclusively given by its position.
- When a node is added to the network, it can chose independently which cluster to join, based on the smallest distance from the cluster center.
- After joining a cluster, the node broadcasts with maximum power its coordinates and the cluster ID, so that all the other nodes within other clusters are aware of topology changes.

Negotiation mechanism

- The negotiation mechanism illustrated in Fig. 9 deals with the control message exchange and coordination of the actions of the CR users. This negotiation occurs over a CCC and is composed of two phases:
  - (i) inquiry stage
  - (ii) formal negotiation stage.
- The aim of the inquiry stage is to identify the nodes that wish to start data communication.
- After this stage, the nodes that have packets to transmit will then become quasi-game players and will be considered in the formal negotiation stage.

Negotiation process in the DSA–MAC



Negotiation process in the DSA–MAC(Cont.)

- An example summarizing the entire negotiation mechanism is shown in Fig. 9. Node 2 wants to start a transmission and reports the request to the VH node.
- During the inquiry stage a token inquires all the cluster members but only nodes 2 and 4 become quasi-game players, as they have packet to transmit.
- Then, the formal negotiation stage is carried out in order to coordinate nodes 2 and 4 to process the formal game.

Collision avoidance mechanism

- This mechanism aims at avoiding collisions during negotiations in different clusters and relies on out-of-band busy tones.
- Two different types of busy tones are exploited: inside-cluster and outside-cluster busy tones.
  - Inside- cluster busy tone is set up by a node receiving a message to prevent other nodes external to its cluster from interfering with the ongoing negotiation.
  - Outside-cluster busy tone is set up by a node overhearing messages from other clusters in order to avoid initiating a new round of negotiation within the cluster, as it may result in interference.

MAC protocols for CR ad hoc networks

- These protocols do not have a central entity for the operation of the network.
- Though the resulting architecture is scalable and has flexible deployment, the distributed spectrum sensing, sharing and access necessitate increased cooperation with the neighboring nodes.
- Maintaining time synchronization throughout the network and obtaining the information from surrounding nodes with minimum overhead are some of the factors that must be considered in the protocol design.
- We describe the existing works next based on the classification given in Fig. 3.

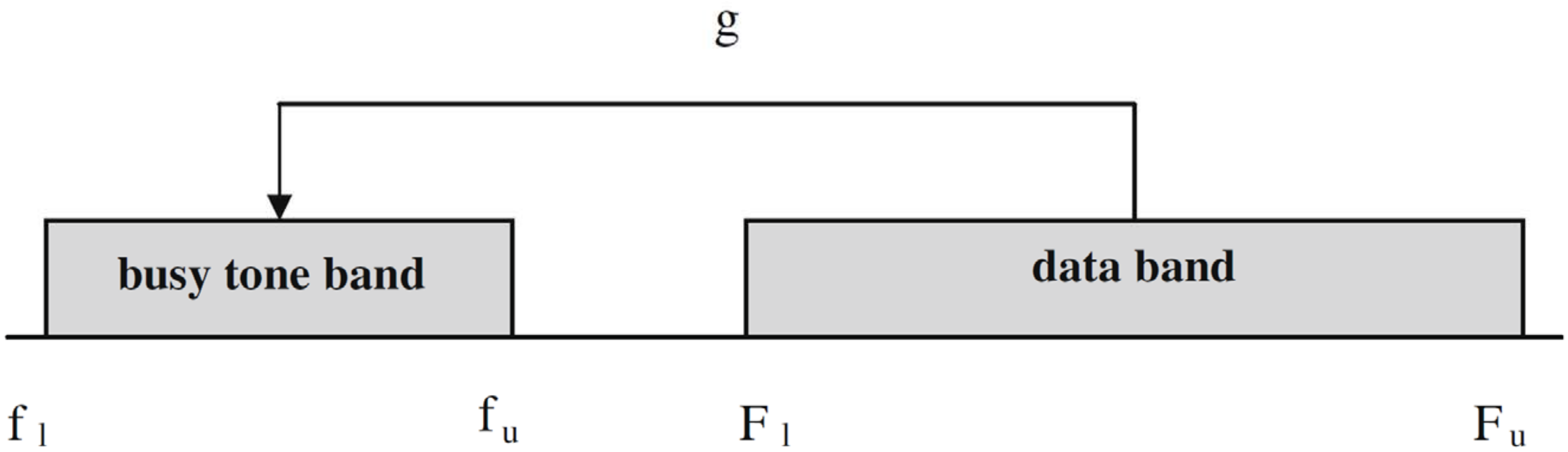
Dynamic open spectrum sharing (DOSS) MAC

- PU detection:
  - Since the CR users can use the spectrum only when the PUs are absent, the CR node continuously monitors the spectrum in its vicinity.
- Set-up of three operational frequency bands:
  - (i) traffic limiting
  - (ii) bandwidth ratio setting
  - (iii) control channel migration techniques to alleviate the control channel saturation problem.

Dynamic open spectrum sharing (DOSS) MAC(Cont.)

- Spectrum mapping:
  - The mapping of the busy tones with the data transmission bands are done as follows.
  - The busy tone band has a frequency range $[f_l, f_u]$, and the data band is contained in $[F_l, F_u]$, as shown in Fig. 10.
  - The data spectrum is considerably larger
    - i.e. $F_u - F_l >> f_u - f_l$ and this linear mapping allows neighboring nodes to realize that the spectrum is actually used by another CR user by observing the corresponding busy tone.

Spectrum mapping in the DOSS MAC



Spectrum mapping in the DOSS MAC(Cont.)

- Spectrum negotiation:
  - The sender sends a request (REQ) packet with the available spectrum bands at its end.
  - The receiver then replies with a REQ_ACK packet containing the information of a mutually acceptable spectrum band.
  - Upon receiving the REQ_ACK, the sender tunes its data transmitter to the negotiated band.
- Data transfer:
  - If a packet is correctly received, the receiver replies with DATA_ACK packet and turns off the busy tone.
  - By receiving the DATA_ACK packet, the sender knows the transmission is successful.
  - Otherwise, after a timeout, it will retransmit the data packet.

Distributed channel assignment (DCA) based MAC

- A simple extension of the IEEE 802.11 CSMA/CA protocol using distributed channel assignment (DCA) is proposed in [20].
- It uses multiple transceivers, with a dedicated out-of-band CCC for signaling.
- In addition, the proposed protocol also utilizes spectrum pooling which helps to enhance spectral efficiency by reliably detecting the primary network activity, thus serving as physical layer signalling.

Distributed channel assignment (DCA) based MAC (Cont.)

- Maintaining spectrum information:
  - (i) current usage list (CUL)
  - (ii) the free channel list (FCL).
- Each node's CUL list records information of its neighbors including their addresses and the corresponding data channels utilized by them as well as the expected time of use.
- Data transfer:
- This process is similar to the data transfer stage, where the FCL is matched at both the sender and receiver ends using the RTS–CTS handshake.

Distributed channel assignment (DCA) based MAC (Cont.)

- The use of a separate CCC results in wastage of the spectrum and may also become the bottleneck on the link.
- Moreover, there is no specific support for spectrum sensing or PU related adaptation that is required for CR networks.
- The protocol proposed has similar functioning and drawbacks, but uses a single transceiver that alternates between monitoring the CCC and the data spectrum bands.

Single radio adaptive channel MAC (SRAC) protocol

- The single radio adaptive channel (SRAC) algorithm is proposed in [19] that adaptively combines spectrum bands based on the CR user requirement, called as dynamic channelization.
- In addition, it uses a frequency division multiplexing (FDM)-like scheme, called as cross-channel communication, in which a CR user may transmit packets on one spectrum band but receive messages on another.
- These two features are described as follows:

Single radio adaptive channel MAC (SRAC) protocol (Cont.)

- Dynamic channelization:
  - Based on the spectrum demand, the usable transmission spectrum can be adaptively changed. Moreover, the spectrum bands are based on the observed load and the usage by the PUs.
- Cross-channel communication:
  - In order to avoid frequency jamming and PU activity, a CR user may use different transmission spectrums for sending and receiving.
  - This also allows for reserving larger spectrum for sending data, while the return acknowledgments may be received over smaller spectrum bands for efficient utilization of the spectrum.

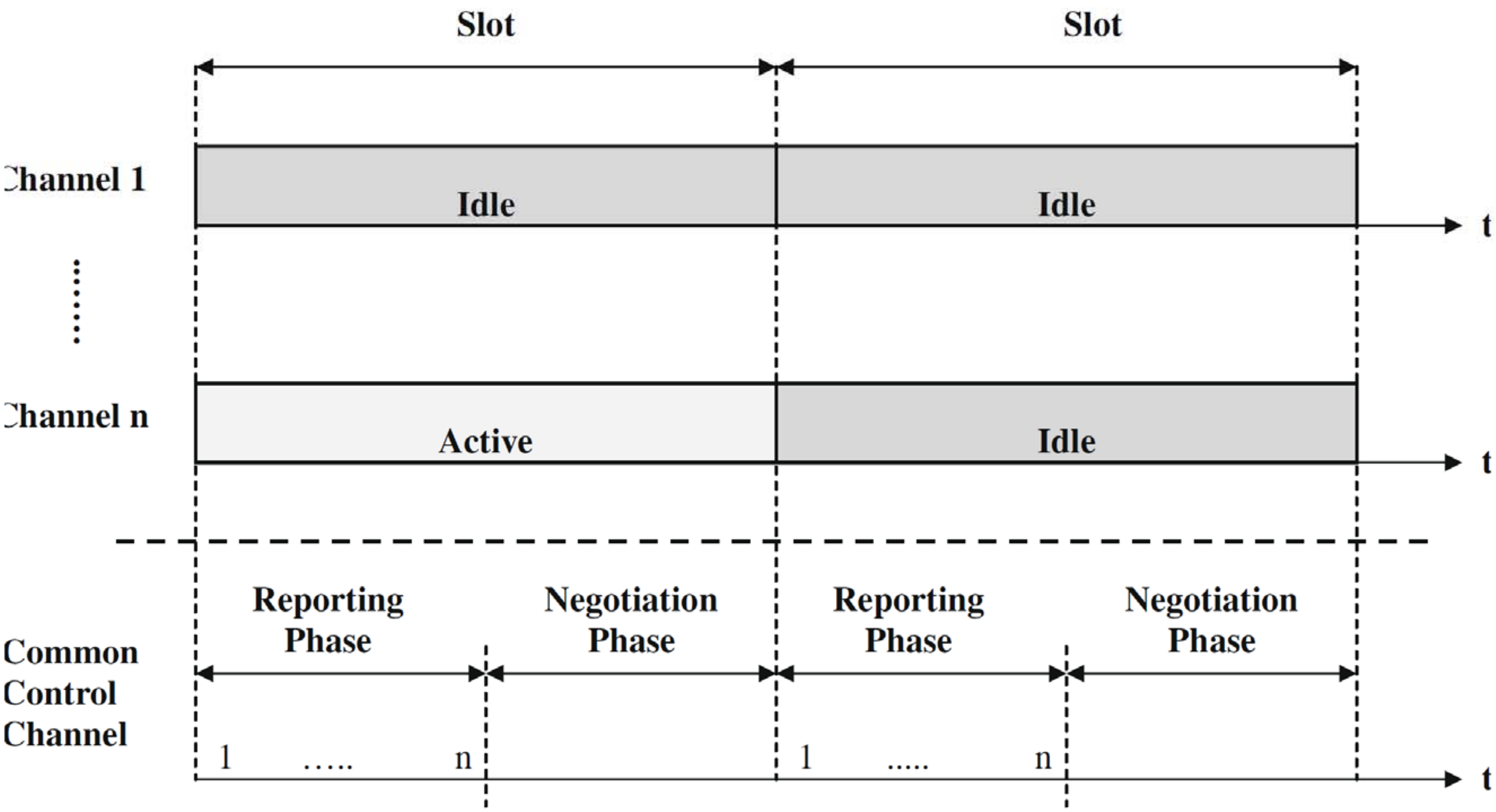
Single radio adaptive channel MAC (SRAC) protocol (Cont.)

- However, this work does not completely address the means to detect the presence of a jammer and distinguish malicious activity from legitimate network conditions.
- Though this approach uses a single radio, it will result in significant deaf periods, where control messages not sent on the receive spectrum band of the node will not be monitored.
- Moreover, the signaling overhead for maintaining updated receive spectrum bands of all the neighbors continuously adds to the traffic.

Opportunistic MAC

- The opportunistic cognitive MAC protocol proposed in uses two transceivers, one for a dedicated CCC, and the other that can be dynamically tuned to any chosen spectrum.
- As shown in Fig. 14, the time is slotted for the data transfer over the licensed channels, while the CCC operation is partly slotted, followed by a random access negotiation phase. Thus, it is a hybrid protocol.
- The detailed explanation of the working of the MAC protocol is described below with reference to Fig. 14. The CCC has the following two phases.

Working principle of opportunistic MAC



Working principle of opportunistic MAC(Cont.)

- Reporting phase:
  - The reporting phase is further divided into n mini-slots, where n is the number of channels.
  - At the beginning of each time slot, the cognitive user senses one of the channels.
  - If the ith channel is perceived to be idle, it sends a beacon over the CCC during the ith mini-slot of the reporting phase.
  - No beacons are sent if no PU is detected. These beacons serve to inform the neighbors of the PU activity.
- Negotiation phase:
  - During the negotiation phase, the CR users negotiate via contention-based algorithms, such as those based on the IEEE 802.11 and p-persistent carrier sense multiple access.

Conclusion

- In this paper, we present an overview of the state of the art for medium access protocols in cognitive radio networks.
- The existing works in the two main functions of the MAC protocol, namely the spectrum sensing and spectrum access were discussed.
- For this, the simplified ON/OFF PU traffic model may not be suitable in a practical environment where the licensed users may be cellular, contention-based, or have other possible access technologies.

Homework #7:

1. What's Spectrum functions at the CR MAC？
2. What's Classification of CR MAC protocols？