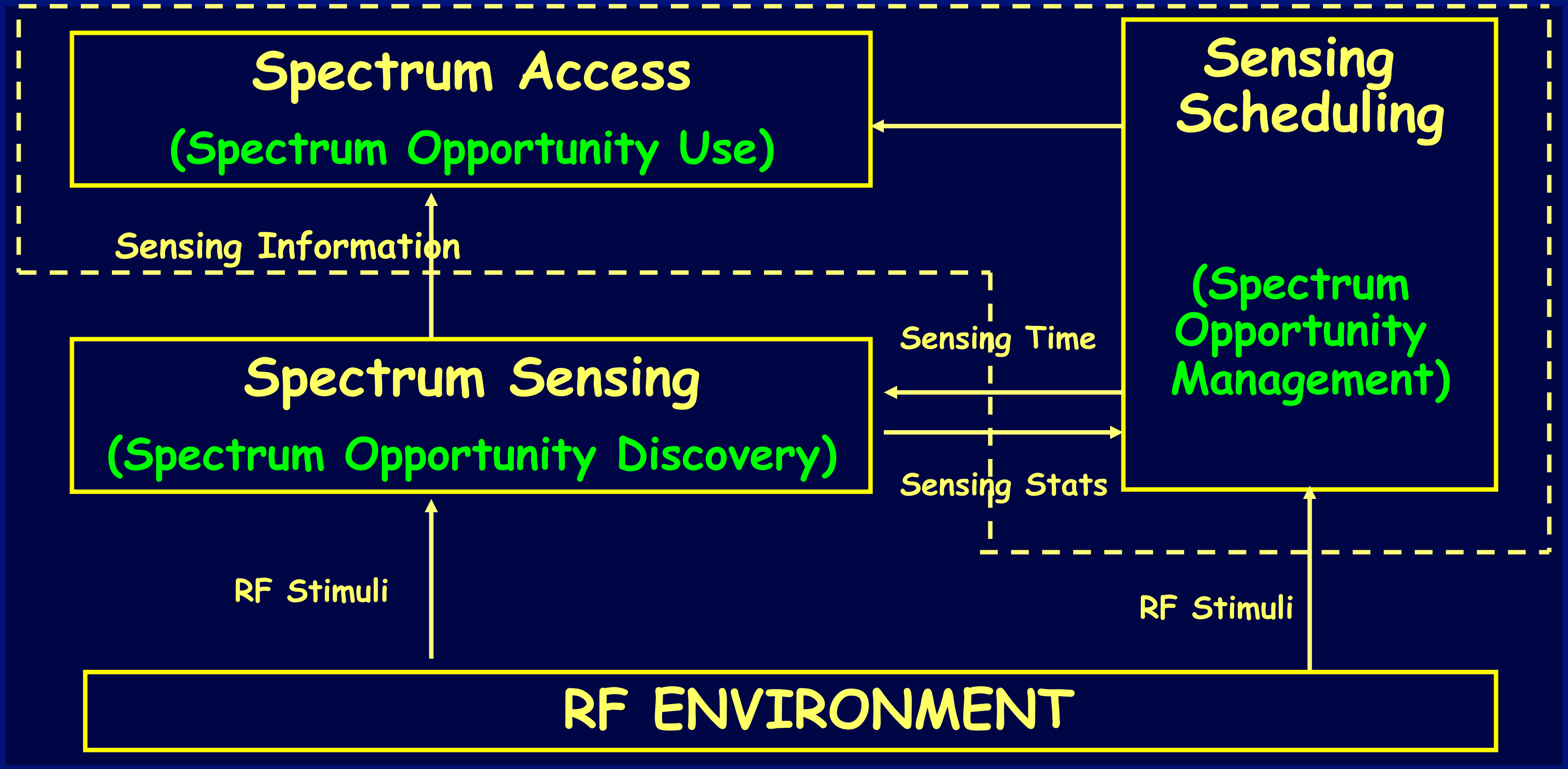
CHAPTER 10.
COGNITIVE RADIO MACs

Classical vs. Cognitive MAC

C. Cormio and K. R. Chowdhury, "A Survey on MAC Protocols for Cognitive Radio Networks", Ad Hoc Networks Journal (Elsevier), Sept. 2009

Classical MACs	Cognitive Radio MACs
Channel access control within one particular spectrum	Channel access across several available spectrum bands dynamically
No distinction between PUs and SUs	Interference to PUs should be avoided PUs have higher priority

Spectrum Functions at the CR MAC



Spectrum Functions at the CR MAC (2)

- **Sensing Scheduling**
  - Determines the sensing and transmission times
    (covered in Chapter 5, along with spectrum sensing)
  - Maximize overall discovery of opportunities by CR users in the licensed bands
- **Spectrum Access**
  - Coordinates the spectrum availability whenever there is a data packet to send

Spectrum Access

Definition:

Enables multiple CR users to share the spectrum by determining who and when will access the channel

Two possible classifications based on:

- Protocol behavior
- Network architecture

Protocol Behavior based Classification

C. Cormio and K. R. Chowdhury, "A Survey on MAC Protocols for Cognitive Radio Networks", Ad Hoc Networks Journal (Elsevier), Sept. 2009

Random Access	Time Slotted	Hybrid
CSMA/CA is used for both control and data packets	Synchronized time slots for both control and data packets	Synchronized time slots for control packets and random access for data packets or Superframes for both control and data packets but random access within them

Network Architecture based Classification

Centralized	Distributed
A central entity (BS) manages network activities, synchronizes and coordinates users	Network operations are carried out without the need of a central entity
The static architecture allows the BS to collect information about the network and helps the coordination among nodes	Cooperation needed for maintaining synchronization and exchanging information

Classification of Centralized CR MAC Protocols

C. Cormio and K. R. Chowdhury, "A Survey on MAC Protocols for Cognitive Radio Networks", Ad Hoc Networks Journal (Elsevier), Sept. 2009

Random Access	Time Slotted	Hybrid
(CSMA/CA for Data/Control packets)	(Time Synchronized Control/Data Slots)	(Partially time slotted, Partially random access)
CSMA/CA MAC	IEEE 802.22	DSA Driven MAC

Note: All are single-radio MAC protocols

Classification of Distributed CR MAC Protocols

C. Cormio and K. R. Chowdhury, "A Survey on MAC Protocols for Cognitive Radio Networks", Ad Hoc Networks Journal (Elsevier), 2009

	Random Access (CSMA/CA for Data/Control packets)	Time Slotted (Time synchronized Control/data slots)	Hybrid (Partially time slotted, Partially random access)
Single Radio	SRAC MAC HC MAC		OS MAC POMDP
Multiple Radio	DOSS DCA MAC	C-MAC	SYN-MAC Opport. MAC

Centralized CR MAC Protocols

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(CSMA/CA for Data/Control packets)	(Time synchronized Control/data slots)	(Partially time slotted, Partially random access)
CSMA/CA MAC	IEEE 802.22	DSA Driven MAC

Note: All are single-radio MAC protocols

CSMA/CA based MAC

S.-Y. Lien, C.-C. Tseng, K.-C. Chen, "Carrier Sensing Based Multiple Access Protocols for Cognitive Radio Networks", IEEE Int. Conference on Communications (ICC), May 2008.

CR users are allowed to transmit even if the channel is partially busy by a PU transmission
(with a tolerable interference)

Transmission power and rate are controlled !

CSMA/CA based MAC

S.-Y. Lien, C.-C. Tseng, K.-C. Chen, "Carrier Sensing Based Multiple Access Protocols for Cognitive Radio Networks", IEEE Int. Conference on Communications (ICC), May 2008.

Features:

- Carrier sensing based with four-way handshaking
- Single transceiver
- In-band signaling

Protocol Behavior

→ PU users follow classical CSMA/CA (RTS/CTS etc)

→ CR user senses the carrier for a longer time τ_s than PUs before transmission

- If the channel is idle, it sends an RTS packet to the CR Rx

- CR BS computes a feasible transmission power and rate and adds that information to the CTS

Transmission Parameter Adjustment

Transmission parameters (power/rate) are decided by the CR BS based on the

i) Distance of the CR users from the BS
ii) Noise power

Note that only one packet can be sent with the suggested parameter in order to minimize the interference risks

Protocol Behavior

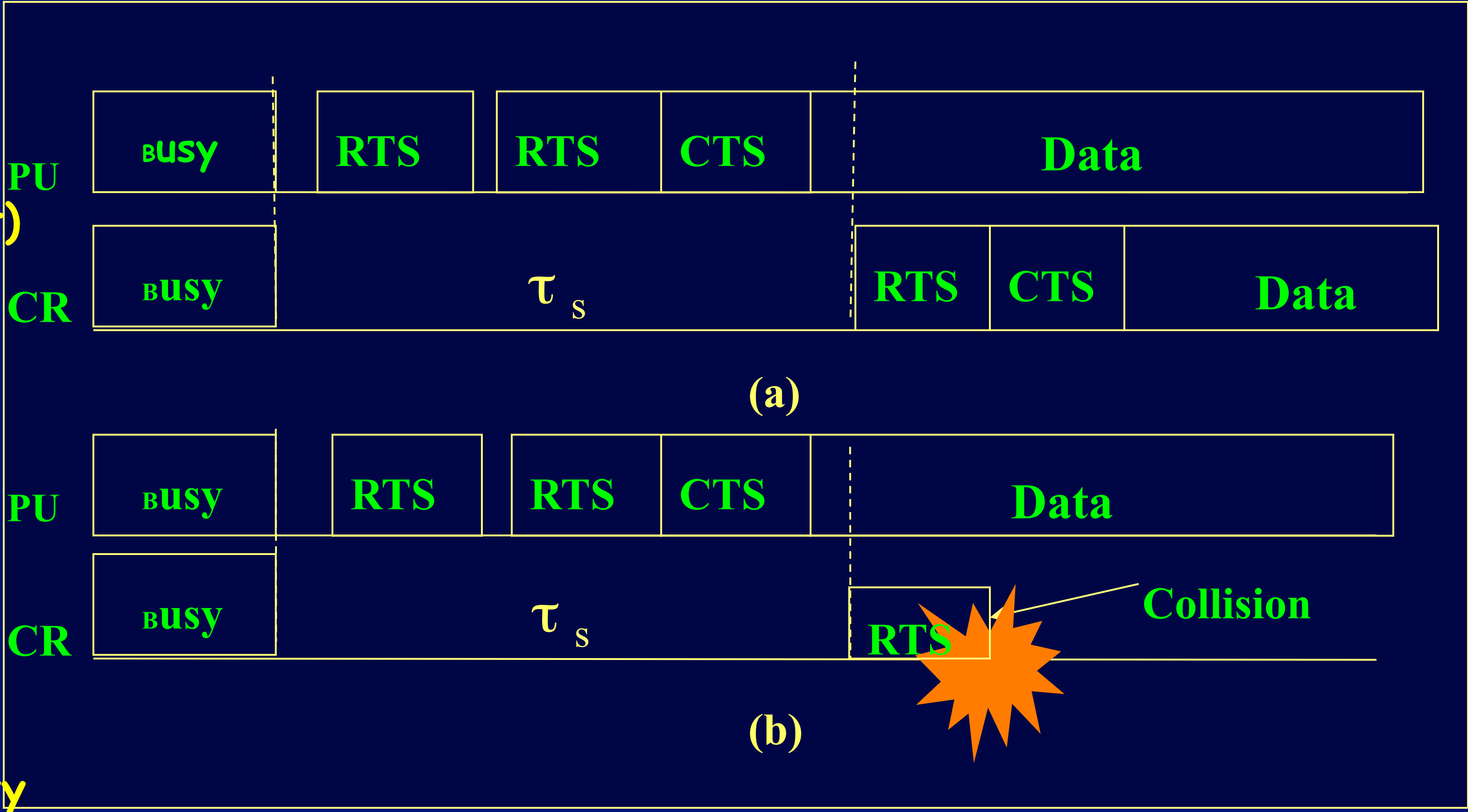
- If a feasible power and rate cannot be found, the CTS is not sent back to the CR transmitter

- If a CTS is received, the packet transmission starts with the suggested power and rate

Four-Way Handshaking (1)

a) PU gains the access to the channel. CR senses the channel for τ_s and finds a channel idle (assume PU and CR are far apart) and starts transmission with power and rate suggested by the BS

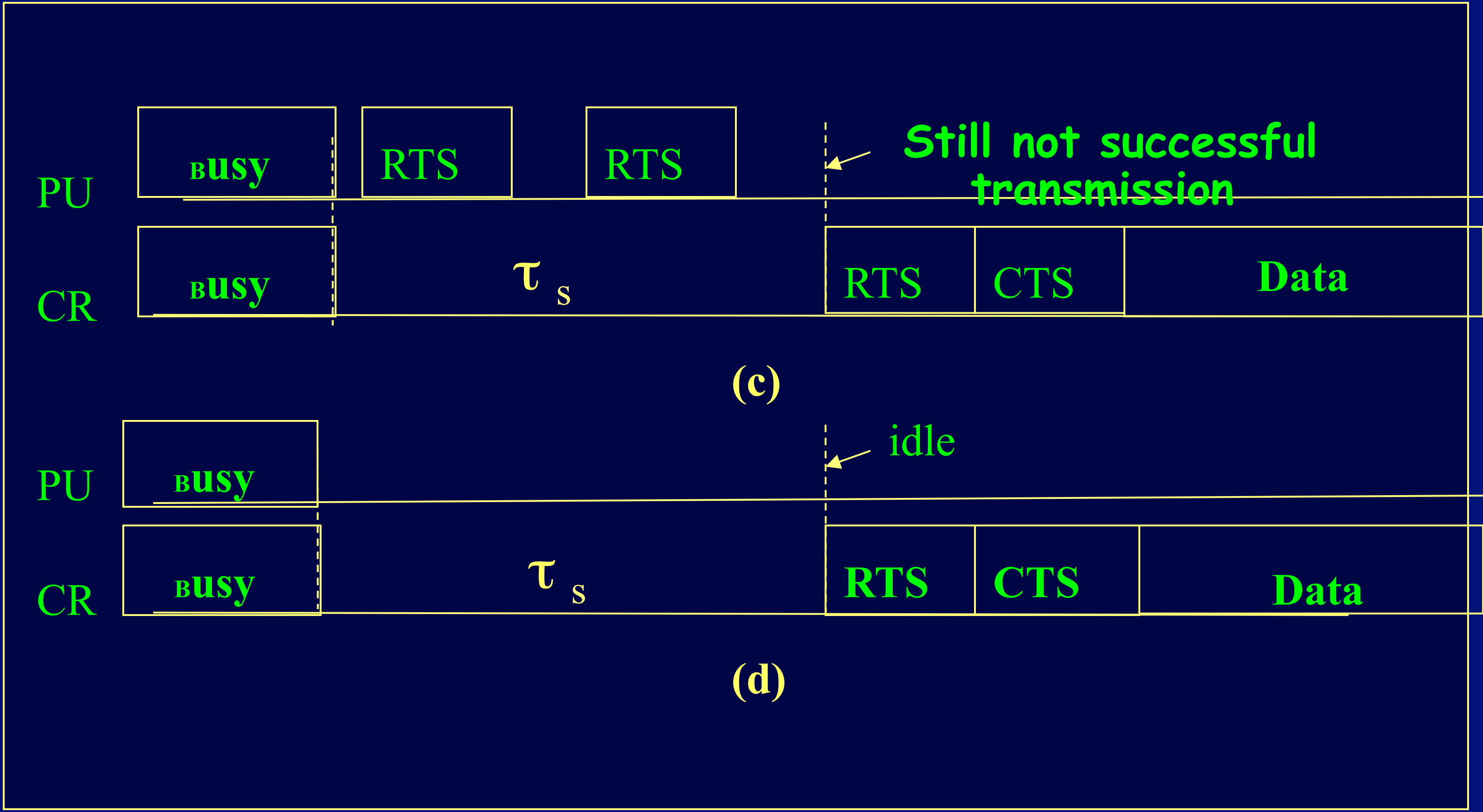
(b) When RTS messages from different CR users are collided, the CR must wait for the next transmission opportunity after repeated sensing



Four-Way Handshaking (2)

(c) PU sends repeated RTS packets which are colliding; the CR can transmit regardless of the PUs without power and rate adjustment

(d) PUs have no packets to send; CR can start the RTS/CTS exchange and starts transmission



Drawbacks

- CR users cannot determine if the PUs experience multiple failed transmission attempts in case (c)
- CR users are just able to partition power into two discrete levels (low or high)
- A concrete assignment of the transmit power, coding scheme and transmission rate to the CR users is missing

Centralized CR MAC Protocols

Random Access	Time Slotted	Hybrid
(CSMA/CA for Data/Control packets)	(Time synchronized Control/data slots)	(Partially time slotted, Partially random access)
CSMA/CA MAC	IEEE 802.22	DSA Driven MAC

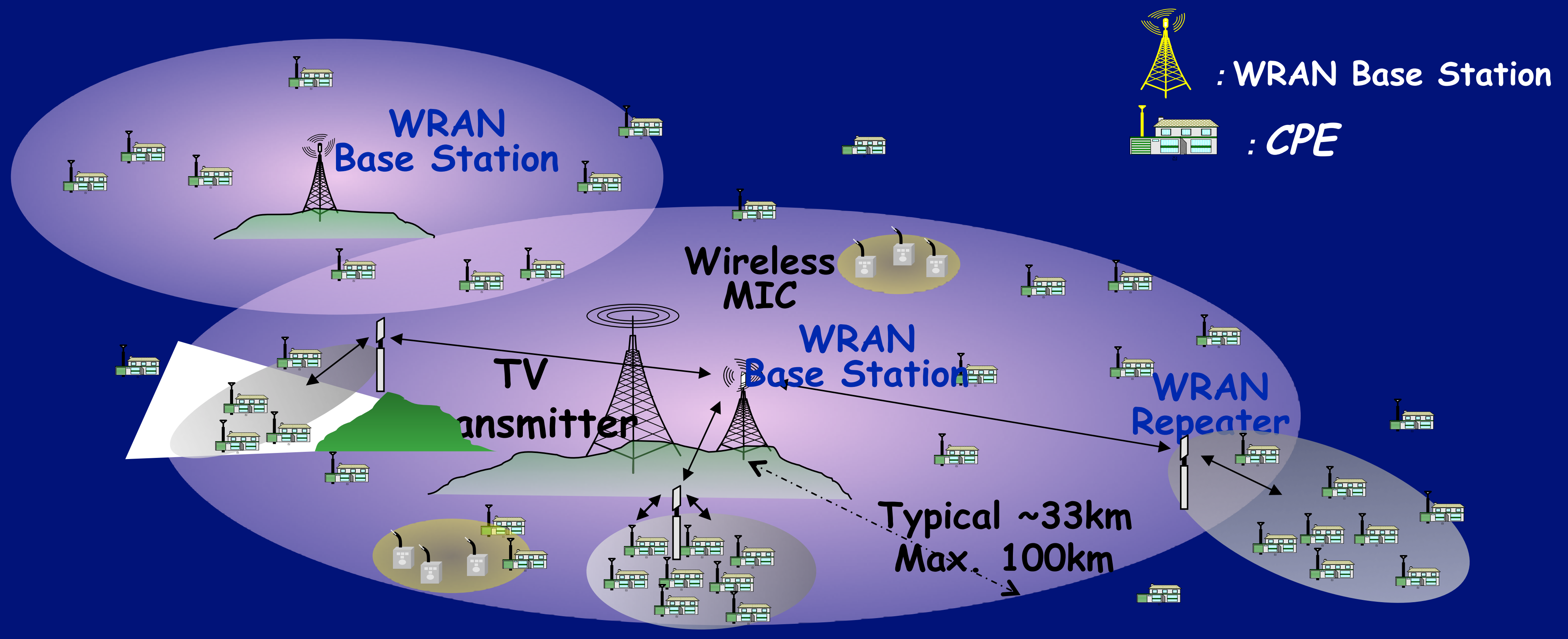
Note: All are single-radio MAC protocols

Centralized CR MAC in IEEE 802.22

C. Cordeiro, K. Challapali, M. Ghosh, "Cognitive PHY and MAC Layers for Dynamic Spectrum Access and Sharing of TV Bands," IEEE Int. Workshop on Technology and Policy for Accessing Spectrum (TAPAS), Aug. 2006.

- Uses BSs to achieve spectrum access and sharing
  - Specifies a fixed Point-to-Multipoint wireless air interface whereby a BS manages its own cell and all associated CPEs
  - Demand Assigned TDMA for UpStream (US) direction
  - TDMultiplexing for DownStream (DS) direction

IEEE 802.22 Network Architecture



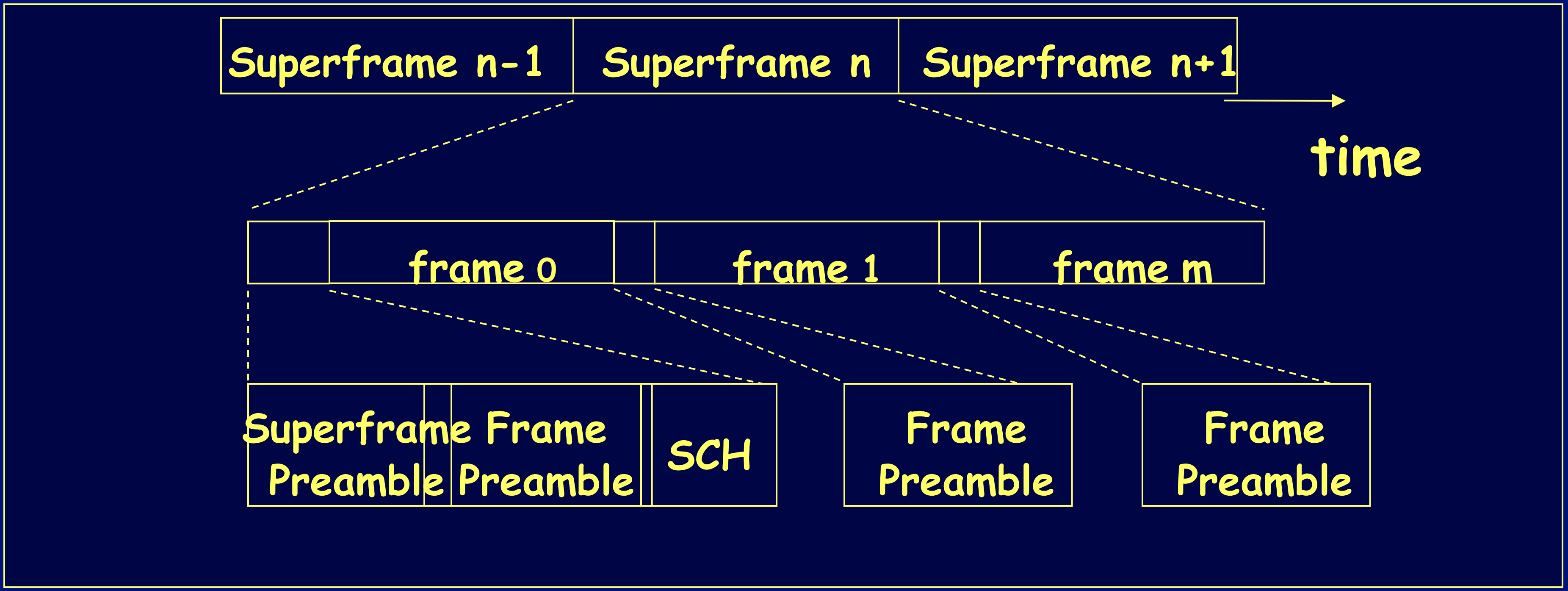
TIME SLOTTED OPERATION

802.22 specifies time slotted operation with the frame hierarchy:

- Each Superframe contains multiple frames preceded by the frame preamble

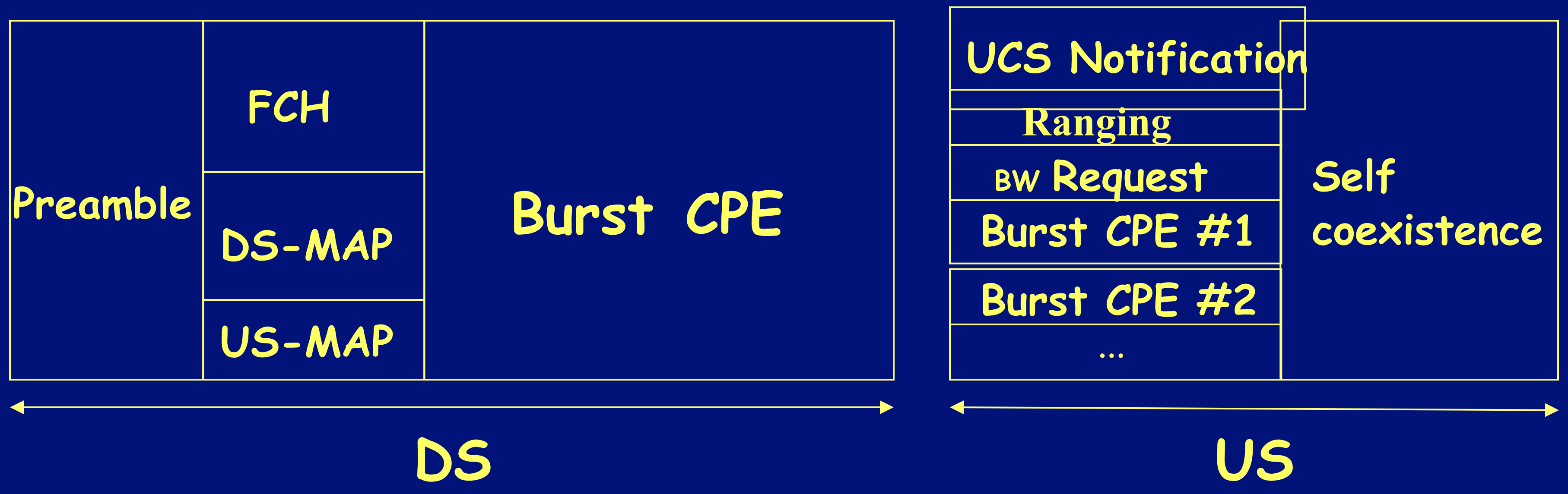
- Each frame embraces a period dedicated to the downstream (DS) traffic and one to the upstream (US) traffic

Superframe Structure



At the start of each superframe there is a Superframe Control Header (SCH) containing information such as current available channels, different bandwidth supported, future spectrum access time, future quiet period schedules

MAC Frame Structure



Two parts: DS subframe and US subframe

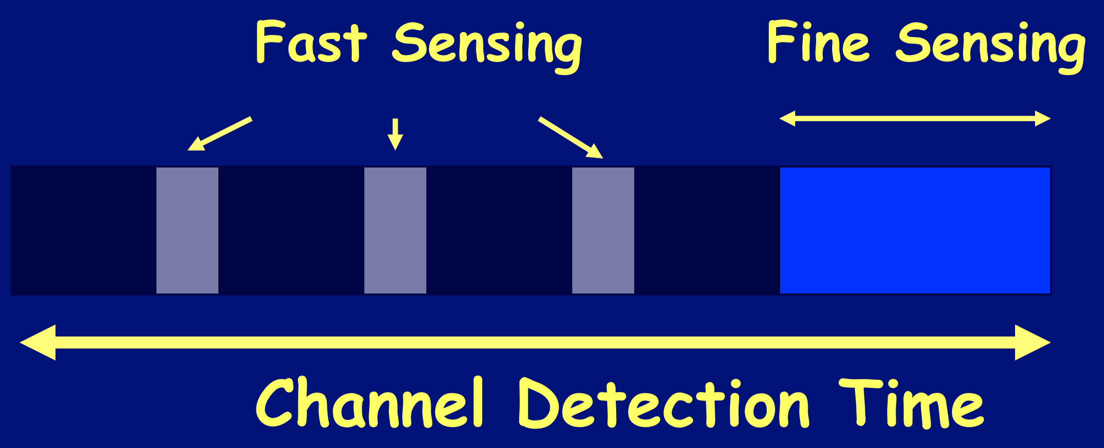
- DS consists of a single packet burst from a given CPE while US consists of multiple packets from several CPEs
  - * Preamble: deals with synchronization and channel estimation
  - * Frame Control Header (FCH): contains the size of the DS- and US-MAP fields with channel descriptors
  - * DS/US-MAPs: give the scheduling information for user bursts

* US consists of
  - * Urgent Coexistence Situation (UCS) Notification: informs of the incumbent PUs just been detected
  - * Ranging: derives the distance from the BS
  - * BW Request: derives the individual BW requests

Centralized CR MAC in IEEE 802.22

- Main topics covered
  - Spectrum Sensing support
  - Spectrum Recovery
  - Coexistence with PUs

Spectrum Sensing Support



- TSS (two-stage sensing) mechanism
  - Fast Sensing
    - Under 1ms/channel-highly efficient but low accuracy
    - Evaluates the need for a Fine Sensing
  - Fine Sensing (on demand)
    - Determined by BS and previous Fast Sensing stage
    - More detailed sensing is performed on the target channel in order to decrease the false alarm rate
    - Performed only when required
    - Allows CR network to meet the stringent QoS requirements

Spectrum Recovery

Restore the normal activity when a PU is detected with minimal performance degradation

- Employs the Incumbent Detection Recovery Protocol (IRDP)
  - Backup channels kept in priority list in case a channel must be vacated in favor of a PU
  - CPE can use them when looking for a BS during the recovery procedure

Coexistence with Users

Allows communication among cells (multiple BSs) through the use of beacons

- Employs the Coexistence Beacon Protocol (CBP)
  - CBP beacons carry information about cells and the DS/US bandwidth allocation for the users
  - CBP beacons are sent during the Self Coexistence window (certain specific times)

Drawbacks

- Extensive control header exchange → lower throughput and reduced channel utilization!
- Synchronization among different CR BSs and CR users in a given cell is difficult

Centralized CR MAC Protocols

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Note: All are single-radio MAC protocols

Game Theoretic DSA-Driven MAC

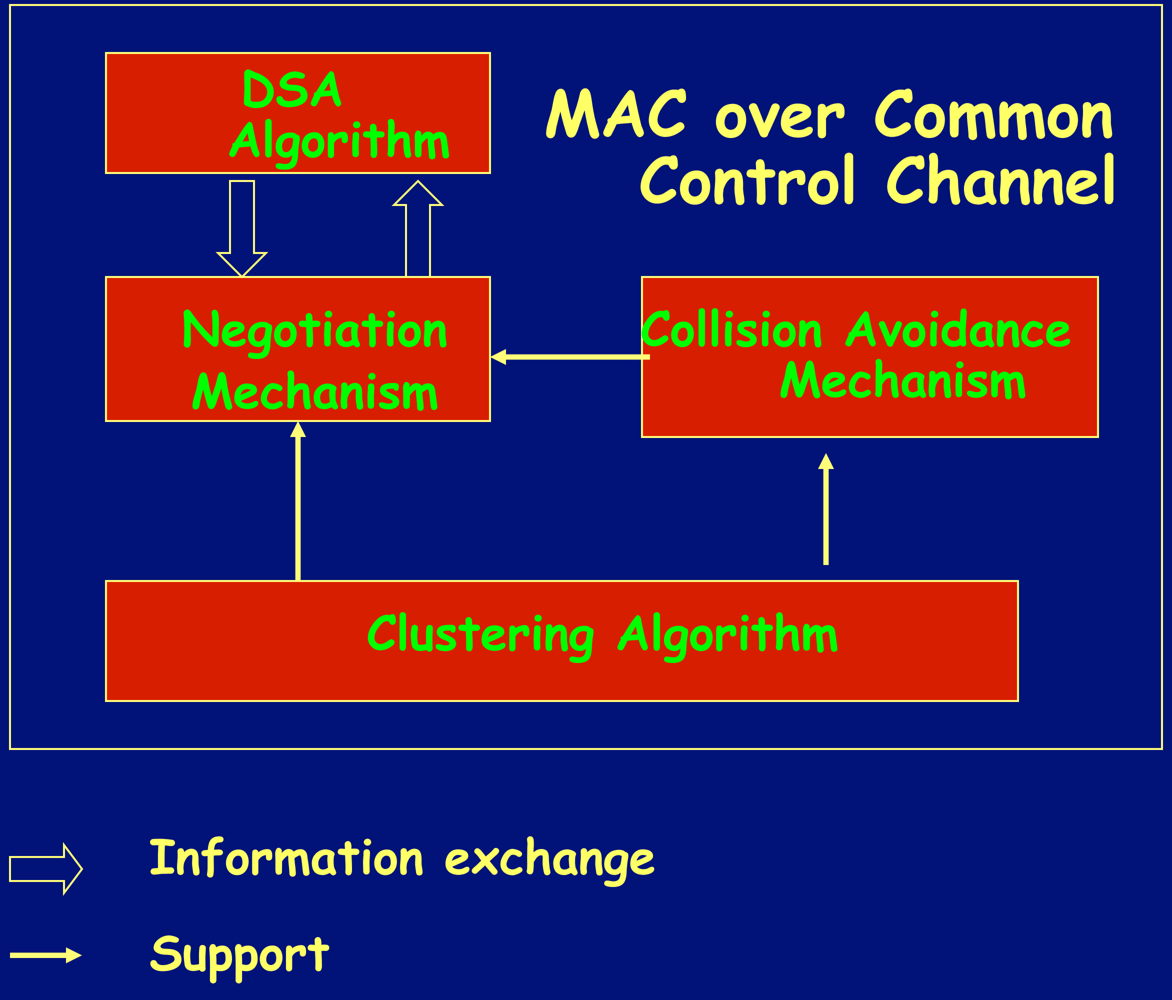
C. Zhou & C. Chigan, "A Game Theoretic DSA-Driven MAC Framework for Cognitive Radio Networks", IEEE Int. Conf. on Communications (ICC), May 2008.

- Data transfer in pre-determined time slots
- Control signaling uses random access
- Cluster based
- Game policy in each cluster is managed by a central unit
- High spectrum utilization
- Collision free spectrum access with QoS and fairness support

DSA-Driven MAC Framework

Four integral components

- -DSA Algorithm
- -Clustering Algorithm
- -Negotiation Mechanism
- -Collision Avoidance Mechanism



DSA Algorithm

- CR behavior is modeled as a repeated game model

$$\Gamma = < N, \{S_i\}, \{u_i\}, T >$$

N: Number of players

S_i: Strategy of player i

u_i: Local utility function of player i

T: Decision timing

Fairness and QoS requirements could be reflected by the utility function

DSA Algorithm

- Each game player updates its strategy in order to maximize its local utility function until the game process converges to the Nash Equilibrium
- Successively all players can experience collision free channel access

Clustering Algorithm

- Hexagonal clusters are assumed for simplicity
- ID of each cluster is given by its position
- A node chooses a cluster to join based on the smallest distance from the cluster center
- After joining the cluster, the node broadcasts its coordinates and the cluster ID

Clustering Algorithm

- Concept of VIRTUAL HEADER is used.
- It is a packet unique to a cluster that carries a token
- Token contains the updated player list
- The cluster head is the node owning the Virtual Header (VH) packet in that round of the game

Negotiation Mechanism

Control message exchanges and coordination of CR users;

Occurs over a CCC!!!

Two stages:

a) Inquiry Stage and

b) Formal Negotiation Phase

Negotiation Mechanism

- **Inquiry Stage**

  (Identify the nodes who wish to start communication)

  - All cluster members will be asked (inquired) by a TOKEN PACKET of their intention to communicate.
  - Nodes wishing to tx a packet will become quasi game players and put their information into the token.
  - These players conduct the formal game in the formal negotiation phase.
  - The game information is piggybacked on a negotiation token packet and passed among players.

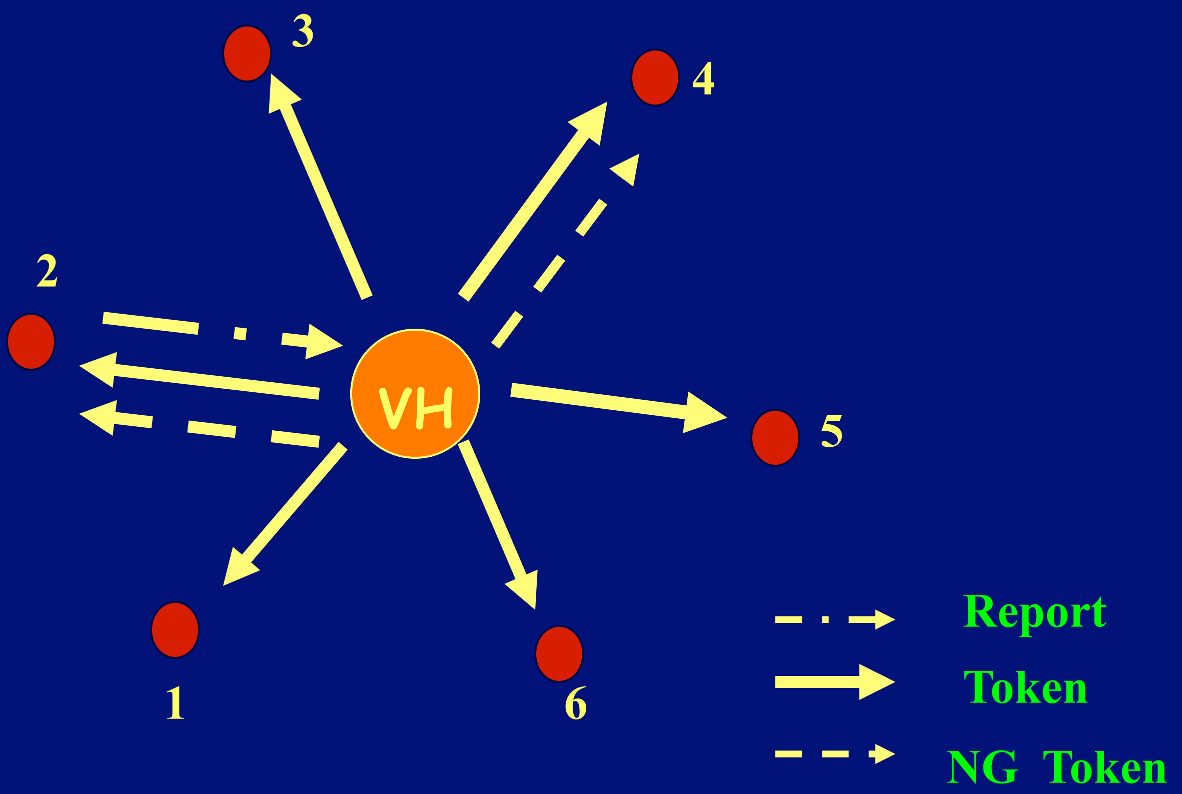
Negotiation Mechanism

Formal Negotiation Stage

- VH now carries the NeGotiation (NG) token containing the dynamic game information required by the game players
- Game players can update their local strategy and the related information in the NG token
- NG token is passed to the next player in the list
- The stage ends when the Nash Equilibrium is achieved

Negotiation Mechanism (Example)

- Suppose NODE 2 wants to start a tx
- 2 sends a "report packet" to VH
- During the inquiry stage, VH sends a token to all cluster members but only 2 and 4 become quasi-game players, as they have packets to tx
- The formal negotiation stage is carried out in order to coordinate nodes 2 and 4 to process the formal game



Collision Avoidance Mechanism

Avoiding collisions during negotiations in different clusters;

Based on "out-of-band busy tones"

- **Inside-cluster busy tone**
  - is set up by a node receiving a message to avoid external nodes to interfere with the ongoing negotiation inside the cluster

- **Outside-cluster busy tone**
  - is set 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.

Drawbacks

- High number of iterations may be required to converge to the Nash Equilibrium
- No sensing support provided (assumed existing)
- Low scalability with the number of players (negotiation delay increases)
- Synchronization difficult to maintain
- Possible collisions in the game info packets

Distributed CR MAC Protocols

	Random Access (CSMA/CA for Data/Control packets)	Time Slotted (Time synchronized Control/data slots)	Hybrid (Partially time slotted, Partially random access)
Single Radio	SRAC MAC HC MAC		OS MAC POMDP
Multiple Radio	DOSS DCA MAC	C-MAC	SYN-MAC Opport. MAC

Single Radio Adaptive Channel MAC (SRAC)

L. Ma, C.-C. Shen, and B. Ryu, "Single-Radio Adaptive Channel Algorithm for Spectrum Agile Wireless Ad Hoc Networks", in Proc. of IEEE DySPAN, Apr. 2007.

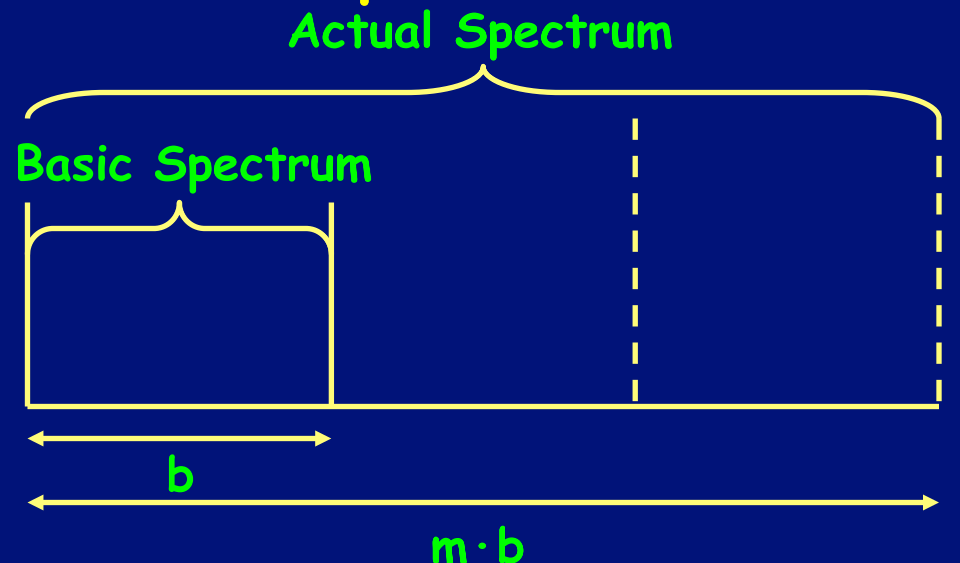
Overview:

- Dynamically chooses the usable channel BW based on the spectrum demand (Dynamic Channelization)
- Uses FDM like scheme called (Cross-channel Communication) in which a CR user may transmit packets on one spectrum and receive packets on another.

Dynamic Channelization

Definition:

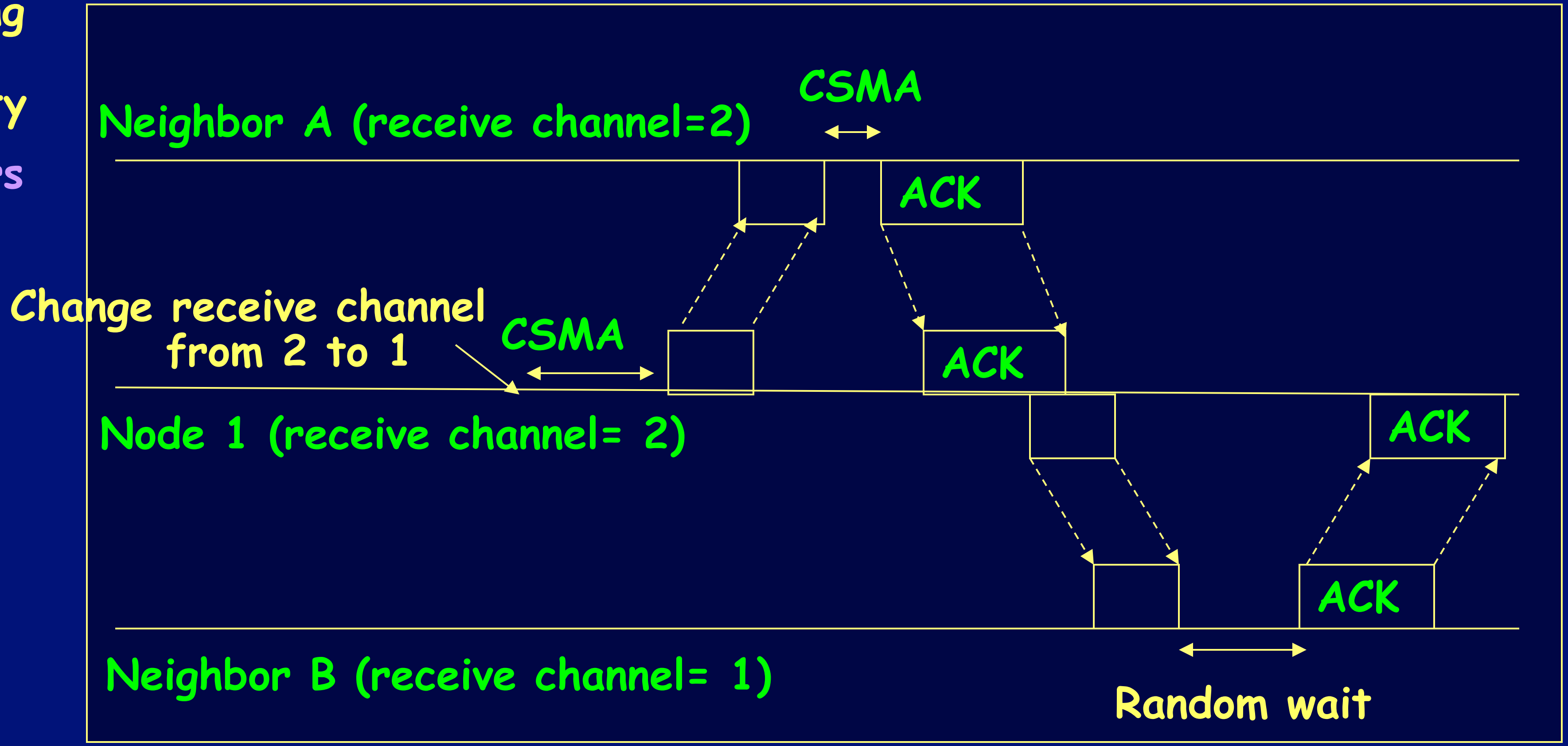
Adaptive combination of spectrum bands based on the CR requirement



- Basic spectrum unit *b* is decided
- Actual spectrum used is an odd multiple of this unit, i.e., $m \cdot b$
- *m* is varied based on the spectrum demand

Cross-Channel Communication

- Different spectrums can be used for sending and receiving to avoid jamming and PU activity
- Node 1 has 2 neighbors A & B; their receive channels are 2,2, & 1
- If node 1 needs to change its receive channel, it sends a notification to its neighbors in their receive channels which reply with an ACK
- CSMA channel access with random wait is assumed



Drawbacks

- Means to detect the presence of jammers not well investigated
- The use of a single radio may imply deafness to control packet sent to different channels than the receiving one
- High overhead to keep the receive bands of neighbors updated

HC-MAC

J. Jia, Q. Zhang, X. Shen,
"HC-MAC: A Hardware-Constrained Cognitive MAC for Efficient Spectrum Management"
IEEE Journal on Selected Areas in Communications (JSAC), Jan. 2008.

Provides efficient spectrum sensing and spectrum access while taking into account the hardware constraints

(e.g., single radio, partial spectrum sensing and spectrum aggregation limit)

Uses a Common Control Channel & a single radio

Hardware Constraint Classification

Sensing Constraint	Transmission Constraint
Tradeoff between time taken for sensing and resulting accuracy (e.g., fine sensing can be only conducted within a limited portion of the spectrum)	When SUs are active they should not create INTERFERENCE to PUs. Idle spectrum is discontinous. OFDM is suitable to aggregate discontinous spectrum (i.e., can switch off unwanted subcarriers & produce a signal with non-contigous freq spectrum). However, spectrum which can be utilized by a single SU is limited by HW constraints

Main Contributions

* Two constraints raise the question:
  How to optimize the sensing decision for each sensing slot?

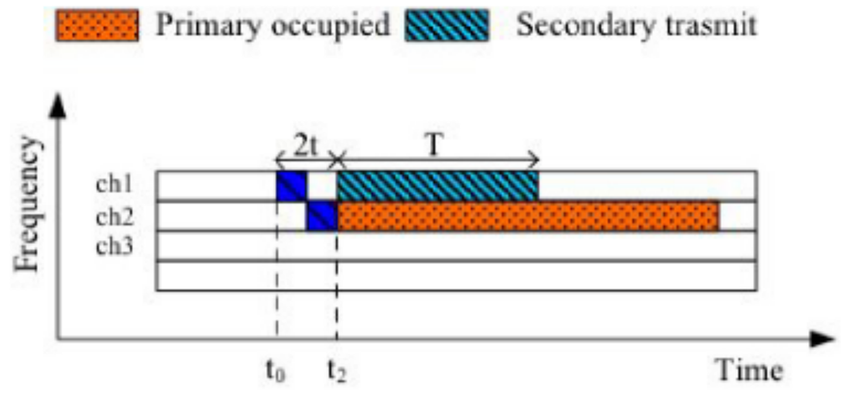
* Need for intelligent Sensing Decision
  - A stopping rule for the number of channels to sense is required

* Protocol Operation
  - Contention Phase
  - Sensing Phase
  - Transmission Phase

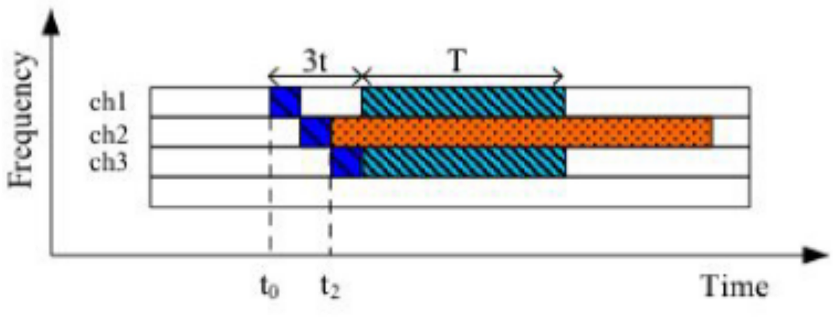
Intelligent Sensing Decision

t: sensing time for each channel

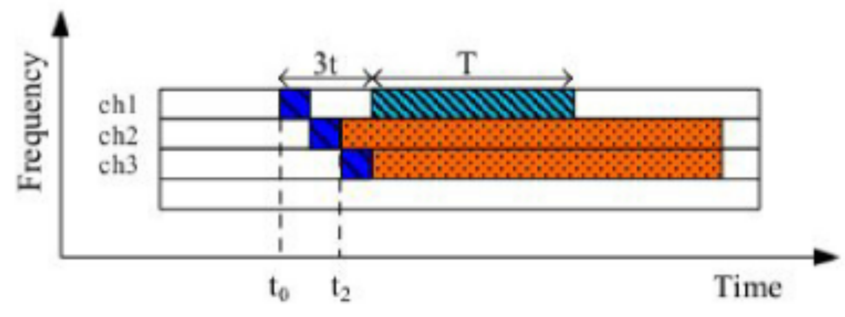
T: maximum transmission time



(a) Decision A: Stop Sensing at t_2



(b) Decision B: Continue Sensing at t_2 with *ch3* available



(c) Decision B: Continue Sensing at t_2 with *ch3* unavailable

Intelligent Sensing Decision

a) CR user stops after 2 sensing time slots and just exploits ch_1 for transmission (B→ data rate)

Achievable Data Rate=B*T/(T+2t)

b) CR user aggressively continues to sense the unknown channels and, after 3 sensing time slots, exploits ch_1 and ch_3 for transmission

Achievable Data Rate=2B*T/(T+3t)

c) CR user continues to sense the unknown channels but ch_2 & ch_3 are occupied by PU transmission

Achievable Data Rate=B*T/(T+3t)

Optimal Stopping of Spectrum Sensing

- Spectrum decision problem can be formulated as an optimal stopping problem.

- **Stopping Rule is defined by 2 objects:**

- Sequence of random variables $X_1, X_2, \ldots$ whose joint distribution is assumed to be known.

- Sequence of real-valued reward functions

  $y_0, y_1(x_1),\ y_2(x_1, x_2), \ldots,\ y_\infty(x_1, x_2, \ldots)$

Optimal Stopping of Spectrum Sensing

Given these 2 objects, the stopping rule problem is described as follows:
The sequence of X_1, X_2, .. can be observed for as long as possible

For each n=1,2,,.. After observing

$X_1=x_1, X_2=x_2, \ldots, X_n=x_n$ and the decision is either to stop and receive the known reward $y_n(x_1, x_{2,\ldots,} x_n)$ or to continue to observe and observe X_{n+1} for a further/wiser decision?

Optimal Stopping of Spectrum Sensing

If the decision is not to take any observations then the received award is a constant amount of y_0

If never stopping, the received award is $y_{inf}(x_1, x_2, \ldots)$

GOAL: Choose a time to stop s.t. the expected reward is maximized.

Optimal Stopping of Spectrum Sensing

- Stopping rule problem has a finite horizon if there is a known upper bound N on the number of channels at which one may stop.

- Finite Horizon Stopping Rule is solved with the method of backward induction

  - Starting from stage N, the optimal stopping rule is found at stage N-1

  - Knowing the optimal stopping rule at stage N-1, it is easy to find it at stage N-2 and so on… until back to the initial stage.

Protocol Operation

- **Contention Phase**

  C-RTS/C-CTS for contention and spectrum reservation over the CCC

- **Sensing**

  Tx and Rx pair who wins the above contention then exchange S-RTS/S-CTS for each channel sensed.

  At the end of each sensing round, the decision is made whether to initiate the sensing on a new channel based on the stopping rule.

- **Data Transmission** (after channels are decided for Tx/Rx)

  At the end, T-RTS/T-CTS for transmission completion notification over the CCC to release the channels for other users.

Drawbacks

- Control messages for channel negotiation may be not received by neighbors if engaged in data transfer
- High overhead caused by control signaling
- CCC may become a bottleneck

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DOSS (Dynamic Open Spectrum Sharing) MAC

L. Ma, X. Han, C.-C. Shen,
"Dynamic Open Spectrum Sharing MAC Protocol for Wireless Ad Hoc Networks,"
Proc. of IEEE Int. Symp. on New Frontiers in Dynamic Spectrum Access Network (DySPAN), 2005.

- Addresses Hidden Node and Exposed Node Problems
- Three Radios for Control, Data, Busy Tone Bands

- FIVE STEPS:

  1. Detection of PUs' presence
  2. Set-up of three operational frequency bands/channels
  3. Spectrum mapping
  4. Spectrum negotiation
  5. Data transmission

Step 1: Detection of PU

- Continuously monitor the open spectrum over the geographic area of deployment for some time
- Mark the spectrums being used by PUs
- Decide on the spectrum that is available for opportunistic sharing

Step 2: Set-up of Three Operational Frequency Bands/Channels

- **Control Band** (for negotiation)
- **Data Band** (to send data through any continuous fraction)
- **Busy-Tone Band** (hidden/exposed node problems can be eliminated by raising the busy tone signals)

Step 3: Spectrum Mapping

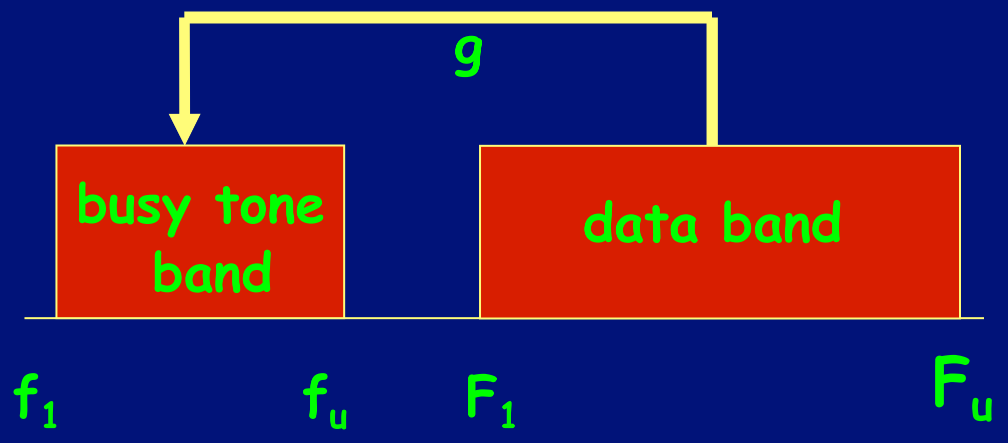
- Establish a linear mapping between busy tone bands and frequency bands (data channels)

A receiver can convert the receiving spectrum to a busy tone and send the busy tone to inform other neighbors not to send at the same time

Step 3: Spectrum Mapping

* (f_1, f_u) freq. range for busy tone band
* Data band is contained in (F_1, F_u)
* Data spectrum is considerably larger !!

Purpose: Allow neighboring nodes to realize that the spectrum is actually used by another CR user by observing the corresponding busy tone.



Step 4: Spectrum Negotiation

- Sender sends a REQ packet with the channel parameters of the available channels
- Receiver compares the sender's available channels with its own channels and selects an intersection available to both

Step 4: Spectrum Negotiation

- Replies with REQ_ACK packet containing the channel parameters of the negotiated channel
- It also turns on the corresponding busy tone telling to its neighbors not to send within this data channel
- Upon receiving REQ_ACK, the sender tunes into negotiated channel

Step 5: Data Transmission

- The sender sends a data packet over the negotiated dynamic data channel to the receiver

- If the packet is correctly received, the receiver replies with a DATA_ACK packet over the negotiated data channel and turns off the busy tone

Step 5: Data Transmission

- Upon receiving the DATA_ACK packet, the sender realizes the transmission is successful
- If the sender does not receive the DATA_ACK packet within a timeout, it retransmits the data packet

Control Channel (Out-of-Band) Saturation Problem Solution

- Techniques to alleviate the Control Channel Saturation problem are also proposed:
  - **Traffic Limiting:** traffic over the control channel kept under a threshold
  - **Bandwidth Ratio:** BW ratio of the control and the data band is adjusted such that the control channel is not the bottleneck
  - **Control Channel Migration:** the control channel can be slowly migrated towards a better channel

Drawbacks

- Use of a CCC
- Use of a separate spectrum for the busy-tones
- Multiple radio transceivers are needed for the tri-band design

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C-MAC

C. Cordeiro, K. Challapali,
"C-MAC: A Cognitive MAC Protocol for MultiChannel Wireless Networks," in Proc. of IEEE Int. Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2007.

- Slotted behavior is enhanced by the use of Superframes
- Two key concepts: RC and BC
- Rendezvous channel (RC) is exploited for neighbor discovery, load and scheduling information exchange
- Backup channels (BC) are employed for Coexistence

Important Concepts in C-MAC

- RC (Rendezvous Channel)
  - Coordinate nodes in different channels in order for the Beacon Periods (BP) not to overlap
  - Multi-channel resource reservation
  - Coordination for PU detection

Important Concepts in C-MAC

BC (Backup Channel)

- Determined by out-of-band measurements
  (even a device has already a RC, it still periodically scans other available channels)
  → Detect presence of PUs
  → Identify other overlapping RCs
  → Determine a suitable BC
  → Collect channel quality information

Important Concepts in C-MAC

BC (Backup Channel)

- Carried out by nodes when they are not engaged in communication or during quiet period
- Provides a choice for alternate spectrum bands in case PUs appear.

SUPERFRAMES

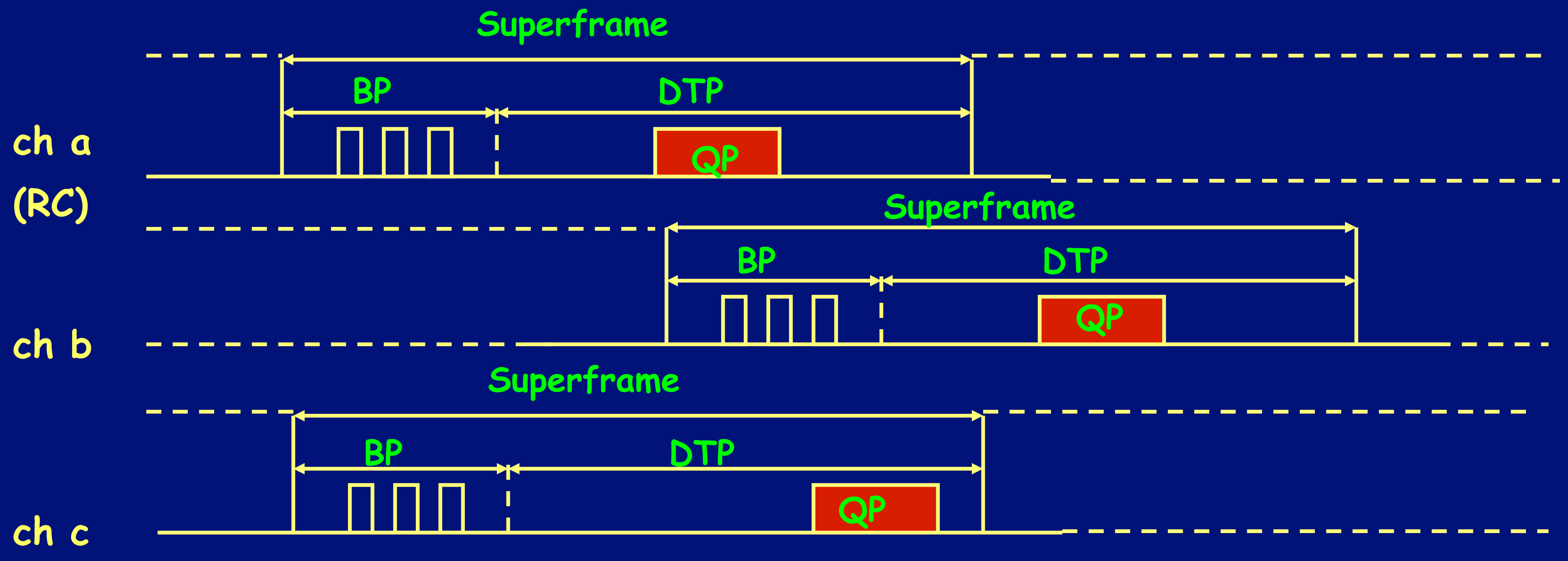
Each spectrum band has recurring SUPERFRAMES

Each superframe is composed of

* Beacon Period (BP)
* Data Transfer Period (DTP)

Multi-Channel and Superframe Structures

(BPs are non-overlapping; through inter-channel synchronization)



BP (Beacon Period) DTP (Data Transfer Period) QP (Quiet Period)

Selection of RC

Steps:

1. Upon power up, each device scans all the available channels and looking for any beacon frames transmitted by any other device

2. If no PU signals are sensed, the device dwells on the channel for at least one superframe length

3. When a device receives a beacon frame on one channel, it reads the RC field from the beacon frame header

Selection of RC

4. If RC bit is set, the device may decide to join this BP by sending its own beacon during the signaling slot and then move to a designated beacon slot

5. Otherwise, the device may decide to continue the scan procedure looking for a RC

6. If the device scans all channels without detecting any beacon frame with RC field set, it will itself select a channel as a RC

Drawbacks

- Low scalability as beacons can be sent only in the BP of a superframe
- Convergence of the RC to a constant spectrum band cannot be guaranteed
- Delay in spectrum switching can impact performance
- Non-overlapping nature of the QPs and the BPs is difficult to achieve without a central entity

Distributed CR MAC Protocols

	Random Access (CSMA/CA for Data/Control packets)	Time Slotted (Time synchronized Control/data slots)	Hybrid (Partially time slotted, Partially random access)
Single Radio	SRAC MAC HC MAC		POMDP
Multiple Radio	DOSS DCA MAC	C-MAC	SYN-MAC Opp.-MAC

Opportunistic Spectrum MAC (OS-MAC)

B. Hamdahoui, and K. G. Shin,
"OS-MAC: An Efficient MAC Protocol for Spectrum-Agile Wireless Networks",
IEEE Trans. on Mobile Computing, Aug. 2008.

- Uses pre-determined windows to coordinate the spectrum choice and to divide the CR users into groups
- Within each window the spectrum access is random
- A CCC is used for control signaling among nodes on different channels

Protocol Operation

- Network Initialization Phase (Cluster Formation)
- Session initialization Phase
- Data Communication Phase
- Update Phase
- Select Phase
- Delegate Phase

Network Initialization Phase

- Cluster formation in such a way that CR users which want to communicate to each other are in the same group
- All CR users are tuned to the CCC
- Only one CR user in the cluster is active as a delegate at any given time

Session Initialization Phase

- The active delegate chooses a spectrum band for the group
- The active delegate communicates its choice to all cluster members

Data Communication Phase

- The IEEE 802.11 DCF is used for accessing the spectrum band
- The delegate continuously monitors the CCC and informs the cluster members of any changes in the spectrum usage

Update Phase

- Each delegate sends the traffic information of its own cluster over the CCC
- Each delegate also updates its information about the global spectrum usage

Select Phase & Delegate Phase

- During the Select Phase, the delegate may change the spectrum used in its cluster based on the spectrum usage statistics from the other clusters
- During the Delegate Phase the delegate role is passed to the following user in the cluster for the next round

Drawbacks

- Cluster information exchange in order to build clusters properly is not considered
- Coordination among delegates in order to enforce quiet period for sensing is not provided
- No protection to the PU activity by adapting transmission power

POMDP-based Decentralized Cognitive MAC

Q. Zhao, L. Tong, A. Swami, and Y. Chen,

"Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework,"

IEEE Journal on Selected Areas in Communications, April 2007.

- An optimal and a suboptimal greedy decentralized cognitive MAC along with an analytical framework of Partially Observable Markov Decision Process
  - A channel occupancy model that captures the dynamics of channel availability
  - A performance metric that guides the design of MAC strategies
  - A method that makes decision on selecting a channel to sense and access

Channel Occupancy Model

- Occupancy of N channels follows a discrete-time Markov process with $M = 2^N$ states
- Assume that spectrum usage statistics of primary network remain unchanged for T slots

Performance Metric

- **Reward:** $$r_{j,A_1,A_2}(t) = \sum_{i \in A_2} S_i(t) B_i$$

  A_1: Sensing channel sets

  A_2: Access channel sets

  j: Network state

  $S_i(t) \in \{0, 1\}$: State of channel i in slot t

  B_i : Bandwidth of channel i

Decision-Theoretic Method

Choose the sensing and access action sequentially in each slot so that the total expected reward accumulated over T slots (wherein the spectrum occupancy statistics remain unchanged) is maximized.

Protocol Description

- At the beginning of slot t with a belief vector $\Omega(t)$ at both the transmitter and the receiver

  1) Both the transmitter and the receiver choose channel a_*

  2) Transmitter senses channel a_* and obtains the sensing outcome Θa_*

  3) Transmitter chooses the access action Φa_*

Protocol Description

4) If $\Phi a_* = 1$, the transmitter transmits data over channel a_* using carrier sensing

5) If a data packet is successfully received, the receiver transmits ACK Ka_*

6) Both transmitter and receiver obtain the new belief vector $\Omega(t+1)$ using $\{a_*, Ka_*\}$

Drawbacks

- Assumes the spectrum usage statistics of the primary network remain unchanged for several slots
- The optimal behavior is achieved only after several iterations

SYNC-MAC

Y. R. Kondareddy and P. Agrawal,
"Synchronized MAC Protocol For Multi-hop Cognitive Radio Networks",
IEEE International Conference on Communications (ICC), May 2008.

No need for a CCC

It synchronizes and coordinates data transfer in dedicated slots for each channel

Control traffic can be performed in any available channel

Main Idea

- Time is divided into time slots
- Each slot represents a particular data channel
- Each time slot is dedicated to a channel for control signal exchange
- At the beginning of each time slot, CR users listen to the channel represented by that time slot
- For the data transfer any channel found suitable between a node pair can be used

Network Initialization State

When there are no nodes in the network

- The first node divides time into N time slots of fixed duration T_c, where N is the number of available channels
- Then it beacons in each time slot over the related channel
- Consequently, all nodes are synchronized and have information about the neighbors channel sets

At the beginning of each time slot, each node tunes the listening radio to the related channel

Control Signal Exchange

- A node chooses one of the channels common with its neighbors
- It waits for the time slot which represents that channel

Control signals are exchanged when one of the following events occurs:

IE-1: a new node enters the network

IE-2: the available channel list at a node changes

IE-3: a node changes its channel of communication

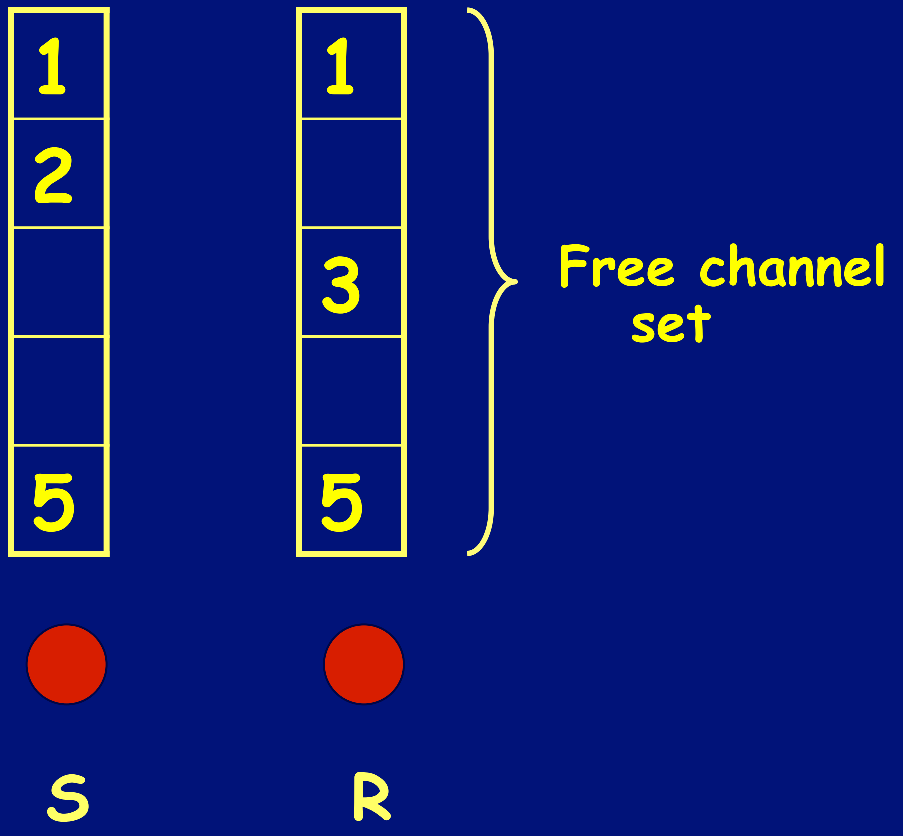
IE-4: a node wants to communicate with its neighbors

Example:
Channel Selection

- S (Sender) wants to start a communication with R (Receiver)
- Have the free channel sets

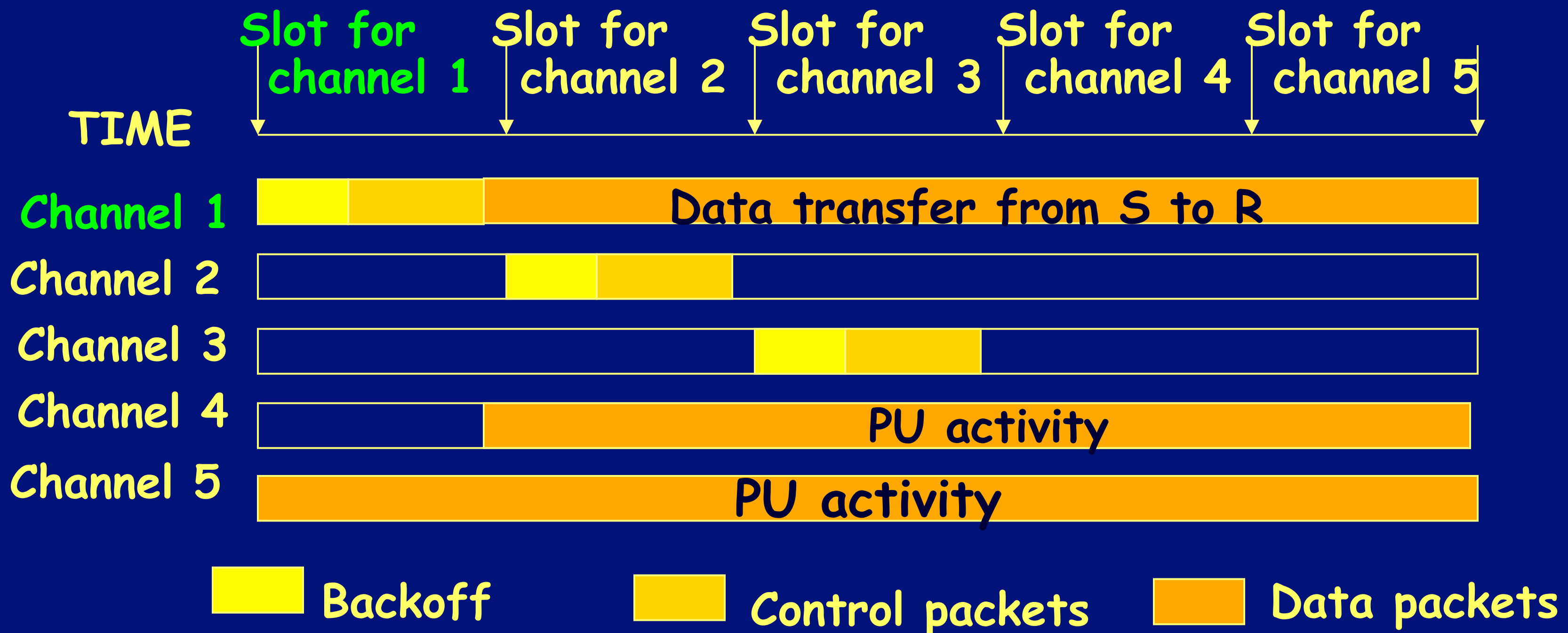
{1,2,5} and {1,3,5}

- Channels common in the free channel sets are 1 and 5
- S chooses CHANNEL 1 and waits for the related time slot to tune the listening radio and to exchange control signals



EXAMPLE:
Negotiation and Data Exchange

- S chooses channel 1
- S waits for a random backoff and starts negotiation (similar to IEEE 802.11 DCF)
- If negotiation is successful data transmission can start



Drawbacks

- No guarantee of protection to the PU activity as it is notified only in specific time slots
- Spectrum not utilized efficiently as a channel can be used only in one time slot in a given cycle

Opportunistic MAC

H. Su and X. Zhang.
"Opportunistic MAC Protocols for Cognitive Radio Based Wireless Networks,"
in Proc. of Annual Conference on Information Sciences and Systems, 2007.

- Allows opportunistic spectrum use for data transfer based on the reporting and negotiation operations carried out over the CCC

- Two transceivers
  - One for dedicated control channel
  - The other as a cognitive radio

Main Issues

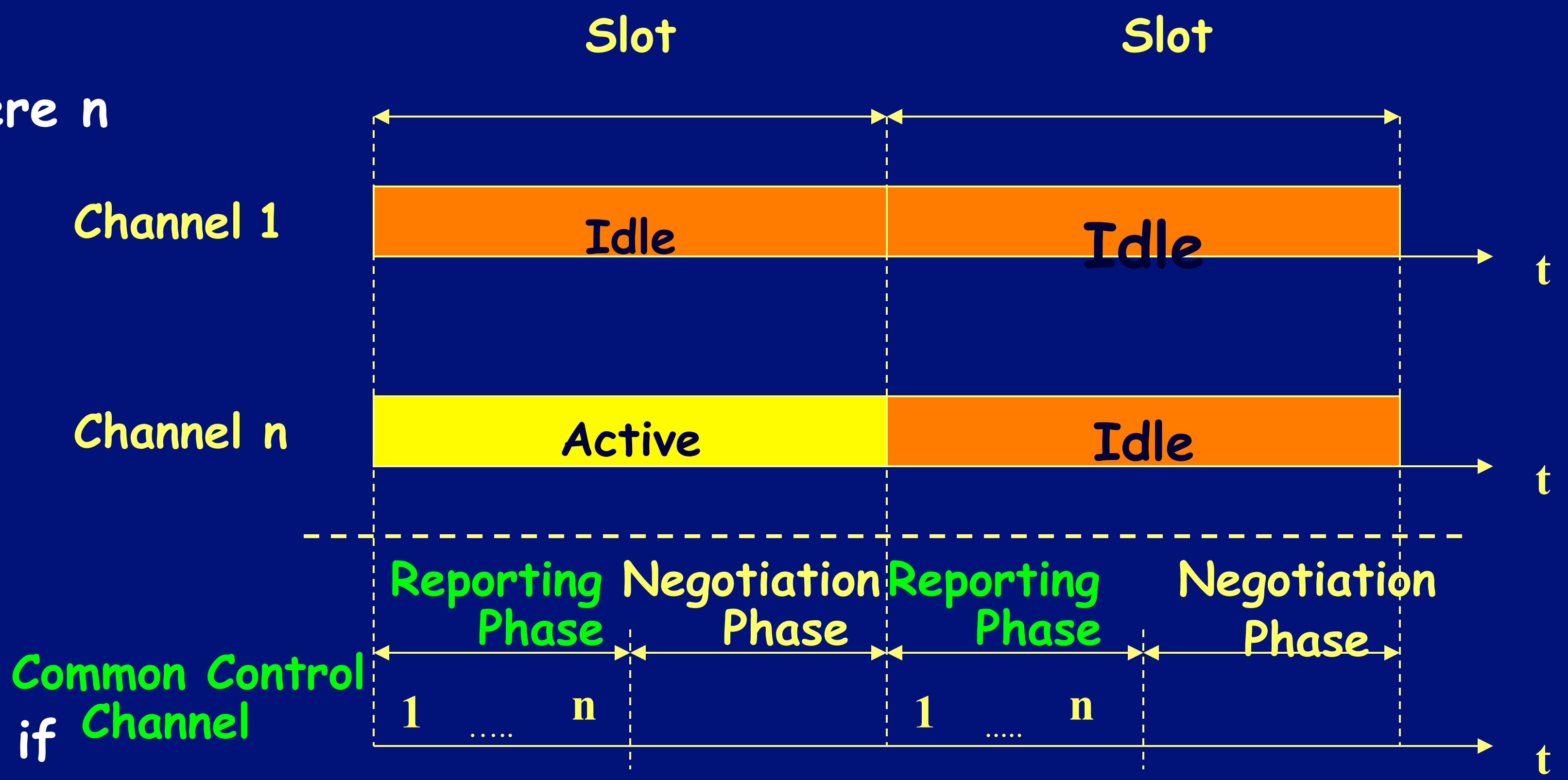
Two phases can be distinguished over the CCC:

- Reporting Phase
  - To report to neighbors the detected PU activity
- Negotiation Phase
  - To negotiate channels reported available during the reporting phase

HYBRID PROTOCOL

(time is slotted for data transfer over the licensed channels while the CCC operation is partly slotted followed by a random access negotiation phase)

- Divided in n minislots, where n is the number of channels
- During the i_{th} minislot
- (reporting phase)
- the i_{th} channel is sensed
- A beacon is sent over the CCC during the i_{th} minislot if the i_{th} channel is found occupied

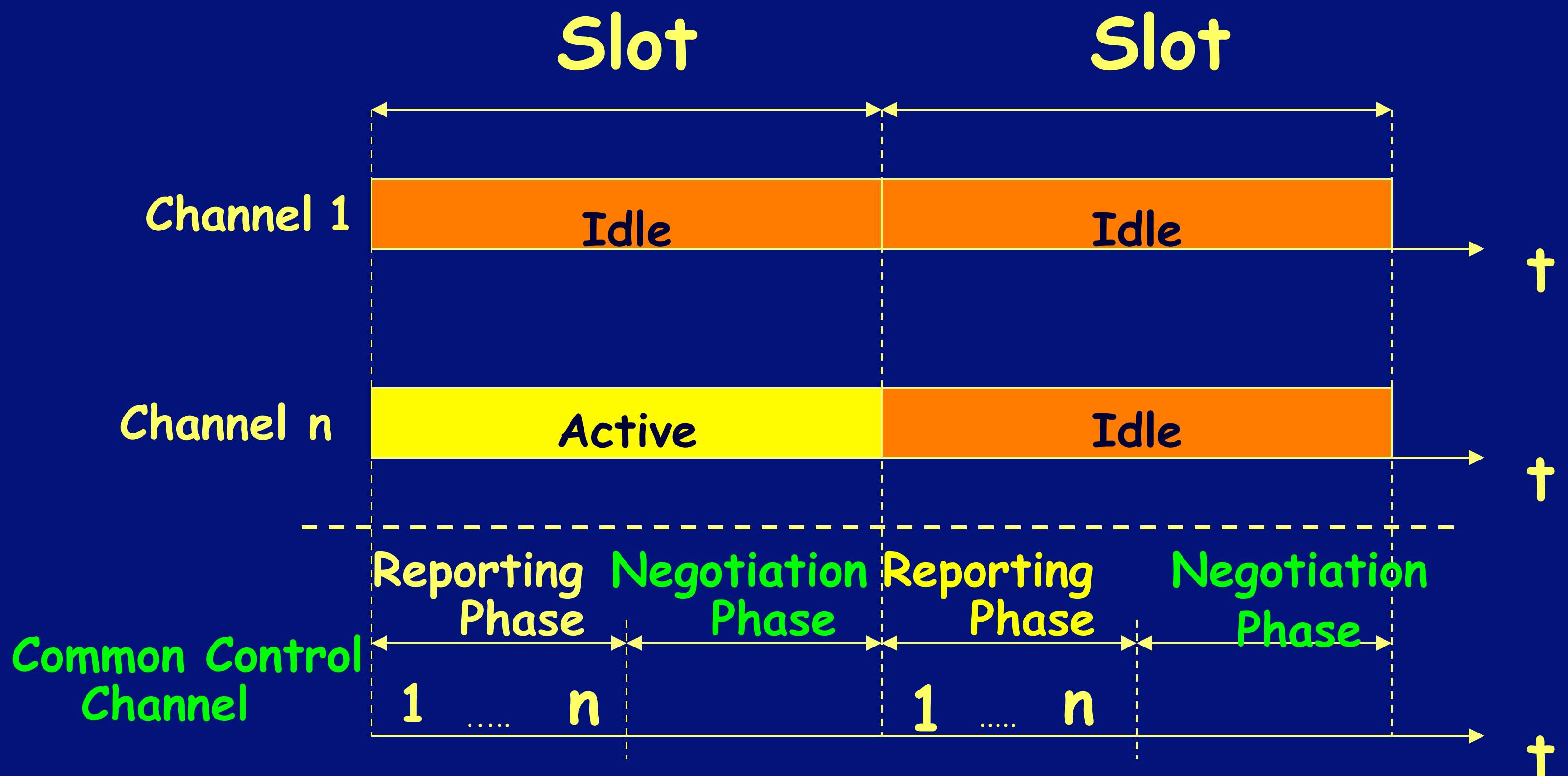


Operation

- At the beginning of each time slot, the CR user senses one of the channels
- If the i-th channel is occupied, it sends a beacon over the CCC during the i-th mini-slot of the reporting phase.
- These beacons serve to inform the neighbors of the PU activity.

Negotiation Phase

CR user negotiates via contention-based algorithm, such as those based on the IEEE 802.11 and p-persistent carrier sense multiple access



OPERATION

- To ensure that all channels are sensed, each CR user independently chooses a channel with equal probability

- If there are sufficient number of CR users present, then all channels can be covered with high probability.

Drawbacks

- Quiet periods for sensing are not guaranteed as the channels for sensing are chosen randomly
- The exact link-layer interactions among nodes are not specified

Conclusions and Future Directions

- Accurate models for the false alarm and missed detection probabilities
- Integration at the MAC layer of the information from other layers
- Devising of protocols able to adapt the CR tx to the type of PU
- New performance metric to evaluate the CR specific improvement