CHAPTER 9.
COMMON CONTROL CHANNELS

Outline

- Introduction to Common Control Channel (CCC)
  - CCC Classification
- CCC Design Challenges
- CCC Solutions
  - CCC Solutions in CR MAC Protocols
  - Sequence-based CCC Solutions
  - Group-based CCC Solutions
  - Underlay CCC Solutions
  - Our CCC Solutions
- Research Challenges

Common Control Channel (CCC)

B. F. Lo, "A survey of common control channel design in cognitive radio networks," Physical Communication (Elsevier) Journal, vol. 4, no. 1, March 2011.

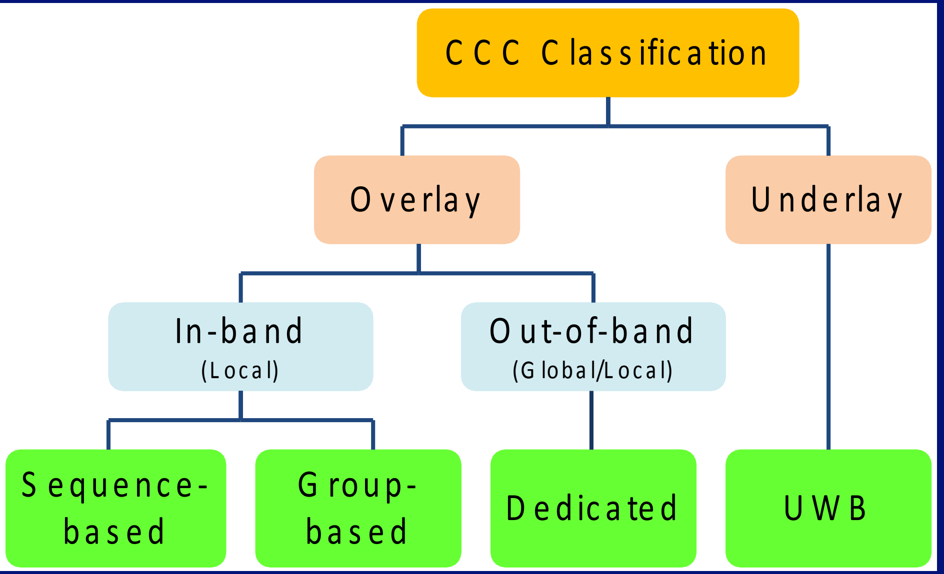
- **Definition**
  - A CCC in a CR network is defined as a medium temporarily or permanently allocated in a portion of licensed or unlicensed spectrum commonly available to two or more CR users for control message exchange

Why CCC?

- CCC facilitates CR network operations
  - Physical (PHY) layer
    - Exchange spectrum sensing information for CR user cooperation
  - Link/MAC layer
    - Notify PU activity and spectrum opportunities
    - Signal beacons or broadcast Hello packets for neighbor discovery
    - Channel access negotiation
    - Transmitter–receiver (RTS-CTS) handshake
  - Network layer
    - Broadcast route requests
    - Notify topology updates

CCC Classification

- Overlay vs. Underlay
  - Overlay
    - CCC allocated to the spectrum temporarily or permanently not used by PUs
    - Must vacate CCC if a PU occupies CCC
    - ➔CCC is subject to PU activity
  - Underlay
    - CCC can be allocated to the spectrum currently used by PUs
    - Control transmissions are spread over a large bandwidth in the spectrum and appear to PU as noise
    - ➔CCC is not affected by PU activity



CCC Classification: Overlay

- In-band vs. Out-of-band
  - Out-of-band CCC (Dedicated CCC)
    - A predefined channel dedicated to CR users for control message exchange
    - Channel exclusively used for control purposes
      - Reserved by regulatory authorities (e.g. FCC)
      - Predefined or statically allocated in unlicensed or licensed band
      - Always available to CR users locally or globally

➔ Not affected by PU activity (usually assumed in CR MACs)

CCC Classification: Overlay

- In-band vs. Out-of-band
  - In-band CCC
    - Channels are dynamically allocated to and temporarily shared among CR users for control message exchange
    - CCC shares the same channel used for data
      - Dedicated CCC not always feasible in some applications
      - Allocated dynamically and locally for a temporary duration
    - Major design choices: group-based or sequence-based CCC

→ Subject to PU activity anytime

CCC Classification: Major Solutions

- Major CCC Design Solutions
  - Sequence-based CCC (overlay, in-band)
  - Group-based CCC (overlay, in-band)
  - Dedicated CCC (overlay, out-of-band)
  - Ultra Wideband (UWB) CCC (underlay)
- Different design challenges encountered in each type of CCC solutions

CCC Design Challenges (CCC Problems)

- Control Channel Saturation
  - Performance degrades as a large number of CR users compete for CCC access
- Robustness to PU Activity
  - CCC may not be available all the time due to PU activity
- CCC Coverage
  - Limited CCC coverage creates control signaling overhead
- Control Channel Security
  - Vulnerability to security attacks (e.g., jamming)

CCC Problem: Control Channel Saturation

L. Ma, X. Han, and C.-C. Shen, "Dynamic Open Spectrum Sharing MAC Protocol for Wireless Ad Hoc Networks," Proc. of IEEE DySPAN 2005, Nov. 2005

- **Problem Definition**
  - Collision rate significantly increases as a large number of nodes compete for CCC access resulting in considerably reduced throughput

Possible Solutions: Control Channel Saturation

- Limit control traffic
- Adjust CCC bandwidth
  - SRAC
- Migrate CCC to a better channel
  - SOCC
- Balance control traffic over several channels
  - SYN-MAC, Sequence-based Rendezvous

CCC Problem: Robustness to PU Activity

I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury,
"CRAHN: Cognitive Radio Ad Hoc Networks,"
Ad Hoc Networks (Elsevier) Journal, 2009

- **Problem Definition**
  - CR users cannot be guaranteed a new CCC when they must immediately vacate CCC upon a PU arrives !
    - CCC may not be available all the time due to PU activity

Possible Solutions: Robustness to PU Activity

- **Dynamic CCC allocation**
  - Dynamic CCC allocation based on spectrum opportunity and PU activity
    - C-MAC, SI-based CCC, ERCC

- **Efficient CCC Recovery**
  - Recover CCC efficiently and maintain CR network topology
    - ERCC

CCC Problem: CCC Coverage

I. F. Akyildiz, W.-Y. Lee, and K. R. Chowdhury,
"CRAHN: Cognitive Radio Ad Hoc Networks,"
Ad Hoc Networks (Elsevier) Journal, 2009

- **Problem Definition**
  - Dynamic PU activity and connectivity make a fixed CCC for all CR users infeasible
    - In-band CCC coverage usually limited to a local area
    - High communication overhead for large number of CCCs

Possible Solutions: CCC Coverage

- **Clustering**
  - Use clustering structure with topology management
    - SOCC
- **Neighbor Coordination**
  - Combine neighbor's information locally for CCC allocation
    - SI-based CCC, ERCC

CCC Problem: Jamming Attack

L. Ma, C.-C. Shen, and B. Ryu,

"Single-Radio Adaptive Channel Algorithm for Spectrum Agile Wireless Ad Hoc Networks,"

IEEE DySPAN 2007, Apr. 2007

- **Problem Definition**
  - Control traffic on CCC maliciously interfered or blocked by adversaries

Possible Solutions: Jamming Attack

B. F. Lo, "A survey of common control channel design in cognitive radio networks," Physical Communication (Elsevier) Journal, vol. 4, no. 1, March 2011.

- Possible Solutions
  - Anti-jamming by dynamic CCC allocation
    - Use different in-band CCCs for outgoing and incoming control traffic in response to jamming (SRAC: cross channel communication)
    - Distribute controls over several channels to avoid single point of failure (Sequence-based rendezvous, quorum-based CCC: frequency hopping)
  - Anti-jamming by CCC key distribution
    - Control messages are repeatedly transmitted on multiple CCCs
    - Any compromised nodes having only partial keys in the key space will not be able to jam all the CCCs
    - Jamming-resilient key assignment can be polynomial-based or randomly distributed

Overview of Solutions for CCC Problems

Solutions for CCC Problems			
Control Channel Saturation	Robustness to PU Activity	CCC Coverage	CCC Security (Jamming)
• SYN-MAC • SRAC • Sequence-based Rendezvous	• OFDM-based CCC • ERCC • UWB CCC	• C-MAC • SOCC • Swarm Intelligence-based CCC • ERCC	• SRAC • Quorum-based CCC

CCC Solutions in CR MAC Protocols

- CCC is an inseparable part of every CR MAC protocol
  - Dedicated CCC approach
    - Not affected by PU activity (generally assumed)
  - In-band CCC approach
    - CCC subject to PU activity anytime
    - In spotlight
      - Synchronized MAC (SYN-MAC)
      - Single-Radio Adaptive Channel (SRAC) MAC
      - C-MAC

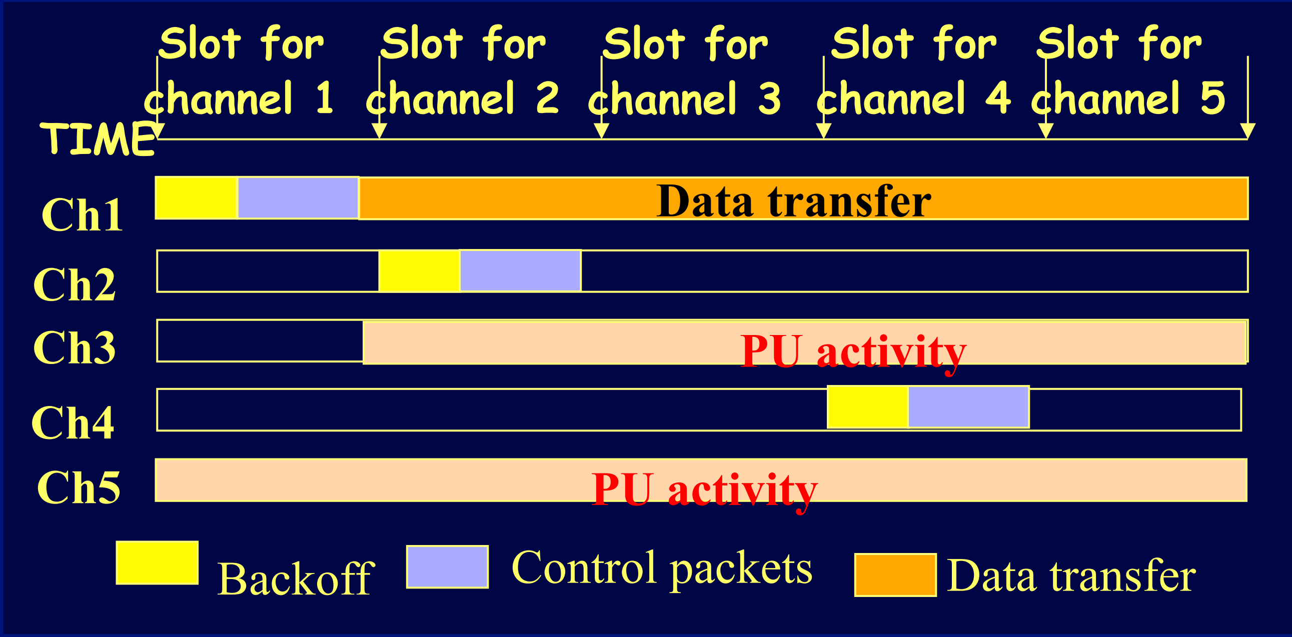
SYN-MAC

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

- In-band CCC Solution
  - CR users are synchronized to coordinate data transfer in dedicated slots for control message exchange
  - One of the data channels is used as the CCC in each dedicated slot
- Sequence-based CCC Solution
  - Control radio switches to a channel based on hopping sequence
  - Channel hopping is sequential (e.g. 1,2,3,4,5,1,2,3,4,5…)
  - CCC is allocated in round-robin fashion

SYN-MAC Main Idea

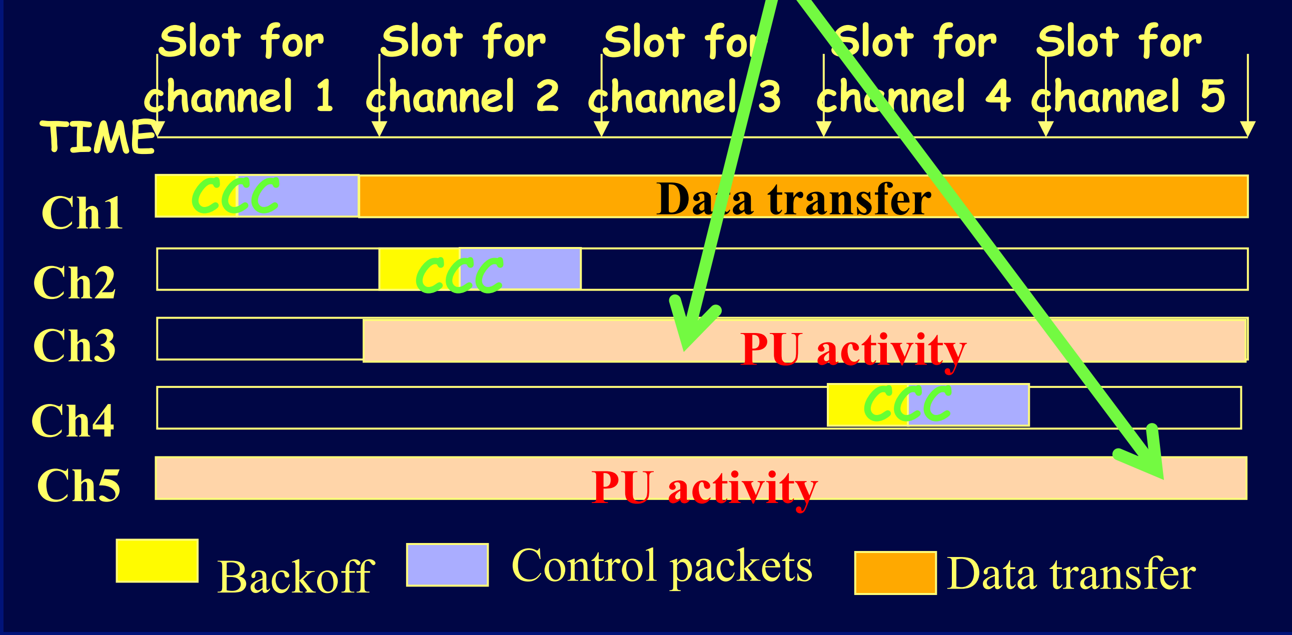
- Time is divided into time slots
- Each time slot is dedicated to a channel for control signal exchange
- At the beginning of each time slot, CR users with control packets wait for a random backoff and start negotiation (similar to IEEE 802.11 DCF)
- If negotiation is successful, data transmission can start



CCC in SYN-MAC

- Each slot dedicated to a channel for all control exchanges
- All nodes in the neighborhood listen to the in-band CCC in the given slot
- Dedicated radio for in-band CCC

No CCC in Slots 3 & 5 due to PU activity



CCC Solution: SYN-MAC

- **Advantage**
  - Alleviate control channel saturation problem
    - Control traffic distributed over channels in time slots
- **Drawbacks**
  - Disrupted CCC coverage
    - No CCC available when control slots occupied by PUs
  - No guarantee on timely PU protection
    - PU activity can only be reported in specific time slots
    - Vacating channels for PUs may not be in a timely fashion
  - Predictable hopping pattern exposes the security risk

Single Radio Adaptive Channel (SRAC) MAC

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.

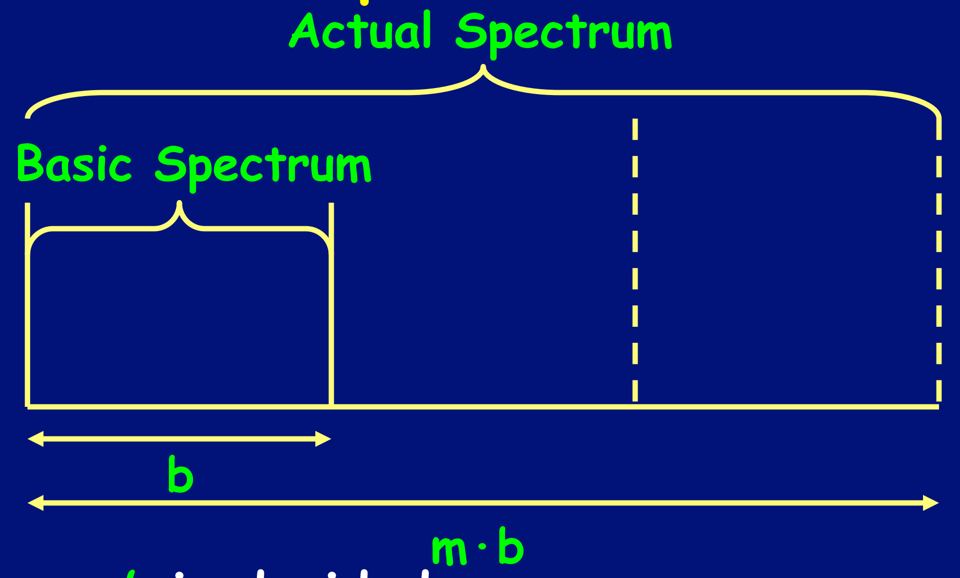
Overview

- Dynamic Channelization for Control Channel Saturation
  - Choose the usable channel BW dynamically based on the spectrum demand
- Cross-channel Communication for Jamming Attacks
  - Uses different channels for transmitting and receiving when a channel is jammed

Dynamic Channelization for CCC Saturation

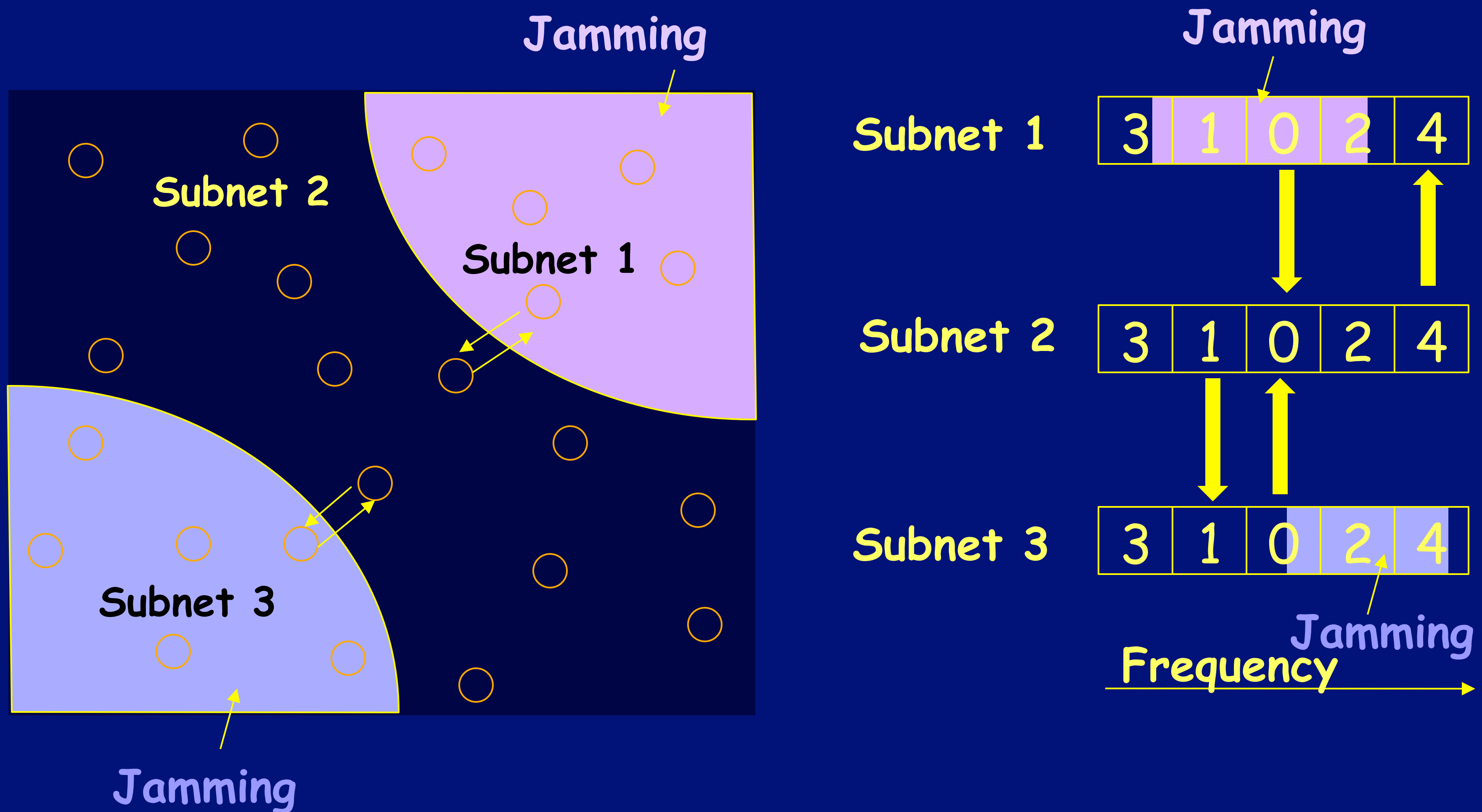
Definition:

Adaptive combination of spectrum bands based on the CR requirement



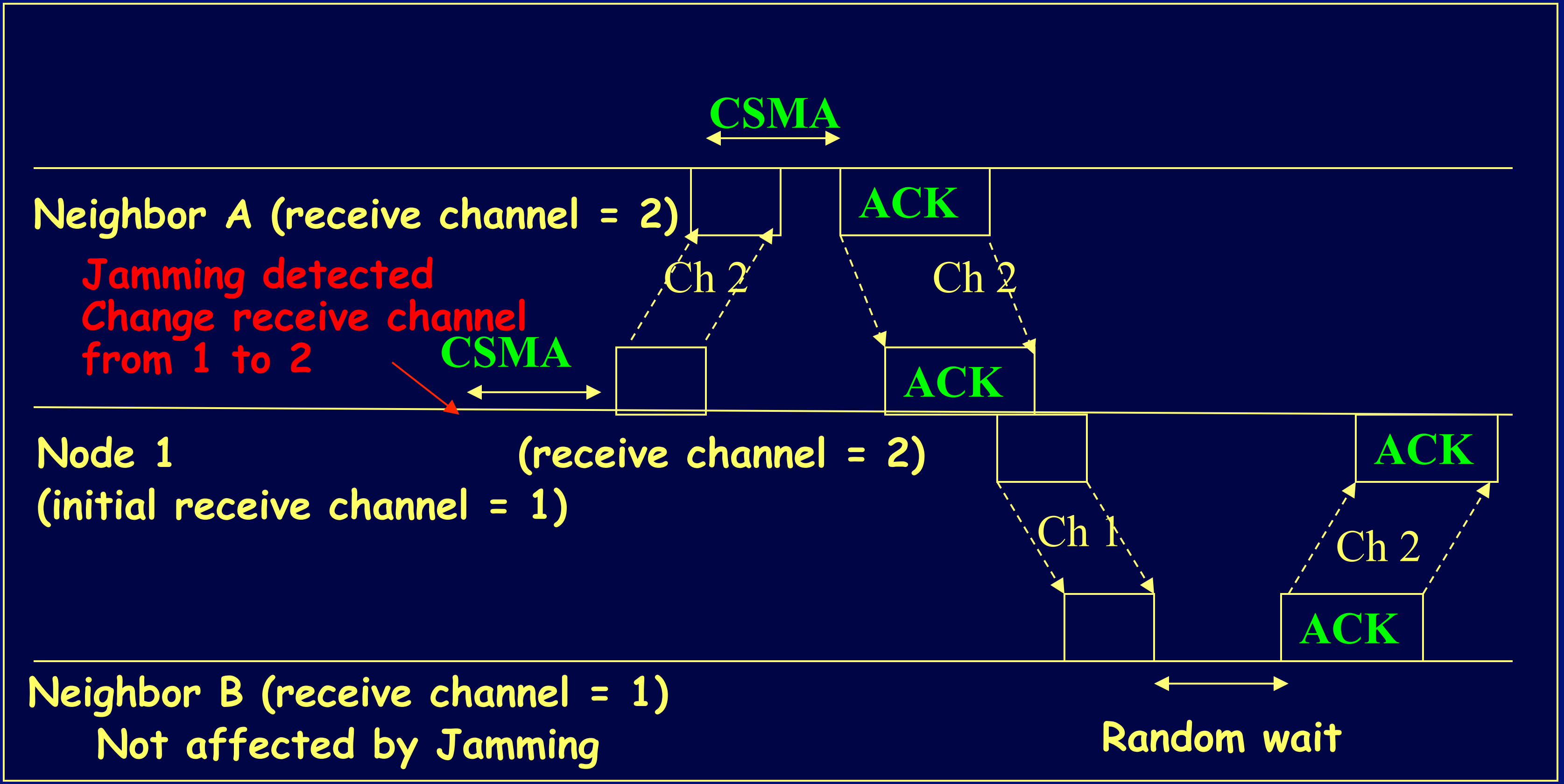
- Basic spectrum *b* is decided
- Actual spectrum is an odd multiple *m·b* of basic spectrum
- *m* is varied based on the spectrum demand

Cross-Channel Communication for Jamming Attacks



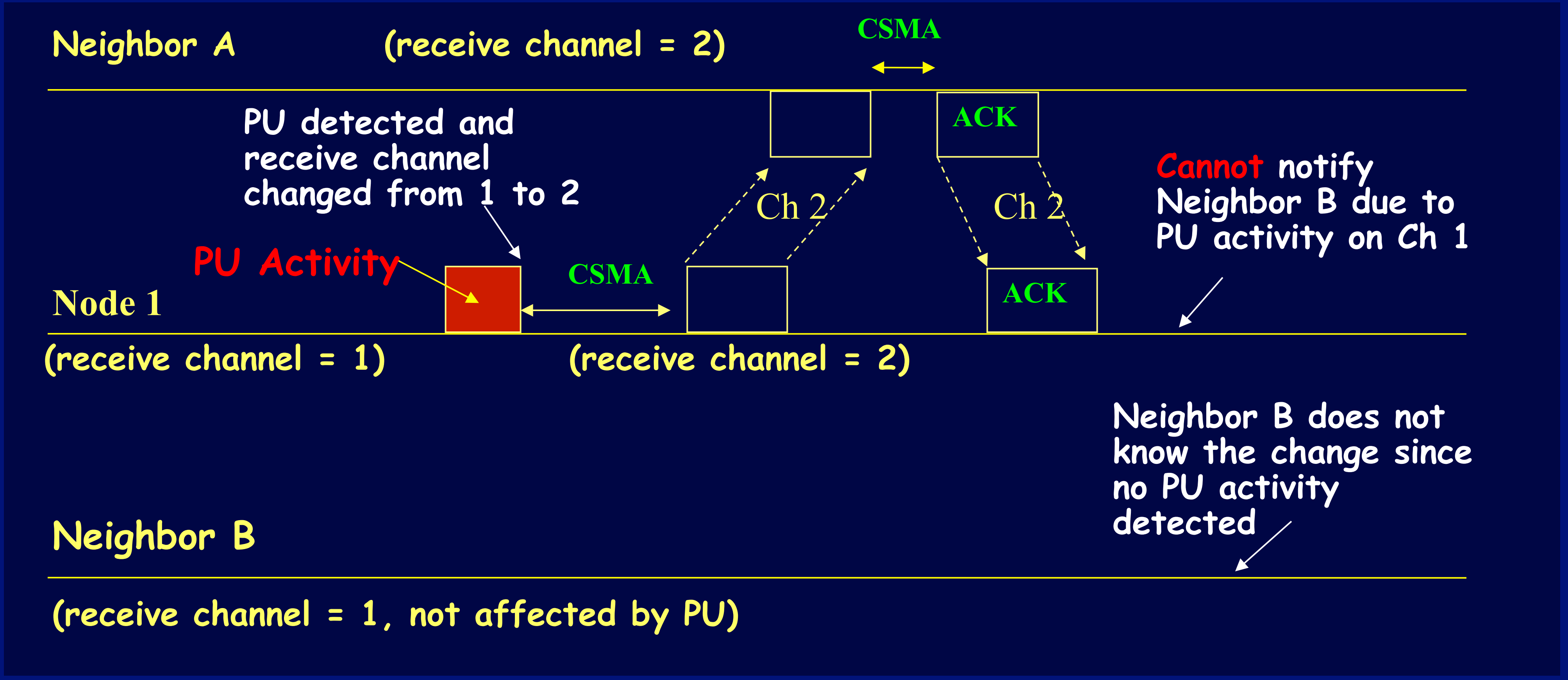
Cross-Channel Communication for Jamming Attacks

- Different spectrums can be used for sending and receiving to avoid jamming and PU activity
- If node 1 needs to change its receive channel, it sends a notification to its neighbors which reply with an ACK
- CSMA channel access with random wait is assumed



PU Activity Notification Problem

- Cross-channel communication does not solve this problem



CCC Solution: SRAC

- **Advantages**
  - Alleviate saturation and jamming problems
    - CCC bandwidth adaptively increased to avoid saturation
    - Receive channel adapted for cross-channel communications in response to jamming
- **Drawbacks**
  - PU activity notification problem
  - Limited CCC coverage

C-MAC

C. Cordeiro, K. Challapali, "C-MAC: A Cognitive MAC Protocol for MultiChannel Wireless Networks," in Proc. of IEEE DySPAN, Nov. 2007.

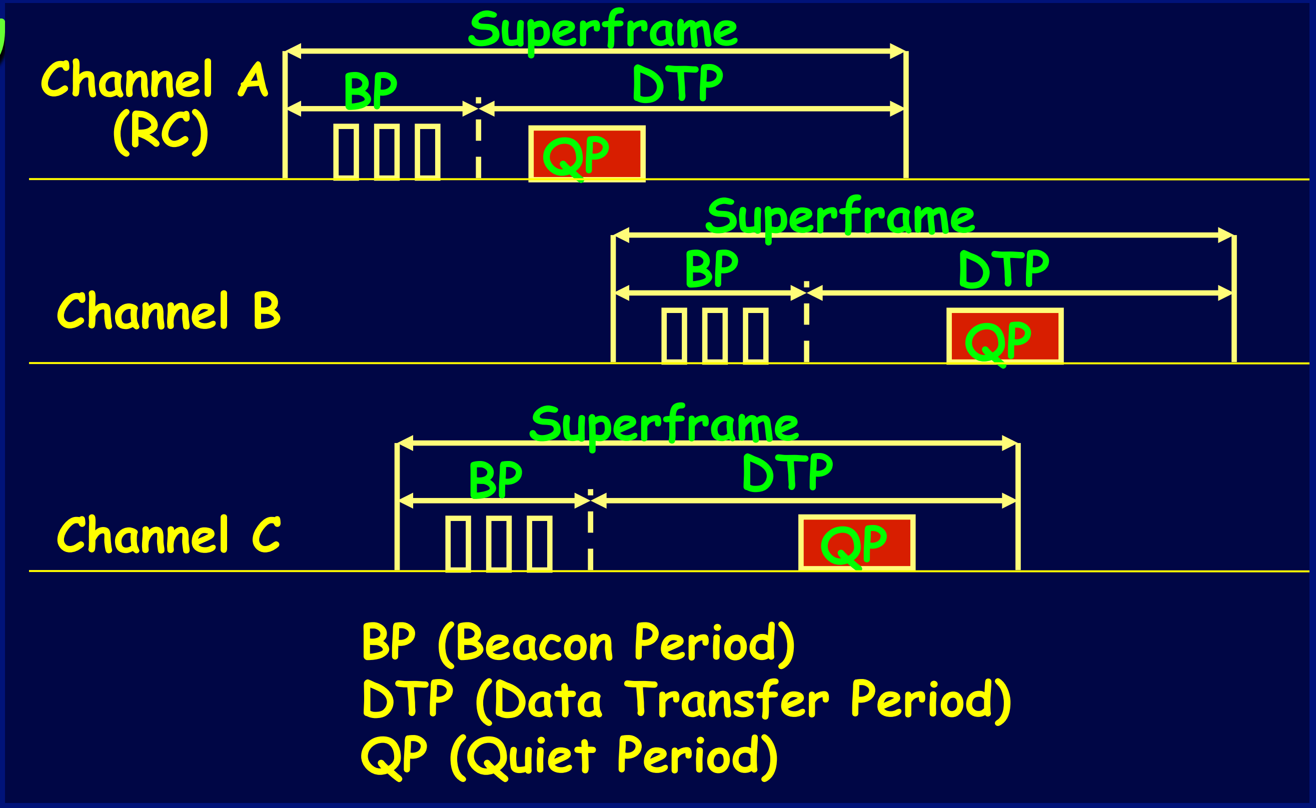
- **Main Idea**
  - Slotted behavior is enhanced by the use of superframes
  - Rendezvous channel (RC) is exploited for neighbor discovery, load and scheduling information exchange
  - Backup channels (BC) are also employed for coexistence

Important Concepts in C-MAC

- RC (Rendezvous Channel)
  - Used to coordinate nodes in different channels in order for the Beacon Periods (BP) not to overlap
  - Multi-channel resource reservation
  - Coordination for PU detection
- BC (Backup Channel)
  - Determined by out-of-band measurements
  - Carried out by nodes when they are not engaged in communication or during quiet period

C-MAC

- **Rendezvous Channels (RC)**
  - Primary CCC subject to PU activity
- **Backup Channels**
  - Backup CCC when PU returns to RC



CCC Solution: C-MAC

- **Advantages**
  - Increased robustness to PU activity
    - Backup channel provides fast CCC recovery from PU activity on CCC
  - Flexible CCC coverage
    - RC can be distributed or extended for network-wide broadcast
- **Drawbacks**
  - Control overheads due to large volumes of beacon exchanges
  - Single converging RC not always possible
  - Inter-channel synchronization required for reliable RC
    - Scheduling of non-overlapping beacon and quiet periods over a large number of channels is a nontrivial task

Overview of Major CCC Solutions

Major CCC Design Solutions			
Sequence-based CCC	Group-based CCC	Dedicated CCC	Underlay CCC
• SYN-MAC • Sequence-based Rendezvous • Quorum-based CCC	• C-MAC • SOC • SI-based CCC • ERCC	• OFDM-based CCC	• UWB CCC

Sequence-based CCC Solutions

- CCCs are allocated according to a random or predetermined channel hopping sequence
- Objective
  - Diversify the control channel allocation over spectrum and time spaces in order to minimize the impact of PU activity and jamming attacks
- In Spotlight
  - Sequence-based Rendezvous
  - Quorum-based CCC

Sequence-based Rendezvous

L. A. DaSilva and I. Guerreiro, "Sequence-based Rendezvous for Dynamic Spectrum Access," in Proc. of IEEE DySPAN 2008, Oct. 2008

Definition:

Rendezvous (Link rendezvous)

- Two or more CR users establish a link on a common channel
- In-band CCC solution
  - All rendezvous channels used for both control and data

Sequence-based Rendezvous

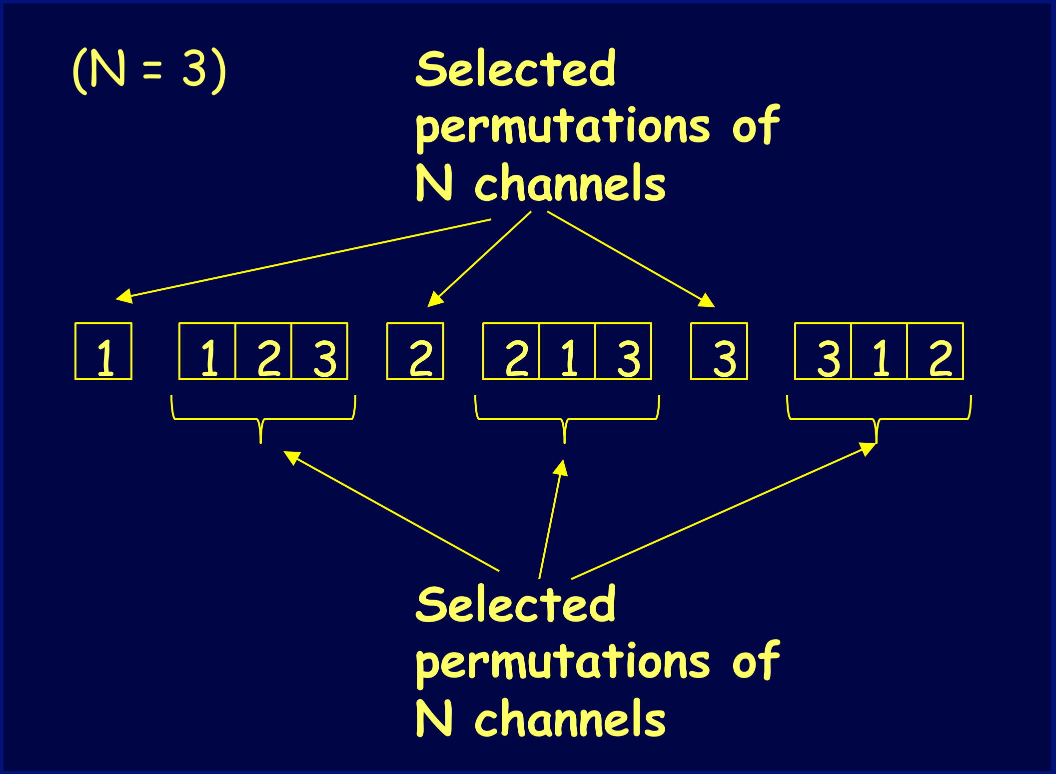
L. A. DaSilva and I. Guerreiro, "Sequence-based Rendezvous for Dynamic Spectrum Access," in Proc. of IEEE DySPAN 2008, Oct. 2008

- **Blind Rendezvous**
  - Random channel selection for scanning
    - No bound on the time required for rendezvous

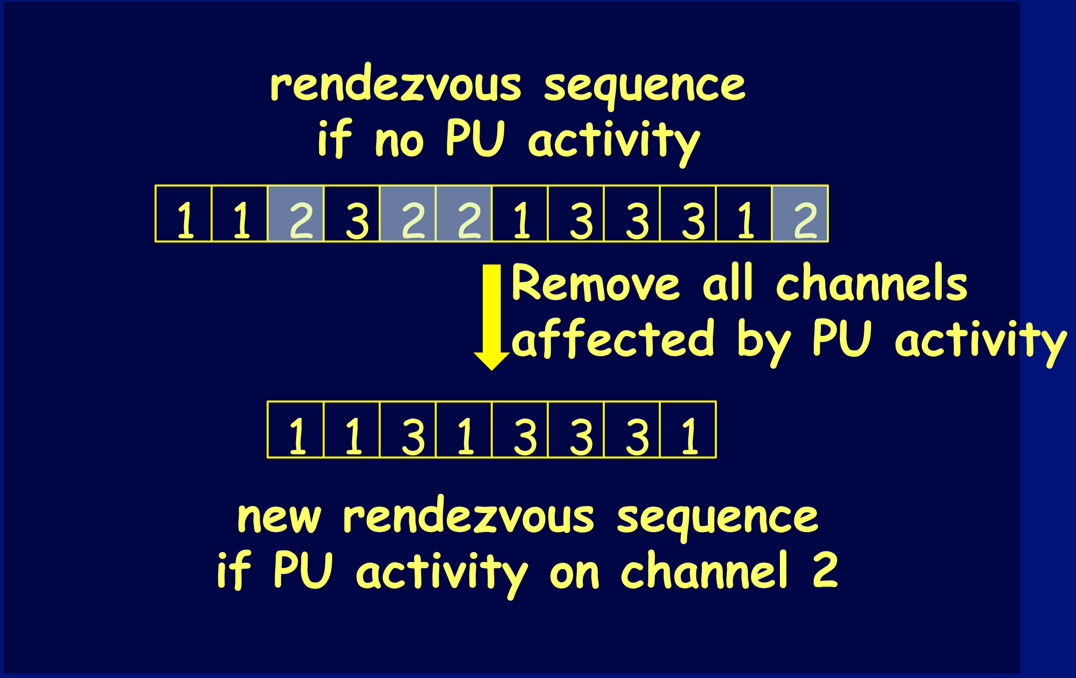
- **Sequenced-based Rendezvous**
  - Use non-orthogonal sequence for channel scanning
  - Establish in-band CCCs on a link-by-link basis
  - No dedicated CCC
  - Robust to CCC saturation problems

Sequence Selections

- **Predefined Sequence**

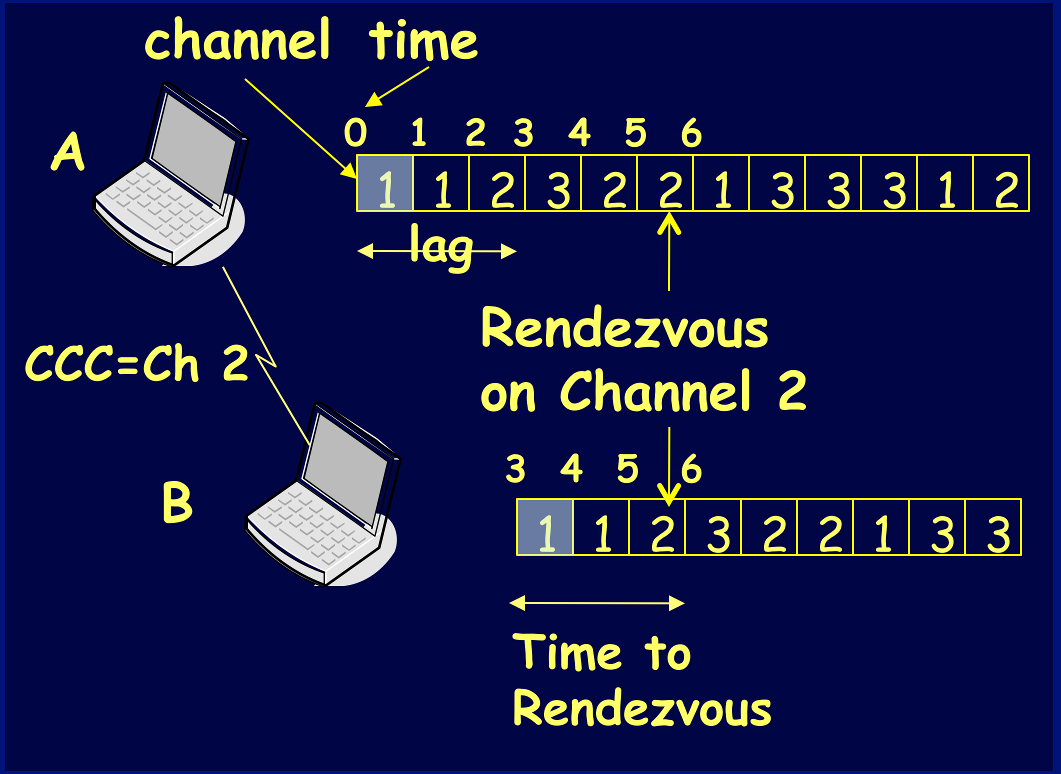


- **Sequence Change in Response to PU Activity**



Sequence-based Rendezvous Example

- **Predefined Sequence**
  - 3 channels available
  - {1, [1,2,3], 2, [2,1,3], 3, [3,1,2]}
- **Channel Scanning**
  - Node A starts at t=0
  - Node B starts at t=3
  - Lag = 3
- **Rendezvous**
  - Complete at t=6 on Channel 2
  - Time to Rendezvous = 3



CCC Solution: Sequence-based Rendezvous

- **Advantage**
  - Robustness to CCC saturation problem
- **Drawbacks**
  - Limited adaptability to PU activity
    - Not adaptable to new spectrum opportunities
    - Responding to PU activity only by eliminating channels
  - Long or unbounded rendezvous time
    - No guarantee on bounded time to rendezvous if affected by PUs
  - Very limited CCC Coverage
    - Rendezvous only for point-to-point links with no broadcast support

Quorum-based Common Control Channel

K. Bian, J.-M. J.-M. Park, and R. Chen, "Control Channel Establishment in Cognitive Radio Networks using Channel Hopping," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 4, April 2011.

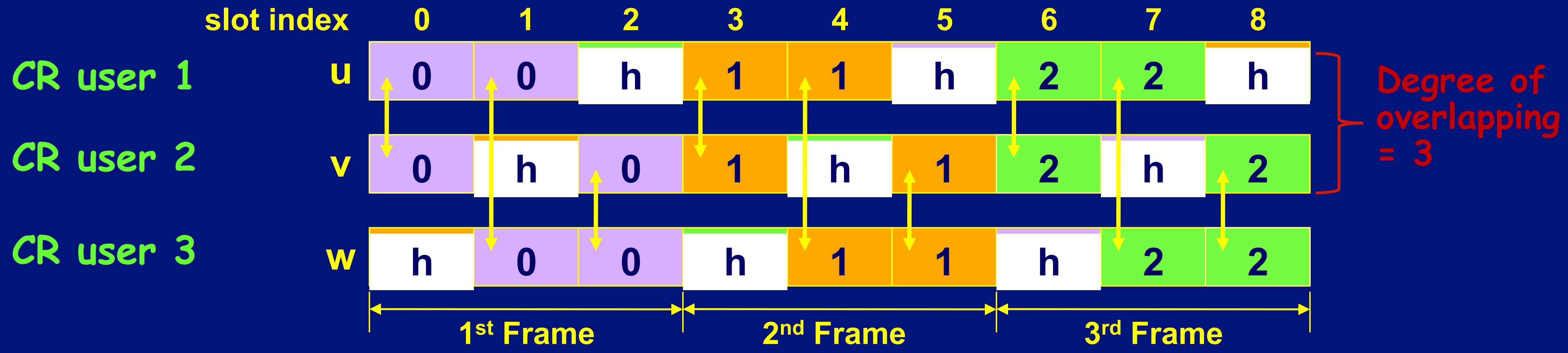
- **Quorum-based Channel Hopping**
  - Control channels established by rendezvous using channel hopping sequences constructed from cyclic quorum systems
  - Using sequences constructed from quorum systems increases the probability of rendezvous
    - At least one channel common to two hopping sequences in each slot
  - Rendezvous channels spread out in time and frequency
  - Common hopping for data exchange after rendezvous

Quorum System

- **Quorum System S under U**
  - A collection of non-empty subsets of U
    - U = {0,…,n-1} is a finite universal set of n elements
  - Satisfy the intersection property: $p \cap q \neq \phi, \forall p, q \in S$
  - Each p or q in S is called a quorum

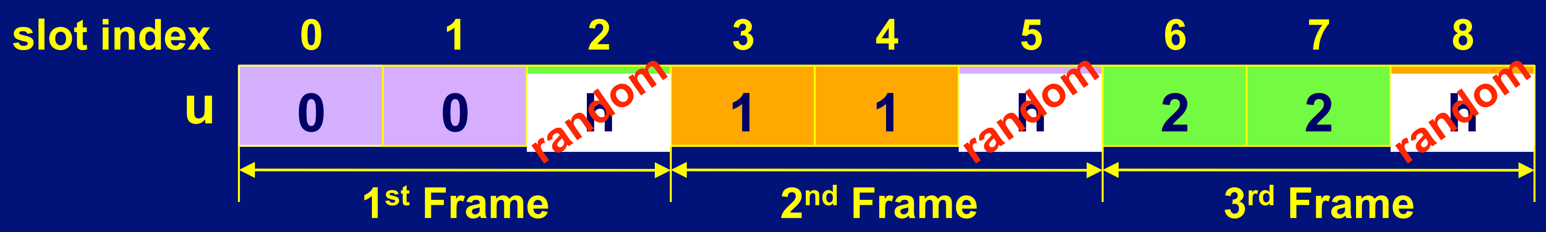
- **Example**
  - S = {{0,1},{0,2},{1,2}} is a quorum system under U = {0,1,2}
  - {0,1}, {0,2}, and {1,2} are quorums in S

Example: Quorum-based Channel Hopping System

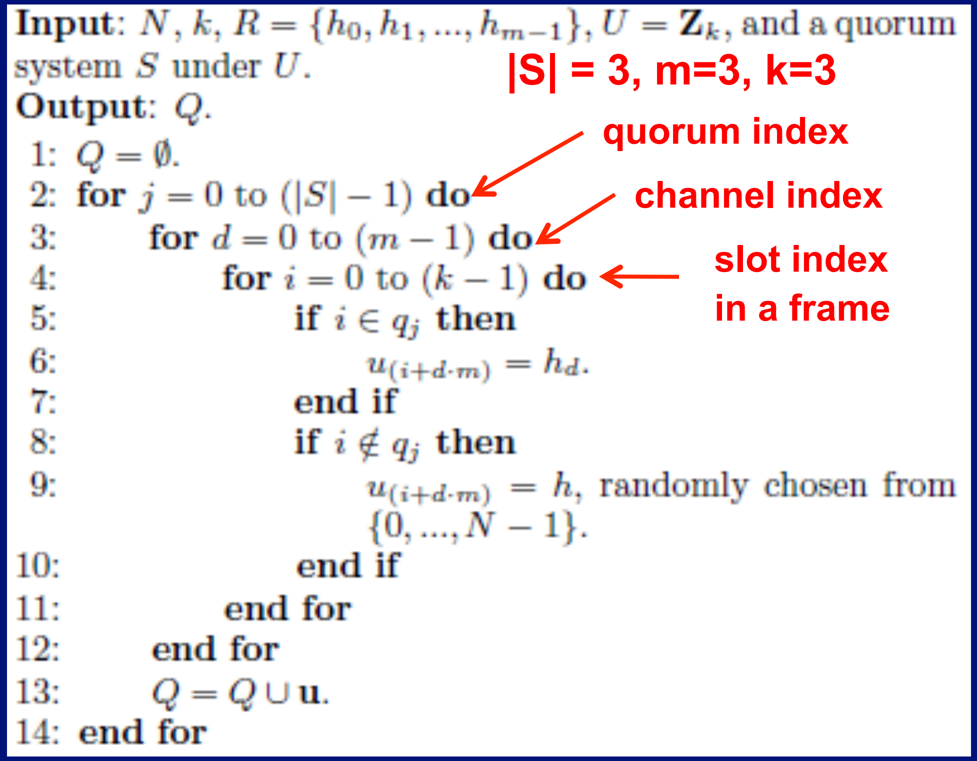


- Each sequence consists of m frames, each frame consists of k slots
  - Period of channel hopping (CH) sequence T = m • k = 9 (m = 3, k = 3)
- Every pair of CH sequences rendezvous in m=3 different channels
  - Set of rendezvous channels: $R = \{h_0,\ldots,h_{m-1}\} = \{h_0, h_1, h_2\} = \{0, 1, 2\}$
- Construct a quorum system $S = \{q_0, q_1, q_2\} = \{\{0,1\}, \{0,2\}, \{1,2\}\}$ under Z_k
  - Sequences u, v, and w are constructed from quorums q_0, q_1, q_2, respectively

Example: Constructing a Sequence from a Quorum



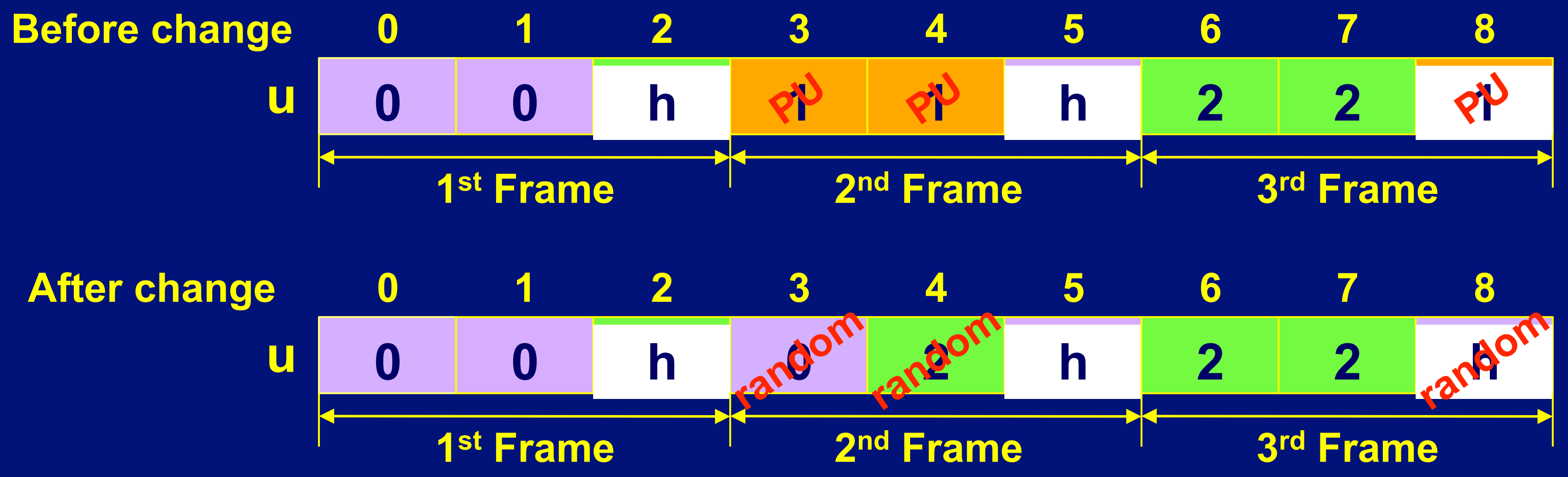
- **Construct Sequence u from q_0={0,1}**
  - u_0=0: j=0, d=0, i=0 ϵ q_0, h_0=0
  - u_1=0: j=0, d=0, i=1 ϵ q_0, h_0=0
  - u_2=h: j=0, d=0, i=2
  - u_3=1: j=0, d=1, i=0 ϵ q_0, h_1=1
  - u_4=1: j=0, d=1, i=1 ϵ q_0, h_1=1
  - u_5=h: j=0, d=1, i=2
  - u_6=2: j=0, d=2, i=0 ϵ q_0, h_2=2
  - u_7=2: j=0, d=2, i=1 ϵ q_0, h_2=2
  - u_8=h: j=0, d=2, i=2



Input: N, k, $R = \{h_0, h_1, ..., h_{m-1}\}$, $U = \mathbf{Z}_k$, and a quorum system S under U.
Output: Q.

```
Q = ∅.
for j = 0 to (|S| − 1) do
    for d = 0 to (m − 1) do
        for i = 0 to (k − 1) do
            if i ∈ q_j then
                u_(i+d·m) = h_d.
            end if
            if i ∉ q_j then
                u_(i+d·m) = h, randomly chosen from {0, ..., N − 1}.
            end if
        end for
    end for
    Q = Q ∪ u.
end for
```

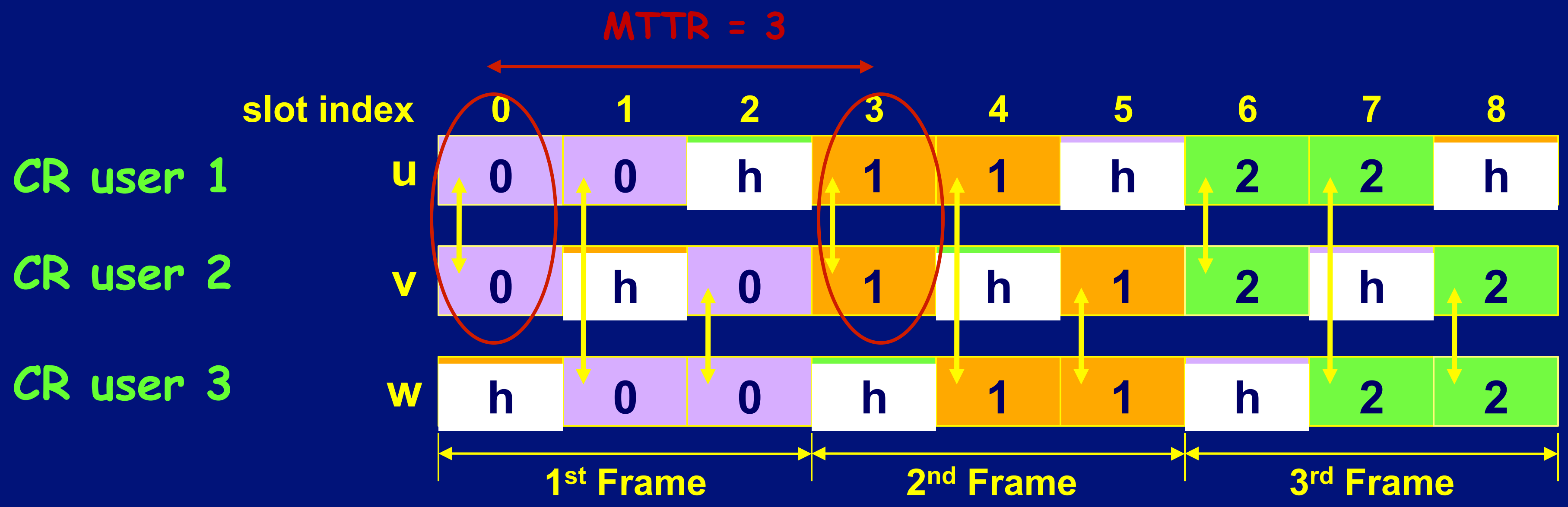
Example: Sequence Change Due to PU Activity



- PU Activity
  - Channels affected by PU activity are replaced by a channel randomly selected from the set of available channels
  - The rest of the sequence remains unchanged

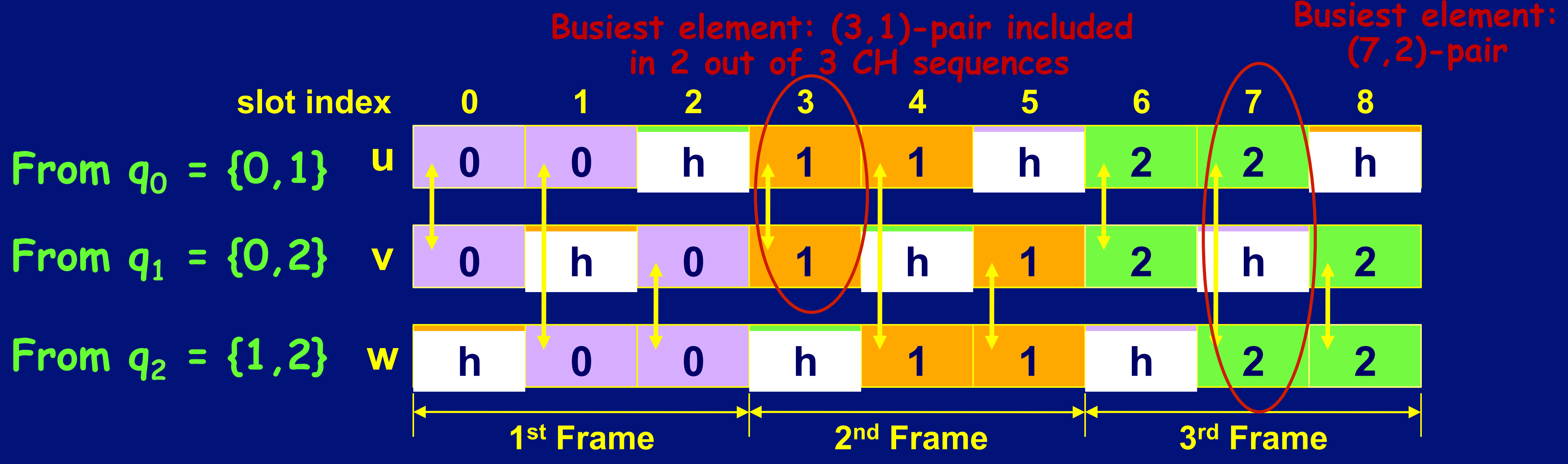
Metrics of Channel Hopping Systems

- **Maximum Time-To-Rendezvous (MTTR)**
  - Maximum time for any pair of sequences to rendezvous
    - Example: The MTTR is 3 in the example



Metrics of Channel Hopping Systems

- Load of Channel Hopping (CH) Systems
  - The fraction of number of the times the busiest element used
    - Busiest element: the (timeslot, channel)-pair included in the largest number of CH sequences
  - Example: The load is 2/3 in the example



Cyclic Quorum Systems (1)

- **Relaxed Cyclic (n,k)-difference Set D**
  - $D = \{a_1, \ldots, a_k\}$ is a relaxed cyclic (n,k)-difference set under Z_n if for every $d \neq 0 \pmod{n}$ there exist a_i and a_j such that $a_i - a_j = d \text{ (mod) } n$

- **Example**
  - $D = \{0,1,3\}$ is a relaxed cyclic (7,3)-difference set under Z_7

    $1-0 \equiv 1 \text{ (mod) } 7$, $3-1 \equiv 2 \text{ (mod) } 7$, $3-0 \equiv 3 \text{ (mod) } 7$

    $0-1 \equiv 6 \text{ (mod) } 7$, $1-3 \equiv 5 \text{ (mod) } 7$, $0-3 \equiv 4 \text{ (mod) } 7$

Cyclic Quorum Systems (2)

- **Cyclic Quorum System**
  - A group of sets $B_i = \{a_1+i, a_2+i, \ldots, a_k+i\}$ (mod) n, $i = \{0, 1, \ldots, n-1\}$, is a cyclic quorum system if and only if $D = \{a_1, a_2, \ldots, a_k\}$ is a relaxed cyclic (n,k)-difference set

- **Example**
  - Given $D = \{0,1,3\}$ under Z_7, Bi = $\{0+i, 1+i, 3+i\}$ mod 7, $i = \{0, 1, \ldots 6\}$, is a cyclic quorum system

    $B_0 = \{0,1,3\}$, $B_1 = \{1,2,4\}$, $B_2 = \{2,3,5\}$, $B_3 = \{3,4,6\}$,
    $B_4 = \{4,5,0\}$, $B_5 = \{5,6,1\}$, $B_6 = \{6,0,2\}$

Majority Cyclic Quorum Systems

- **Majority Cyclic Quorum System**
  - A cyclic quorum system S based on the difference set D that contains more than half of the elements in Z_n
    - D = {0,1,2} under Z_4 (k = 3 > 4/2)
    - S = {{0,1,2},{1,2,3},{2,3,0},{3,0,1}} is a majority cyclic quorum system
- **M-QCH System**
  - Constructed with a majority cyclic quorum system over Z_3
  - Optimal QCH design: minimize MTTR (k=3) while keeping the load < 1

Minimal Cyclic Quorum Systems

- **Minimal Cyclic Quorum System**
  - A cyclic quorum system S based on the singer difference set D whose size k approximates the lower bound $\sqrt{n}$
    - D = {1,2,4} under Z_7 is a singer difference set ($k = 3 \approx \sqrt{7} = 2.65$).
    - S = {{1,2,4}, {2,3,5},{3,4,6},{4,5,0},{5,6,1},{6,0,2},{0,1,3}} is a minimal cyclic quorum system

- **L-QCH System**
  - Constructed with a minimum cyclic quorum system over Z_τ
  - Near Optimal in terms of the load (close to theoretical minimum $1/\sqrt{\tau}$)
    - τ is the maximum allowed MTTR

Comparison of Channel Hopping Systems

MCTTR: Maximum conditional TTR between 2 CH nodes when PU is present and at least one PU-free common channel is available

Synchronous Quorum-based CCC → M-QCH, L-QCH

Asynchronous Quorum-based CCC → A-QCH

	Degree of overlapping	Load	MTTR	MCTTR
Blind Rendezvous	0	-	-	-
SSCH	1	1/(N-1)	N+1	-
M-QCH	N	2/3	3	3N
L-QCH	N	$\geq 1/\sqrt{T}$	K	kN
Seq Rendezvous	1	1/N	N(N+1)	-
A-QCH	2	≈1/2	≥9	-
A-MOCH	N	1	N^2-N+1	N^2

Quorum-based Control Channels

- **Advantages**
  - Performance improvement over Sequence-based Rendezvous schemes
  - Robust to control channel saturation and jamming problems
- **Disadvantages**
  - Subject to PU activity even with sequence adjustment
  - No broadcast support and limited CCC coverage
  - Long rendezvous time when the number of channel is large

Group-based CCC Solutions

- CCC is allocated to a channel commonly available to a group of CR users in proximity
- Objective
  - Form groups of CR users with common channels to increase CCC coverage and facilitate control message broadcast
- In Spotlight
  - Spectrum Opportunity-based Clustering (SOC)
  - Swarm Intelligence-based CCC

Spectrum Opportunity-based Control Channel

L. Lazos, S. Liu, and M. Krunz, "Spectrum Opportunity-Based Control Channel Assignment in Cognitive Radio Networks," in Proc. of IEEE Secon'09, Jun. 2009.

- Spectrum Opportunity-based Clustering (SOC)
  - Cluster-based Control Channel Solution
  - Clustering design formulated as a maximum edge biclique graph problem
    - Clusterhead is inherently selected during clustering
    - CCC determined by the clusterhead
  - CCC subject to PU activity
  - Re-clustering is needed in response to PU activity

SOC Algorithm

- Spectrum-Opportunity Clustering (SOC) Algorithm
  - Step 1: Maximum edge biclique computation
    - CR users individually compute their cluster memberships by solving the maximum edge biclique problem
  - Step 2: Exchange and update cluster membership information
    - CR users broadcast the computed information to neighbors
    - Update cluster membership accordingly
    - New cluster information is rebroadcasted
  - Step 3: Finalize cluster membership
    - CR users compute the final and unique cluster membership information
    - Broadcast the final clusters and CCCs to ensure consistency with neighbors

Step 1: Maximum Edge Biclique Computation

- Clustering is formulated as a maximum edge biclique graph problem

From Graph Theory:

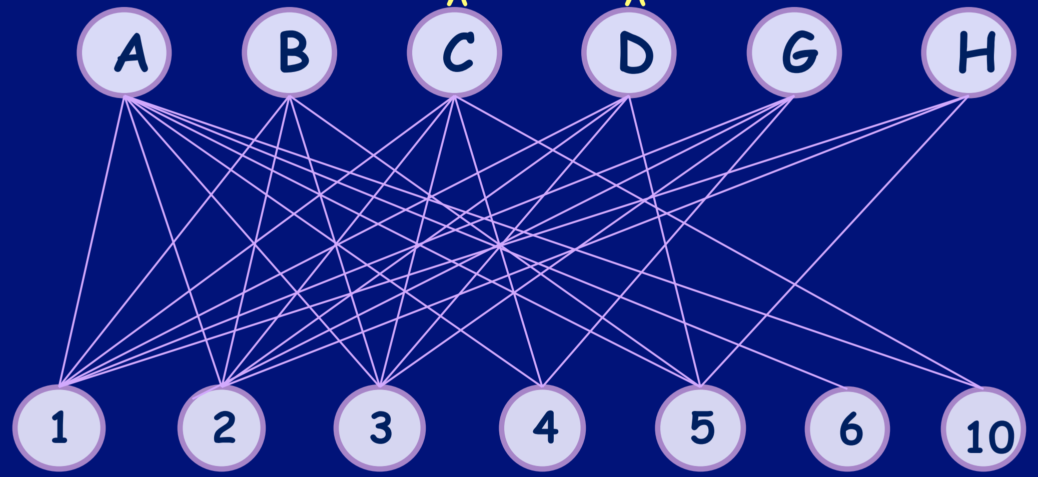
- Bipartite Graph
  - A graph $G(V,E)$ is bipartite if V can be partitioned into two disjoint sets A and B ($A \cup B = V$) such that all edges in E connect vertices from A to B
- Biclique
  - A bipartite graph $Q(X,Y)$ is a biclique if for each $x \in X$ and $y \in Y$ there exists an edge $e \in E$ between x and y

Bipartite Graph Example

Bipartite Graph Constructed by CR user A (CR_A)

Set of A and A's neighbors

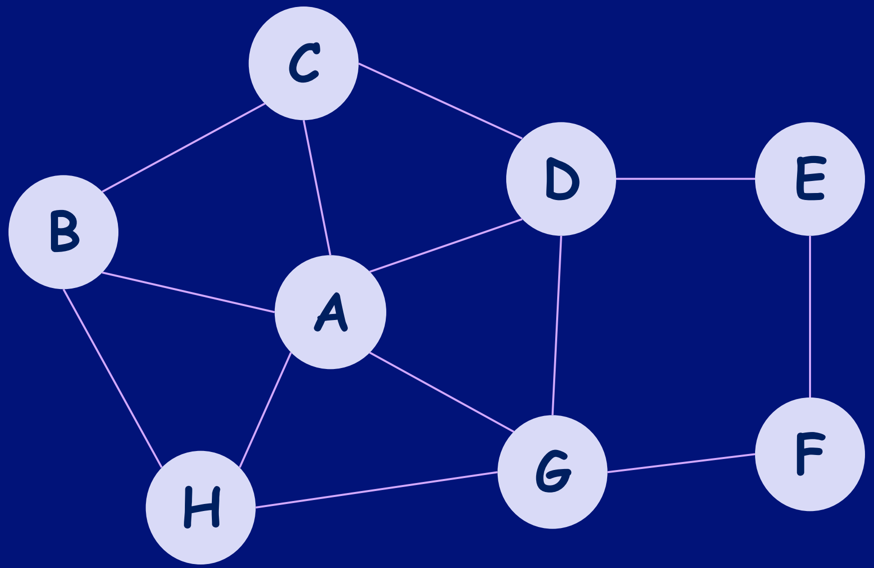
$A_A = Nbr_A \cup A$



$B_A = C_A$

Set of available channels at A

Connectivity Graph and Channel Availability

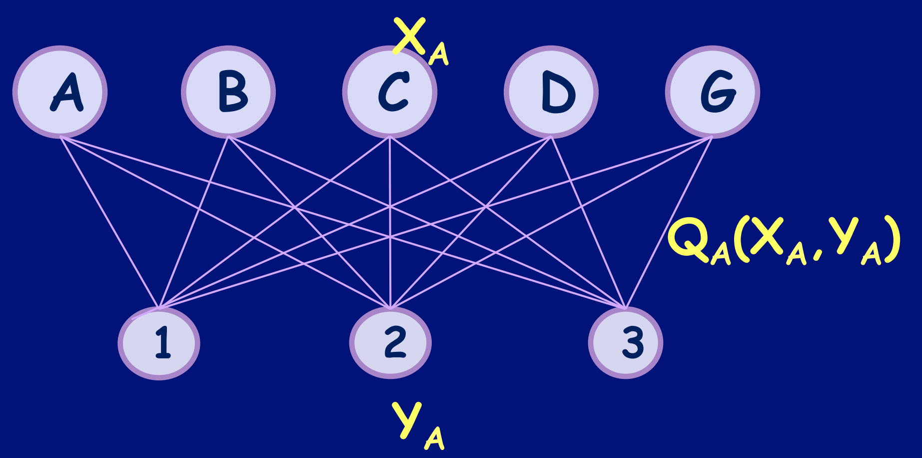


C_A = {1,2,3,4,5,6,10}
C_B = {1,2,3,5,7}
C_C = {1,2,3,4,10}
C_D = {1,2,3,5,7}
C_E = {2,3,5,7}
C_F = {2,4,5,6,7,10}
C_G = {1,2,3,4,8}
C_H = {1,2,5,8}

Maximum Edge Biclique Graph

- **Maximum Edge Biclique Graph Constructed by CR_A**
  - j=1: X_A={A}, Y_A=C_A, P_A[1]=7
  - j=2: X_A={A,C}, Y_A={1,2,3,4,10}, P_A[2]=10
  - j=3: X_A={A,C,D}, Y_A={1,2,3}, P_A[3]=9
  - j=4: X_A={A,C,D,B}, Y_A={1,2,3}, P_A[4]=12
  - j=5: X_A={A,C,D,B,G}, Y_A={1,2,3}, P_A[5]=15
  - j=6: X_A={A,C,D,B,G,H}, Y_A={1,2}, P_A[6]=12
  - j*=5: $Q_A(X_A,Y_A)$: X_A={A,B,C,D,G}, Y_A={1,2,3}

➔ **Maximizing the product of number of common channels and number of cluster members**



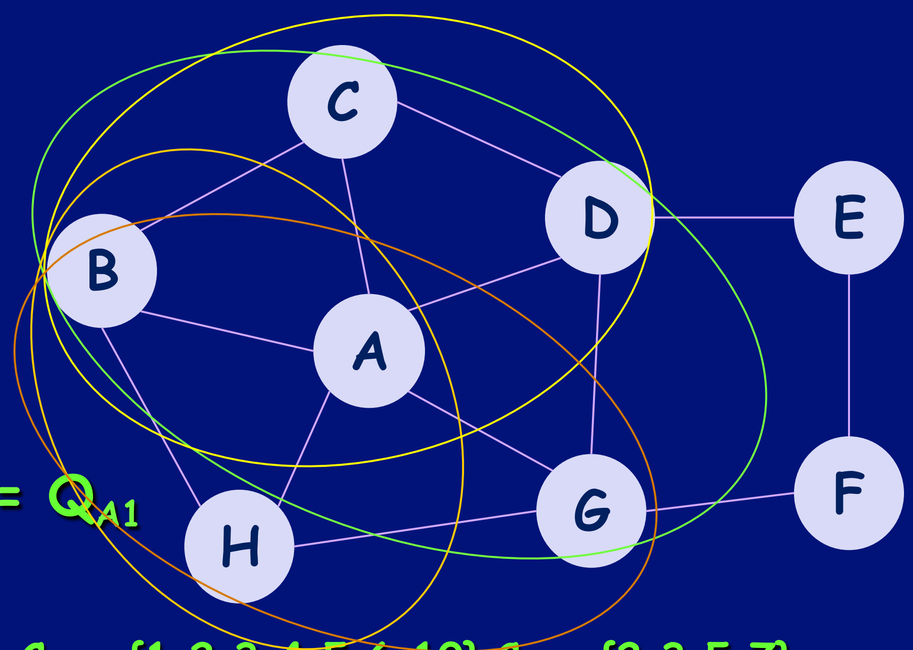
INPUT $\mathcal{G}_i(\mathcal{A}_i, \mathcal{B}_i, \mathcal{E}_i)$
$Y_i \leftarrow \mathcal{B}_i$
for $j = 1$ to $|\mathcal{A}_i|$ **do**
  Find $CR_k \in \mathcal{A}_i$ such that $|Y_i \bigcap C_k|$ is max
  if $Y_i \bigcap C_k = \emptyset$ **then**
    break
  else
    $S_i[j] = k$;
    $\mathcal{A}_i \leftarrow \mathcal{A}_i - CR_k$, $X_i \leftarrow X_i \bigcup CR_k$, $Y_i \leftarrow Y_i \bigcap C_k$,
    $P_i[j] = |X_i| \times |Y_i|$
  end if
end for
Find $j^* = \arg\max_j P_i[j]$
return $Q^*(X_i, Y_i)$; $X_i = \{CR_{S_i[1]}, \ldots, CR_{S_i[j^*]};\}$ $Y_i = \bigcap_{k=1}^{k=j^*} C_{S_i[k]}$

Step 2: Exchange and update information

- CR user A receives updates from one-hop neighbors
  - Q_{A1}: $X_A=\{A,B,C,D,G\}$, $Y_A=\{1,2,3\}$
  - Q_{B1}: $X_B=\{A,B,H\}$, $Y_B=\{1,2,5\}$
  - Q_{C1}: $X_C=\{A,B,C,D\}$, $Y_C=\{1,2,3\}$
  - Q_{D1}: $X_D=\{A,B,C,D,G\}$, $Y_D=\{2,3\}$
  - Q_{G1}: $X_G=\{A,D,G,H\}$, $Y_G=\{1,2\}$
  - Q_{H1}: $X_H=\{A,B,G,H\}$, $Y_H=\{1,2\}$

  ➔ $Q_{G1} < Q_{H1} < Q_{B1} < Q_{D1} < Q_{C1} < Q_{A1}$

  ➔ $Q_{G2} = Q_{H2} = Q_{B2} = Q_{D2} = Q_{C2} = Q_{A2} = Q_{A1}$



$C_A = \{1,2,3,4,5,6,10\}$

$C_B = \{1,2,3,5,7\}$

$C_C = \{1,2,3,4,10\}$

$C_D = \{1,2,3,5,7\}$

$C_E = \{2,3,5,7\}$

$C_F = \{2,4,5,6,7,10\}$

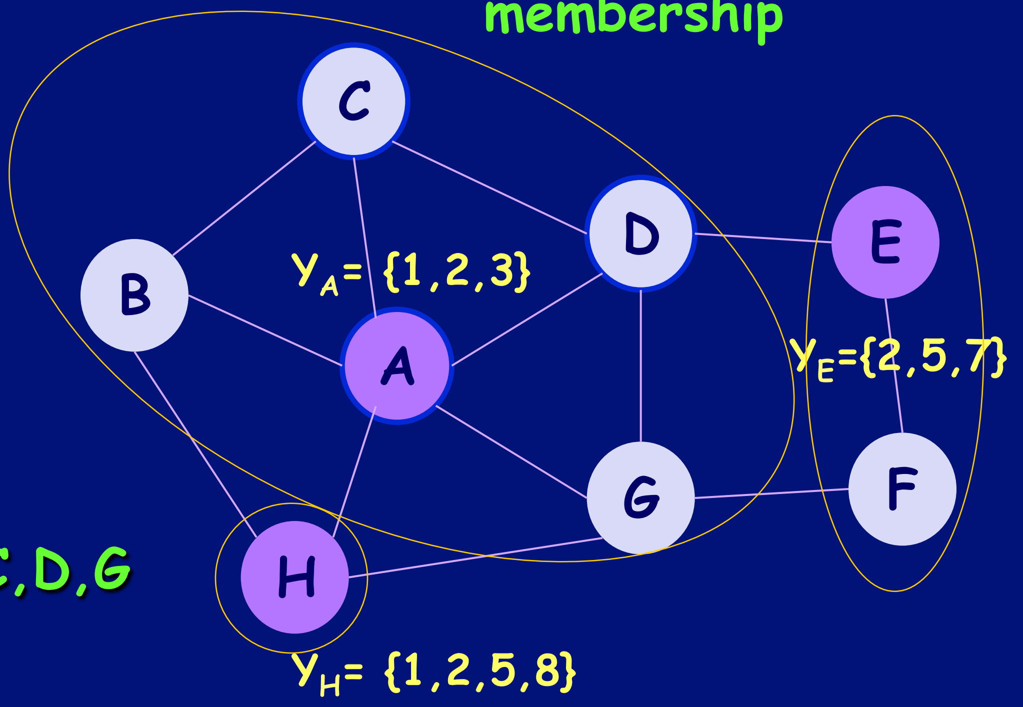
$C_G = \{1,2,3,4,8\}$

$C_H = \{1,2,5,8\}$

- $Q_i < Q_j$ if and only if
  - $|X_i| \times |Y_i| < |X_j| \times |Y_j|$
  - $|X_i| \times |Y_i| = |X_j| \times |Y_j|$ and $|X_i| < |X_j|$
  - $|X_i| \times |Y_i| = |X_j| \times |Y_j|$, $|X_i| = |X_j|$, $|y_i| = |y_j|$, $i<j$

Step 3: Finalize Cluster Membership

- Determine final cluster membership
  - CR user A: $Q_{A3} = Q_{A2}$
    - $X_{A3} = X_{A2}$, $Y_{A3} = Y_{A2}$
  - CR user B: $Q_{B3} = Q_{B2}$
    - $X_{B2} = \{A,B,C,D,G\}$
    - B is included in bicliques of A,C,D,G
    - $X_{B3} = X_{B2}$, $Y_{B3} = Y_{B2}$
  - CR user H forms its own cluster
    - $X_{H2} = \{A,B,C,D,G\}$
    - H is not included in bicliques of A,B,C,D,G
    - $X_{H3} = \{H\}$, $Y_{H3} = \{1,2,5,8\}$



CCC Solution: SOC

- Problems
  - Inter-cluster coordination problem
    - Caused by heterogeneous channel availability between clusters
  - Control channel migration problem
    - Caused by PU activity or fading

- Proposed solution: control channel hopping
  - Control channel hops among the common channels within each cluster
    - From previous example:

cluster A: {1,2,3} => 1,2,3,1,2,3,1,2,3,1,2,3,1,2,…
cluster H: {1,2,5,8} => 1,2,5,8,1,2,5,8,1,2,5,8,1,2…

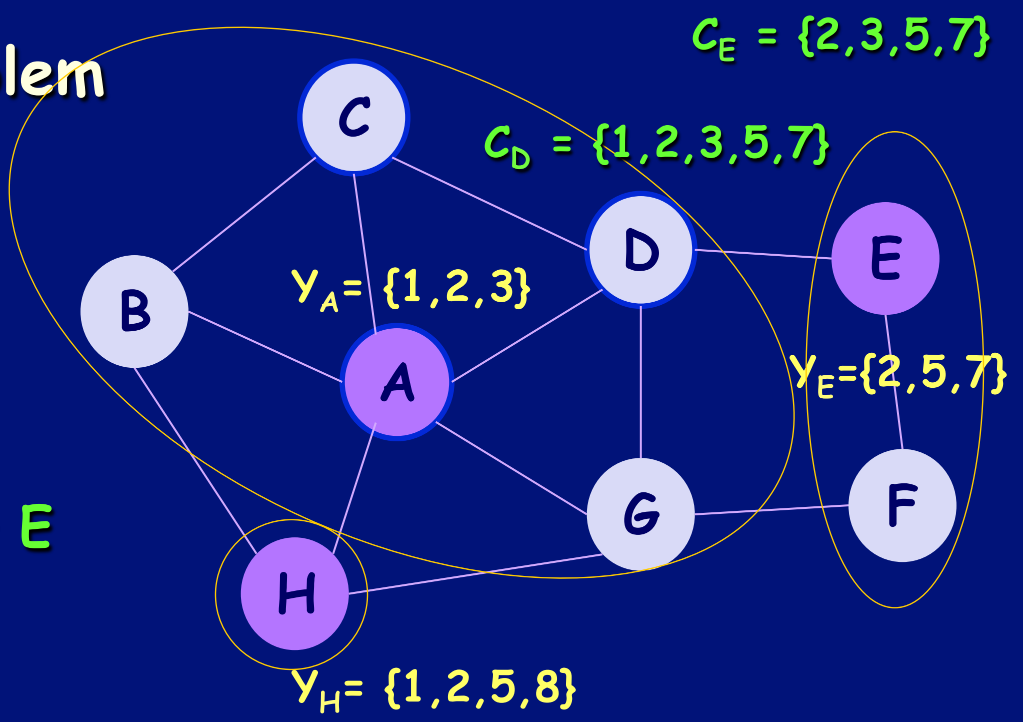
CCC Solution: SOC

- Drawbacks
  - Inter-cluster communication problem is not solved!
    - From the example:

    cluster A: {1,2,3} => 1,2,3,1,…

    cluster E: {2,5,7} => 2,5,7,2,…

    Members in cluster A (e.g. D) cannot communicate with members in cluster E (e.g. E)!
  - Which CCC is used for control message exchange in cluster formation (Step 2 & 3)???



Swarm Intelligence Based CCC

T. Chen, H. Zhang, M. D. Katz, and Z. Zhou, "Swarm Intelligence Based Dynamic Control Channel Assignment in CogMesh," IEEE ICC 2008, May 2008

- Swarm Intelligence (SI)
  - High efficiency achieved by specialized workers performing specialized tasks in parallel
    - Example: ants or bees cooperate to build nests or forage for food

Ant Foraging Analogy to SI-Based CCC

Ant Foraging	CCC Assignment
Each ant individually deposits a small amount of pheromone on a trail	Each CR User sends Hello messages and selects a CCC independently
The trail with the highest pheromone level becomes the choice of the working trail (best route to food)	The best channel selected by most CR users becomes the CCC, fewer CCCs exist in the network
More ants go on the best routes, faster they return with food, and more work achieved overall	More CR users on the same CCC, less control message overheads, faster broadcast, and larger coverage
Efficiency improves because the best routes chosen by majority of ants	System performance improves because of cooperative CCC selection

Swarm Intelligence Based CCC

- Objective of SI-based CCC
  - In response to PU activity
    - Use the best channel chosen by the majority of CR users as the CCC to increase system efficiency
  - In response to CCC coverage improvement
    - Reduce the number of CCCs in the network to minimize the control overhead and delay

Master Channel (CCC) Selection

- **Channel Quality (a single value Q)**
  - Quantized quality value Q is obtained from spectrum sensing

$$Q = q_i \quad \text{for } \gamma_i \leq P < \gamma_{i+1}$$

  - The value of Q is inversely proportional to the accumulated interference imposed by surrounding PUs

Master Channel (CCC) Selection

- The Q values are broadcast periodically by HELLO messages
- Each node updates its p-List based on Q values of its and neighbor's master channels
  - p-list indicates the probability of a channel selected as the CCC
- Master Channel (CCC) Selection
  - The channel with the highest probability in p-List

P list Update

- P list update is based on the difference of Q values in master channels
- Principles
  - $\Delta Q = Q_j - Q_i > 0$ (i.e. neighbor's Q value is larger)

    → The current user increases its Q value of MC
  - $\Delta Q = Q_j - Q_i < 0$ (i.e. neighbor's Q value is smaller)

    → The current user decreases its Q value of MC

Swarm Intelligence Example

- User 1,2,3 with 2 available channels
- Assume $q_i = i$, q_1: lowest quality, q_{10}: highest quality
  - User 1: Q list: {6, 4}
  - User 2: Q list: {4, 6}
  - User 3: Q list: {8, 2}
- Each node constructs initial p list and selects a master channel (MC) based on max p in p list
  - User 1: p list: {0.6, 0.4}, MC: Channel 1
  - User 2: p list: {0.4, 0.6}, MC: Channel 2
  - User 3: p list: {0.8, 0.2}, MC: Channel 1

Swarm Intelligence Example (2)

- User 1 & 3 broadcast Hello messages in Channel 1
  - User 1 have two Q lists:
    - Its own: Q list {6, 4} and MC = 1
    - From user 3: Q list {8, 2} and MC = 1
  - User 1: calculate $\Delta Q = 8-6 = 2$ (for MC = 1)
  - User 1: update its p list from {0.6, 0.4} to {0.8, 0.2}
  - Similarly, User 3 updates p list from {0.8, 0.2} to {0.9, 0.1}
  - User 1 & 3 still select Channel 1
- User 2 broadcast Hello message in Channel 2
  - No one receives this broadcast

Swarm Intelligence Example (3)

- If User 2 next broadcasts Hello message in Channel 1
  - User 1 has two Q lists:
    - Its own: Q list {8, 2} and MC = 1
    - From user 2: Q list {4, 6} and MC = 2
  - User 1: calculate $\Delta Q = 6-2 = 4$ (for MC = 2)
  - User 1: update its p list from {0.8, 0.2} to {0.7, 0.3}
  - User 2:
    - Its own: Q list {4, 6} and MC = 2
    - From user 1: Q list {8, 2} and MC = 1
  - User 2: calculate $\Delta Q = 8-4 = 4$ (for MC = 1)
  - User 2: update its p list from {0.4, 0.6} to {0.6, 0.4}

Swarm Intelligence Example (4)

- If User 2 next broadcasts Hello message in Channel 1
  - User 3 has two Q lists:
    - Its own: Q list {9, 1} and MC = 1
    - From user 2: Q list {4, 6} and MC = 2
  - User 3: calculate $\Delta Q = 6-1 = 5$ (for MC = 2)
  - User 3: update its p list from {0.9, 0.1} to {0.7, 0.3}

- Master Channel Update
  - User 1: p list = {0.7, 0.3}, MC = 1
  - User 2: p list = {0.6, 0.4}, MC = 1
  - User 3: p list = {0.7, 0.3}, MC = 1
  - All three nodes select Channel 1 as the master channel

CCC Solution: Swarm Intelligence CCC

- Advantages
  - PU activity protection and CCC coverage improvement
    - Adaptive CCC selection by the majority increases robustness to PU activity on the selected CCC
    - CCC coverage increases as the number of CCCs reduced

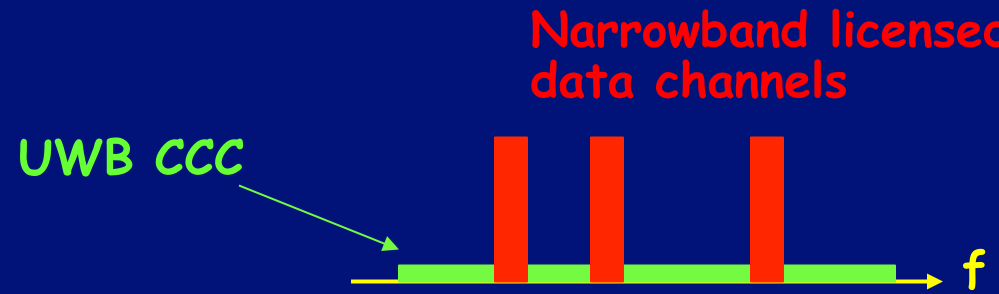
CCC Solution: Swarm Intelligence CCC

- **Drawbacks**
  - Accuracy of Q value as PU activity indicator
    - Q and p values may not accurately reflect true PU activity
  - Control overheads
    - Frequent HELLO broadcasts contribute to control overheads
    - Broadcast rate needs to be controlled
  - Slow converging rate and response to dynamic PU activity
    - Speed of responding to PU activity is a concern
    - Ping pong effect may occur as a result of neighbors with different MC selections

Underlay CCC Solutions

A. Masri, C.-F. Chiasserini, and A. Perotti, "Control information exchange through UWB in cognitive radio networks," IEEE International Symposium on Wireless Pervasive Computing, ISWPC'10, 2010

- **Underlay CCC by UWB Communications**
  - Control messages modulated on spreading sequences
  - Transmitted in low power as short pulses
  - Exhibit an ultra wide signal bandwidth compared to channel bandwidth
  - Appear to PUs as noise
  - No harmful interference with the PU traffic in licensed data channels



Issues in UWB CCC Design

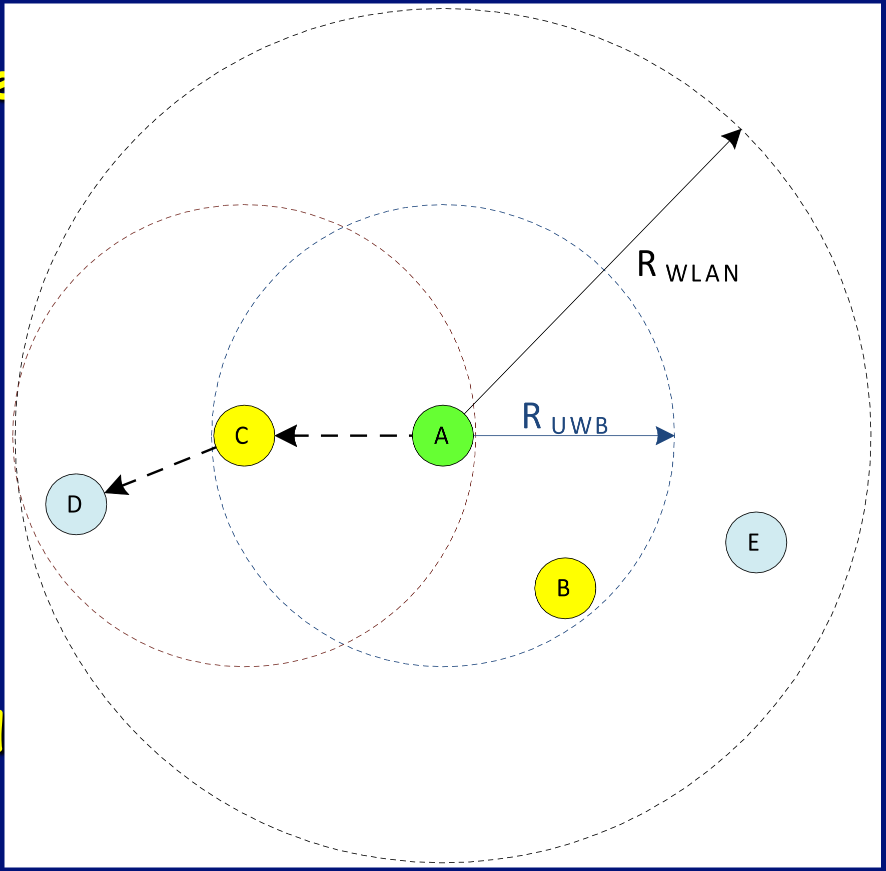
- UWB transmissions are known to have short transmission range
- Two Issues Related to UWB transmission range
  - How to increase the limited transmission range
    - Spreading code may be utilized to increase the range
  - How to resolve the range difference between the UWB control radio and other type of data radio
    - A neighbor that can be reached by the data radio in one hop may not be reachable by the UWB radio

UWB CCC Solution

- **UWB CCC with Multi-hop Control Routing**
  - Address the range difference issue
  - CCC routing table is established during neighbor discovery for routing control packets to all neighbors
  - Intermediate nodes between source and destination forward control packets back and forth to complement the difference between control and data radio ranges

UWB CCC and Range Difference Example

- R_{UWB} and R_{WLAN} represent the transmission range of UWB radio and WIFI radio
- CR users B and C are both one-hop UWB neighbor and one-hop WLAN neighbor of A
- CR users D and E are one-hop WLAN neighbor but not reachable by UWB radio of A
- Intermediate node (CR user C) needs to forward control packets back and forward between CR users A and D



CCC Solution: UWB CCC

- **Advantage**
  - Robust to PU activity and jamming

- **Drawbacks**
  - Short transmission range (small CCC coverage)
  - Range difference issues if different radios are used
  - Control overhead increase with the multi-hop control routing

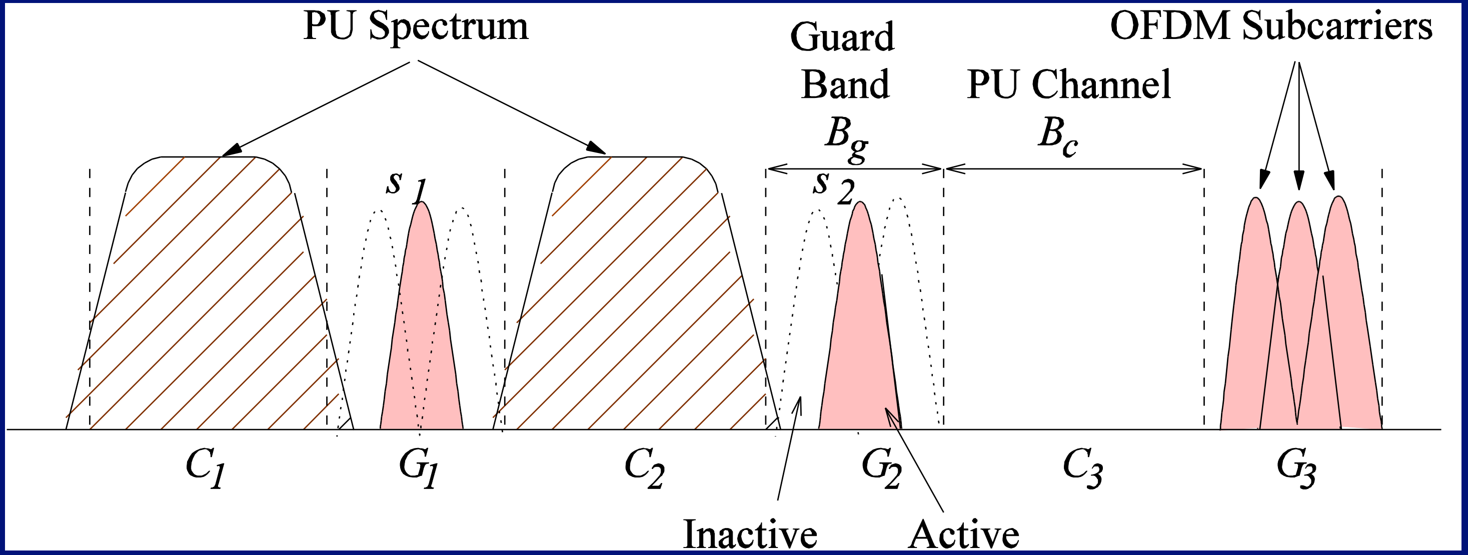
Our CCC Solutions

- Dedicated CCC Solution
  - OFDM-based common control channel design
- In-band CCC Solution
  - Efficient recovery control channel (ERCC) design

OFDM-based Common Control Channel

K. R. Chowdhury and I. F. Akyildiz, "OFDM-based common control channel design for cognitive radio ad hoc networks," IEEE Trans. Mobile Computing, vol. 10, no. 2, Feb. 2011.

- "Always-on" dedicated CCC Solution
  - Utilize the white space in guard bands
  - Select OFDM subcarriers in guard bands as CCCs



OFDM-based CCC: Motivation

- Guard bands are always available
  - Using them minimizes the disruption to an ongoing CR data transfer and to a newly arriving PU
- Guard band may be allotted a large total bandwidth
  - Using them makes efficient use of the scarce spectrum resource

OFDM-based CCC Design Steps

- **Step1: OFDM Subcarrier Allocation**
  - Use optimization framework for network initialization
  - Select OFDM subcarrier and transmission parameters
    - Number of subcarriers per guard band (m), symbol time (τ), transmit power (P_{tx})
- **Step 2: CCC Operations**
  - Select center subcarriers for broadcast messaging
  - Select active guard bands for unicast messaging
  - Use learning framework for normal network operations

OFDM Subcarrier Allocation

OFDM-based Subcarrier Optimization Framework

Symbol	Description
n	Number of CR users
$s_{a_n}(t)$	Time domain signal for the ${a_n}^{th}$ subcarrier
$d(a_n)$	Data rate for the ${a_n}^{th}$ subcarrier
D_{min}	Minimum required data rate
N_g	Number of guard bands in the licensed spectrum
m	Number of OFDM subcarriers in a guard band
τ	Time for transmitting one OFDM symbol
t_g	Guard time between two OFDM symbols
α, β	Free space propagation constants
P_{tx}	CR OFDM subcarrier transmission power
P_R^T	CR receiver threshold power
R_{min}	Minimum CR transmission range
v	Node velocity
p	Pause time between successive displacements
B_g	Guard band bandwidth
B_c	Licensed spectrum channel bandwidth
B_s	Bandwidth of a single OFDM subcarrier
O_t	Interference power overlap threshold for PUs

Given : $B_c, B_g, N_g, D_{min}, P_{max}, R_{min}, PAPR_{max}, t_g$

To find : m, τ, P_{tx} (1)

Subject to :

Constraints:

Orthogonality

$$\int_0^{\tau} s_{a_1}(t) \cdot s_{a_2}(t) \mathrm{d}t = \begin{cases} 0, & a_1 \neq a_2 \\ \frac{\tau}{2}, & a_1 = a_2 \end{cases} \quad (2)$$

where

$$s_{a_n}(t) = \cos(\frac{2\pi a_n}{\tau} \cdot t + \theta_{a_n}) \ a_n \in [1, m \cdot N_g]$$

GB Bandwidth

$$\frac{1}{\tau} \cdot (1 + m) \leq B_g \quad (3)$$

Peak to Avg. Power Ratio (PAPR)

$$m \cdot N_g \leq PAPR_{max} \quad (4)$$

Tx range

$$\left[\frac{P_{tx} \cdot \alpha}{P_R^T}\right]^{\frac{1}{\beta}} \geq R_{min} \quad (5)$$

Data rate

$$\sum_{i=1}^{N_g} d(i) \geq D_{min}, \quad (6)$$

Tx time

$$t_g + \tau < T_{min} \quad (7)$$

Interference

$$\left| \frac{2P_{tx}}{\pi} \sum_{i=0}^{\frac{m-1}{2}} \int_{\frac{B_g}{2} - \frac{i}{\tau}}^{\frac{B_g}{2} + B_c} \frac{\sin(\pi \tau f)}{f} \mathrm{d}f \right| < O_t. \quad (8)$$

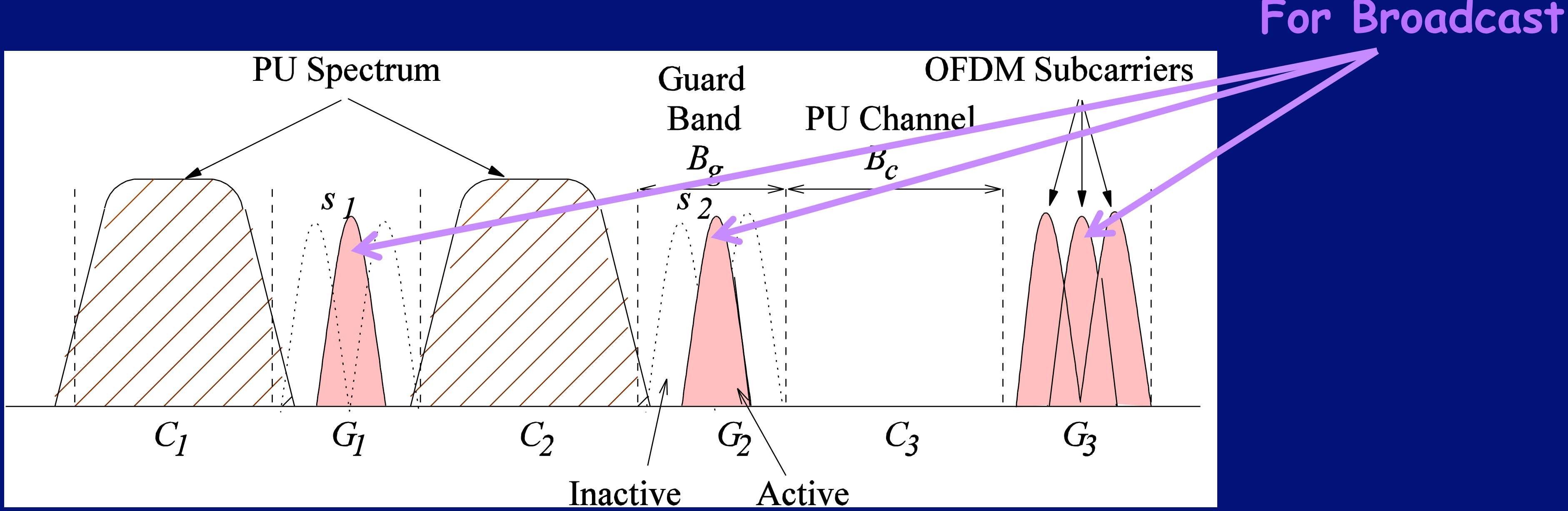
CCC Operations: Broadcast Messaging

- Message Broadcast on CCC
  - Broadcast facilitates higher layer operations
  - Examples of broadcast messages
    - Cooperative decision sent by the fusion center in cooperative sensing
    - Hello packet exchange during neighbor discovery
    - RTS-CTS handshake at the link layer
    - Route request packets sent at the network layer

➔ Broadcast messages may interfere with ongoing PU transmissions outside the immediate sensing range

CCC Operations: Broadcast Messaging

- All center subcarriers are utilized for broadcast
  - Central subcarrier of a guard band has the largest frequency separation between itself and adjacent PU spectrum

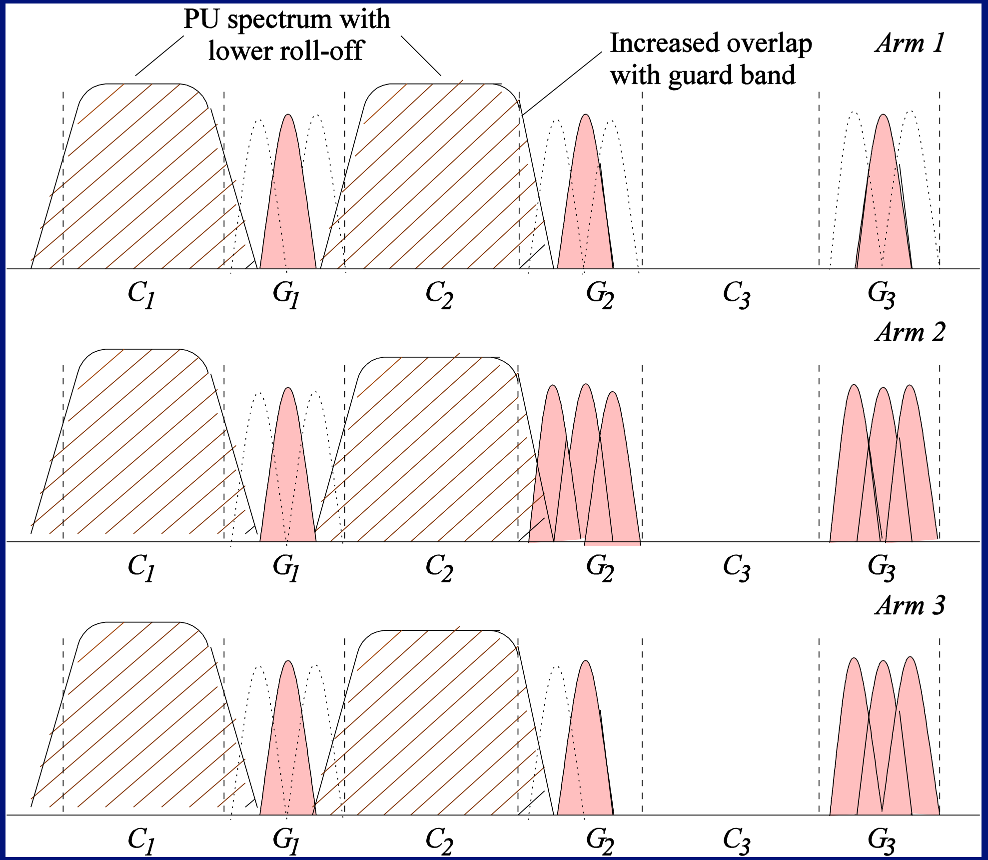


CCC Operations: Unicast

- PU activity affects the choices of active guard bands
- Multi-armed bandit algorithm is used to learn the best combination of active guard bands over time
  - *Exploit* the current choice of the arm and get the known level of immediate reward
  - *Explore* a new arm to get potentially higher expected reward in the long run

Unicast: Multi-Armed Bandit Algorithm

- **Rules of Creating Arms**
  - A guard band (GB) is active if all subcarriers in it are used
  - Center subcarriers are always used
  - An arm is a combination of GBs
  - Ex: 3 GBs: 2^3 = 8 possible arms



Bandit Algorithm: Step 1

- **Initialization:**
  - Set weights $w_i(t) = 1$ for $i = 1,\ldots,K$
- **Step 1: Choosing the Arm**
  - Probability of choosing each arm $p_i(t)$:
    - Tuning parameter γ helps decide the arm selection probability as a function of their weight:
    - Set g = number of rounds of the arm selection
  - CR user s sends packet PKT_q to intended receiver r on the CCC by selection of the q^{th} arm

$$p_i(t) = (1-\gamma)\cdot\frac{w_i(t)}{\sum_{j=1}^{K} w_j(t)} + \frac{\gamma}{K}$$

$$\gamma = \min\{1, \sqrt{\frac{K\ln K}{(e-1)g}}\}$$

Bandit Algorithm: Step 2

- **Step 2: Assigning the Reward**
  - Receiver r receives PKT_q and identify the set of I
    - I: Set of subcarriers whose signal power exceeds interference threshold
  - Reward assigned by the receiver R_c:

$$R_c^q = \left[1 - \frac{|I|}{m \cdot \nu}\right] \cdot \frac{m \cdot \nu + (N_g - \nu)}{m \cdot N_g}$$

    - v: number of guard bands used for the q^{th} arm
    - m: number of carriers in a guard band
    - N_g: number of guard bands
    - 1^{st} term: fractional number of interference-free subcarriers
    - 2^{nd} term: the ratio of current data rate to maximum possible data rate
  - Receiver r sends ACK packet with reward R_c back to CR user s by broadcast

Bandit Algorithm: Step 3

- **Step 3: Updating Arm Selection Probability**
  - Receiver receives PKT_q and identify the set of I
  - Weight update: $$w_j(t+1) = w_j \exp(\gamma \cdot \hat{R}_c^j(t)/K)$$
    - Scaled reward: $$\hat{R}_c^j(t) = \begin{cases} \frac{R_c^j(t)}{p_j(t)} & if\ j = q \\ 0 & if\ j \neq q \end{cases}$$
- **Go back to Step 1:**
  - For the next packet sent by the CR user s, the new weights are used in order to calculate the probabilities of choosing arms $p_i(t)$

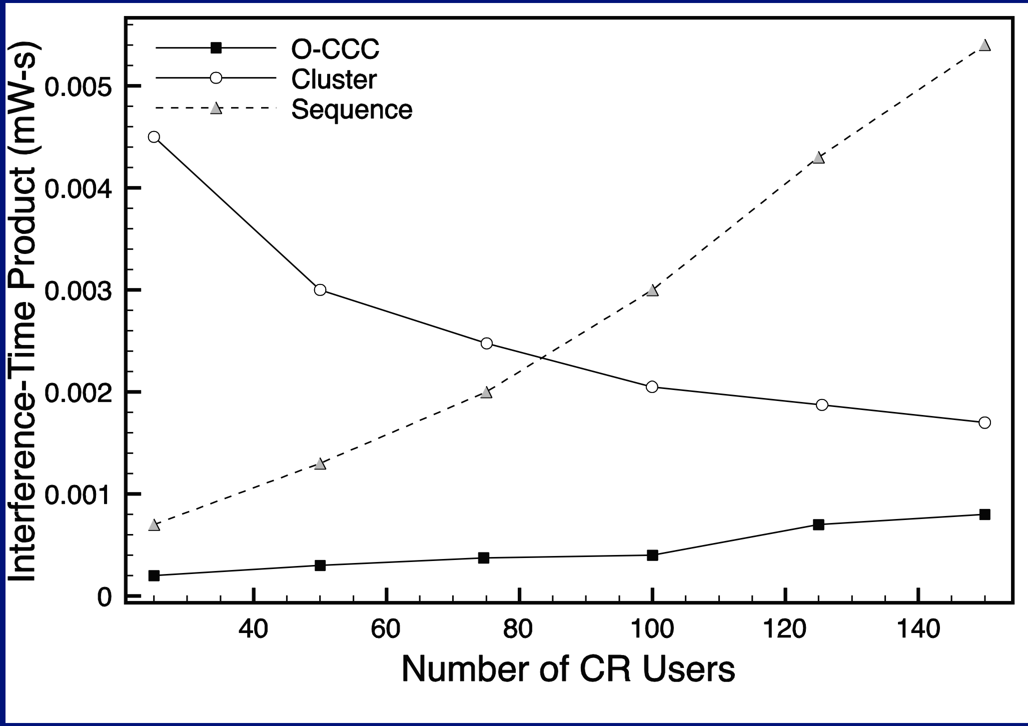
OFDM-based CCC: Performance Metrics

- **Broadcast Messaging**
  - Interference with PUs
  - Spectrum utilization efficiency
  - Throughput

- **Unicast Messaging**
  - Spectral interference
  - Fairness of subcarrier selections
  - Rewards

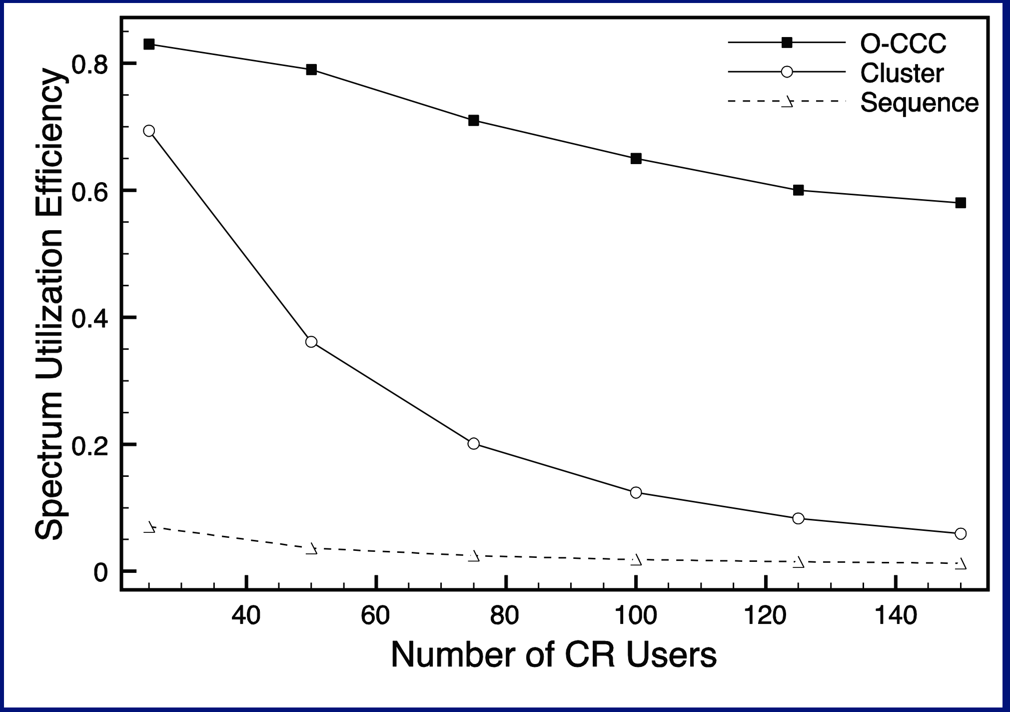
Broadcast Performance: Interference with PUs

- Interference-Time Product Ω
  - Product of interference caused to PUs and the time for which this interference in effect
    - **Cluster (SI-based):** the preference of neighbors outside PU range outweighed the choice of the CR user, leading to higher local interference
    - **Sequence (Seq Rendezvous):** each CR user must successively synchronize with all neighbors in turn, leading to high Ω



Broadcast Performance: Spectrum Efficiency

- **Spectrum Utilization Efficiency**
  - Measure the ratio of time spent in useful transmission to total time needed
    - O-CCC: gradual decrease with no. of users due to guard time per OFDM symbol (to reduce multipath effect)
    - Cluster: several rounds of message exchange before a CCC is determined
    - Sequence: lowest utilization due to channel hopping in discrete intervals
      - Next channel is switched only after current hopping duration is completed

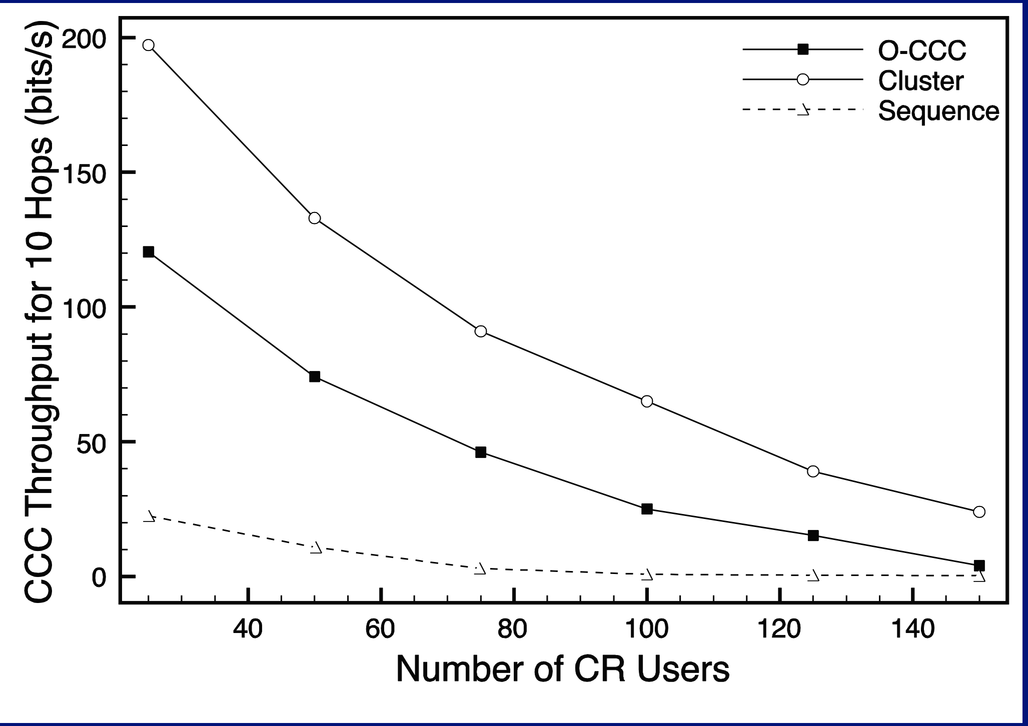


Broadcast Performance: Throughput

- Average Broadcast Throughput
  - For scenarios in which messages are forwarded over 10 hops
    - O-CCC: only a limited number of central subcarriers exist, lowering effective link bandwidth and end-to-end data rate

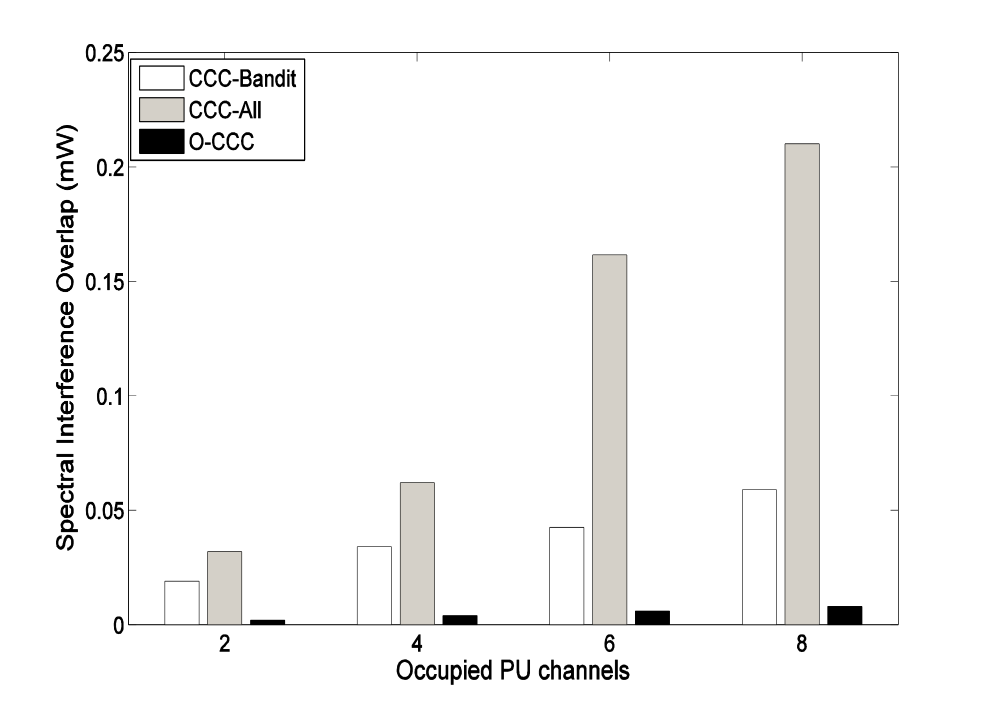
  → O-CCC lower than Cluster

    - Sequence: long synchronization time at each hop lowers the throughput significantly over multiple hops



Unicast Performance: Spectral Interference

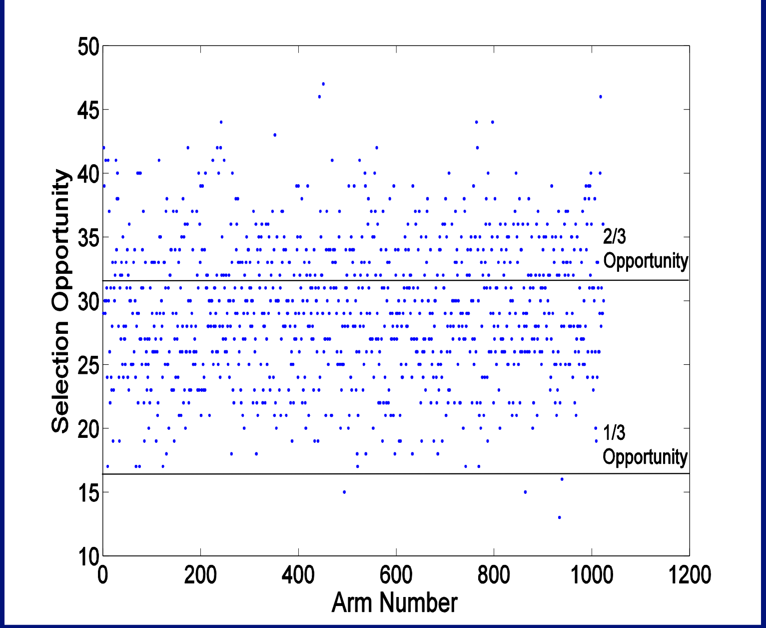
- Spectral Interference
  - Schemes for comparison
    - CCC-Bandit: using bandit algorithm
    - CCC-All: all subcarriers activated
    - O-CCC: the broadcast scheme
  - CCC-Bandit
    - Interference of CCC-Bandit is bounded between that of other two schemes
    - Low percentage increase in interference
    - For a given PU occupancy, CCC-Bandit dynamically converges on the best set of guard bands

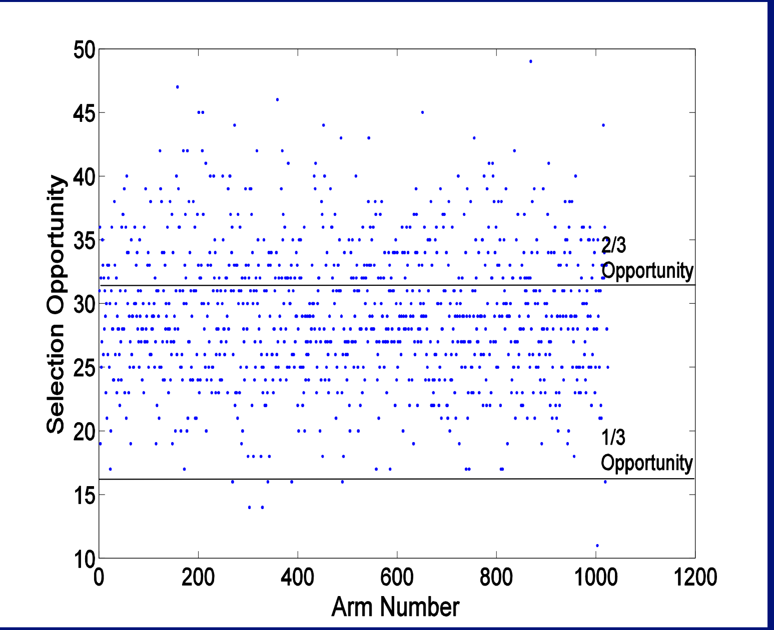


Unicast Performance: Fairness of Selections

- **Fairness of Subcarrier Selections**
  - Spectrum opportunity Γ: number of trials undertaken for each arm
    - Most of the arms lie in the range of 1/3 to 2/3 of the maximum possible Γ
    - Outliers are very limited

2 occupied PU channels





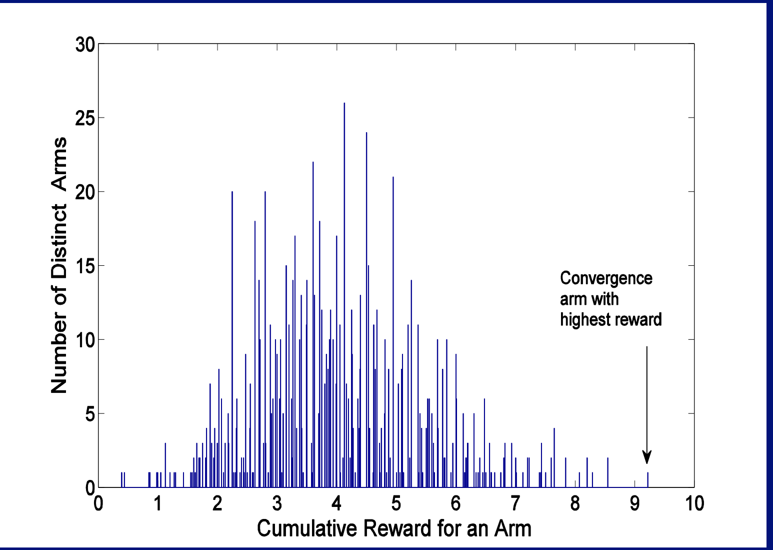
6 occupied PU channels

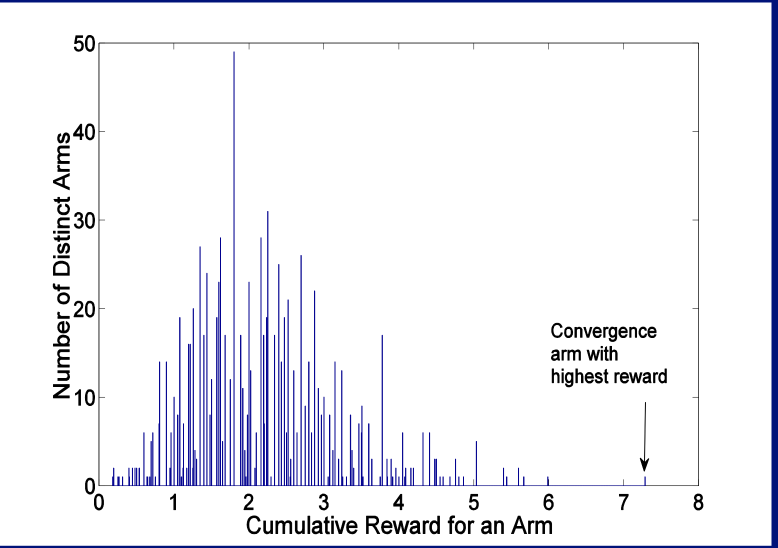
Unicast Performance: Rewards

- **Cumulative Rewards**
  - Convergence to the best channel is slow when number of affected channels is small (Top Fig.)
    - Higher rewards being accumulated by several different arms
  - Convergence to the best possible combination is speeded up as number of affected channels increases (Bottom Fig.)
    - Most of the arms incur a reward lower than 2
    - Very few arms with maximum reward earned

➔The procedure identifies the best arm combination over time and exploits it over the others

2 occupied PU channels





6 occupied PU channels

Efficient Recovery Control Channel (ERCC)

B. F. Lo, I. F. Akyildiz, and A. M. Al-Dhelaan, "Efficient recovery common control channel design in cognitive radio ad hoc networks," IEEE Trans. Vehicular Technology, vol. 59, no. 9, Nov. 2010.

- **Heuristic Distributed CCC Solution**
  - Establish and maintain a common channel list (CCL)
  - Exchange CCL with neighbors
  - Utilize CCL for recovering CCC if current one occupied by PUs

- **Design Goals**
  - Responsiveness to PU activity
  - Improved CCC coverage
  - Reduced overhead for CCC establishment

ERCC: Motivation

- **Channel Availability**
  - CR users in a neighborhood observe similar channel availability
- **Common Channels**
  - Finding common channels is similar to finding longest common subsequences
- **CCC Recovery**
  - Efficient recovery from PU activity can be achieved with well-designed and updated common channel lists and neighbor information

ERCC in Actions

- Neighbor Discovery
  - Establish initial network topology and CCL
  - Establish connection in case of losing neighbors due to PUs
- Common Channel List Update
  - Update channel and neighbor information regularly with local and neighbor's channel availability
- Efficient CCC Recovery from PU Activity
  - Recover the majority of neighbors efficiently by using common channel list

ERCC: Neighbor Discovery

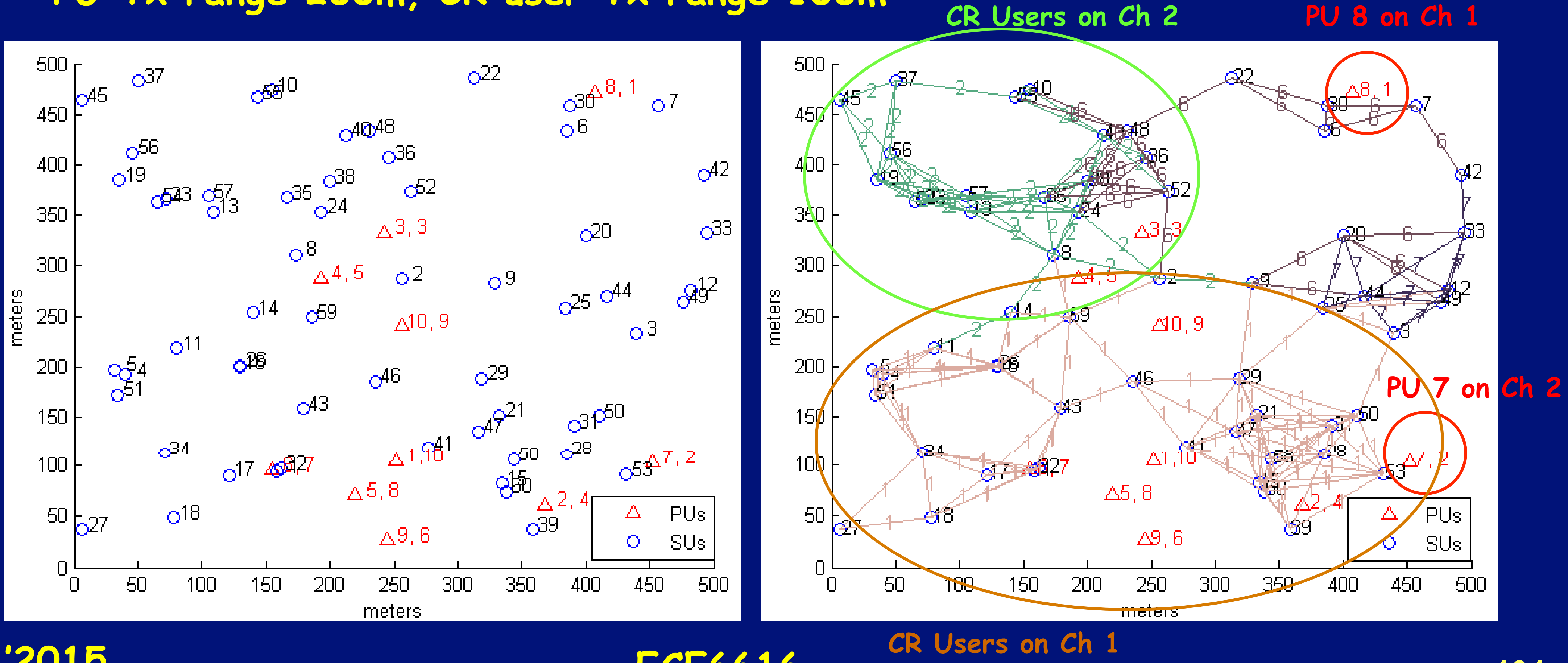
- Channel Hopping for Neighbor Discovery
  - Neighbors rendezvous on common channels of good channel quality in the neighborhood with higher probability
  - Neighbor pair exchanges common channel list after rendezvous
- Algorithm
  - Sequence generated from uniform distributed random numbers
    - Common channel list L_C of length n
    - Probability of selecting C_i:

$$\Pr(C_i) = \frac{n+1-i}{\sum_{j=1}^{n} j} = \frac{2(n+1-i)}{n(n+1)}$$

    - Value of CDF at $C=C_i$ is $F_C(C_i)$
    - Given a sequence of random numbers r_m, m=1,2,…
      $S_m = C_i$ for $F_C(C_i-1) < r_m \leq F_C(C_i)$

Example: Neighbor Discovery and Initial Network Topology

10 PUs, 60 CR users, 10 channels, one PU per channel
PU Tx range 200m, CR user Tx range 100m



ERCC: Common Channel List Update

- **Advantages of Common Channel List**
  - Selecting the channel common to the largest number of neighbors as the control channel increases CCC coverage
  - When a PU occupies the current CCC, the common channel with the highest preference from the list can be immediately allocated as the new control channel

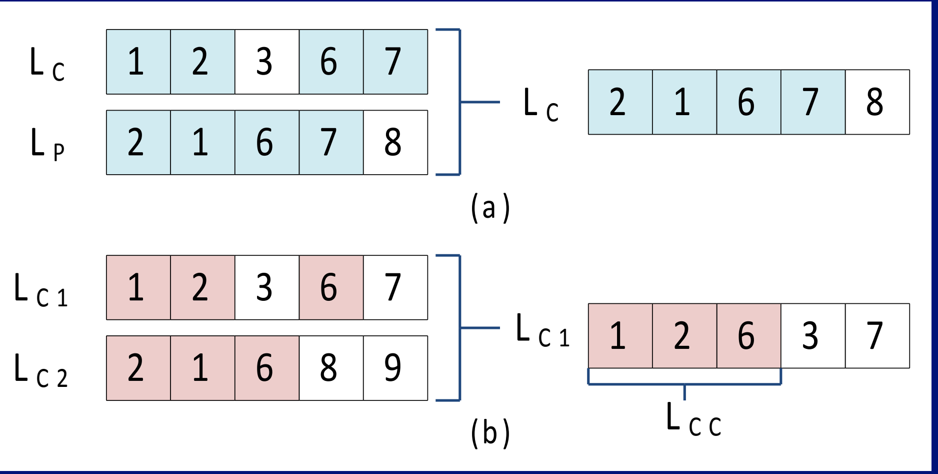
ERCC: Common Channel List Update

- **Update with Local Sensing Information**
  - PU activity affects channel availability
    - Channels in the list may be no longer available
    - New channel opportunities may be available
  - Periodic local sensing to obtain latest channel availability

- **Update with Neighbors' Information**
  - Determine a list of common channels shared with neighbors
  - Collect and combine neighbors' common channel preference for dissemination of CCC candidates

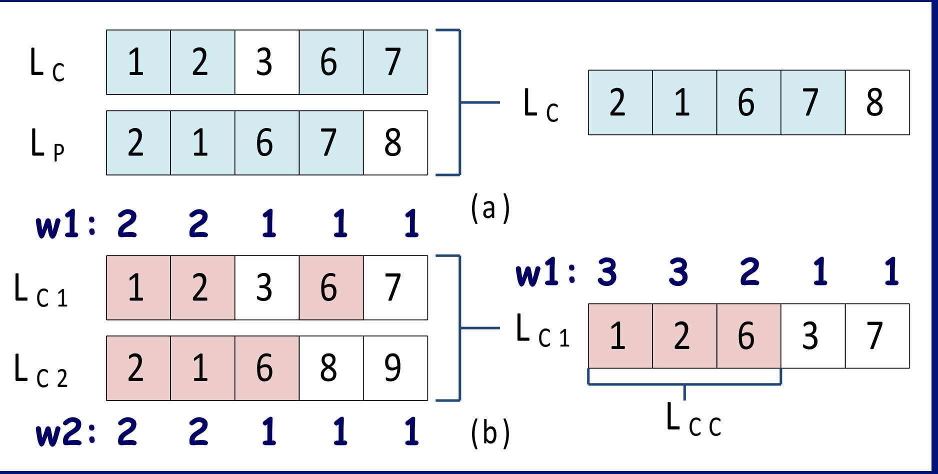
ERCC: Common Channel List Update

- **Update with Sensing Information**
  - Obtain a preferred channel list L_P from spectrum sensing
    - L_P is a channel list of observed quality in monotonically decreasing order
  - Add new available channels
  - Remove channels no longer available
  - Example: Figure (a)
    - Compare a L_p to a CCL L_C
    - Ch3 is no longer available
    - Ch8 is newly available
    - Note that the order is preserved in the updated list



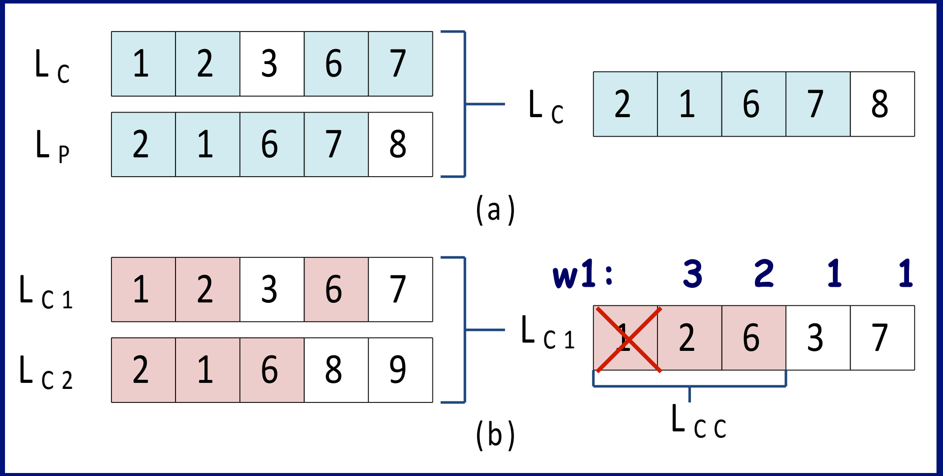
ERCC: Common Channel List Update

- Update with Neighbor's Information
  - Broadcast local CCL and receive CCL broadcast from neighbors
  - Find the largest number of common channels from two CCLs
  - Sort new list based on channel weights and channel quality (interference level)
    - Channel weight (w): Number of neighbors reached by the channel
    - Channel quality: Conversely proportional to accumulated interference with surrounding PUs
  - Example: Figure (b)
    - L_{C1} is local and L_{C2} is from a neighbor
    - Ch3 & Ch7 are locally available
    - They are included in the list for broadcast



ERCC: Efficient Recovery from PU Activity

- PU's Return to CCC
  - Example: Figure (b)
    - CCC is Ch 1 between CR user 1 and 2
    - PU returns to Ch1
    - Both CR users 1 & 2 change CCC to Ch2 without communicating with each other
    - CR users 1, 2, and others rendezvous on Ch 2
    - Most neighbors are recovered on Ch2 immediately



ERCC Performance Metrics

- **CCC Link Indicator (CLI)**
  - Percentage of CCC links over all available links
  - Indicate how fast CR users establish links with new neighbors and recover links with old neighbors
  - Evaluate neighbor discovery rate and the responsiveness to PU activity
- **CCC Coverage Indicator (CCI)**
  - Normalized standard deviation of control channel distribution over all licensed channels
  - Indicate the footprint of CR users sharing a CCC
    - CCI achieves unity when all CCC links in the network are established in the same channel

ERCC Performance Metrics

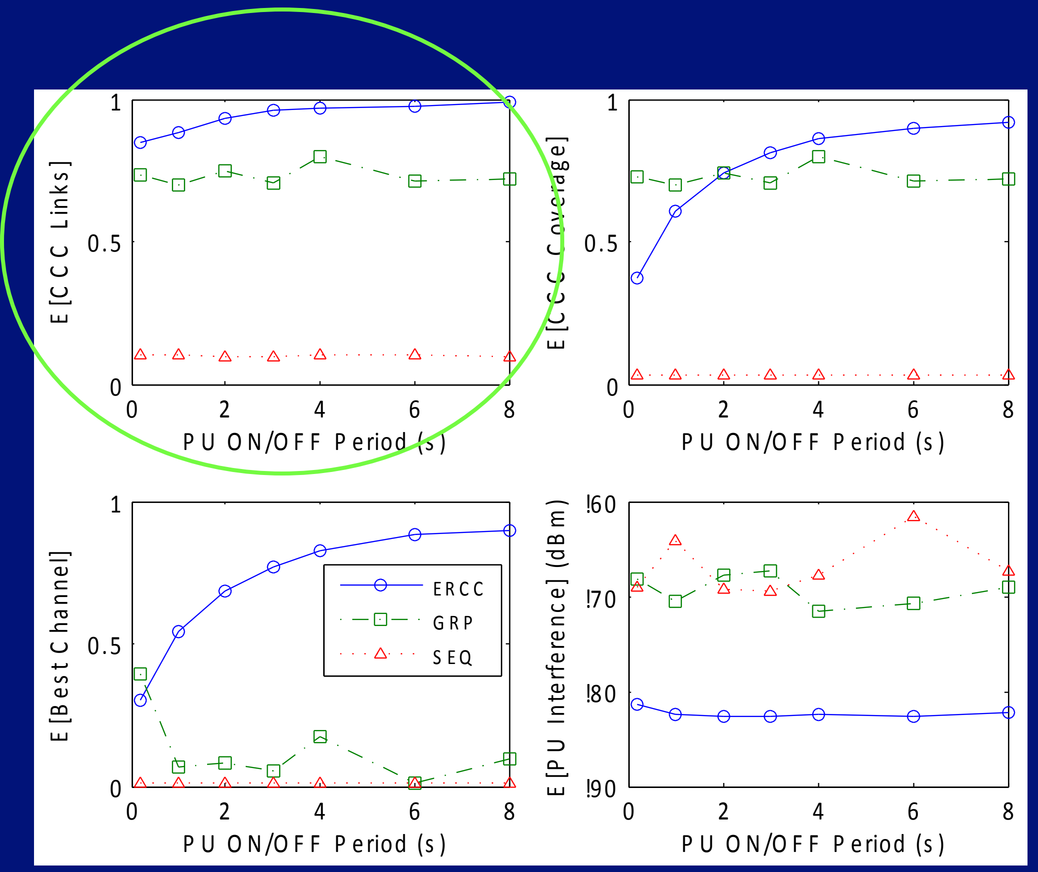
- **Best Channel Indicator (BCI)**
  - Percentage of CCC links to which the best quality channel observed at each CR user is allocated
  - Indicate the quality and reliability of CCC selections
- **Average PU Interference Level (PUI)**
  - Average accumulated interference from PUs on the CCC
  - Indicates the average level of interference from PUs per SU during control transmission
    - Higher PUI implies higher possibility of PU activity in surrounding areas
  - Evaluate the level of achievable control throughput
    - The higher the PUI level, the lower the control throughput

ERCC Performance Evaluation

- Test Cases
  - PU ON/OFF period
  - PU transmission range
  - PU density as the number of PUs per channel
  - SU transmission range
  - Scalability or density of SU population
  - Shadow fading for a range of decibel spread
- Comparison
  - GRP: Swarm intelligence-based CCC assignment
  - SEQ: Sequence-based rendezvous

ERCC Test Case: PU ON/OFF Period

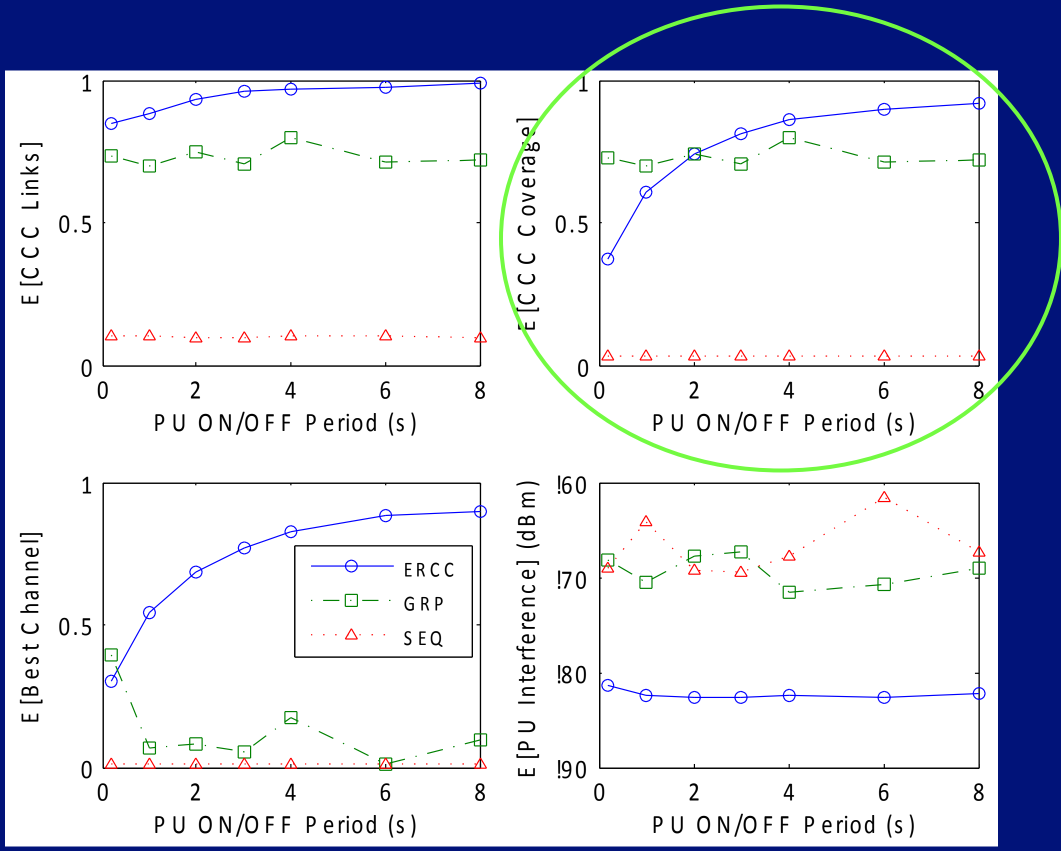
- **CCC Link Indicator (CLI)**
  - ERCC: above 0.8 and close to 1 for medium and low PU activity
  - GRP: at most 0.8
  - SEQ: low CLI values
- **CLI shows Strengths of ERCC**
  - Maintain network connectivity under PU activity
  - Recover CCC efficiently upon PU's return to CCC



ERCC Test Case: PU ON/OFF Period

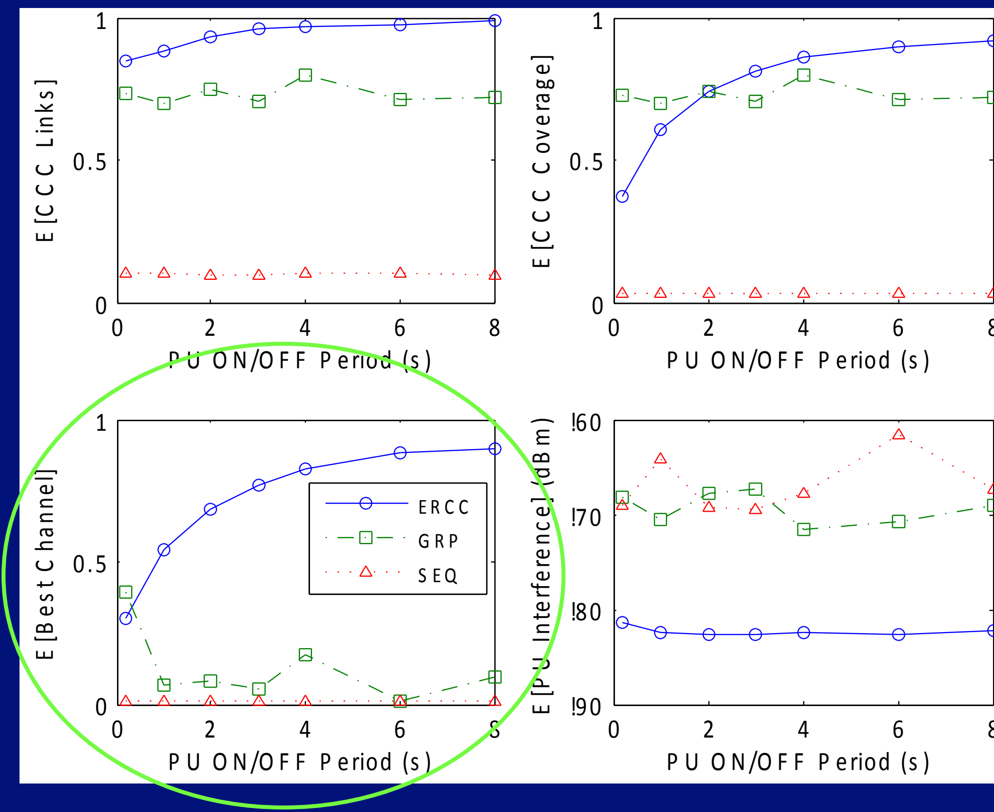
- CCC Coverage Indicator (CCI)
  - For high PU activity, GRP has higher CCI than ERCC
  - For medium and low PU activity, ERCC outperforms GRP
  - SEQ has considerably low CCI value

- ERCC
  - Better balance between coverage and interference avoidance than GRP
  - Extend the coverage with the selection of higher quality CCC



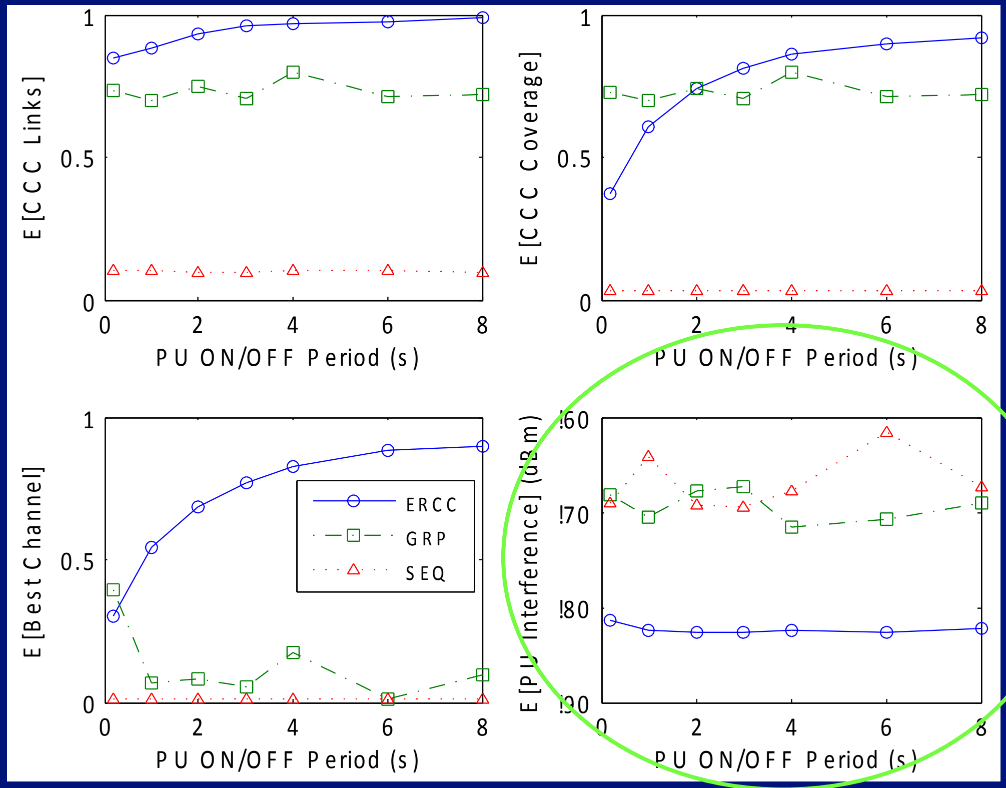
ERCC Test Case: PU ON/OFF Period

- **Best Channel Indicator (BCI)**
  - For high PU activity, ERCC and SI are comparable
  - For medium and low PU activity, ERCC outperforms SI
  - SEQ has considerably low BCI value
- **ERCC**
  - Higher quality CCC selection for increasing coverage and reducing interference



ERCC Test Case: PU ON/OFF Period

- **PU Interference (PUI)**
  - ERCC: Consistently low interference with PUs
  - GRP and SEQ cause significantly higher interference
- **ERCC**
  - Less susceptible to PU's interference
  - Balance among robustness to PU activity (CLI), broadcast operations (CCI), CCC reliability (BCI), PU protection and control throughput (PUI)



CCC Research Challenges

B. F. Lo, "A survey of common control channel design in cognitive radio networks," Physical Communication (Elsevier) Journal, vol. 4, no. 1, March 2011.

- **Sequence-based CCC Challenges**
  - Hopping Sequence design for PU activity and CCC coverage
    - Existing schemes react to PU activity after sequences are constructed
    - Existing designs seldom consider control broadcast in hopping sequences
- **Group-based CCC Challenges**
  - Effective intergroup communications
    - Without reliable inter-group communications, CR network may be partitioned into isolated groups
  - Efficiency of regrouping
    - Regrouping efficiency are crucial to the responsiveness to PU activity

CCC Research Challenges

B. F. Lo, "A survey of common control channel design in cognitive radio networks," Physical Communication (Elsevier) Journal, vol. 4, no. 1, March 2011.

- **UWB CCC Challenge**
  - Spreading code design for range-rate tradeoff
    - Spreading code can be utilized to group CR users for cooperation and balance the tradeoff between range and data rate
    - Required control message rate may be compromised by the spreading sequences for enlarging transmission range
- **Control Channel Security Challenge**
  - Impact of Jamming on PU Activity
    - PUs are also under attack when CR users are attacked
    - CCC challenges when PU activity changes due to jamming