CHAPTER 11.
CR ROUTING ALGORITHMS

Routing in CR Networks

- Routing involves setting up of the optimal packet forwarding path between a source and destination
  - Involves finding the set of nodes that are in the optimal path (route setup)
  - Adapting to the changes in the network environment (route reconfiguration)
- Key challenge:

Maximize the end-to-end performance without affecting the PU's operations

Differences in Routing between CR and Classical Wireless Networks

- Classical routing protocols require either local or global broadcast messages for specific functionalities, such as

  neighbor discovery, route discovery, route establishment, route maintenance.

- Broadcasting is a major problem (no CCC) in CR networks.

Differences in Routing between CR and Classical Wireless Networks

- In classical networks, only the path is optimized.
- In CR networks both the path, as well as the spectrum on each link of the path, must be decided during route setup
- The need for external environment information in CR networks is significantly larger
  - PU information, traffic statistics, channel characterization
- Routing is necessarily cross-layered in CR networks

Differences in Routing between CR and Classical Wireless Networks

Traditional Routing Metrics	Cognitive Routing Metrics
Number of hops between source-destination	Spectrum availability along the chosen path for long durations
Energy Constraints	Handoff frequency between channels that may increase route latency
Link quality in terms of PER/RSS	
Application specified QoS deciding longer/shorter paths	

Differences in Routing between CR and Classical Wireless Networks

Traditional Packet Forwarding

- Geographical and location based, greedy progress algorithms
- Graph theory based;
  e.g., best connected backbone in the network
  - Connected Dominating Sets

Cognitive Packet Forwarding

- History of the PU users along the route,
  e.g., Tx frequency, specific activity time during the day
- Information contained at the CR about the path
  - PU location,
  - PU transmission technology (GSM, CDMA etc)

ROUTING CHALLENGES

M. Cesana, F. Cuomo and E. Ekici
"Routing in Cognitive Radio Networks: Challenges and Solutions",
Ad Hoc Networks (Elsevier) Journal, Volume 9, Issue 3, May 2011.

1. Spectrum Awareness

2. Routing Quality

3. Route Maintenance

CHALLENGE 1: Spectrum Awareness

- Routing module must be aware (cognitive) of the surrounding spectrum availability.

- **Two possible scenarios:**

  information on the spectrum occupancy
  - provided by external entities (i.e., database of white spaces of TV towers)
  - locally acquired by each CR user through distributed sensing mechanisms

CHALLENGE 2: Setting up "Quality" Routes

- A measure of the "route quality" must be available for selecting the optimal path.

- Classical route quality metrics
  (nominal BW, throughput, delay, etc.)
  must be coupled with novel measurements
  (path stability, spectrum availability, PU activity, etc.).

Setting up "Quality" Routes

Three possible scenarios:

- Low PU activity
  - CR topology almost unaffected by the PU activity
  - Classical routing metrics can be leveraged
- Moderate PU activity
  - CR topology depends on the PU activity
  - Routing metrics designed for CR networks are required
- High PU activity and high PU density
  - CR user topology is with high probability disconnected
  - Routing metrics for disconnected networks could be leveraged

CHALLENGE 3: Route Maintenance/Repair

- Route failures due to:
  - PU activity
  - Wireless channel propagation effects
  - Node mobility
- The "appearance" of a PU may render a certain spectrum band unusable in a certain area
  - re-routing either in terms of nodes or channels is needed

Route Maintenance and Repair

PU Activity vs Wireless Channel Propagation:

- Spectrum band affected by PU activity:
  CR user should
  - stop the transmission
  - reduce the power for that band.

- Spectrum band affected by fading effects:
  CR user should
  - increase the power
  - adopt more effective techniques (network coding, relaying, etc.)

Route Maintenance and Repair

PU Activity vs Node Mobility:

- PU Activity
  - has local and temporary (periodic) effects on the surrounding topology of a CR user.
  - makes a certain spectrum band unusable for a certain time, but the neighborhood does not change.

- CR User Mobility
  - can have global and permanent effects on the surrounding topology of a CR user.
  - changes the neighborhood of a CR user.

Route Maintenance and Repair

PU activity effects in terms of route failures

- are significantly different from those generated by the wireless propagation or by the node mobility
- require effective and dedicated signaling procedures to restore the connectivity “broken” by the PU activity

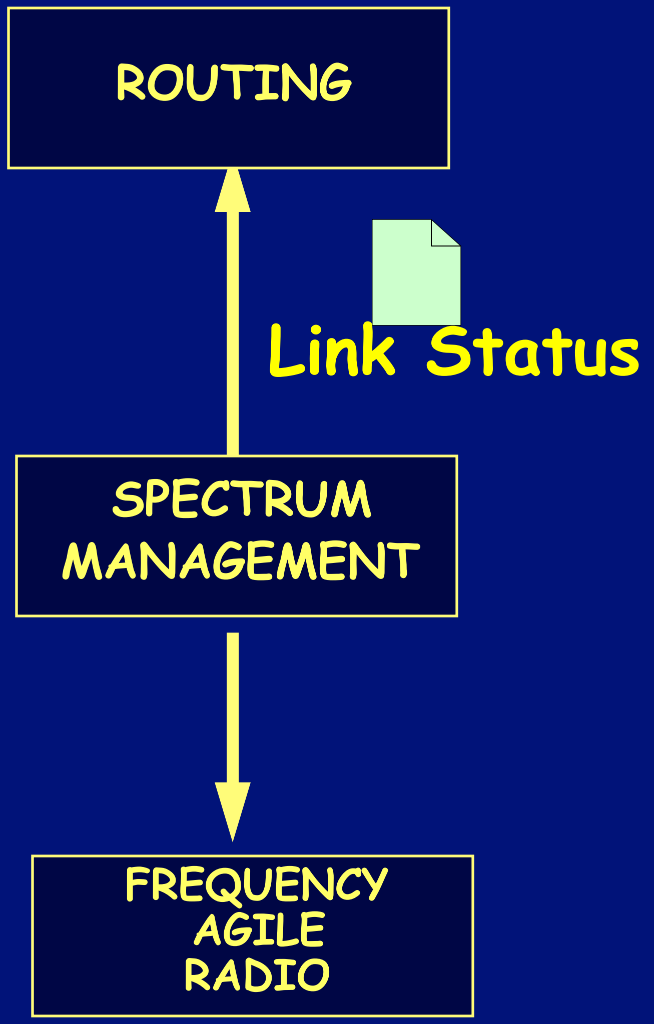
ROUTING vs SPECTRUM MANAGEMENT

Q. Wang and H. Zheng,
"Route and Spectrum Selection in Dynamic Spectrum Networks",
Proc. of the IEEE CCNC, pp. 625-629, 2006.

- **Two Design Trends:**
  - Decoupled Design (Route Selection and Spectrum Management)
  - Collaborative Routing and Spectrum Management

DECOUPLED DESIGN

- Minimum interaction between route selection and spectrum management
- Spectrum management first monitors spectrum usage in the neighborhood and identifies available spectrum and chooses an appropriate channel to use.
- Then the link status is reported to routing protocols in the network layer.
- Each device has a frequency agile radio which reconfigures RF to switch to the newly selected channel and uses the appropriate protocol and modulation on each channel.



Who Acts First?
(ROUTING FIRST)

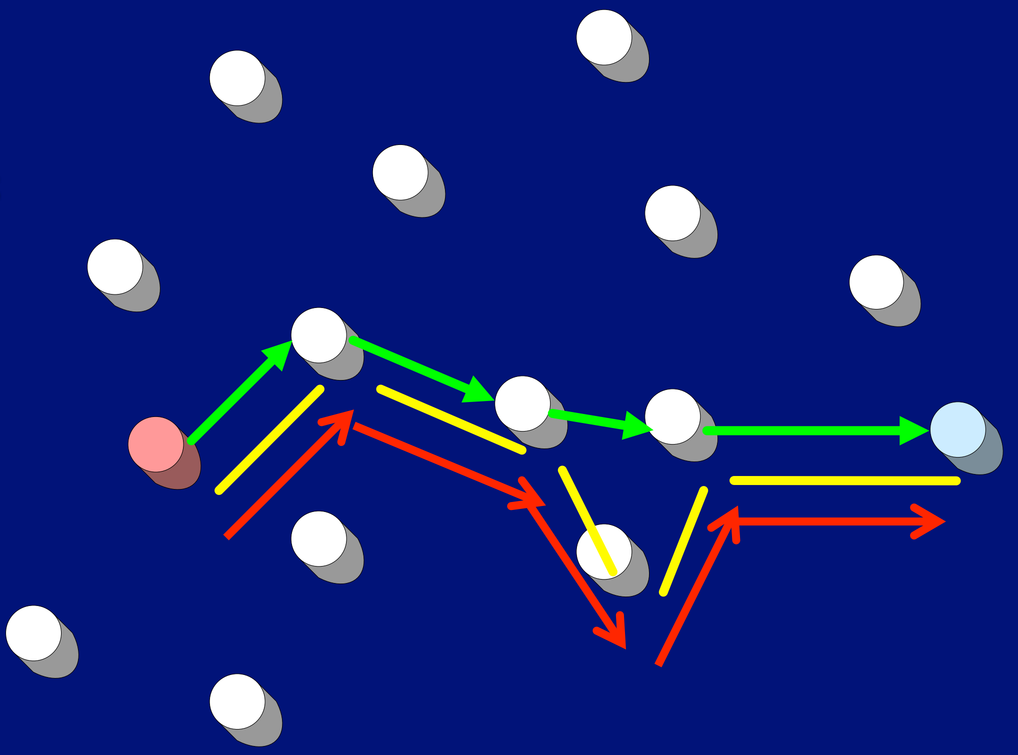
- **STEP 1: Route Selection**

  Source node invokes path discovery to collect information of the nodes and selects the path using a performance metric (shortest hop) (e.g., DSR)

- **STEP 2: Spectrum Management**

  Nodes on the selected path invoke MAC coordination protocol to schedule packet transmissions.

  In particular, each node pair on the route coordinates time and spectrum/channel for each transmission.



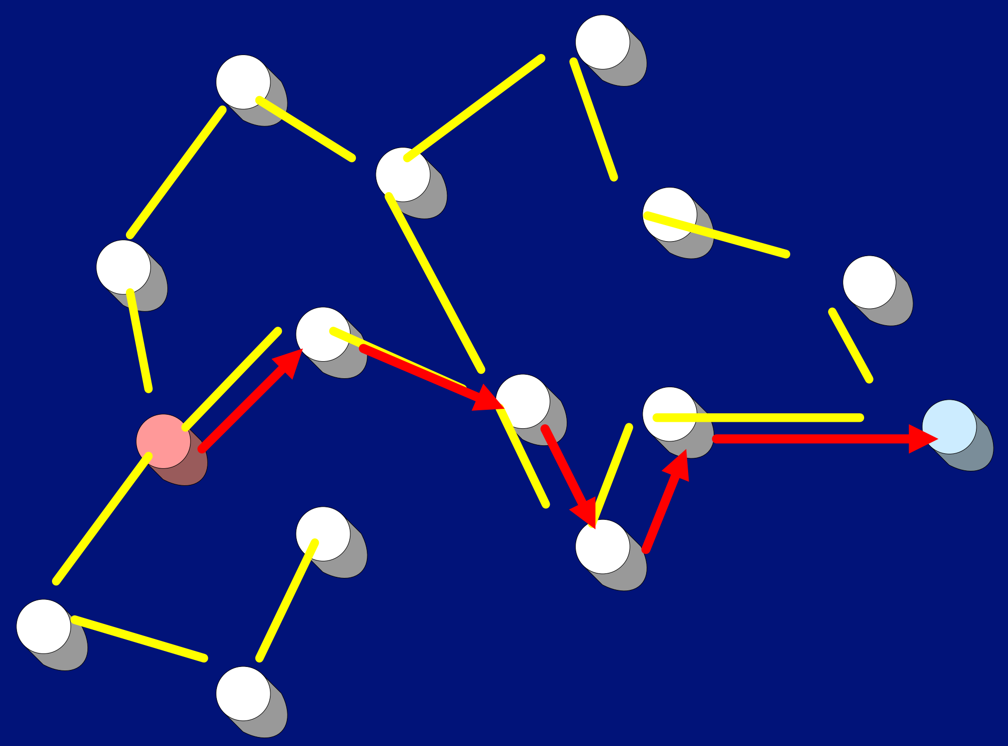
Who Acts First?
(ROUTING FIRST)

- Spectrum fluctuation is not considered
- Spectrum management can only select channels on the chosen route.
- It may create routes that are heavily affected by PU activity, because no route management schemes are proposed that may adapt to sudden PU occurrence

Who Acts First?
SPECTRUM MANAGEMENT FIRST

- Spectrum management first selects spectrum/channel and forms a connected network, then reports the link status to networking layer.

- Routing algorithm selects path based on the link status and other performance metrics
  (e.g., minimum hop number)



Who Acts First?
(SPECTRUM MANAGEMENT FIRST)

- This can guarantee quality of selected channels
  (PUs impact may be minimized)

- Routing acting later is limited to the network topology and the selected route may not be optimal !

Which One is Better?

- First acting algorithm has the dominant effect of the final performance.
- If PU users are very active, it is better to run spectrum management first.
- Otherwise, routing algorithm first.

Overall Problem of Decoupled Design

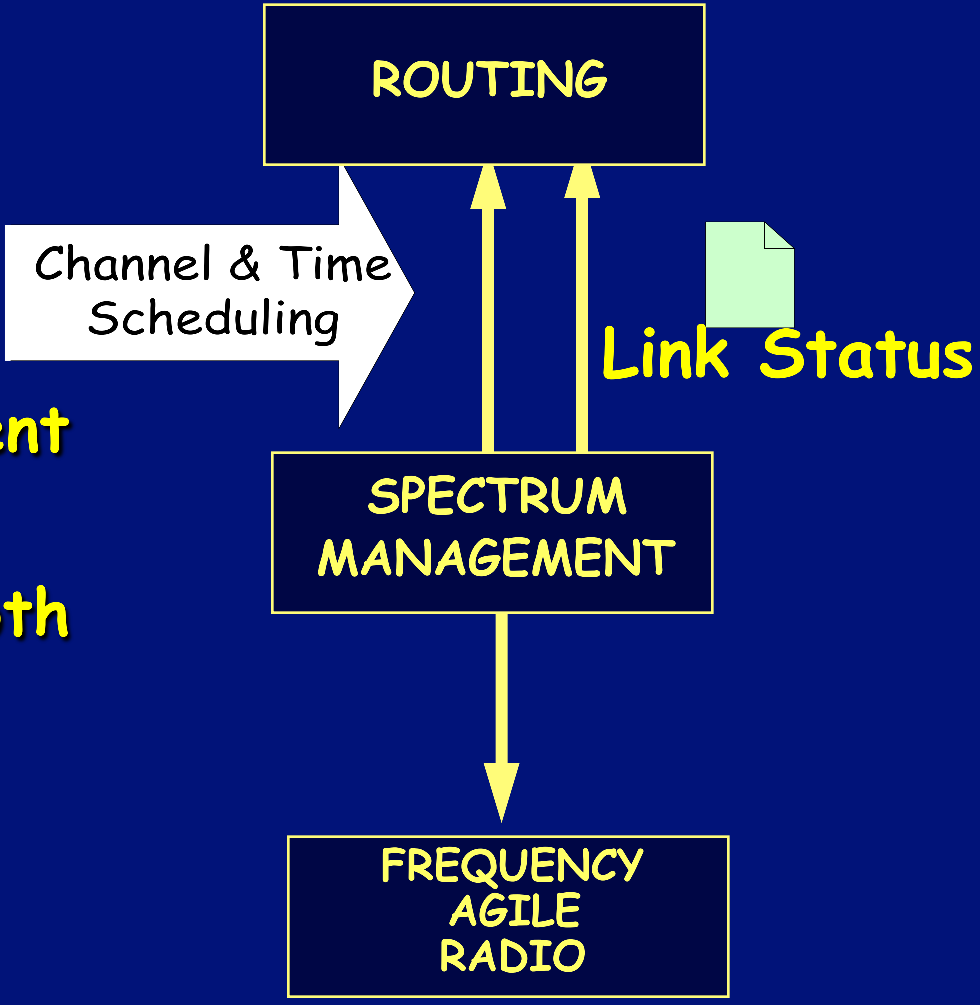
No matter whether routing or spectrum management plays dominant role, it cannot address

end-to-end optimization

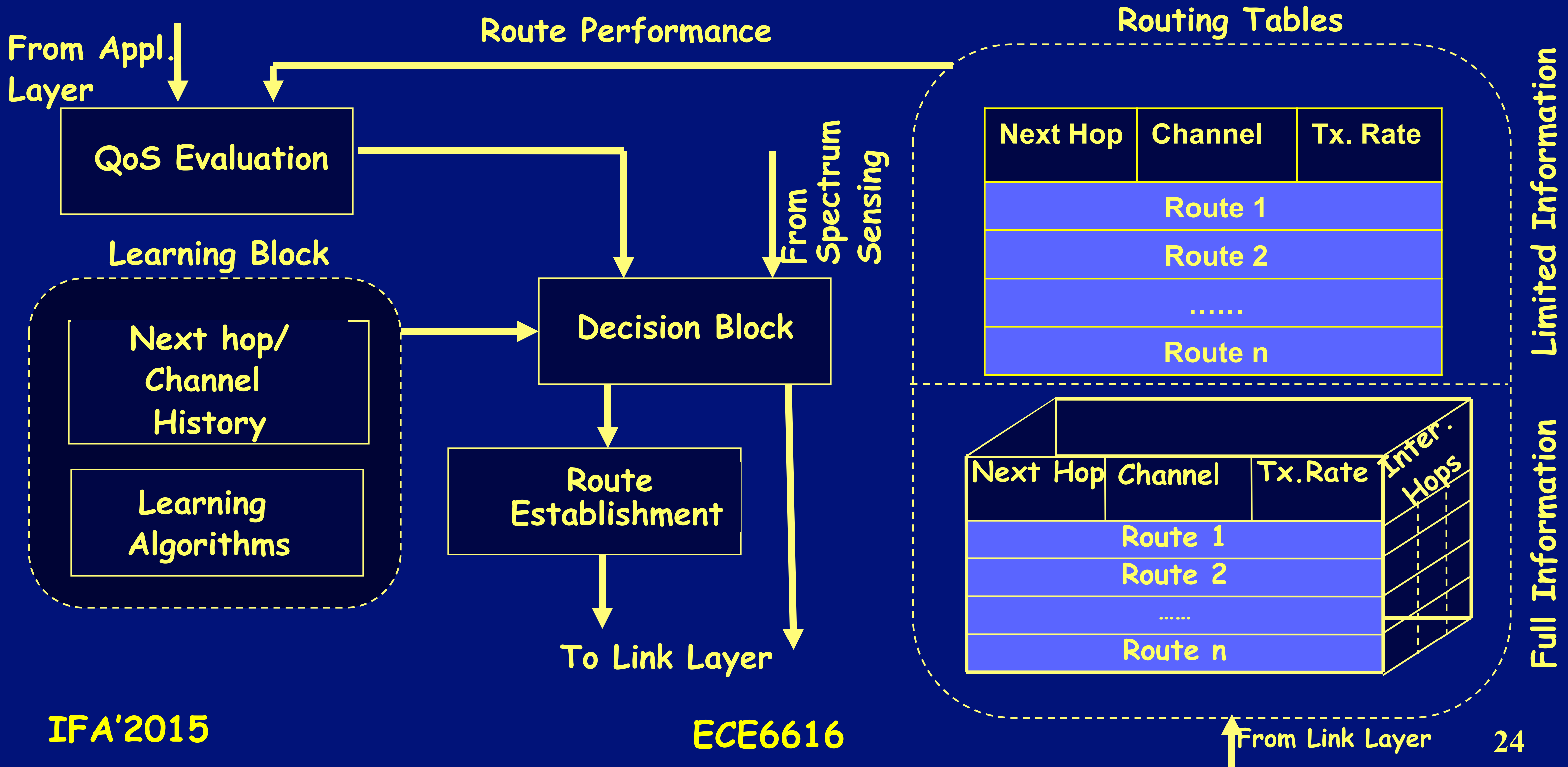
which is essential for multi-hop transmissions.

Collaborative Routing and Spectrum Management: for END-TO-END OPTIMIZATION

- Strong interdependence between routing and spectrum management
- Each source node makes a decision on both route and channel selection and a time schedule for each channel usage



Routing Framework for CR Networks



Routing Framework for CR Networks

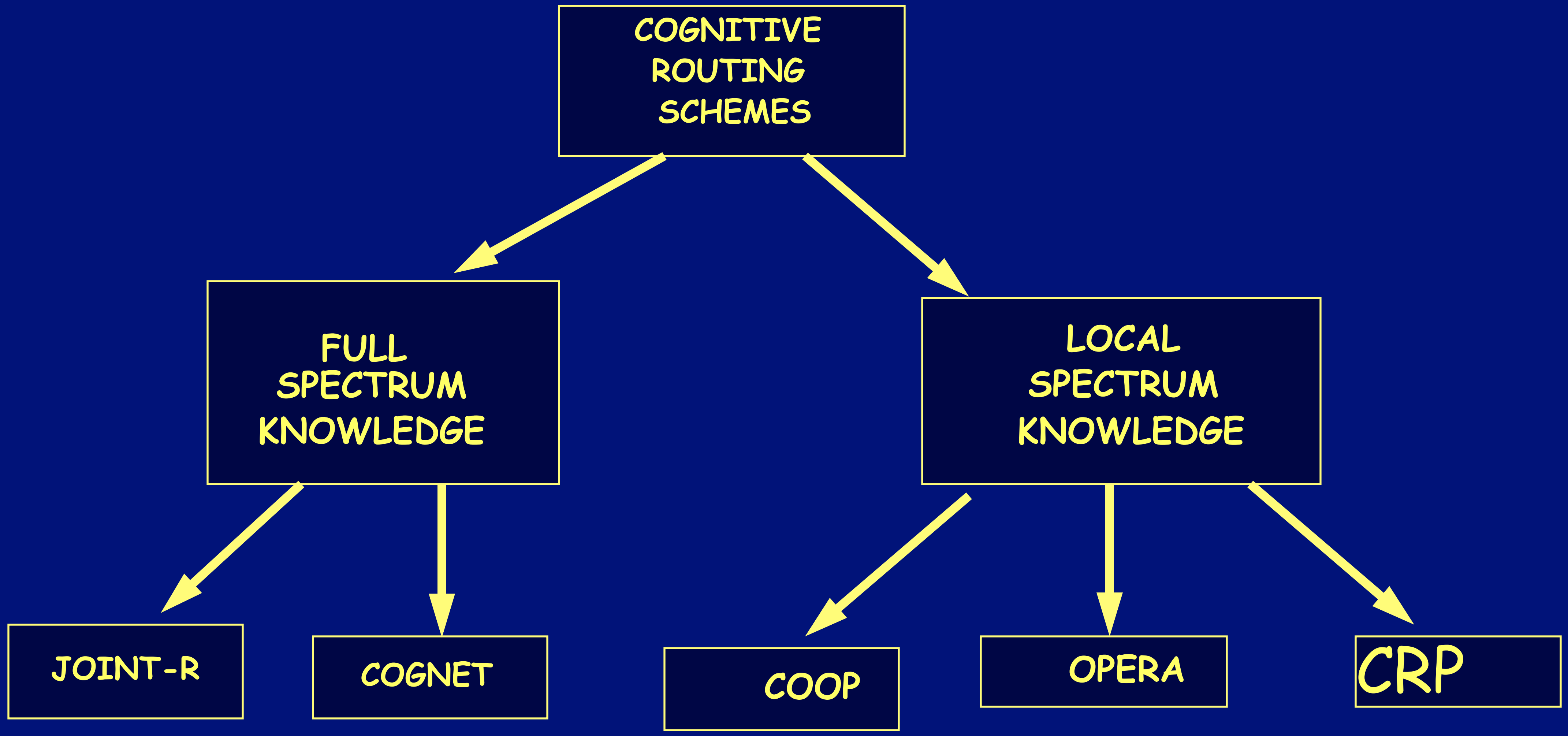
- In CR networks the Routing Table must be expanded to include the parameters that are unique to each link (full information)
  - e.g., channel, transmission rate, modulation.
  - In classical networks only the next hop is maintained (limited information)

- Decision Block chooses to alter an existing route or switch a channel in response to the changing environment
  - e.g., sensing inputs, path information and the current QoS

Routing Framework for CR Networks

- QoS Evaluation Block measures how close the current performance of the routing algorithm fares with the requirements specified by the application layer
- Route Establishment Block facilitates new route formation by issueing a fresh route request (RREQ)
- Learning Block tunes the working of the routing layer over time and helps the decision block to make progressively better channel and path switching decisions

Routing Protocols for CR Networks



Full-Spectrum Knowledge

In 2008, the FCC has promoted the opportunistic use of white spaces in the spectrum below 900MHz and in the 3GHz BW.

- FCC, FCC 08-260, Unlicensed Operation in the TV Broadcast Bands, November 2008.
- Each CR user is required to access to centrally-maintained spectrum databases to obtain the time and space channel availabilities.
- Thus, the route process can be decoupled from the spectrum management.

Local-Spectrum Knowledge

Information on "Spectrum Availability" is locally "constructed" at each CR through distributed sensing protocols

Routing is tightly coupled to the spectrum management

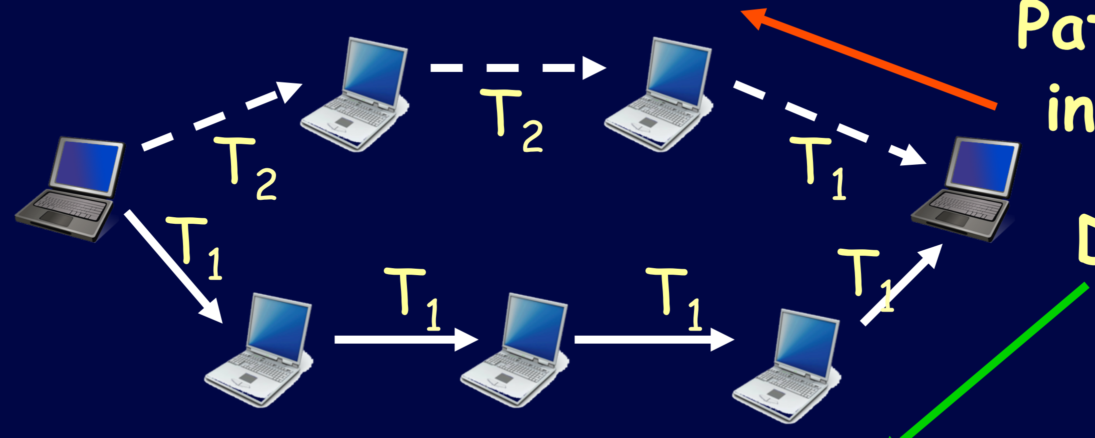
Besides computation of routing paths, routing module should be able to acquire network state information

Routing Protocols for CR Networks

	Whole Path Selection	Next-hop Selection	Spectrum Awareness	PU Location-aware/Power Control	Reconfigurable to Varying Spectrum	Mobility Support	Relaying Support	Priority Classes
Joint-R	✔		✔					
CogNet	✔		✔	✔				
COOP		✔	✔	✔	✔		✔	
OPERA			✔	✔	✔	✔		
CRP		✔	✔	✔	✔	✔		✔

Joint Path-Spectrum Selection (Joint-R)

R. Pal,
"Efficient Routing Algorithms for Multi-Channel Dynamic Spectrum Access Networks," IEEE DySPAN 2007.



Path for sending RREP in classical routing protocols

Desired path with higher Tx rates

T_1 = 10 kbps, T_2=100 kbps

Route	Delay
1	2sec
2	5sec

TTL=3sec

Joint Path-Spectrum Selection (Joint-R)

- Besides routing metrics in traditional algorithms, Collaborative CR routing design has additional metric, i.e., spectrum fluctuations caused by PUs.

- Routing Metrics:
  - Capacity of the links
  - Available spectrum
  - Link disruption probabilities
  - Link propagation time

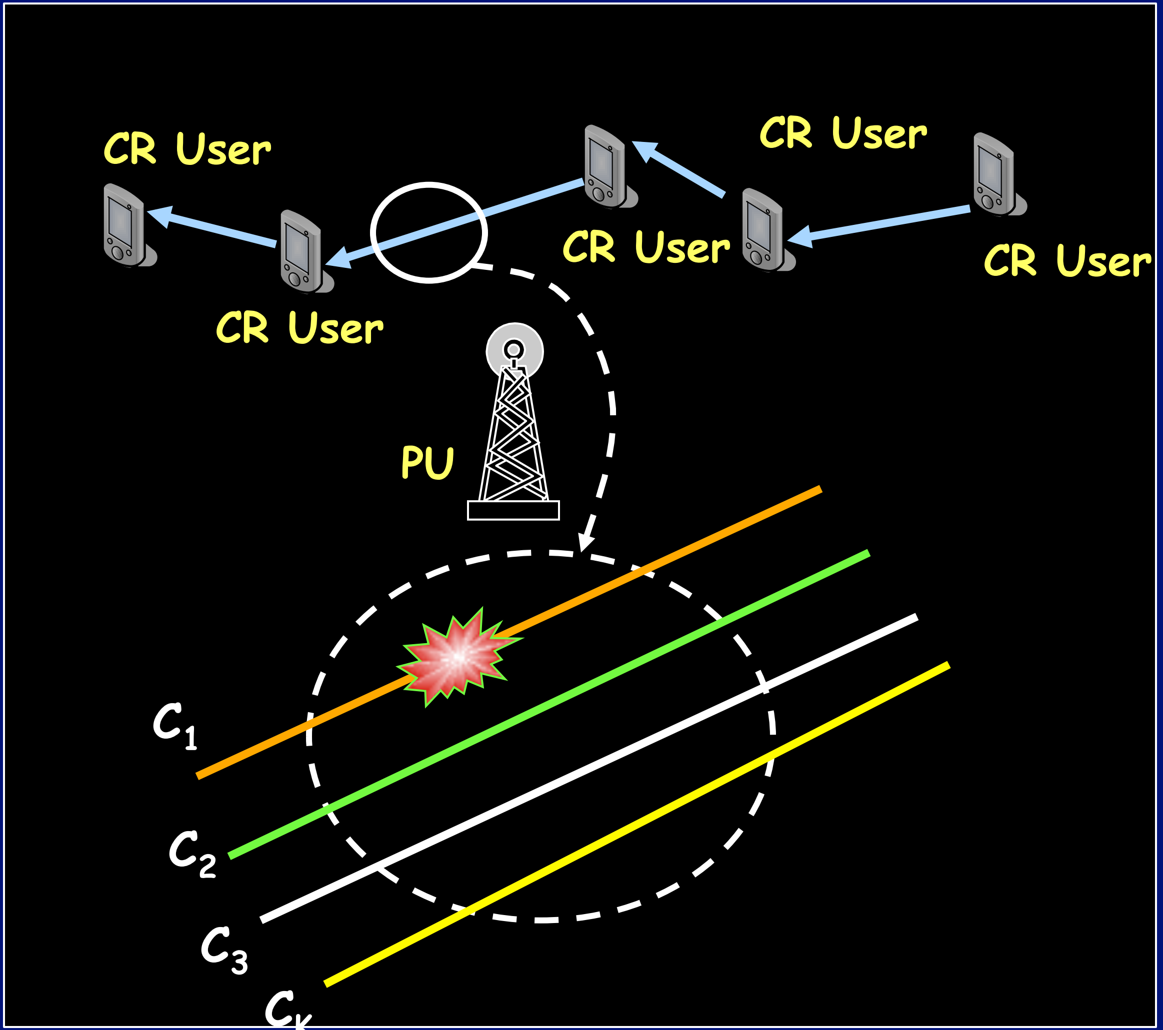
Joint Path-Spectrum Selection (Joint-R)

- Optimization Goal:
  - Minimize total average delay

    Determined by
    - Data amount
    - Mean capacity of the path
    - Total propagation delay

Network Model

- Several channels 1,…,k exist with varying capacities: c_1, c_2, … c_K
- Time is slotted, and each CR decides its Tx/Rx function at the start of the slot
- Assumes a spanning tree for broadcast of information



Spectrum Fluctuation on the Links

- On a particular link, at any time slot, each channel has a 0-1 (inactive-active) probability distribution.

  (Inactive → PU is occupying the channel); (Active → CR users can use the link).

- The distribution is assumed to be known through some estimation techniques. (e.g., from statistical record of PUs activity)

Capacity of the Links

Admittance probability p_i for link i is (prob. that channel from the set of available channels is free for communication of a CR user at any particular time slot):

$$p_i = 1 - \prod_{k=1}^{\psi} (1 - p_k^i)$$

# of orthogonal channels in the network

p_k^i : The probability that channel *k* on link *i* is free for use by CR user at any particular time slot.

C_i denotes the maximum capacity of link i

The expected/mean capacity of each link is given by: $p_i C_i$

Routing Metric

Send γ units of data from s to d on the path P with (s,u_1, u_2, ….., u_k, d) then

Total Average Delay = Propagation Delay + Transmission Delay

Propagation Delay of the route P is

$$pr_d(\gamma_P) = \frac{[d_{s,u_1} + \sum_{i=1}^{k} d_{u_i,u_{i+1}} + d_{u_k,u_d}]}{v}$$

γ_P amount of data through path p E P

γ amount of data shipped from source to destination

v is the velocity of electromagnetic signal and

d_{ij} is the physical length of the link (i,j) on the route P.

Routing Metric

Transmission Delay = Data Amount (Gamma) / Mean Capacity of the Path

Mean capacity of each link is given by $p_i C_i$
(p_i is the admittance prob of link i and C_i is the max capacity of link i).

p_i and the expected capacities are calculated for all links i in the NW.

Mean capacity of route/path P (from source to destination) is:

$$C_p(\gamma_P) = \min[c_{s,u_1}, \min_{1 \le i \le k-1}(c_{u_i,u_{i+1}}), c_{u_k,u_d}]$$

Optimization Function

Objective Function: Minimize the Total Average Delay:

$$t_d(\gamma_P) = pr_d(\gamma_P) + \frac{\gamma}{C_p(\gamma_P)}$$

γ → Data amount of route P

- First component → related to traditional routing
- Second one takes care of the requirements of DSAN

→ Simultaneous-act routing scheme

Conclusions and Drawbacks

- It tries to find an optimal route for only one data flow, not for the entire network.
- Hence it tends to route many data flows through some 'optimal' nodes, which may cause congestions and frequent channel switch
- Energy issues and mobility are not considered
- Channel switch delay is not considered
- Capacity of each channel may not be the same.

Routing Protocols for CR Networks

	Whole Path Selection	Next-hop Selection	Spectrum Awareness	PU Location-aware/Power Control	Reconfigurable to Varying Spectrum	Mobility Support	Relaying Support	Priority Classes
Joint-R	✔		✔					
CogNet	✔		✔	✔				
COOP		✔	✔	✔	✔		✔	
OPERA			✔	✔	✔	✔		
CRP		✔	✔	✔	✔	✔		✔

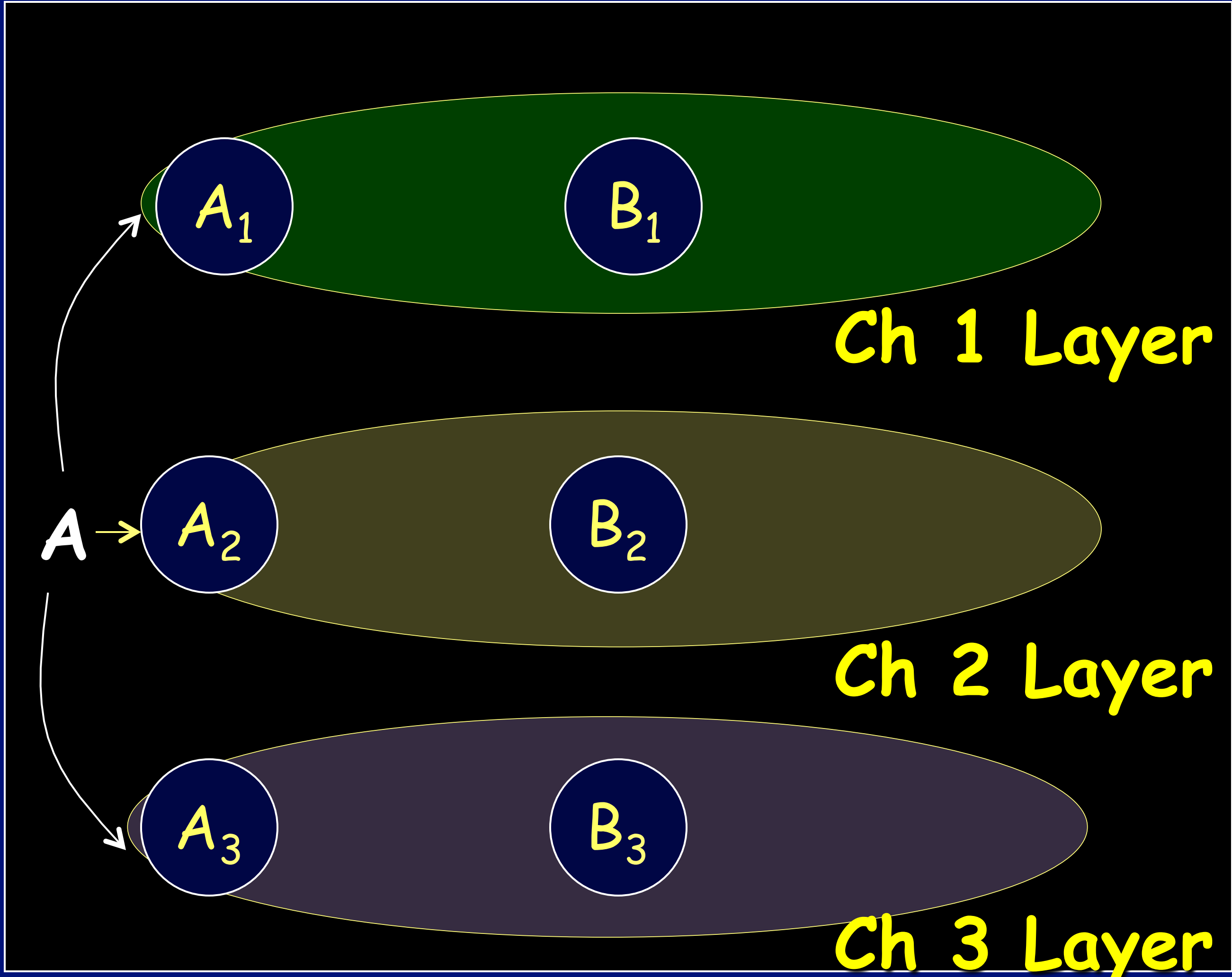
CogNet: A Layered Graph Model

C. Xin, L. Ma, C-C. Shen,
"A Path Centric Channel Assignment Framework for Cognitive Radio Networks,"
ACM/Springer Mobile Networks Applications Journal, Oct. 2008.

- Proposes a "path centric" channel assignment model, called as layered graphs
  - Path and the channel selection occur simultaneously
- Path to the destination can be computed using simple shortest path algorithms
  - Easy to implement but uses global knowledge

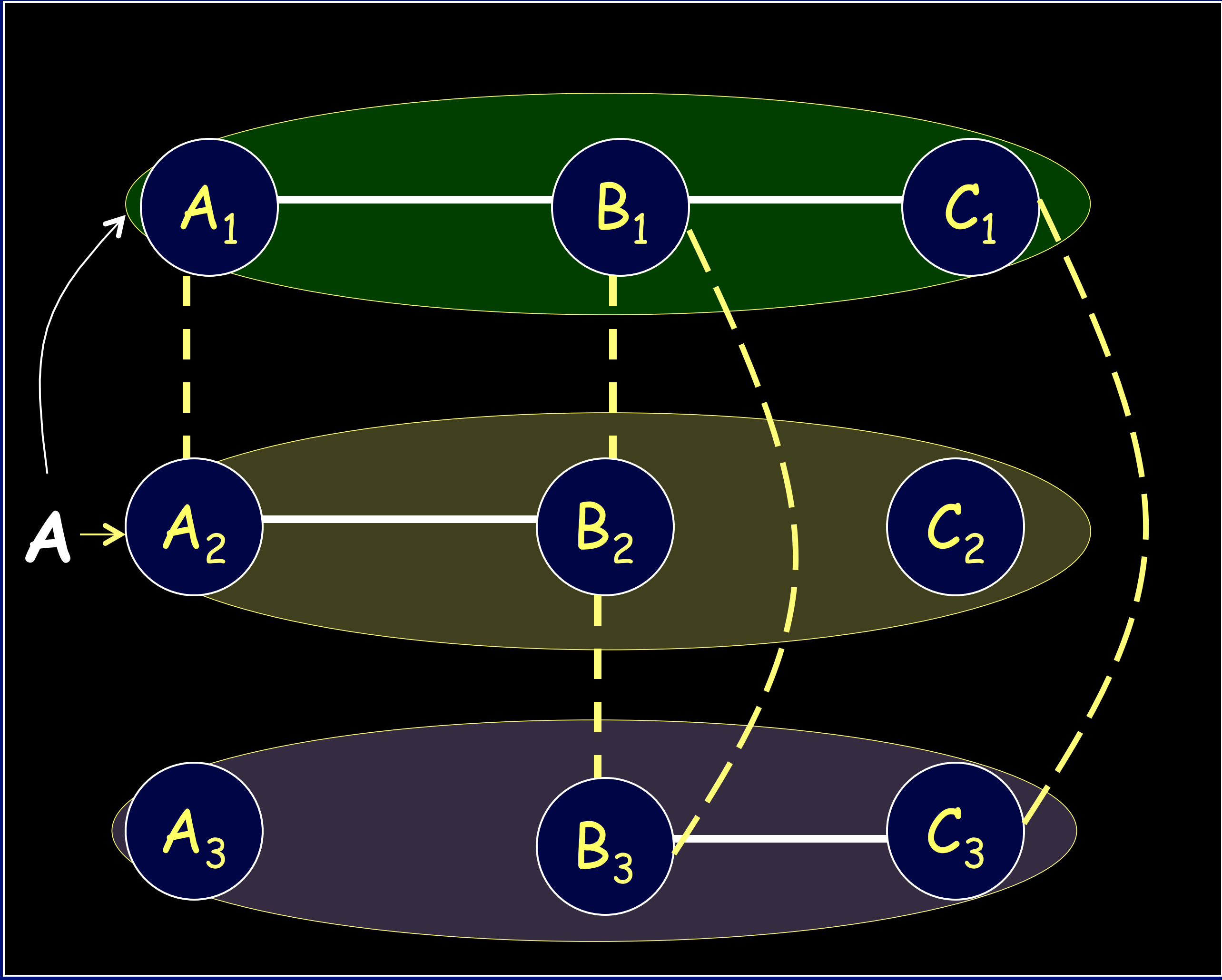
Concept of a Layered Graph

- Each channel is represented by a distinct layer
- A real node has virtual subnode representations, e.g., A has (A_1, A_2, A_3) in the layers 1, 2, and 3



Concept of a Layered Graph

- Two virtual subnodes in the same layer are connected by a horizontal edge
  - If they can be reached within the same channel
  - e.g., A_1-B_1 and A_2-B_2
- The virtual subnodes of a given node are connected if they have at least one horizontal edge
  - e.g., A_1-A_2 for node A



Concept of a Layered Graph

- **Access Edges** connect a node to its subnodes, e.g., connect node *A* to subnode A_1
- **Vertical Edges** connect subnodes in the same logical layer representing the reachability between nodes at the channel corresponding to its logical layer
- **Horizontal Edges** connect subnodes that are associated with the same node and are in different layers, indicating that data forwarding capability between different channels at a node.

Concept of a Layered Graph

- Vertical Edges have a "cost" may be a combination of the channel switching time, channel quality, preferences, among others
  - Offers flexibility to choose different channels on incoming/ outgoing links
- Horizontal Edges indicate reachability
  - Based on Tx range, region of PU influence

Further Design Concepts: EDGE WEIGHTS

- Weight of Horizontal Edges should endorse the specific quality of the wireless link e.g., BW, link availability, link load, etc.

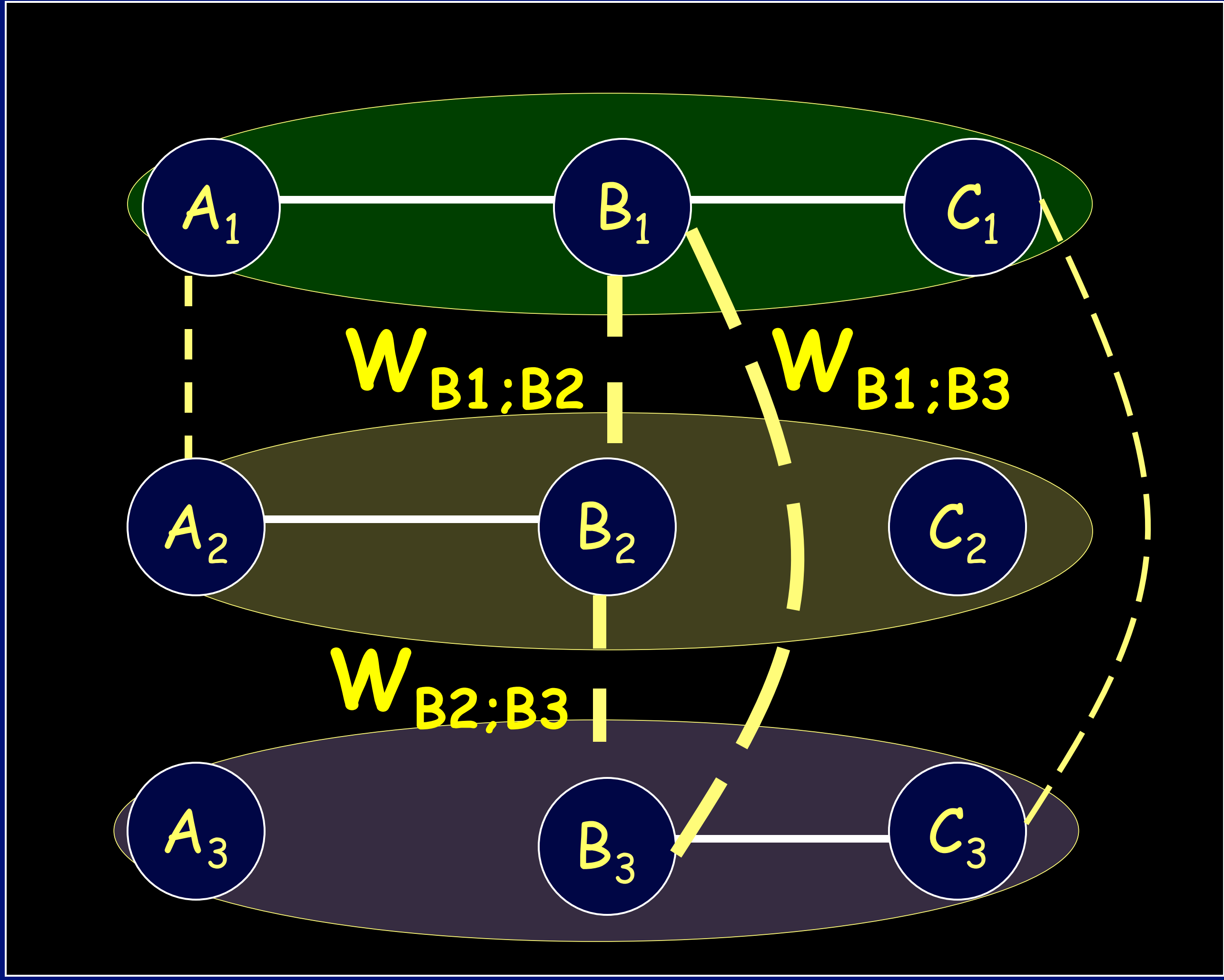
- Vertical Edges could be weighted accounting for different quality parameters including

  * the cost for switching between channels, or
  * the improvement in the SNR when a channel switch occurs.

Further Design Concept: Edge Weights

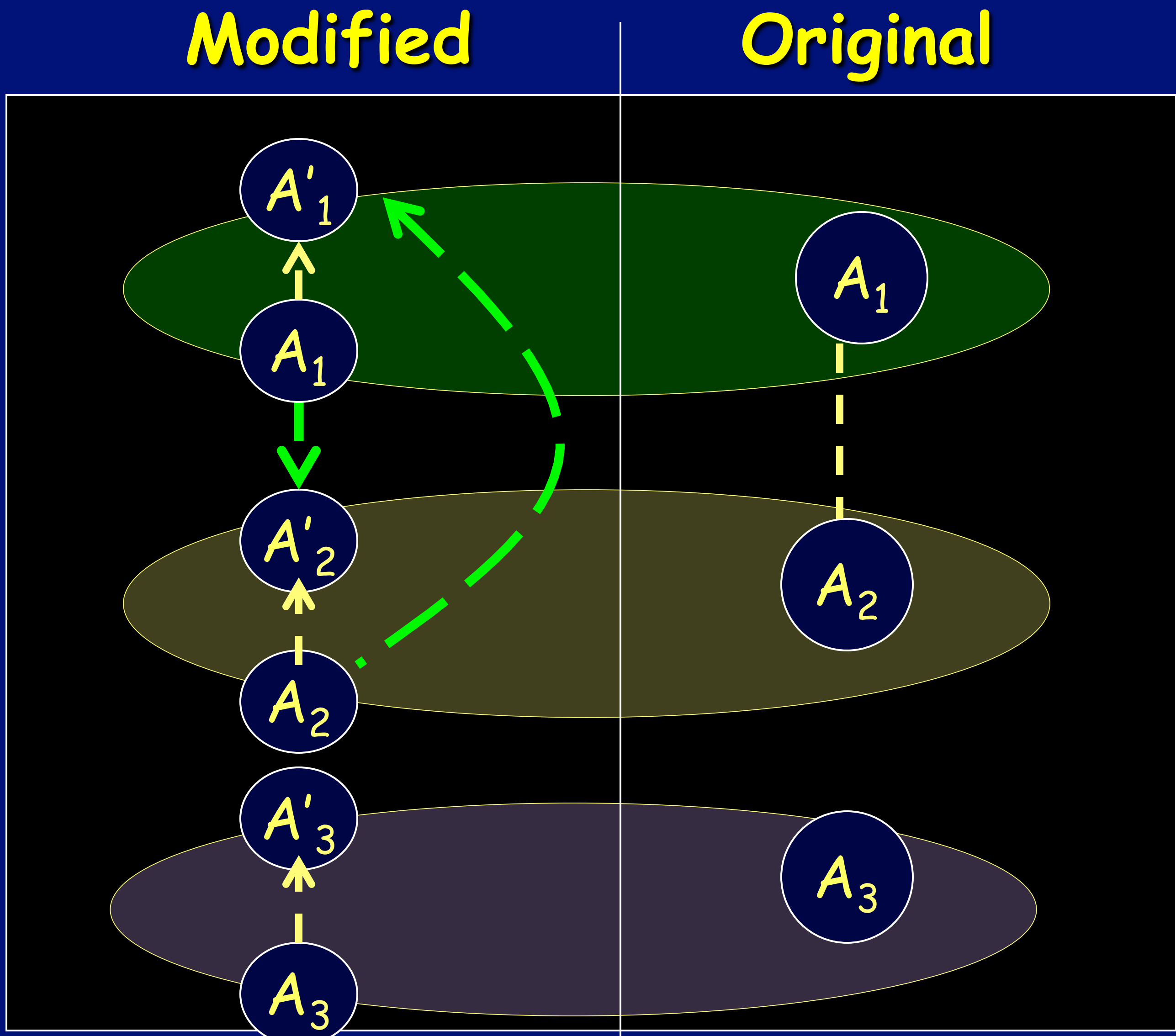
- Vertical edge weights (e.g., $W_{B1;B2}$, $W_{B2;B3}$, and $W_{B1;B3}$) need to be carefully chosen
- E.g., the total cost edge (B_1,B_2) and (B_2,B_3) is less than the cost of edge (B_1,B_3)
  - $W_{B1;B2} + W_{B2;B3} < W_{B1;B3}$

Distinct channels for Tx/Rx



Further Design Concept: AUXILIARY NODE

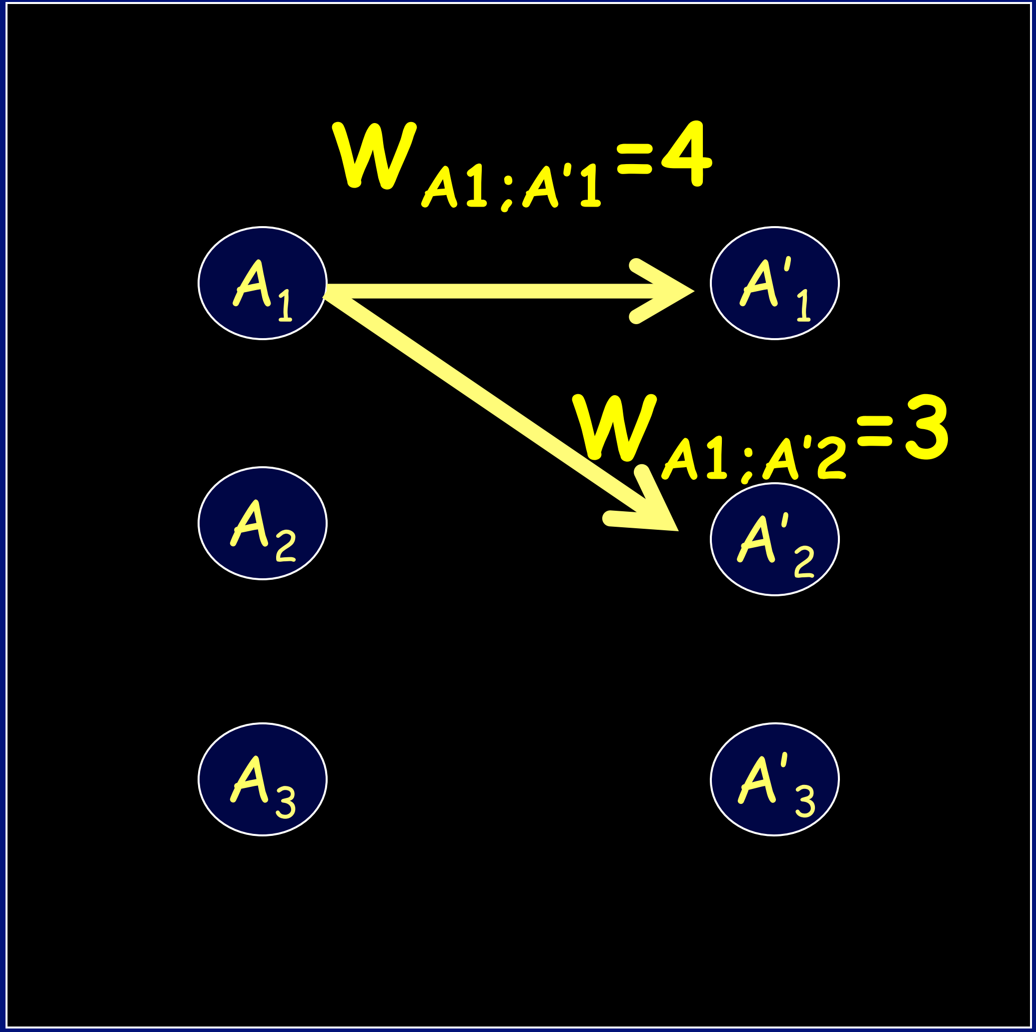
- To provide additional flexibility and control, an auxiliary subnode A_i' for each subnode A_i is introduced.
- Each subnode A_i (receiving channels) has an auxiliary node A'_i (txmitting channels), with a directed edge A_i-A'_i
- Each edge is now directional
  - From A'_i-A_k, where i and k are distinct



Further Design Concepts

- The weights are decided to bias channel selection

- As the edge weight $W_{A1;A'2} < W_{A1;A'1}$ the channel is switched at A
  - Allows distinct Tx/Rx channels

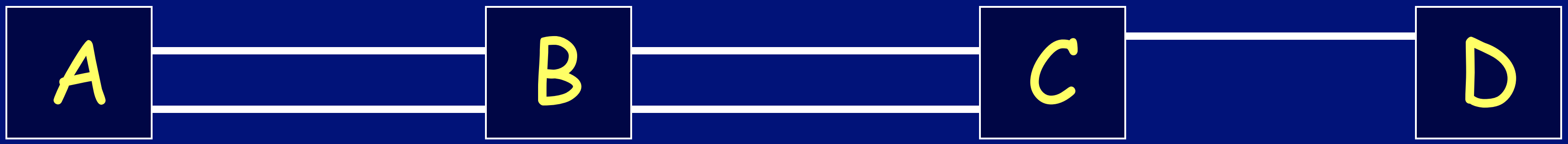


CogNet Routing Protocol

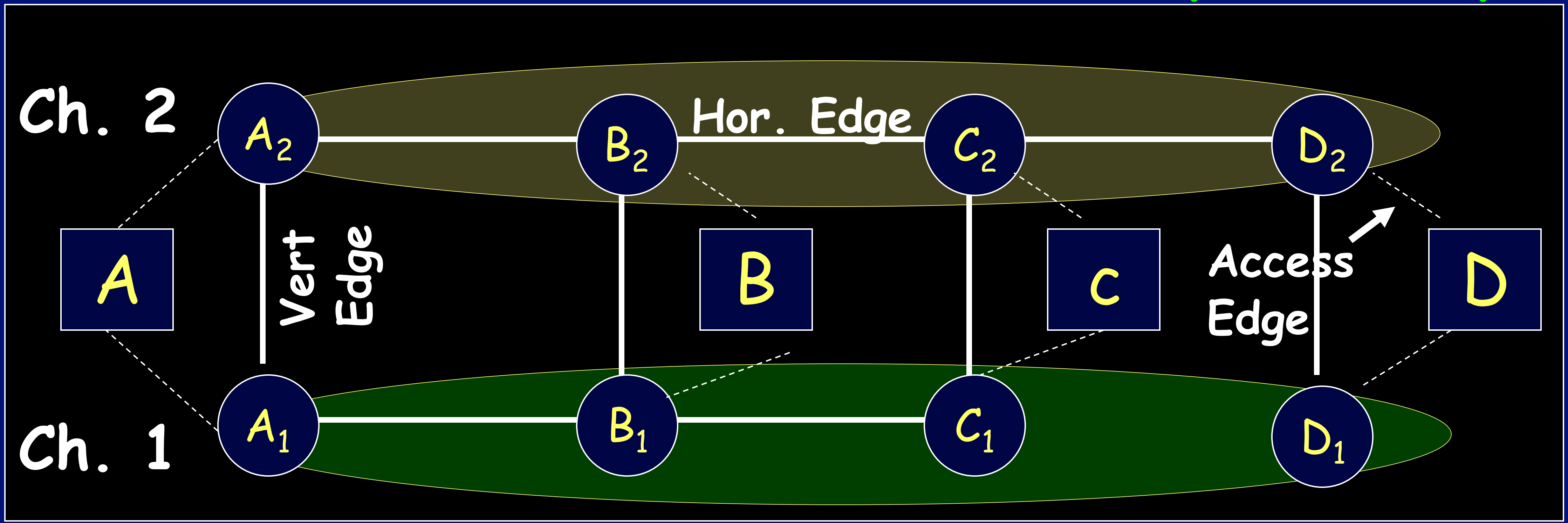
- **Assumptions:**
  - Channels available at each node, the number of radios and the traffic information is disseminated throughout the network
  - Used to establish the network-wide layered graph at each node
  - Assumes the presence of a CCC for the broadcast
  - Edge weights are proportional to the channel/network conditions and current traffic volume between nodes

CogNet Route Setup

Physical Topology



Constructed Layered Graph



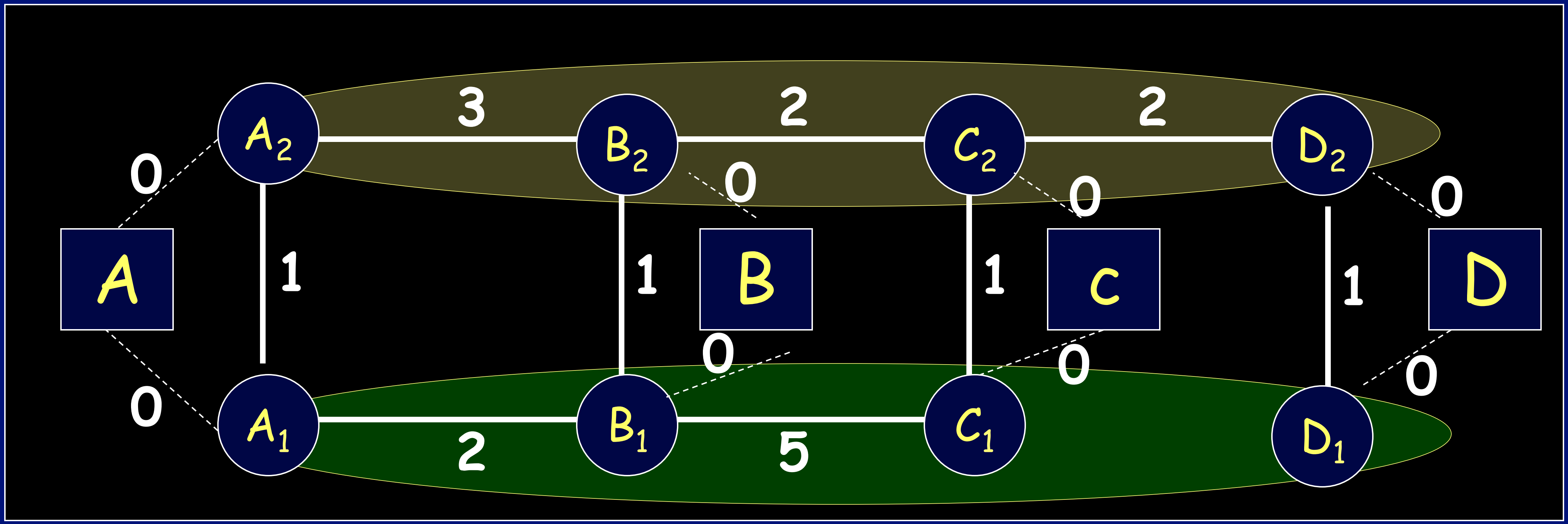
CogNet Route Setup

- **Step 1:**
  Sort the node pairs based on the descending order of a suitable metric, (e.g., traffic volume)

- **Step 2:**
  Pick the next node pair in the sorted list and compute a path between the selected node pair on the layered graph

CogNet Route Setup

Weights: Hor. Edge =2, Vert. Edge =1, Acc. Edge =0



A has the highest originating traffic

Shortest path between A and B: $A-A_1-B_1-B$

CogNet Route Setup

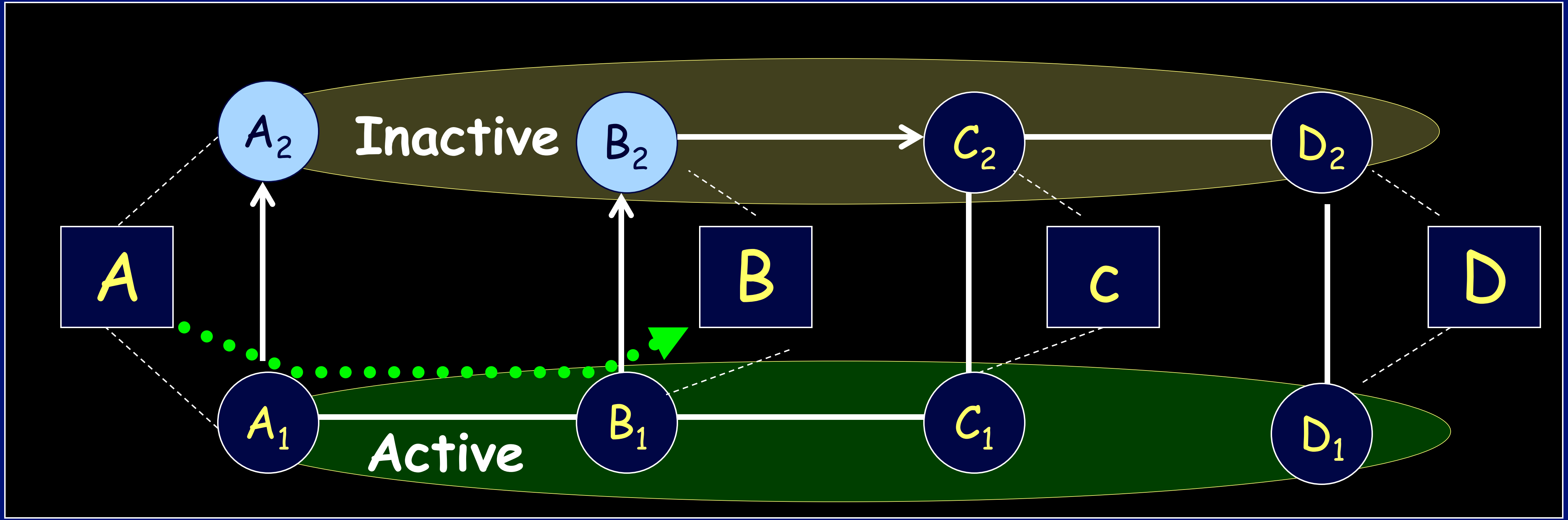
- **Step 3:**

  For each subnode A_i along the path, if there is a radio interface that is not assigned yet, assign it to the available channel.

  If there are no more radios, mark all unassigned subnodes as inactive

CogNet Route Setup

Weights: Hor. Edge =2, Vert. Edge =1, Acc. Edge =0



A has the highest originating traffic (Ch1 active; Ch2 inactive)

Shortest path between A and B: A-A_1-B_1-B

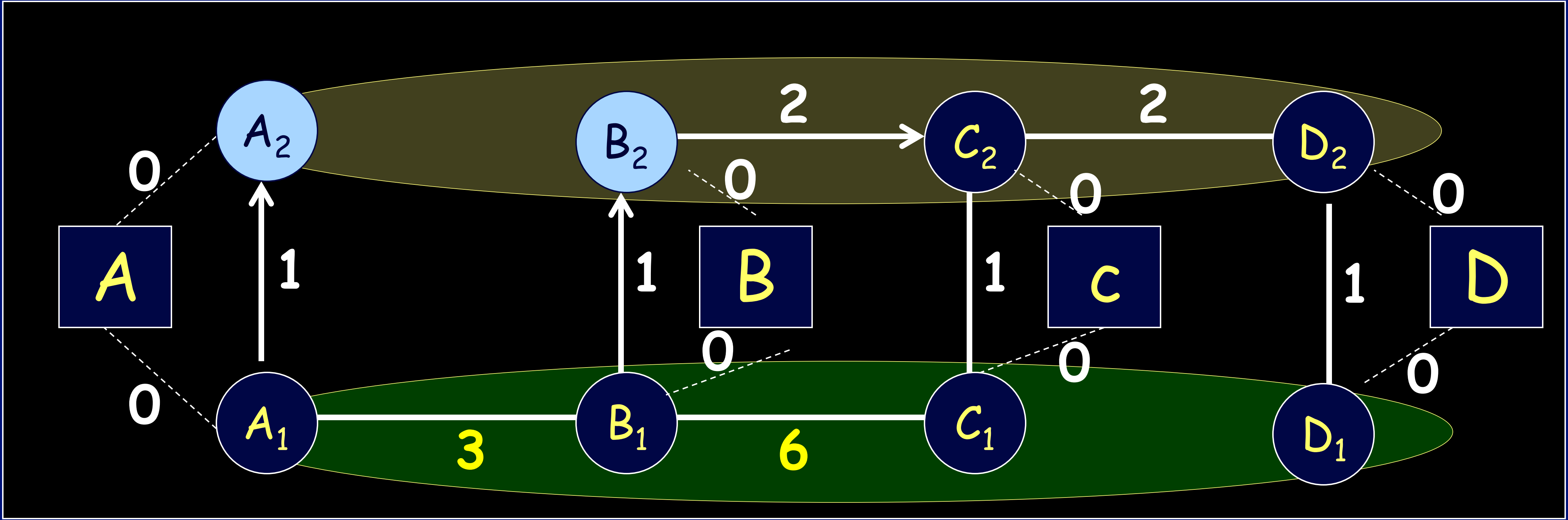
CogNet Route Setup

- **Step 4:**
  Update vertical and horizontal edges incident to the subnodes on the path:
  - Rule 4.a
    Remove all outgoing vertical edges from inactive nodes, but keep incoming vertical edges unchanged
  - Rule 4.b
    Remove all incoming horizontal edges from inactive nodes, but keep all outgoing horizontal edges unchanged
  - Rule 4.c
    Increase the cost of horizontal edges from all subnodes on the path and neighboring subnodes of each subnode on the path
    (to indicate the increased collision prob at these links/nodes)

-Step 5: If there is still a node pair in the sorted list, goto step 2..

CogNet Route Setup

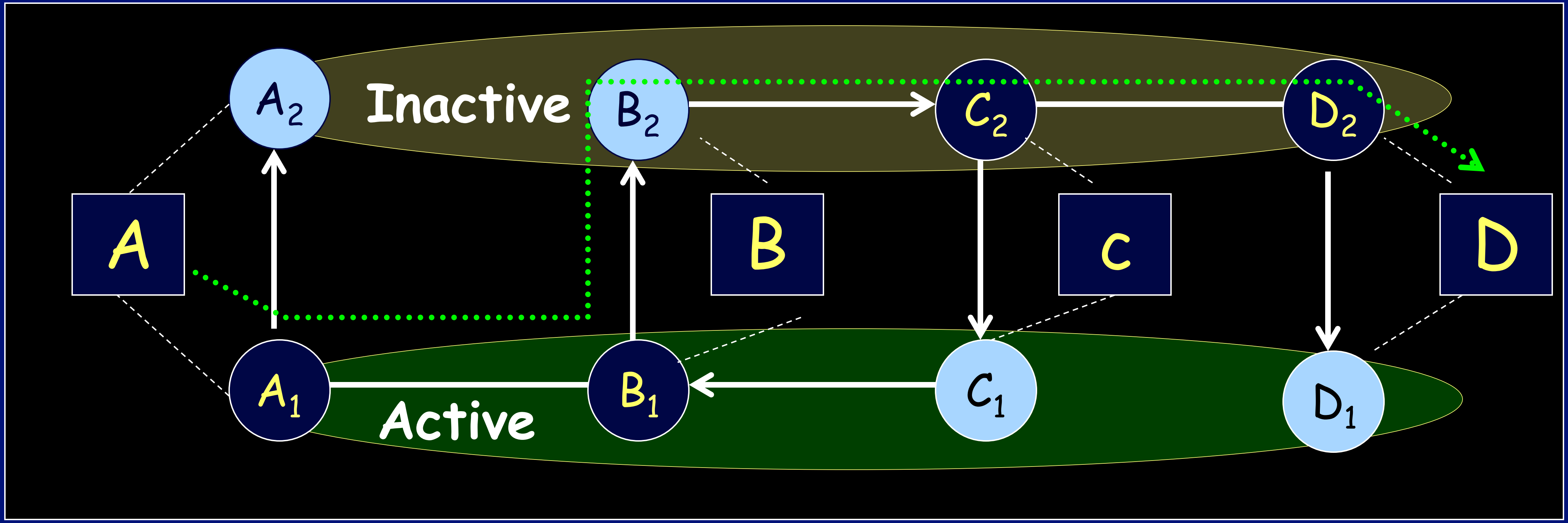
Updated Edge Weights



Edges $A_1;B_1$ and $B_1;C_1$ have increased weights by 1 because they are the edges that will be interfered by data tx on the routing path A, A_1, B_1, B)

CogNet Route Setup

Assume: the pair C→ D has the 2nd largest traffic volume after A→ B; then compute C,C_2,D_2,D); C_2,D_2 are active and C_1,D_1 are inactive nodes;



Node B must periodically switch the channels 1 and 2

Conclusions

- Routing procedure involves a relatively complex layered graph formation, but a simple, minimum cost shortest path algorithm
- Weights of the edges must be appropriately decided for optimal performance
- Cost of collecting the network-wide information to create the network graph must be accounted
- No route reconfiguration

Routing Protocols for CR Networks

	Whole Path Selection	Next-hop Selection	Spectrum Awareness	PU Location-aware/Power Control	Reconfigurable to Varying Spectrum	Mobility Support	Relaying Support	Priority Classes
Joint-R	✔		✔					
CogNet	✔		✔	✔				
COOP		✔	✔	✔	✔		✔	
OPERA			✔	✔	✔	✔		
CRP		✔	✔	✔	✔	✔		✔

COOP: Distributed Routing, Relaying, and Spectrum Allocation

L. Ding, T. Melodia, S.N. Batalama and J.D. Matyjas,
"Distributed Routing, Relay Selection, and Spectrum Allocation in Cognitive and Cooperative Ad Hoc Networks,"
IEEE SECON 2010.

- **Goal:**

  Throughput maximization in ad-hoc CR networks

- **Achieved by means of:**
  - joint routing, relaying and spectrum allocation
  - dedicated MAC layer that relies on a common control channel (CCC)

Network Architecture: Channel Model

Spectrum is organized in two separate bands:

- A CCC for spectrum access negotiation, centered at f_{ccc} *(time slotted)*
- A data channel (DC) for data communications, organized as a set of discrete mini-bands with BW w.

$$\{f_{min}, f_{min+1}, \ldots, f_{max-1}, f_{max}\}$$

Binary vector A indicates PU activity on the data channel:

A(f)=1 → a PU active on mini-band *f*
A(f)=0 → *no PU activity*

Network Architecture: Transmission Mode

COOP supports two different transmission modes:

- **Direct Transmission**
  the source node *s* transmits to destination node *d* in each time period

- **Cooperative Relaying** (Virtual Multiple-Input Single-Output)
  There are two time periods:

  1. Source s transmits to both node d and a relay node r.
  2. Relay r forwards the transmission to the final destination d.

Network Architecture: Transmission Mode

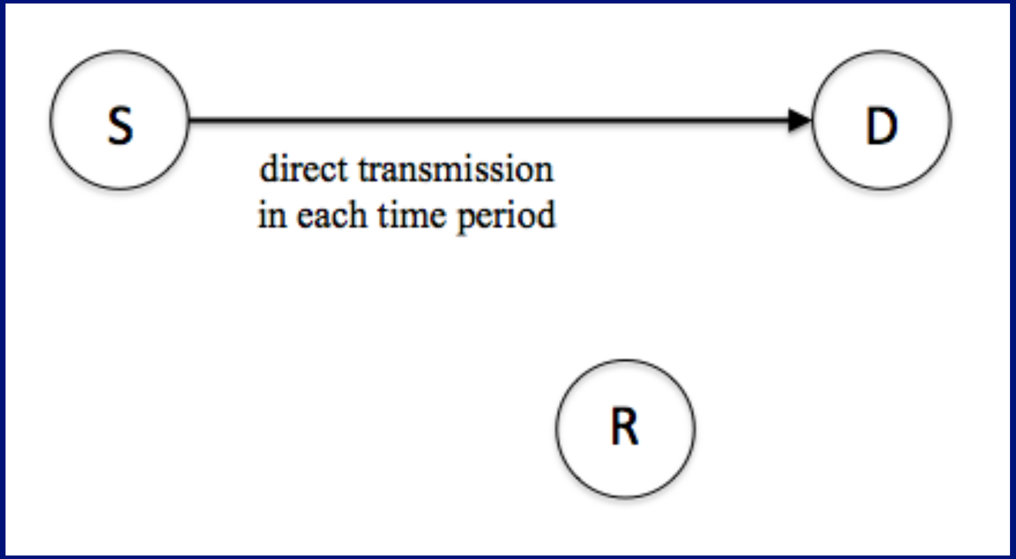
Direct Transmission:

Capacity of the direct transmission is given by: (sent in both time periods)

$$C_{sd} = w\log_2(1 + SINR_{sd})$$

where

- w is the BW
- $SINR_{sd}$ is the signal-to-interference-plus-noise power ratio of the link (s,d)

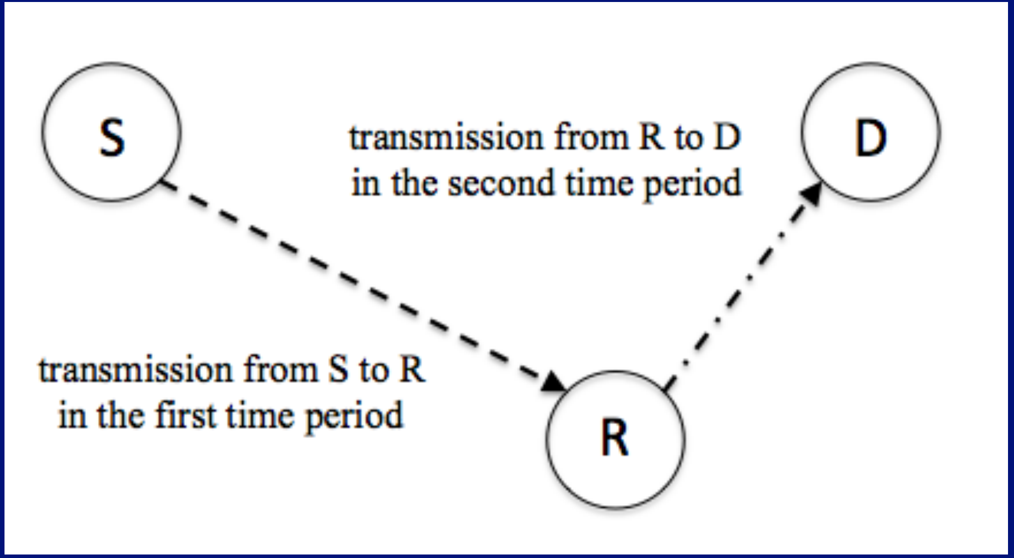


Network Architecture: Transmission Mode

Cooperative Relaying

Capacity of the cooperative transmission is given by:

$$C_{sd} = \frac{w}{2}\min\left\{\begin{matrix}\log_2(1+SINR_{sr}), \\ \log_2(1+SINR_{sd}+SINR_{rd})\end{matrix}\right\}$$



where

- *w* is the BW
- $SINR_{sr}$ and $SINR_{rd}$ are the signal-to-interference-plus-noise power ratios of the links (s,r) and (r,d)

Network Architecture: Queueing Dynamics

Traffic demand consists of a set S of unicast sessions.

Each session s in S is characterized by:

- a fixed source-destination pair;
- an arrival rate $\lambda_i^s(t)$ at node *i* during time slot *t*.

Each node

- forwards immediately the packets for which it acts as relay;
- maintains a separate queue for each session s for which it acts as forwarder.

Network Architecture: Queueing Dynamics

Let $Q_i^s(t)$ define the number of queued packets of session s at time t

At time *t+1*, the length of the queue *$Q_i^s(t+1)$* for the session *s* at node *i is updated as*:

$$Q_i^s(t+1) = \left[Q_i^s(t) + \sum_{\text{neighbor } k} r_{ki}^s(t) - \sum_{\text{neighbor } l} r_{il}^s(t) + \lambda_i^s(t) \right]^+$$

where

- **$r_{ij}^s(t)$ is the transmission rate on link *(i,j)* for session *s* during time slot *t***
- **$\lambda_i^s(t)$ is the arrival rate of session s at node *i* during time slot *t***

OBJECTIVE

Design a distributed xlayer control scheme to maximize the network throughput by jointly, dynamically and distributively allocating

i) the next hop (routing)

ii) cooperative relay

iii) spectrum (minibands) and power on each miniband to be used at the transmitter and relay of each link.

Problem Formulation

Problem P_1:

Maximize: $\sum_{\text{user } i} \sum_{\text{user } j \neq i} U_{ij}$

Subject to:

$$\sum_{s \in S} r_{ij}^{s} \leq C_{ij} \quad \forall \text{ user } i, j \qquad (1)$$

$$A(f)P_i(f) = 0 \quad \forall \text{ user } i, \forall \text{ band } f \qquad (2)$$

$$SINR_j^f \geq SINR^{th}(BER) \quad \forall \text{ user j}, \forall \text{ band } f \qquad (3)$$

$$\sum_{\text{band } f} P_i(f) < P^{\max} \quad \forall \text{ user } i \qquad (4)$$

- U_{ij}: utility function
- **Constraint 1:** traffic transported on link (i,j) is lower than the physical capacity;
- **Constraint 2:** No CR tx is allowed if there is reception PU activity on that miniband
- **Constraint 3** CR user transmission must satisfy a given BER performance while sharing spectrum with other CR users
- **Constraint 4:** limits the total power for each device

Problem Formulation

Utility U_{ij} for the link (i,j) is defined as:

$$U_{i,j}(t) = C_{i,j}(t)\left(Q_i^{s_{ij}^*}(t) - Q_j^{s_{ij}^*}(t)\right)$$

$$s_{ij}^* = \arg\max_s \left\{Q_i^s - Q_j^s\right\}$$

where $C_{i,j}(t)$ is the achievable capacity for link (i,j) given the current spectrum condition at time t and the chosen transmission mode

$s^*_{i,j}$ → session with max differential backlog on link (i,j)

Utility function is defined based on the principle of dynamic backpressure !!

It is throughput-optimal, i.e., able to keep all network queues finite for any level of offered traffic within the network capacity region.

Problem Formulation

Exact solution of Problem 1 requires

- global knowledge of all feasible rates;
- centralized algorithm for solving a mixed-integer non-linear problem (usually NP hard).

Thus, an approximate solution is given:

- based on distributed decisions driven by locally collected information;
- Solution is composed by two algorithms:
    - Algorithm 1: distributed joint routing and relay selection;
    - Algorithm 2: spectrum and power allocation.

Distributed Joint Routing and Relay Selection

Algorithm 1 Overview:

Given a CR user *i* and a traffic session *s*:

1. It allocates spectrum and the power (with Algorithm 2) for each couple of neighbors (j,m)
   - j is the next hop
   - m is the relay candidate.

2. It selects the couple that provides the highest utility U_{ij}

Distributed Joint Routing and Relay Selection

3. Probability of accessing the medium is computed according to U_{ij} by varying the size of the MAC contention window

$$CW_i = -\alpha \frac{U_{ij}}{\sum_{\text{neighbor } k} U_{kl}} + \beta, \quad \alpha, \beta > 0$$

4. Utility values are broadcast to the neighbors on the CCC.

Spectrum and Power Allocation

Algorithm 2 Overview:

Given a couple of neighbors, the algorithm selects:

- the spectrum and the corresponding transmit power that maximizes the capacity for direct transmission
- the spectrums and the corresponding transmit powers that maximize the capacity for relaying transmission

Transmission mode that provides the higher capacity is selected

Spectrum and Power Allocation

Selected spectrum(s) and power(s) must satisfy the following constraints:

- Power satisfies a given BER performance;
- Interference generated at the most vulnerable neighbor must not exceed a threshold value.

COOP: ADVANTAGES

Cooperative relaying can lead to increased throughput and reduced delay with respect to non-cooperative strategies.

Proposed algorithm is distributed and exploits local information.

COOP: DRAWBACKS

- Spectrum and power allocation is decoupled from the routing and the relay selection, and thus a sub-optimal solution is provided.
- Convergence of the protocol in presence of dynamic topologies has not been proved.

Routing Protocols for CR Networks

	Whole Path Selection	Next-hop Selection	Spectrum Awareness	PU Location-aware/Power Control	Reconfigurable to Varying Spectrum	Mobility Support	Relaying Support	Priority Classes
Joint-R	✔		✔					
CogNet	✔		✔	✔				
COOP		✔	✔	✔	✔		✔	
OPERA			✔	✔	✔	✔		
CRP		✔	✔	✔	✔	✔		✔

OPERA: Optimal Routing Metric

M. Caleffi, I.F. Akyildiz, L. Paura,
"OPERA: Optimal Routing Metric for Cognitive Radio Ad Hoc Networks,"
IEEE Transactions on Wireless Communications, August 2012.

- **Goal:**
  - Optimal routing metric for Cognitive Radio Ad Hoc Networks (CRAHNs)

- **OPERA**
  - defines a measure to compare different routes in both static and mobile CR networks
  - does not deal with routing functionalities such as the packet forwarding and the route maintenance processes

OPERA Features

- **Primary user-awareness**
  OPERA explicitly accounts for the PU activity
- **Optimality**
  OPERA is optimal when combined with both Dijkstra-based and Bellman-Ford-based algorithms
- **Scalability**
  OPERA overcomes the primary-activity bottleneck by means of route diversity
- **QoS-Enabling**
  OPERA measures the quality of a path in terms of end-to-end delay

Metric Optimality

- A routing metric is optimal when a routing protocol based on such a metric always discovers the lowest-cost path
  - between every pair of nodes
  - in any connected networks
- In literature there are several routing metrics:
  - Most of them are based on heuristic
  - Several are not optimal!

Un-optimal Metrics

- Un-optimal metrics can route the packets through
  - sub-optimal routes → wasting the resources
  - route loops → un-reachable destinations

Optimality is not a trivial property!

- These issues are even more severe in cognitive radio networks!!!

Un-optimal Metric Example:
Weighted Cumulative Expected Transmission Time WCETT

R. Draves, J. Padhye, and B. Zill,
"Routing in multi-radio, multi-hop wireless mesh networks,"
ACM MobiCom 2004.

- Proposed for multi-channel environments
- Accounts for the inter-flow interference

$$WCETT(p) = (1-\beta)\sum_{\text{link } l\in p} \text{Delay}(l) + \beta \max_{\text{channel } j} X_j$$

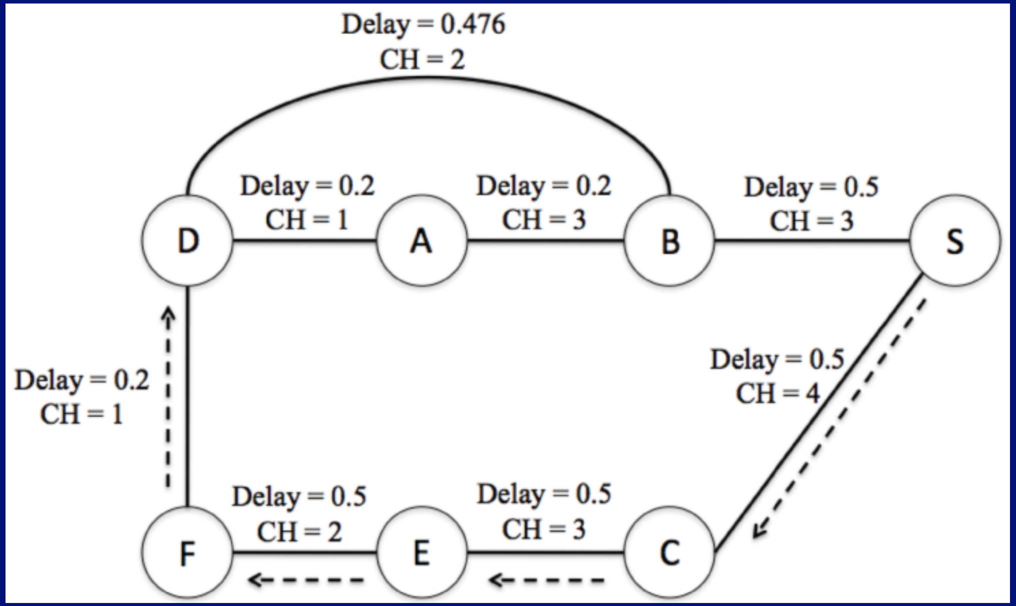
- *p* is a path
- *β* is a tunable parameter
- Delay(l) is tx delay for link l
- X_j counts the number of times channel *j* is used along path *p*

Un-optimal Metric Example: WCETT

Bellman-Ford algorithm fails in discovering the optimal path between S and D when *β>4/9*

- *β=2/3*
- B announces the path B-A-D with cost 1/3 0.4 + 2/3 as the optimal route to reach D since it is preferred to the route B and D
  with a cost (1/3 0.476 + 2/3).

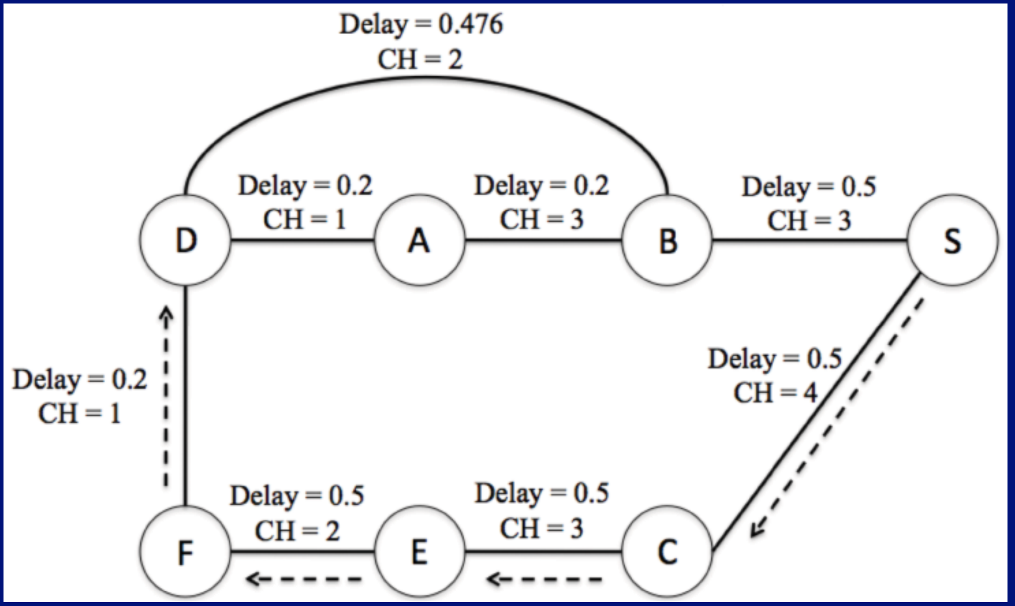
  Hence, node S does not have any chance to check the weight of the route B and D and it incorrectly sets the sub-optimal route S-C,E, F and D with a cost of (1.7/3 + 2/3).



Un-optimal Metric Example: WCETT

Bellman-Ford algorithm fails in discovering the optimal path between S and D when *β>4/9*

- *S* incorrectly sets its path to D as the sub-optimal path S-C-E-F-D with cost 1/3 1.7 + 2/3
- the optimal path between S and D is S-B-D with cost 1/3 0.976 + 2/3



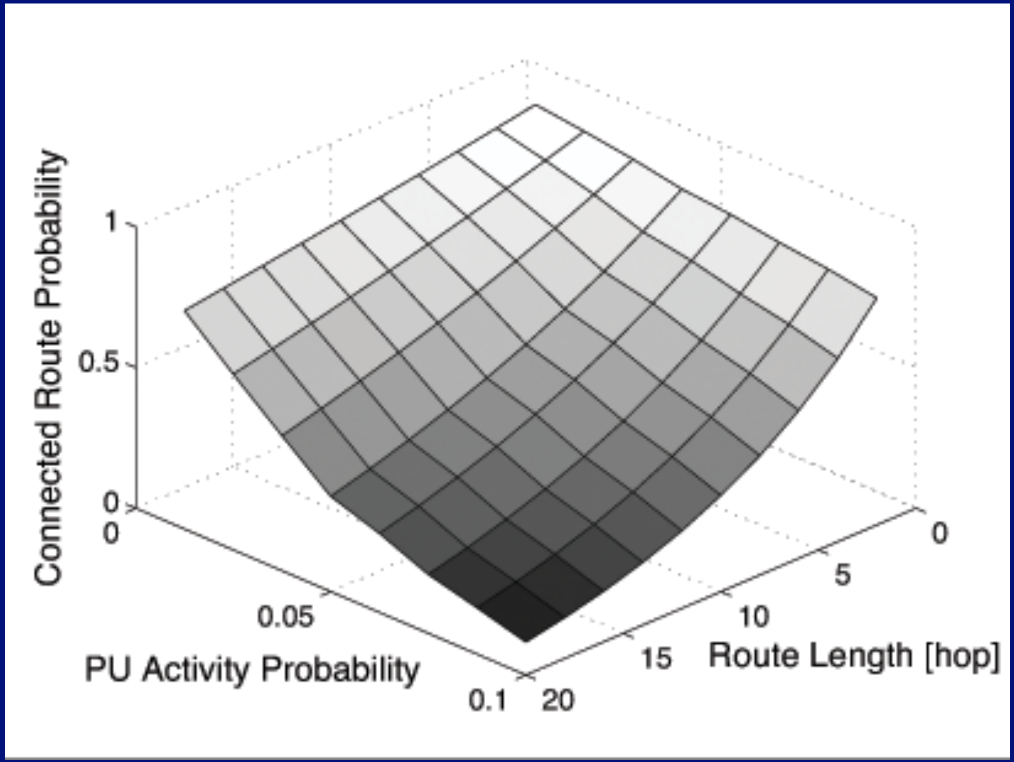
A similar issue arises with a Dijkstra algorithm

Primary-Activity Bottleneck

Traditional Cognitive Metrics

- measure the quality of a path with reference to the routing opportunities available when the route is not disconnected by the PU activity

- they are affected by the primary-activity bottleneck:
  the route quality depends on the probability of a path being not disconnected by PU activity

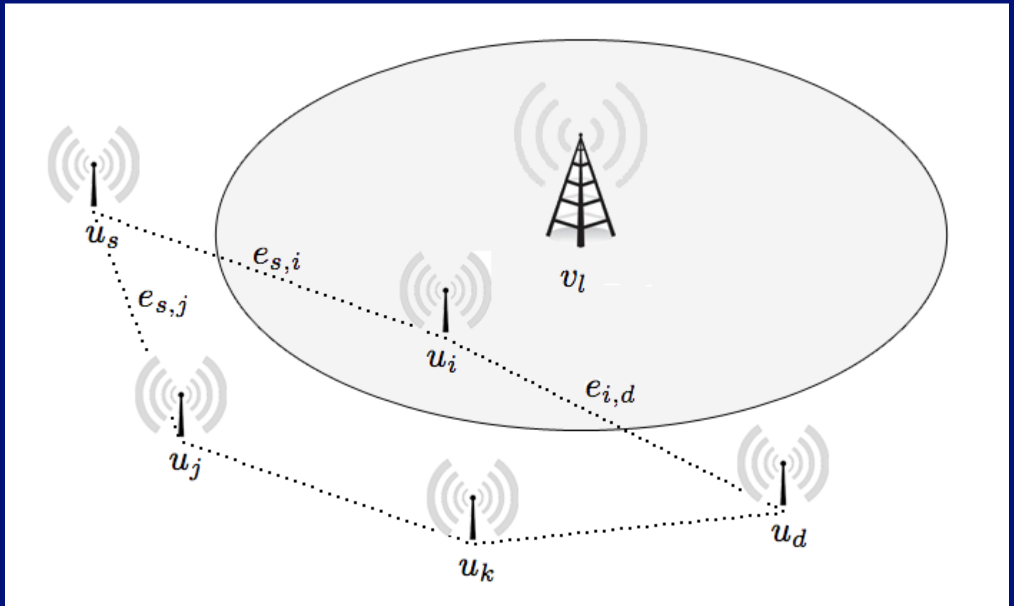


Primary-Activity Bottleneck

OPERA Metric

- accounts for the additional routing opportunities provided by route diversity

- when the optimal path u_s-u_i-u_d is affected by PU v_l activity, the path u_s-u_j-u_k-u_d can provide additional routing opportunities



Expected Link Delay

$$l_{i,j} = \frac{1}{1-\bar{p}_{i,j}^{\tau_N^j}} \left(\sum_{m=1}^{N} \bar{p}_{i,j}^{\tau_{m-1}^j} p_{i,j}^{\tau_m^j} \frac{L}{\mu_{i,j}^{\tau_m^j}} + \bar{p}_{i,j}^{\tau_N^j} T_{i,j}^{on} \right)$$

- Expected delay experienced by a packet sent over the link (i,j)

- It accounts for two factors:
  - PU activity probabilities, with the probabilities $\bar{p}_{i,j}^{\tau_{m-1}^j}$ and $p_{i,j}^{\tau_m^j}$
  - PU activity times, with the time $T_{i,j}^{on}$

Expected Link Delay

$$l_{i,j} = \frac{1}{1-\bar{p}_{i,j}^{\tau_N^j}} \left(\sum_{m=1}^{N} \bar{p}_{i,j}^{\tau_{m-1}^j} p_{i,j}^{\tau_m^j} \frac{L}{\mu_{i,j}^{\tau_m^j}} + \bar{p}_{i,j}^{\tau_N^j} T_{i,j}^{on} \right)$$

- Sum of two delays
  - Delay for packet transmission (the summation), function of packet length L and the channel throughput $\mu_{i,j}^{\tau_m^j}$
  - Delay for the PU activity (the second term), probability function that all channels are not free $\bar{p}_{i,j}^{\tau_N^j}$

Expected Path Delay (without route diversity)

$$d_{i,k} = \min_{u_j \in \mathcal{N}_i} \left\{ \frac{1}{1 - \bar{p}_{i,j}^{\tau_N^j}} \left(\tilde{d}_{i,j} + \bar{p}_{i,j}^{\tau_N^j} T_{i,j}^{on} \right) \right\}$$

-Expected delay experienced by a packet sent over the path (i,k)

-Sum of two delays

- Delay for packet transmission (the first term), function of expected delay for the link u_i-u_j and the expected delay for the path u_j-u_k
- Delay for the PU activity (the second term)

OPERA End-to-End Delay (exploiting route diversity)

$$\mathcal{D}_{i,k} = \frac{1}{1-\bar{q}_{i,c_n}} \left(\sum_{c_j \in \mathcal{C}_{i,k}} \left(\bar{q}_{i,c_{j-1}} \tilde{\mathcal{D}}_{c_j,k} \right) + \bar{q}_{i,c_n} T_i^{on} \right)$$

- Expected delay experienced by a packet sent over the path (i,k) through the set of neighbors $C_{i,k}$
- First term (the summation) represents the route opportunities provided by the neighbors of CR user u_i

OPERA Optimality

Condition for Optimality

Both a Dijkstra-based and a Bellman-Ford-based CR routing protocol are optimal if they are combined with a metric with the following properties:

- Relay Beneficial Condition
- Strictly Preference Preservation
- Relay Order Optimality

- OPERA satisfies the condition

Properties for Optimality

Relay Beneficial Condition

for any CR user u_i, the neighbor set $C_{i,d}$ is composed only by neighbor CR users that are strictly preferred to u_i

$C_{i,d}$ must be composed only by neighbors with a lower minimum cost toward the destination u_d

Properties for Optimality

Strictly Preference Preservation

if a path $P_{r,d}$ is preferred to a path $P_{i,d}$, the path $P_{r,d}$ is preferred also to the concatenation of $P_{i,d}$ with $P_{r,d}$

i.e., the concatenation operation preserves the preference between the paths

Properties for Optimality

Relay-order-Optimality

the neighbor set ordered according to the metric is preferable to any set ordered according to a different criteria

OPERA: ADVANTAGES

- OPERA explicitly accounts for the characteristics of a cognitive environments
  - PU activity probabilities
  - PU activity times
- OPERA is derived for both static and mobile networks (PU/CR user mobility)
- OPERA optimality is analytically proved

OPERA: DRAWBACKS

- Without the definition of all the routing functionalities, OPERA performance cannot be fully evaluated.

Routing Protocols for CR Networks

	Whole Path Selection	Next-hop Selection	Spectrum Awareness	PU Location-aware/Power Control	Reconfigurable to Varying Spectrum	Mobility Support	Relaying Support	Priority Classes
Joint-R	✔		✔					
CogNet	✔		✔	✔				
COOP		✔	✔	✔	✔		✔	
OPERA			✔	✔	✔	✔		
CRP		✔	✔	✔	✔	✔		✔

CRP: CR Routing Protocol for Ad Hoc Networks

K. Chowdhury and I. F. Akyildiz,
"CRP: A Routing Protocol for Cognitive Radio Ad Hoc Networks,"
IEEE JSAC, vol. 29, no. 4, April 2011.

- **Goal:**

  Routing with a "lever" that switches between (i) PU protection and (ii) CR throughput maximization, on a need-basis

- **Achieved by means of:**
  - Creating two routing classes, each weighting the network metrics differently to form distinct optimization functions
  - Joint spectrum and path selection, accompanied by route maintenance

CRP Protocol: Classes and Metrics

CRP Protocol

Two main classes

- Class I (CR-centric) — Low latency
- Class II (PU-centric) — More PU protection

Route selection metrics

- Probability of bandwidth availability
- Variance in no. of bits delivered
- Spectrum propagation characteristics
- PU Receiver protection
- Spectrum sensing consideration

CRP Protocol Features

- **Checks for explicit protection of PU receivers**
  - Typically, protocols detect PU transmitter and not PU receiver
  - Receiver locations are unknown, or hard to detect

- **Allows different routing classes with scalable PU protection**

Class I	Class II
First priority is to minimize CR end-to-end latency, while meeting minimum PU interference avoidance constraints	Higher protection to PUs, by minimizing overlap regions of the CR and PU transmitters with significantly higher path latencies

CRP Protocol Features

Scalable joint spectrum and path selection

- Different spectrum bands are possible, for e.g., 54 – 72MHz, 76 – 88MHz, 174 – 216MHz, and 470–806 MHz bands
- Each band has different propagation distance and channel characteristics
- This resulting spectrum preference is mapped to a route advertisement delay, allowing a CCC to “capture” the eventual quality of the spectrum used

CRP Operational Steps

- **Step 1.**

  Identify the best spectrum band based on local environmental observations

- **Step 2.**

  Form optimization equations based on choice of Class I or Class II routes

  - The equation that is to be optimized is called the "initiative" of a node
  - Higher the initiative, higher is the probability that node participates in the route

CRP Operational Steps

- **Step 3.**

  Map the initiative to a delay function for forwarding the RREQ

  - Higher the initiative, less is the RREQ forwarding delay
  - Greater chance that the path will deliver RREQ first

- **Step 4.**

  Destination picks the route that best meets the goals of the routing class (i.e., Class I or Class II); sends RREP

- **Step 5.**

  Route maintenance allows re-construction of a partially broken route caused by node mobility and PU activity

Description of the Route Selection Metrics

CRP Protocol

Two main classes

- Class I (CR-centric) Low latency
- Class II (PU-centric) More PU protection

Route selection metrics

- Probability of bandwidth availability
- Variance in no. of bits delivered
- Spectrum propagation characteristics
- PU Receiver protection
- Spectrum sensing consideration

Description of Route Selection Metrics:
1. *Probability of Bandwidth Availability*

Channel Description

For the i^{th} channel on spectrum k, let:

$1/\alpha^k_i$ = Average PU on time

$1/\beta^k_i$ = Average PU off time

Then, the probability of this channel being available is

$$p_i^k = \frac{\alpha_i^k}{\alpha_i^k + \beta_i^k}$$

Description of Route Selection Metrics:
1. *Probability of Bandwidth Availability… cont'd*

Channel description… cont'd

The number of channels that need to be used:

$$C^k = \left\lceil \frac{\psi_D}{\psi_k} \right\rceil$$

where, ψ_D is the desired mean BW

ψ_k be BW of each channel of the spectrum band

Finally, spectrum BW availability probability is that C_k channels are available

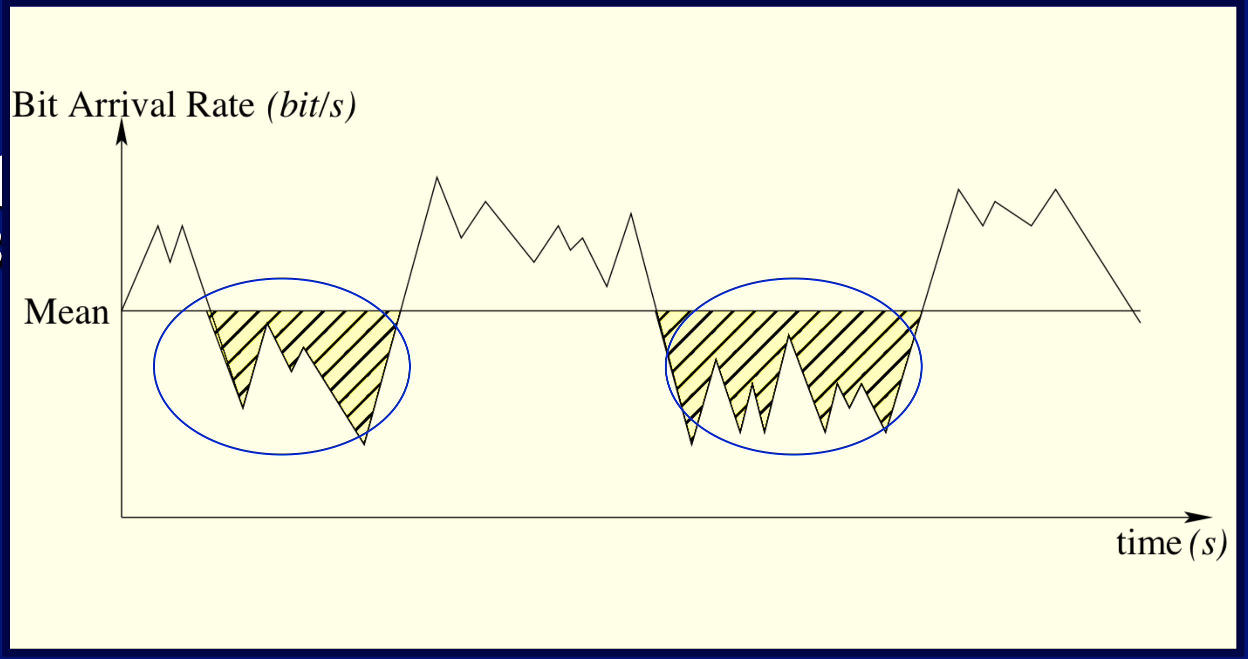
$$M_B^k = \prod_{i \in C^k} p_k^i$$

Description of Route Selection Metrics:
2. *Variance in Number of Bits Delivered*

Bit arrival rate (V^k_B) varies with PU activity and channel characteristics

-measures the cumulative shaded portion, i.e., the number of bits that arrive at the next hop when the link bit rate is lower than the mean value

-directly translates to the packet jitter (variance in the packet arrival times), and must be minimized



Description of Route Selection Metrics:
3. *Spectrum Propagation Characteristics*

Frequencies in the lower MHz range have better propagation characteristics

- Electromagnetic radiation travels farther with lower attenuation.
- Reduces the per-hop distance

We get the propagation distance D_k using as,

$$D_k = \left[\left(\frac{c}{4\pi f_k} \right)^2 \frac{P_{tx}^{CR}}{P_{rx}^{CR}} \right]^{\frac{1}{\beta}}$$

Propagation constant

Transmit and receive power, respectively

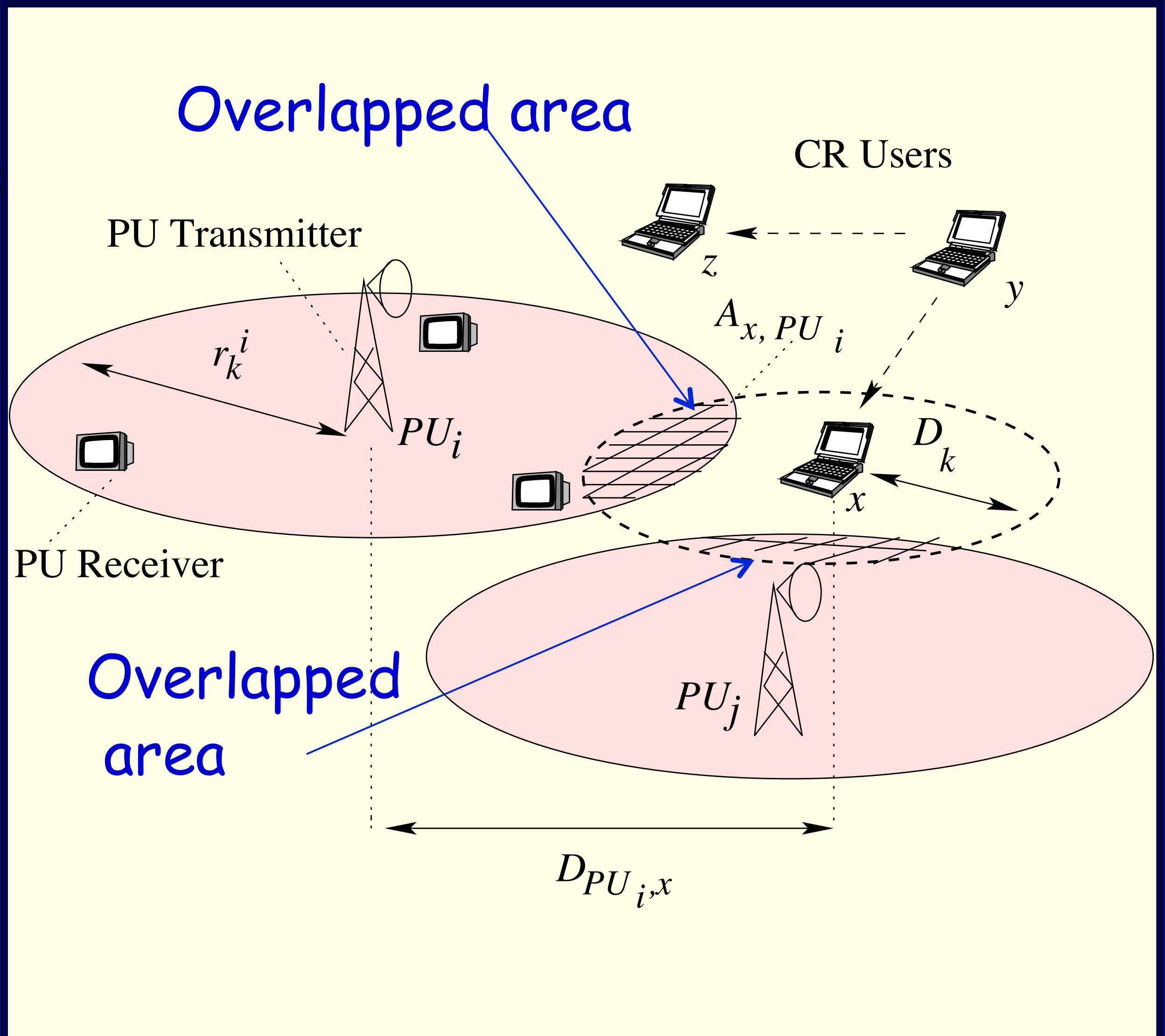
Frequency f_k chosen for Tx

Description of Route Selection Metrics:
4. *PU Receiver Protection*

Aims for minimum overlap between transmission coverage areas of the CR users and PUs

Each CR (here, x) calculates the cumulative overlap area with PUs, $A_{x,PU}$

CR y chooses z as next hop as $A_{x,PU} > A_{z,PU}$



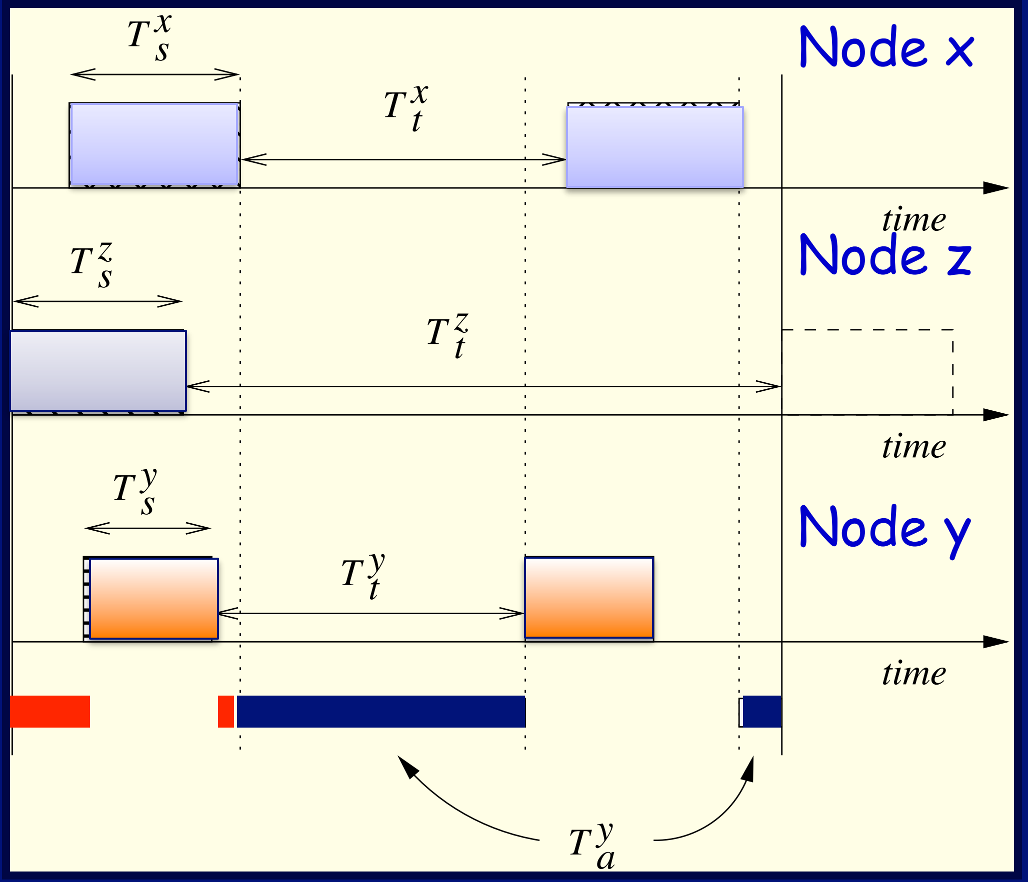
Description of Route Selection Metrics:
5. *Spectrum Sensing Consideration:*

During classical energy detection, neighboring CRs must remain silent

- T^x_s, T^y_s, T^z_s are sensing times of x, y and z, respectively

- CR y can only transmit when other nodes are not sensing (blue bar), even when it is free, say Time: T^y_a

- y cannot transmit at other times, which reduces its suitability for routing



Optimization for Spectrum Selection

Use the routing metrics to formulate the objective functions, constraints

To find : Spectrum $k \in N_s$

Objective Functions (or) "Initiative"

$$O_{Class\text{-}I} = D_k \cdot T^x$$

$$O_{Class\text{-}II} = D_k \cdot A^k{}_x$$

i.e., Maximize $O_{Class\text{-}I}$

i.e., Minimize $O_{Class\text{-}II}$

Optimization for Spectrum Selection

- $O_{Class-I} = D_k \cdot T^x$
  - D_k: Propagation distance dependent on frequency
  - T^x: Effective time for transmission, given other sensing schedules
  - Maximizing $O_{Class-I}$ implies transmit longest distance, for max. time

Best option for CR nodes!

Optimization for Spectrum Selection

- $O_{Class-II} = D_k \cdot A^k_x$
  - A^k_x: Overlap area for CRs and PU transmitter
  - Minimizing $O_{Class-II}$ implies transmit over short distance, and involve nodes with minimal overlap

Best option for PU protection!

Optimization for Spectrum Selection

Optimization Constraints:

$M_B^k > P_B^{|Ck|}$ — Probabilistically meet the user specified constraints of bandwidth

$V_B^k < J_T$ — Bit arrival variance must meet the minimum jitter threshold

$B_C^k > \Psi_K \cdot |Ck|$ — Coherence bandwidth of channel (B_C^k) must be greater than signal bandwidth to prevent fading

$T_\Delta^s + T_\Delta^c(1-M_B^k) < T_{th}$ — The switching time latency, for both inter- (T_Δ^s) and intra-spectrum (T_Δ^c) must be bounded

Mapping Initiative to Forwarding Delay

For Class I:
- Highest value of initiative (maximization of the objective function) = lowest forwarding delay on the CCC

For Class II:
- Lowest value of the initiative (minimization of the objective function) = lowest forwarding delay on the CCC

Destination picks the path and responds with RREP that has the earliest RREQ delivered on the CCC

CRP Discussions

- Requires knowledge of several thresholds for the optimization
  - Not simply a "plug and play" but requires some initial configuration
- Only two routing classes considered
  - No continuous variation and fine-grained adjustment between Class I and Class II
- Strong channel assumptions
  - The transmission range overlap calculation assumes perfect circles
  - Knowledge of coherence bandwidth is assumed a priori

Summary of Open Research Issues

- CR routing protocols are mainly derived from traditional ad hoc networks
  - New routing approaches able to achieve scalability must be defined

- Routing design needs to be evaluated with prototypes and testbed implementations
  - Up to now, the experiments are mainly focused on lower layers.

Summary of Open Research Issues

- Collecting PR statistics like time, duration of activity and then using routing schemes may have a large 'setup' time
- Problem of no common control channel (CCC) for route request/reply broadcasts