Boundary Helps: Efficient Routing Protocol using Directional Antennas in Cognitive Radio Networks

Ying Dai and Jie Wu

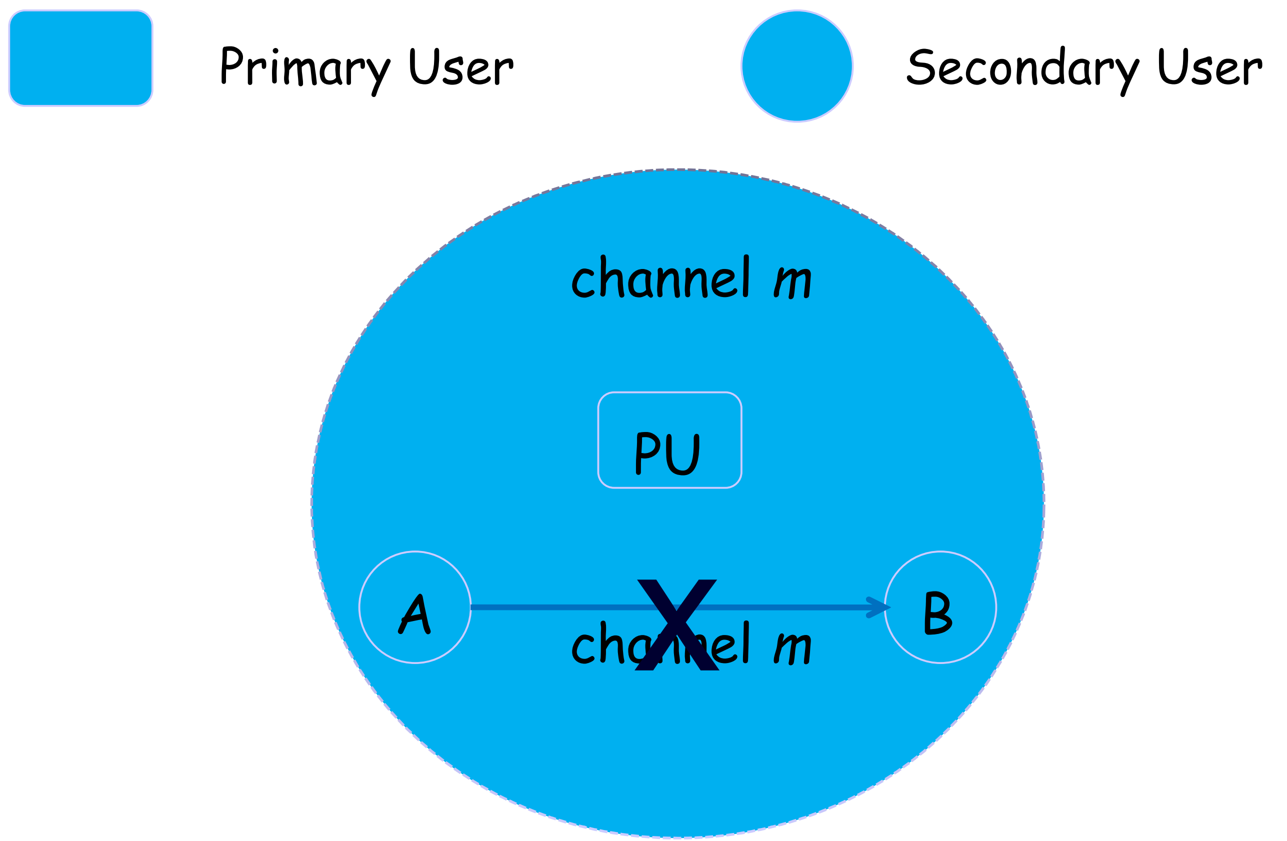
Computer and Information Sciences
Temple University

1. Introduction

- A real life scenario:
  - Privileged User
  - Road blocked
  - Avoid in advance?

Cognitive Radio Networks (CRNs)

- Similar situation in CRNs



Challenges

- Primary users' (PUs') activities are unpredictable and too costly to distribute.
- Routes selected by traditional wireless protocols are unreliable in the presence of PUs.

Q: What if we can select routes that avoid those "restricted areas" in advance?

Q: What is the cost-effective way to collect such information ?

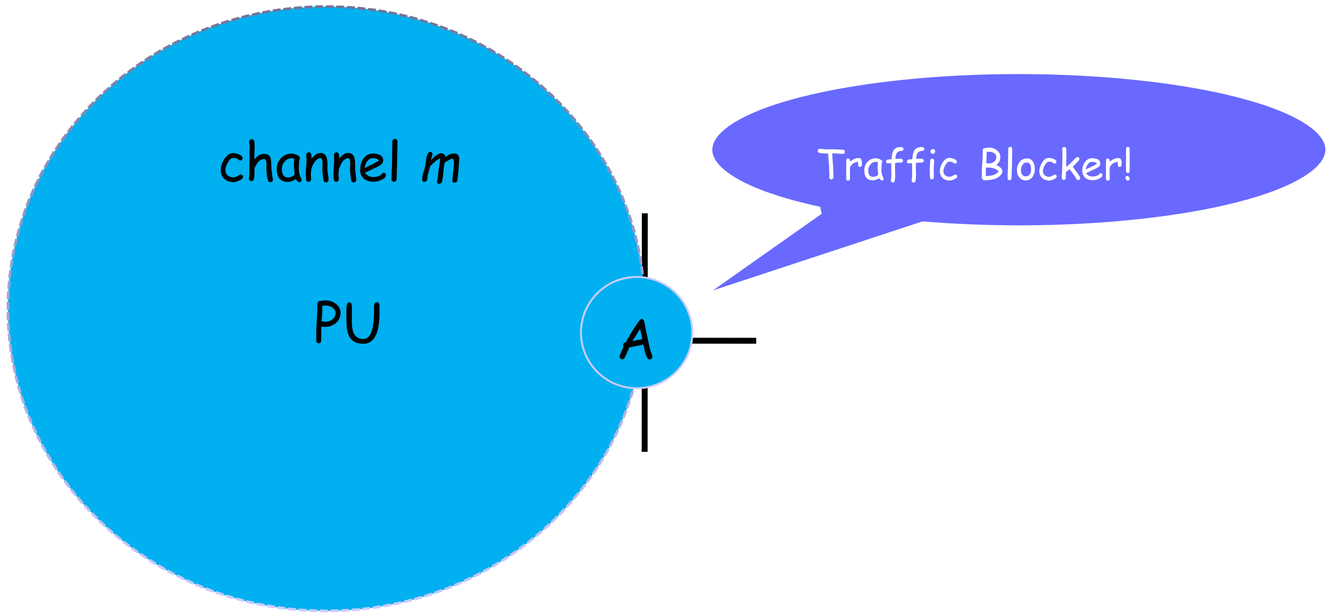
Simple Approach

- Each node collects its own information about PUs in the neighborhood.
- Each node then piggybacks PUs information during the route discovery and reply process.

- Disadvantage
  - Burden on the common channel control for information exchange.

Intuition

- Answer : Make use of boundary nodes.
- Also, we need the help of directional antennas.
- Benefits: 1) tell the direction of PUs; 2) increase the space reuse ratio.



2. Problem Formulation

- Objective: Route selection
  - Delay
  - Reliability
  - SINR requirements of PUs and SUs

Unpredictable PUs' activities → No optimal solution

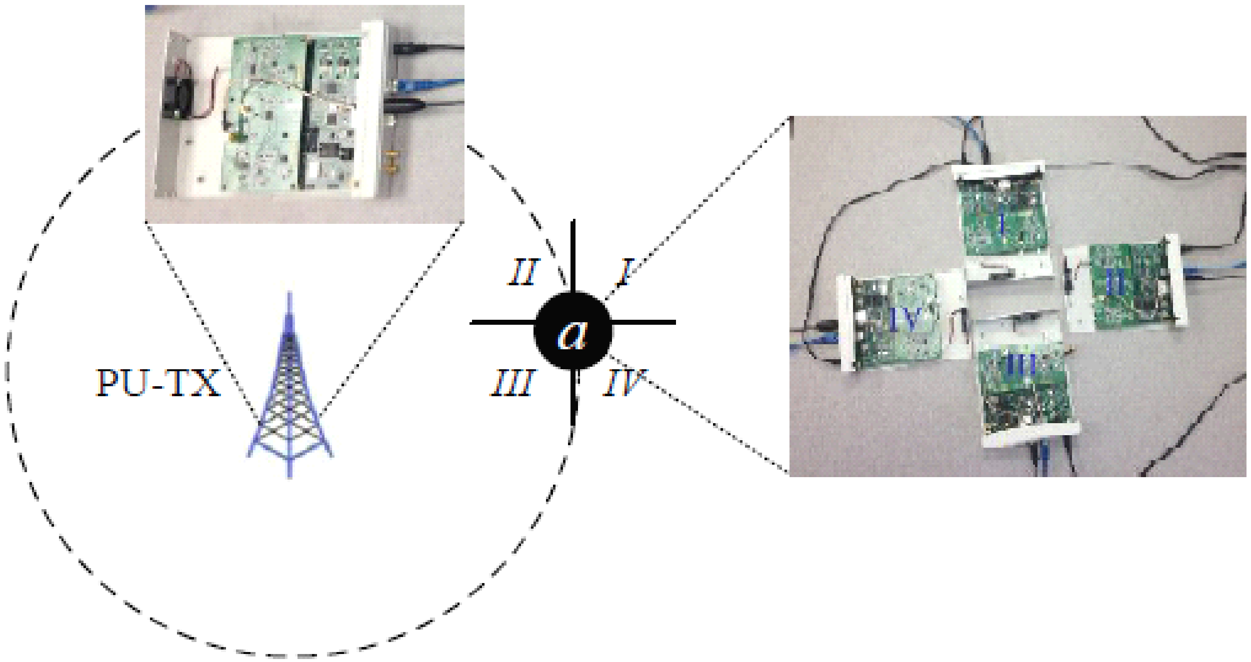
We propose an efficient solution, with the help of boundary nodes

3. Boundary Nodes

- How does a node know if it is a boundary node itself?
- *Answer*: By the variance of its sensing results in different directions!
- We use USRPs to show the properties of a boundary node.
  - USRP: Universal Software Radio Peripheral

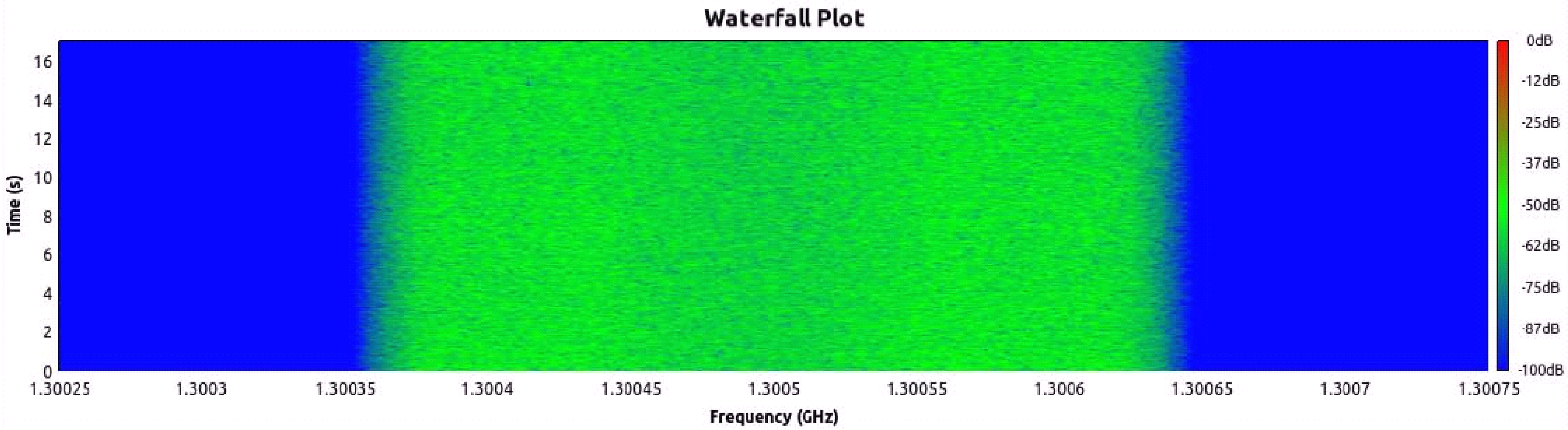
3. Boundary Nodes

- 5 USRP N200s
  - One PU; Others simulate a four-directional SU.
  - Central frequency: 1.3005GHz

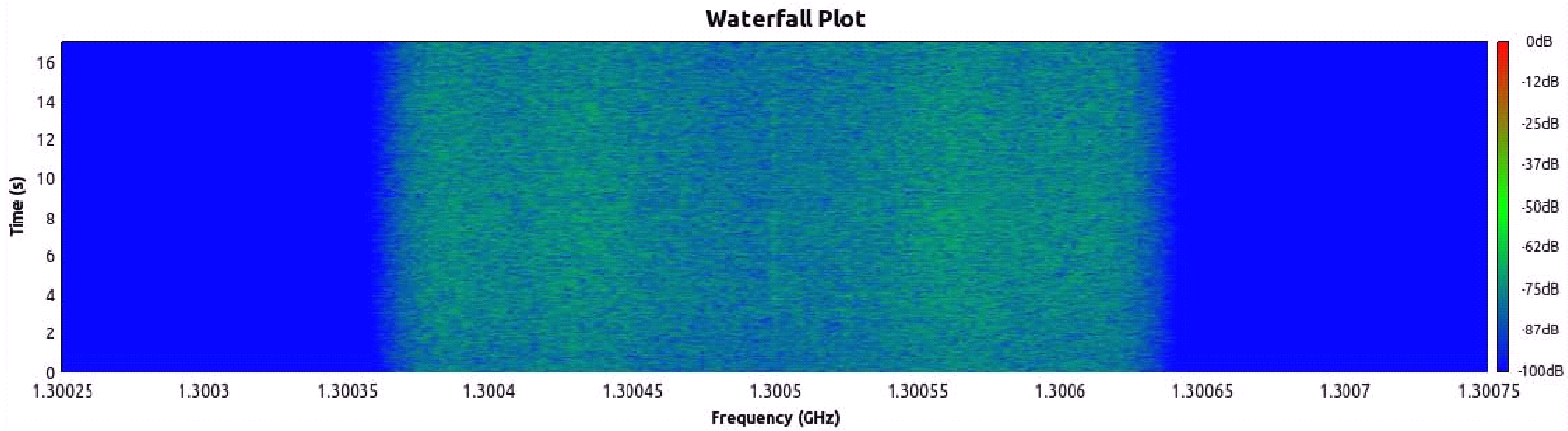


3. Boundary Nodes

- Sector I: -50dB; Sector II: -87dB



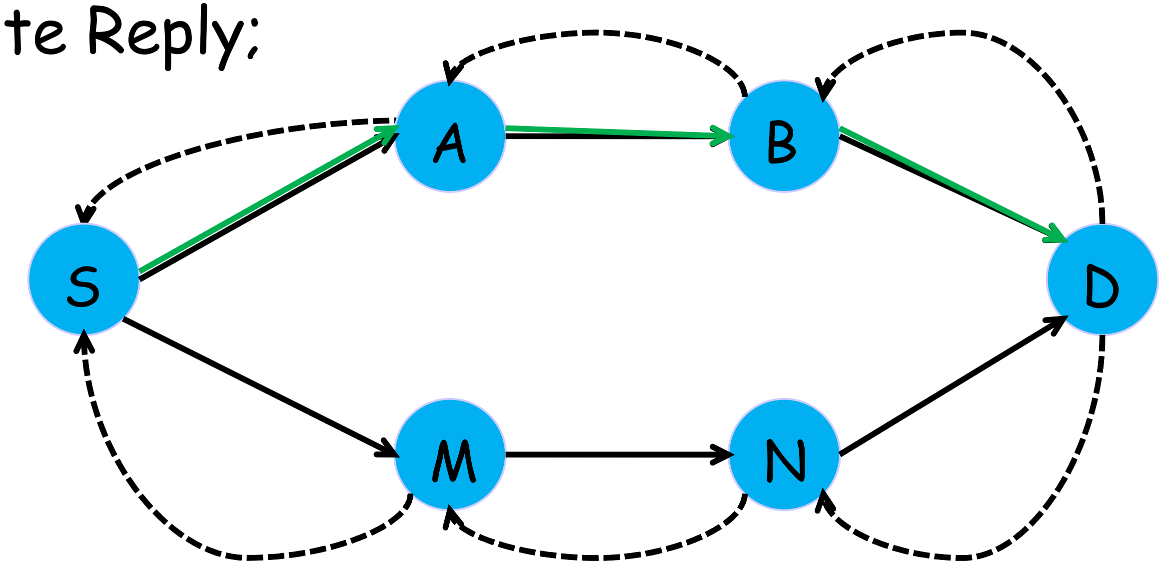
Receiving results at sector I.



Receiving results at sector II.

Routing Overview

- Overview:
  - Route Discovery;
  - Piggyback in Route Reply;
  - Route Selection



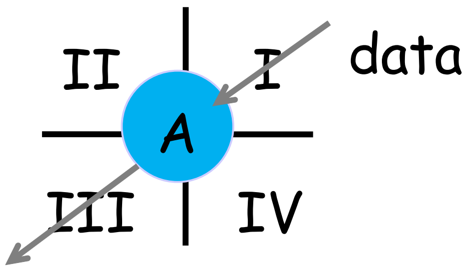
4. Piggyback

- Route discovery : traditional ways
- Piggyback: What kind of information?

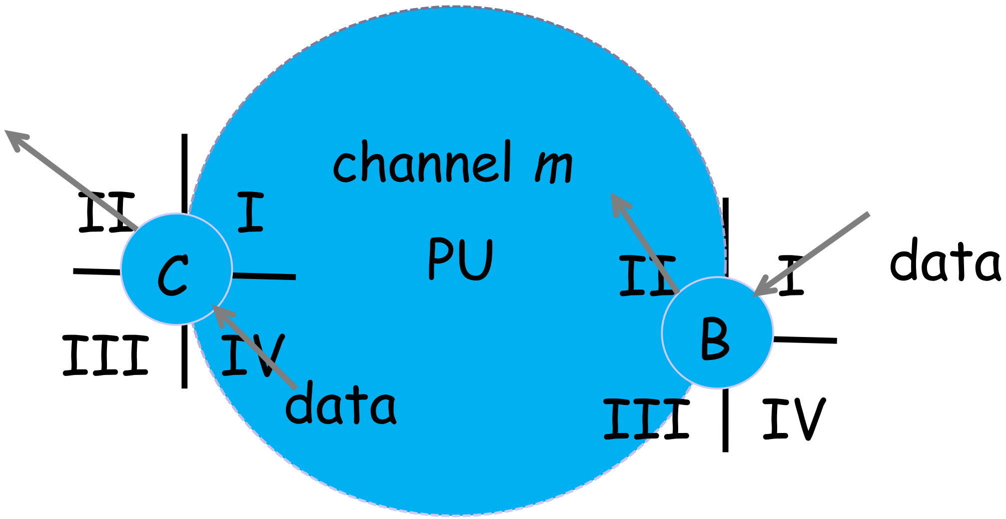
Non Boundary Node:
(IN, OUT, -, -)

Boundary Node:
(IN, OUT, m, μ)

μ = 1: ENTER
μ = -1: EXIT



A: (I, III, -, -)



C: (IV, II, m, -1)

B: (I, II, m, 1)

Link Information

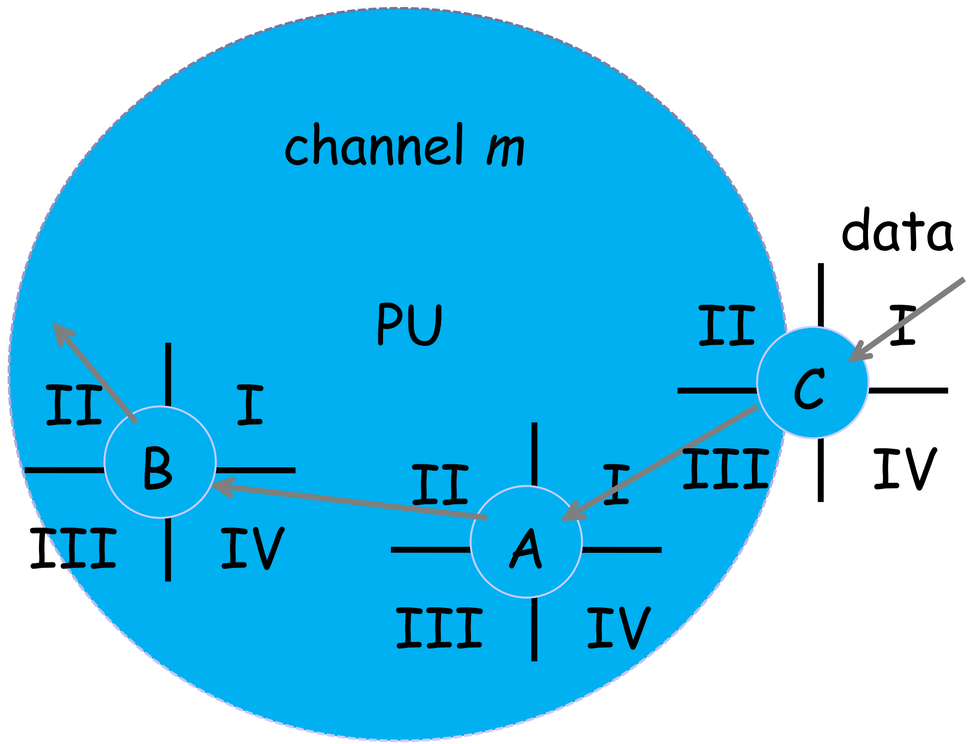
- Based on piggyback information, for a link, we can know:
  - If the link is inside or outside a PU area;
  - How many PU areas the link is located inside.

- Then, we define the link length based on the above information.
  - A larger value for link length will show that the link is within more PU areas.

Four Cases

- Four cases to identify if a link (*AB*) is within a PU area, given the piggyback information:

Case1: Neither *A* nor *B* is a boundary node, but the closest boundary node on the route indicates the entering into a PU area.
C: (I, III, m, 1)
A: (I, II, -, -)
B: (IV, II, -, -)

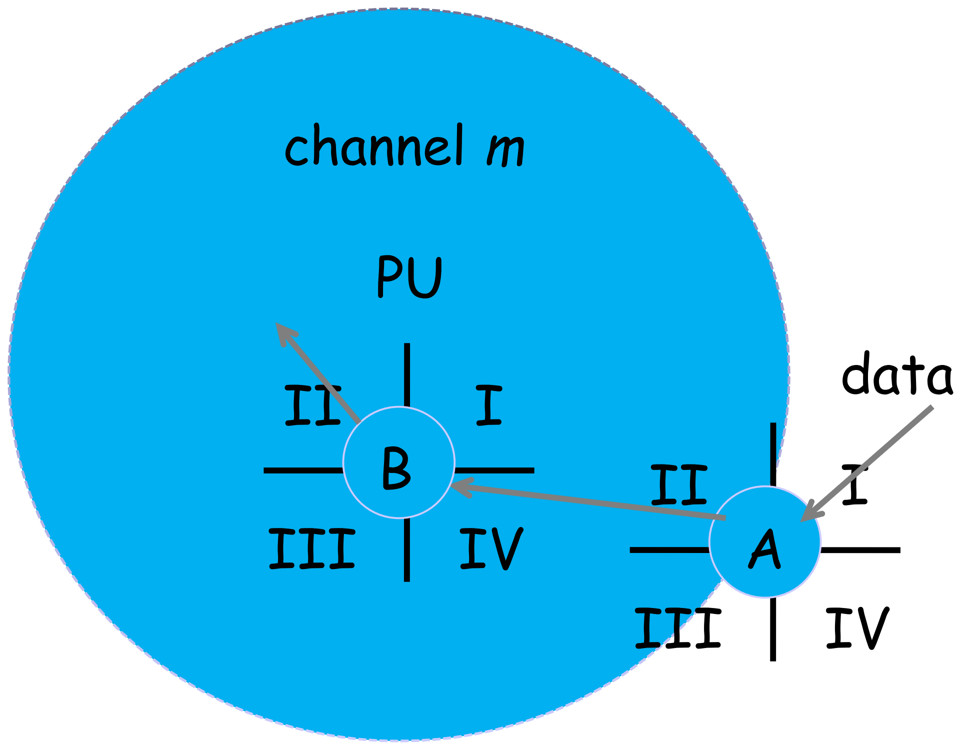


Four Cases (Cont'd)

Case2: *A* is a boundary node and *B* is not. In addition, *A* indicates the entering into a PU area.

A: (I, II, m, 1)

B: (IV, II, -, -)

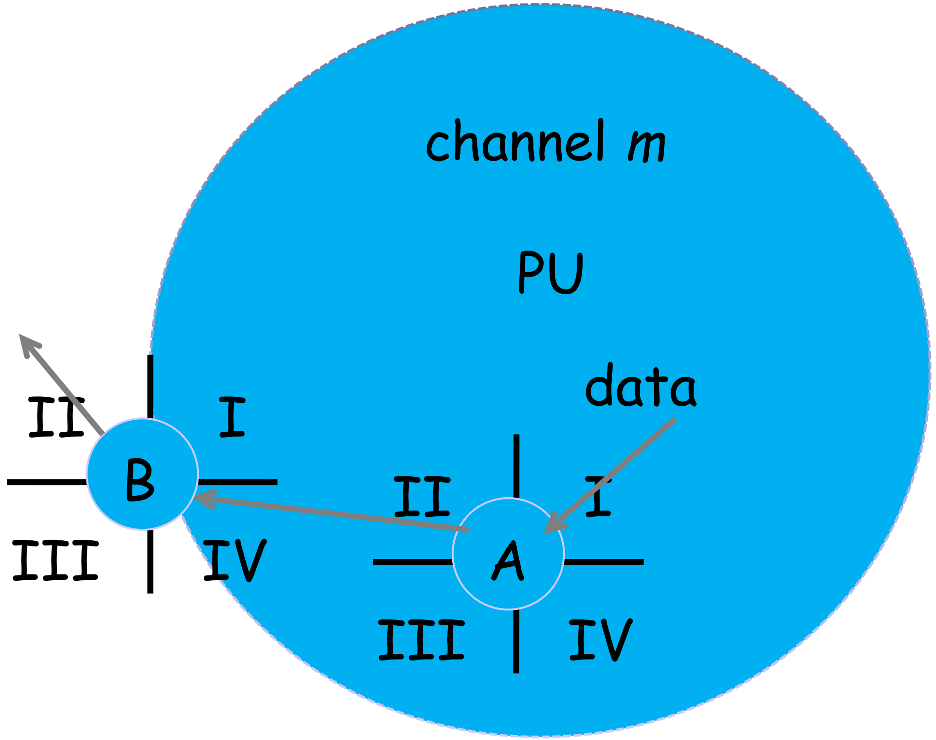


Four Cases (Cont'd)

Case3: *B* is a boundary node and *A* is not. In addition, *B* indicates the exiting from a PU area.

A: (I, II, -, -)

B: (IV, II, m, -1)

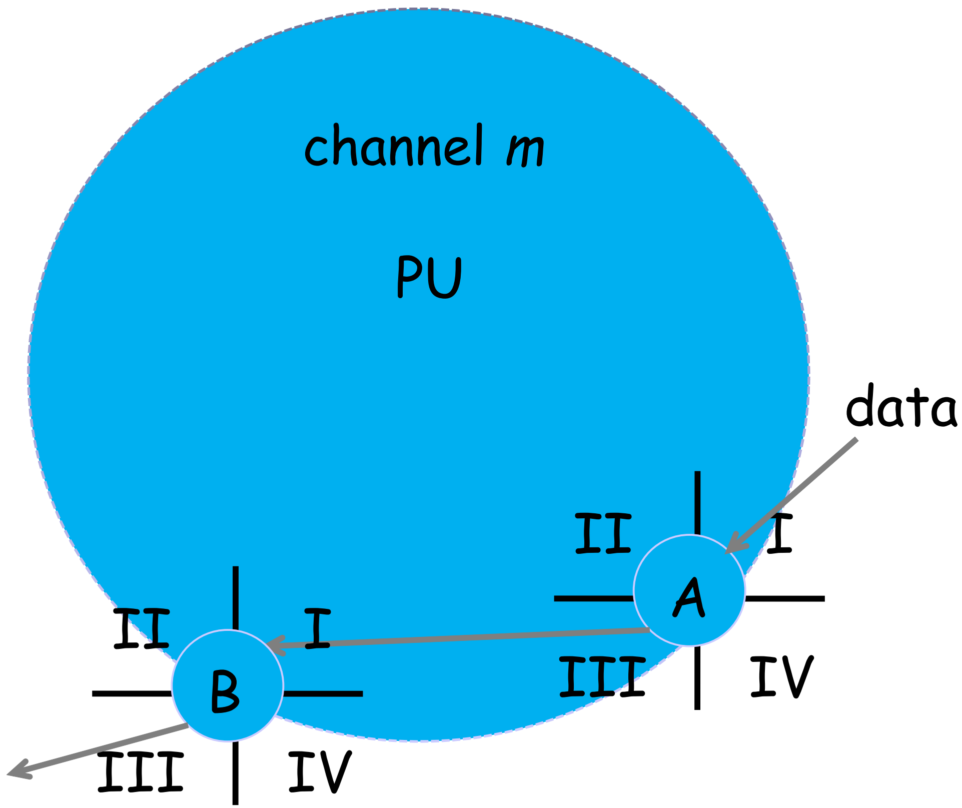


Four Cases (Cont'd)

Case4: Both *A* and *B* are boundary nodes. In addition, *A* indicates the entering into a PU area and B indicates the exiting from the PU area.

A: (I, II, m, 1)

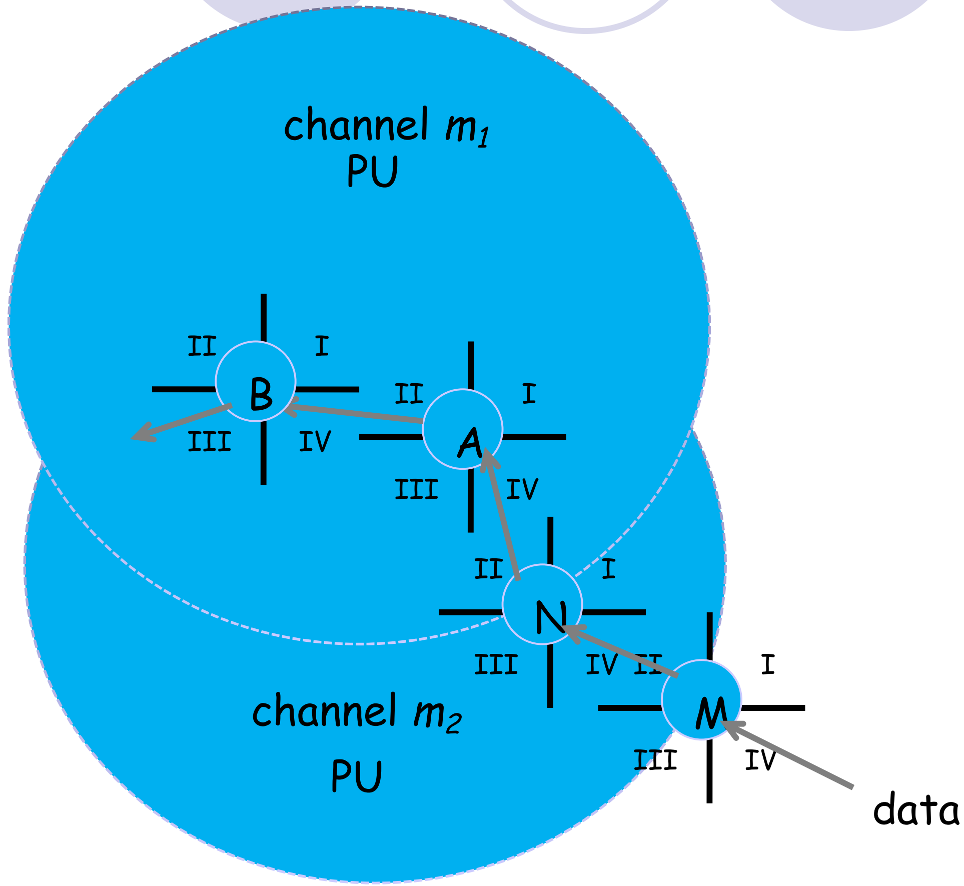
B: (I, III, m, -1)



Special Case

Special case: if a link is within multiple PU areas, we can still detect it.
M: (IV, II, m_2, 1)
N: (IV, II, m_1, 1)
A: (IV, II, -, -)
B: (IV, III, -, -)

The previous boundary nodes both have $\mu = 1$. Link *AB* are in two PU areas, occupying m_1 and m_2 when active.



5. Route Selection

- Intuitively, we can select the route:
  - with less links that pass through a PU area;
  - with less links that are within multiple PU areas.

We need to define the route length

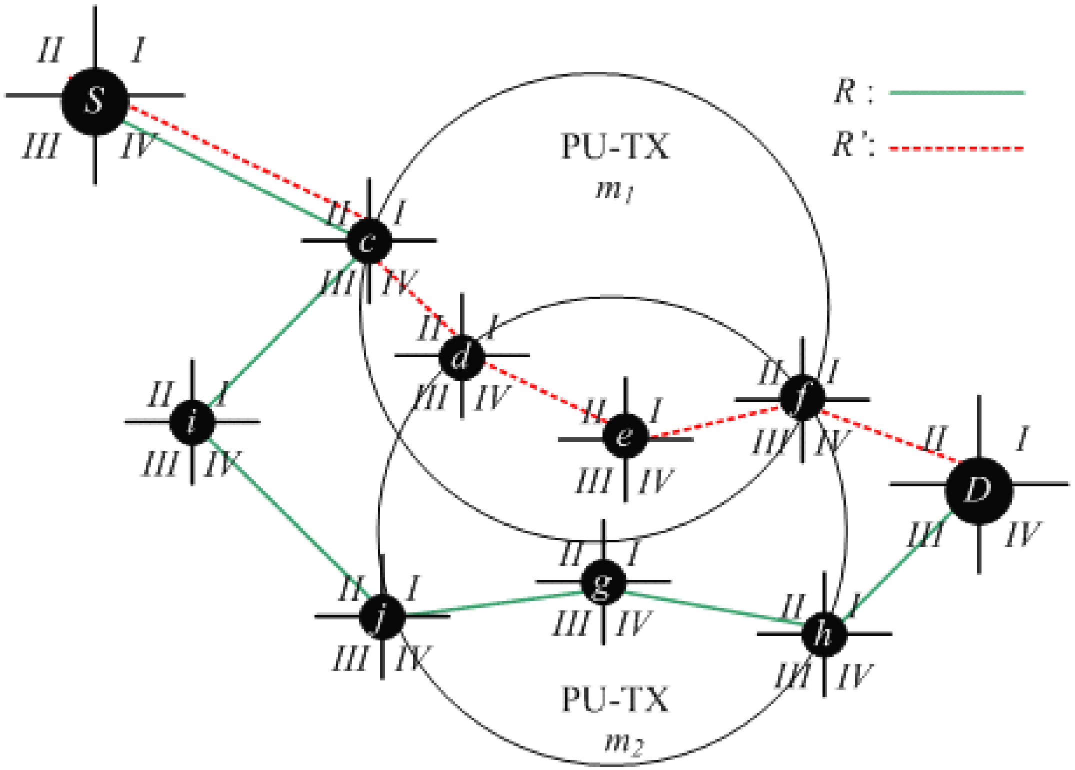
Link Length

- First, we define the length of link *AB*, denoted as (L_{AB}):
  - $L_{AB} = 1$, if link *AB* is not in any of the PUs' areas;
  - $L_{AB} = |M|/(|M| - C(m))$, if *AB* is within the PUs' areas.
    - $|M|$ is the total number of channels in the network;
    - $C(m)$ is the counter of how many PU areas *AB* is in.

Route Length

- The route length is defined as the sum of the link length on the route: $\Sigma(L_{AB})$
  - The route with more links in a PU area will have a larger value of route length.
  - The route that passes through more PU areas will have a larger value for route length.

An Example



1. Route R' has more links in the PU area.
2. Some links of R' are in multiple PU areas.
3. These properties can be shown by the value of route length.

Route Length

- Calculate route length:

EXAMPLE OF WEIGHTED ROUTE LENGTH

R	Sc	ci	ij	jg	gh	hD
7	1	1	1	$\frac{3}{2}$	$\frac{3}{2}$	1

R'	Sc	cd	de	ef	fD
$\frac{19}{2}$	1	$\frac{3}{2}$	3	3	1

- The route with smaller route length will be chosen.
  - In this example, R will be chosen since 7< 19/2.

Supplementary Information

- Our route length calculation is based on the simplified SINR model:
  - It aims at showing the influence of PU areas;
  - It can also be easily extended to other routing protocols using real SINR models.

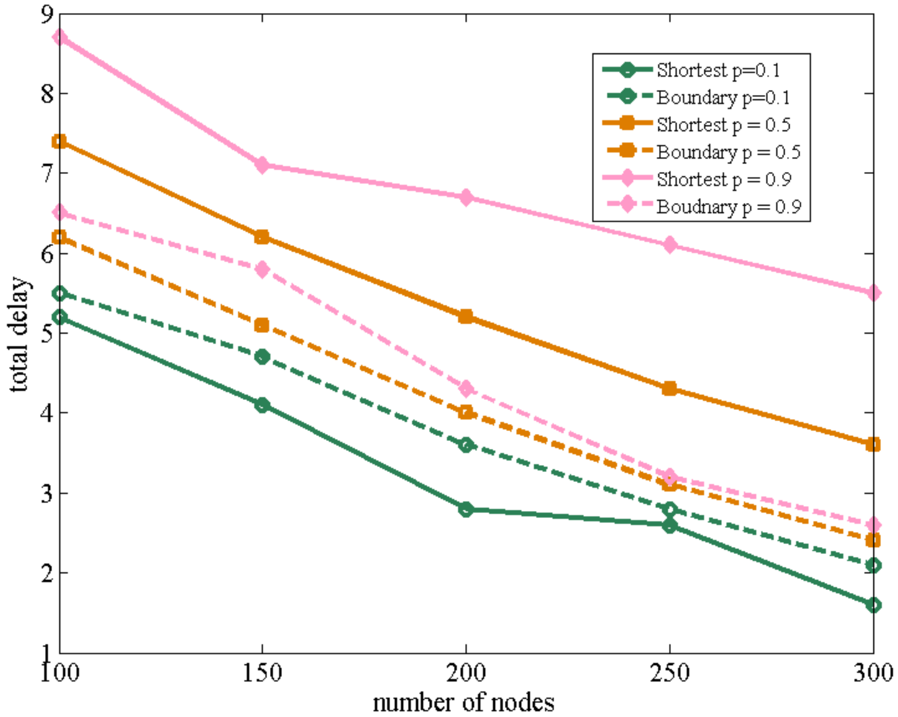
- Our model also assumes the accuracy of boundary node detections:
  - It can be extended to consider the misdetection of boundary nodes.

6. Simulation

- Simulation Settings
  - Network area: 2,000 X 2,000
  - Number of nodes: [100, 300]; TX power: 23 dBm; Noise power: 98 dBm; SINR threshold: 10 dB
  - Number of channels:[10, 25]
  - Number of PUs: [10, 50]; Operation range of each PU: [300, 500];
  - Number of sectors: 4; Delay for one channel switch: 0.1s.

PU Active Probability

- Total Delay:
  - Transmission Delay (based on SINR) + Channel Switch Delay
  - Vary the PU active probabilities, p

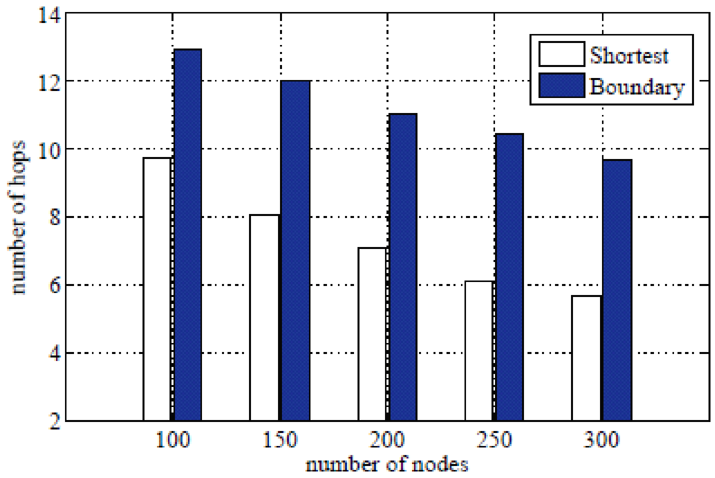


Our model is better when p = 0.5 and 0.9. Shortest path is better when p = 0.1.

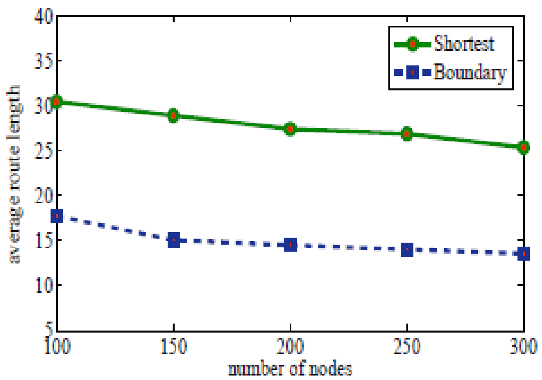
Select 0.5 for the remaining simulation.

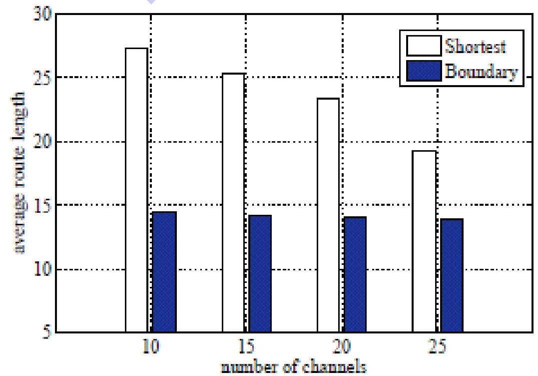
Hop and Length

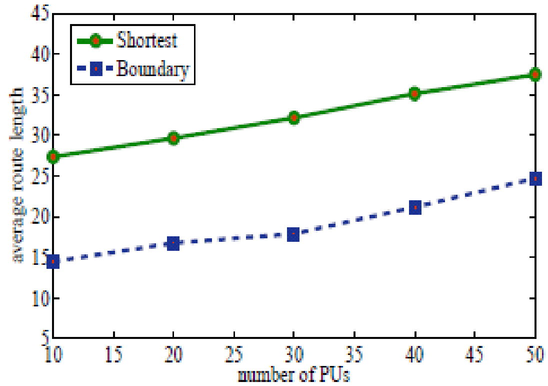
- Number of hops



- Average route length

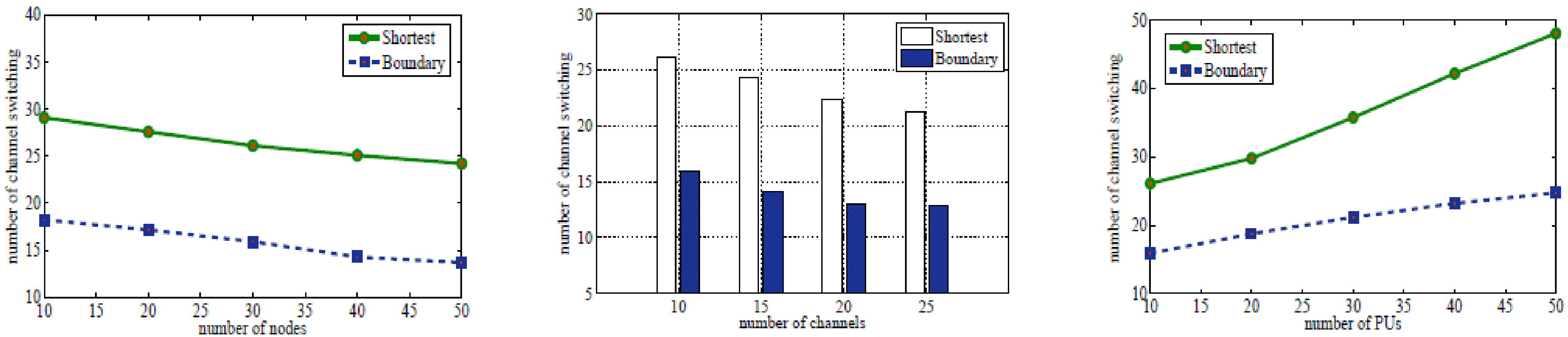






Channel Switches

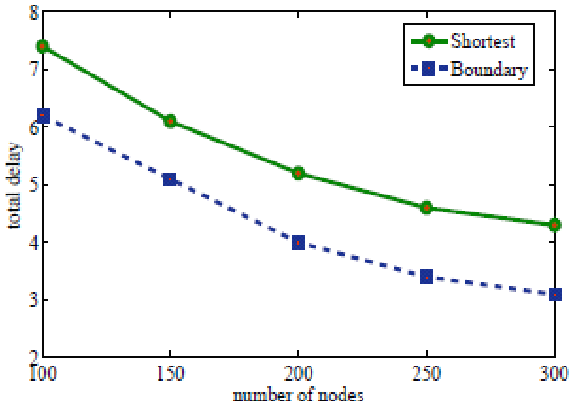
- Number of channel switches:
  - It happens when PUs become active



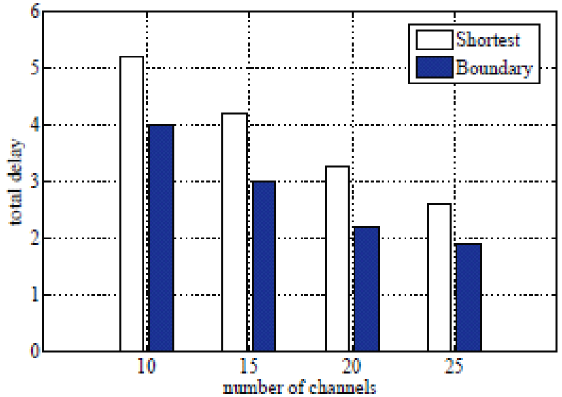
(a) Varying # of nodes (b) Varying # channels (c) Varying # PUs

Total Delay

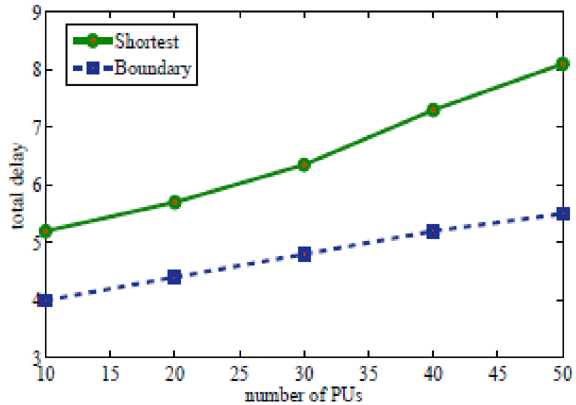
- Transmission Delay (based on SINR) + Channel Switch Delay



(a) Varying # of nodes



(b) Varying # channels



(c) Varying # PUs

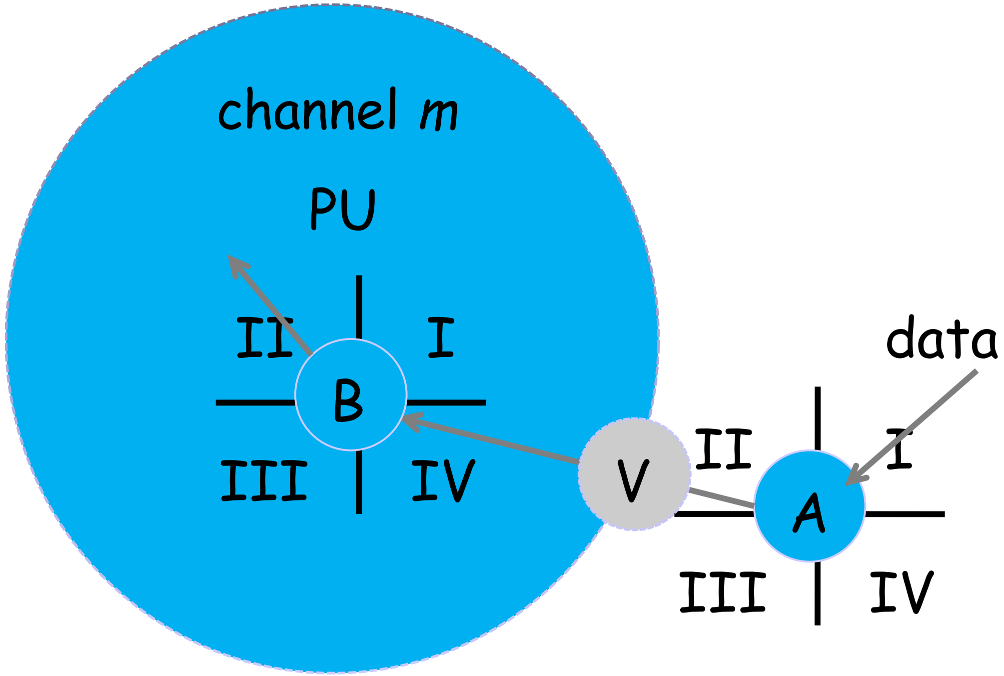
7. Extensions

- Missing boundary node

Neither *A* nor *B* is a boundary node.

However, by the sensing result variance, we can detect the entering of the PU area.

Like a *virtual boundary node.*

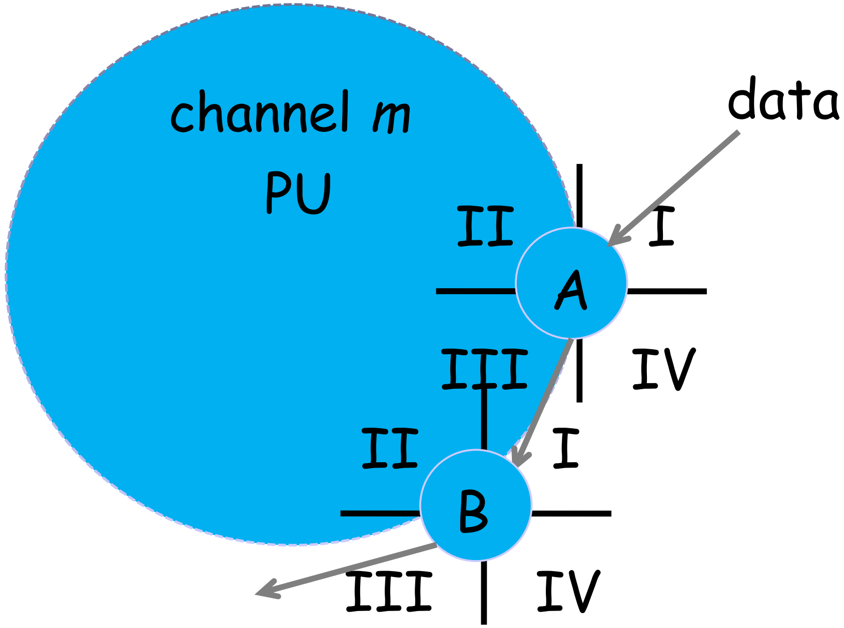


Extensions (Cont'd)

- Imperfect information

Link *AB* located at the boundary area.

Whether to count link *AB* as in the PU area is decided by a predefined threshold.



Extensions (Cont'd)

- Threshold-based Boundary Nodes
  - based on active PU probability
  - Reporting boundary nodes when active level is above the threshold
- More simulation
  - In-depth simulation analysis with traffic

7. Conclusion

- Directional antenna + boundary nodes.
- Detect if a link is outside PU areas, inside a single PU area, or inside multiple PU areas.
- Define the link length and route length.
- Our algorithm can be easily applied or extended in other models.