Radio Co-location Aware Channel Assignments for Interference Mitigation in Wireless Mesh Networks

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Wirless Mesh Networks (WMNs)

A Promising Technology

- Potential for widespread application.
  - Low-cost availability of IEEE 802.11 hardware.
  - Ease of scalability and reconfigurability.
  - Tremendous increase in data communication rates guaranteed by IEEE 802.11 and IEEE 802.16 standards.
- Wireless technologies that benefit from WMN deployments.
  - IEEE 802.11 WLANs, Wireless Metropolitan Area Networks (WMANs), Cellular mobile systems including LTE-Advanced etc.

WMN Model Considered

- A single Gateway WMN.
- Mesh-routers and mesh-clients.
- Multi-Radio Multi-Channel (MRMC) Deployment.
- Only inter mesh-router communication issues considered.

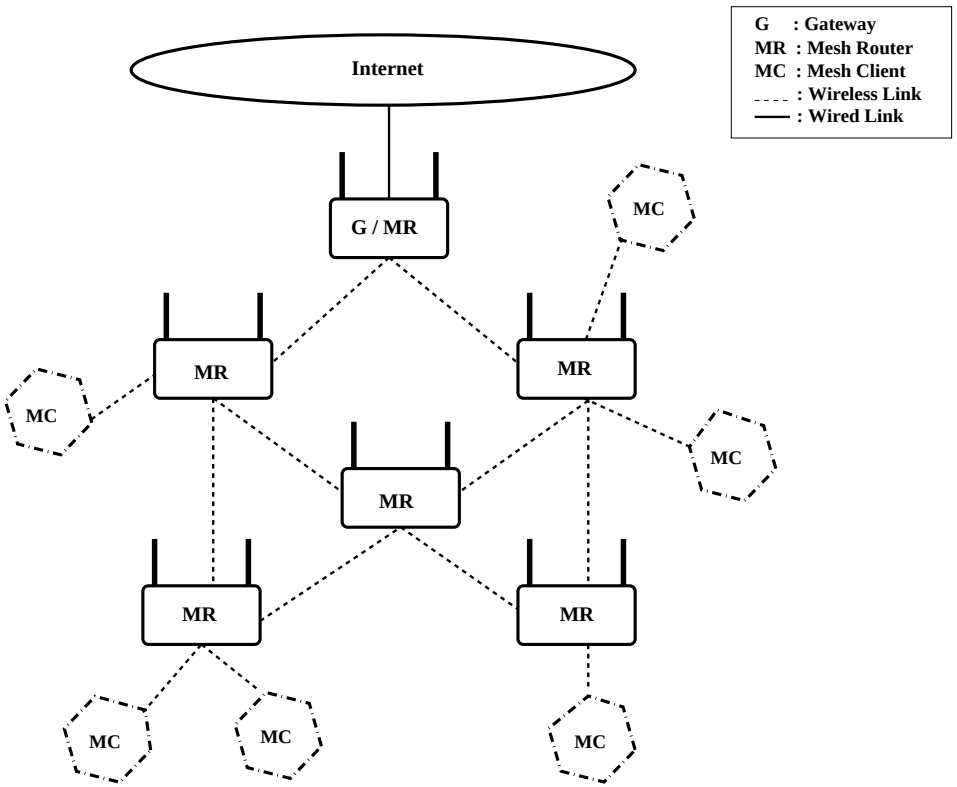


Figure: A Simplistic WMN Architecture

Concepts and Terminology I

Let G = (V, E) represent an arbitrary WMN.
V $\rightarrow$ Set of nodes in G, E $\rightarrow$ Set of wireless links.
Let $i \in V$, $j \in V$, such that $(i, j) \in E$.

Conflict Links

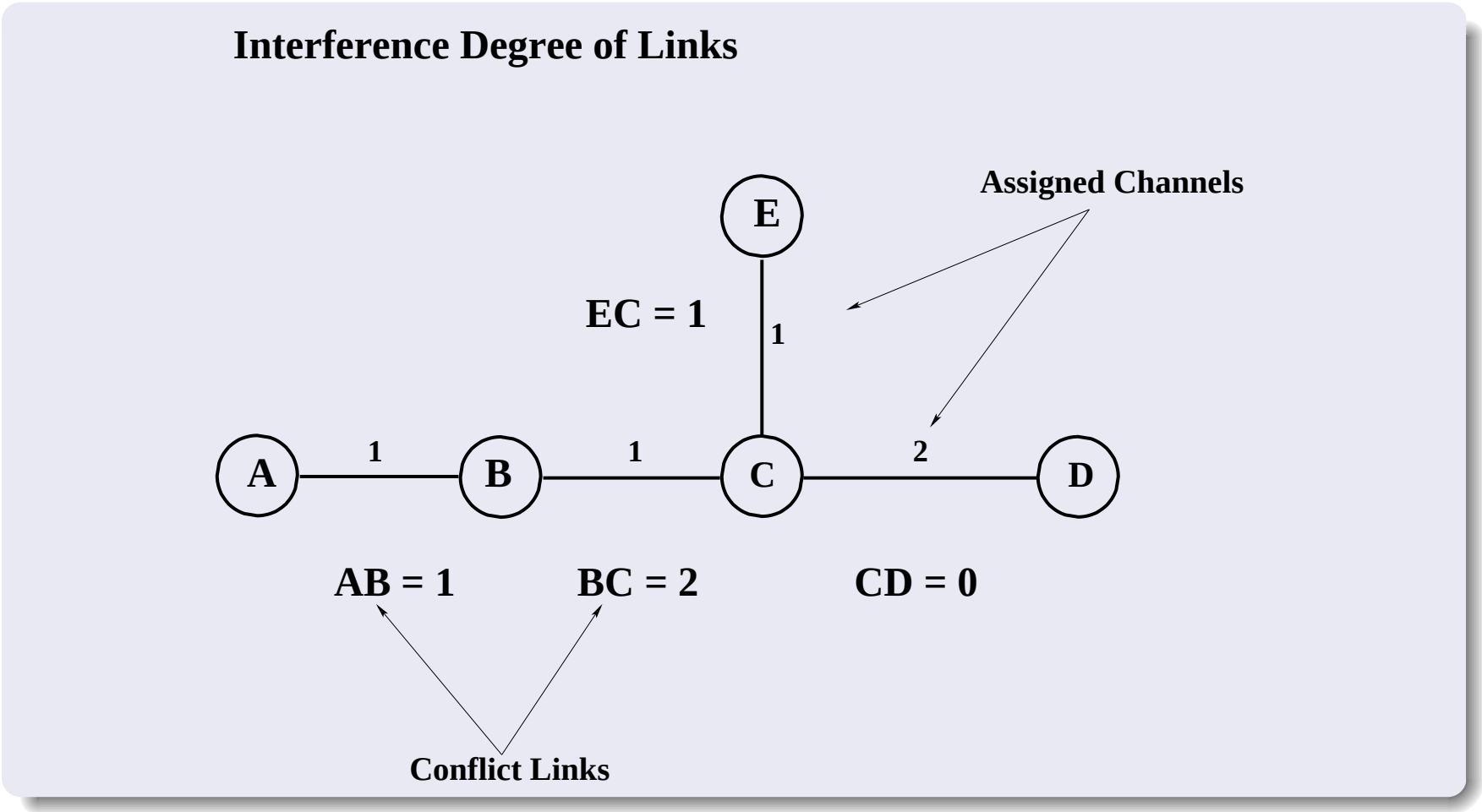
- $\forall (m, n) \in E$, for which the transmitting range of the radio at node m or n, extends upto, or beyond node i or j, are the conflict links of link (i, j).

Interference Degree

- The Interference Degree of link (i, j), is the total number of links in E which are the conflict links of (i, j).

Concepts and Terminology II

An Illustration



Concepts and Terminology III

Total Interference Degree or TID

- An approximate estimate of the interference prevalent in a WMN.
- Computed by halving the summation of the *Interference Degree* of all the links in G.

Conflict Graph or CG ($G_c = (V_c, E_c)$)

- Generated from $G = (V, E)$ where
  - $V_c = E$
  - $\forall (m, n) \in V_c$, $\{(i, j), (m, n)\} \in E_c \; iff \; (m, n)$ is a conflict link of (i, j) in G.
- Wireless communication links in the WMN become the vertices in the conflict graph.
- Any two of these vertices share an edge **iff** the corresponding wireless links in the WMN interfere.

Concepts and Terminology IV

Multi Radio Multi Channel Conflict Graph (MMCG)

- Conflict Graph for MRMC WMNs.
- Multiple radios / WMN Node.
- Several channels are available.
- Creation is complex.

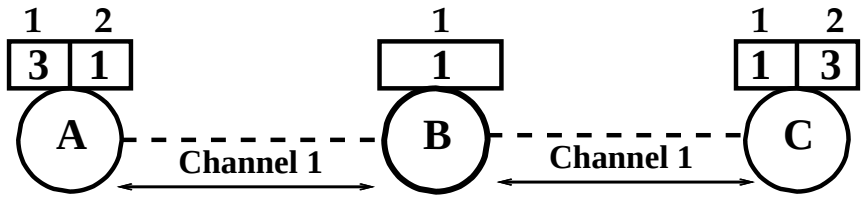
Channel Assignment (CA) Scheme

- CA can be understood as, $C_i = CA(i, R_i)$, where
  - Each node i, has random number of identical radios R_i.
  - $C_i \Rightarrow$ List of channels assigned to R_i.
- Assumption : Number of available channels $> (R_i)_{max}$

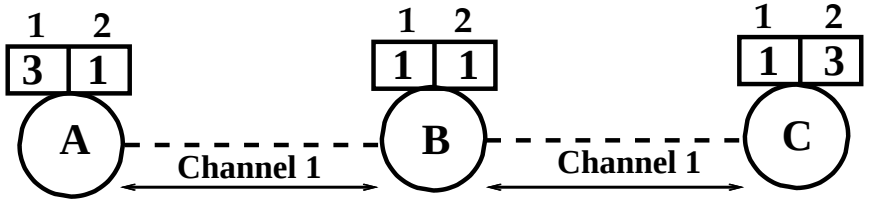
Radio Co-location Interference (RCI) I

Radio Co-location Scenarios

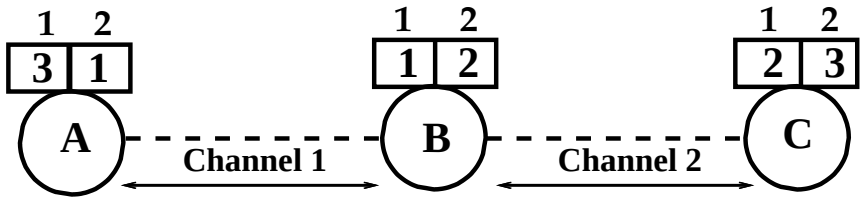
- Common Channel Scenarios
  - Fig. (i) $\rightarrow$ No RCI
    - Single Radio Common Channel at B (SRCC).
  - Fig. (ii) $\rightarrow$ RCI
    - Multiple Radios Common Channel at B (MRCC).
- Different Channel Scenarios
  - Fig. (iii) $\rightarrow$ No RCI
    - Multiple Radios Different Channels at B (MRDC).



(i) **Single Radio On Common Channel**



(ii) **Co−located Radios On Same Channel**



(iii) **Co−located Radios On Different Channels**

Radio Co-location Interference (RCI) II

Impact & Alleviation

- Spatially co-located radios cause RCI.
- Impact of RCI degrades network performance.
- Should be represented in MMCG.
- The Enhanced MMCG (E-MMCG) algorithm represents RCI while the Classical MMCG (C-MMCG) algorithm fails to do so.

Radio Co-location Aware Channel Assignments

Features

Features of Radio Co-location Aware Channel Assignments (RCA CAs)

- RCI Mitigation through Radio Co-location Optimization (RCO) function.
- Equitable distribution of channels among radios in a WMN.
- Topology preserving.

The Proposed RCA CAs

Two RCA CAs are proposed

- RCA Optimized Independent Set (OIS) CA .
- RCA Elevated Interference Zone Mitigation (EIZM) CA.

RCA Optimized Independent Set CA

Motivation

Factors Contributing To Idea Development

- Availability of exhaustive set of Results from Stage 1.
- Performance analysis of a dozen CAs.

The Driving Ideas

- **Notion of Statistical Evenness in Channel Allocation**
  - CA performance has a Statistical Dimension.
  - Even distribution of channels across radios $\rightarrow$ Improved CA performance.
- **Emphasis on RCI Mitigation**

Statistical Evenness in Channel Allocation

Application & Validation

Idea Implementation

Concept of even distribution of channels across links is used in

- Designing RCA OIS-CA.
- Interference Characterization & Estimation.

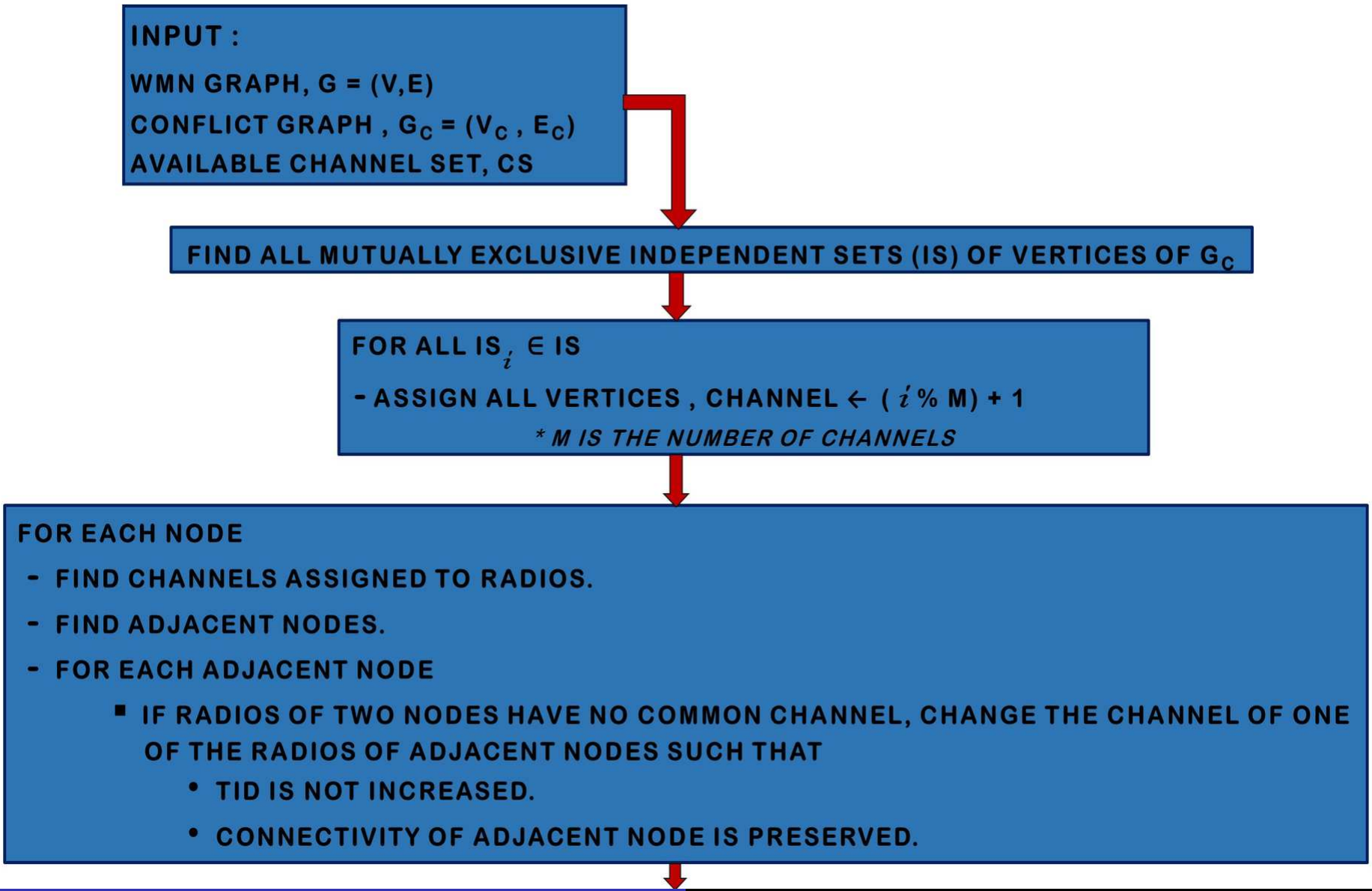
Idea Validation

Validation approach

- Propose OIS-CA and implement it.
- Compare OIS-CA with MaIS-CA (Independent Set based).
  - Theoretically $\rightarrow$ Toy Example.
  - Experimentally $\rightarrow$ ns-3 Simulations.

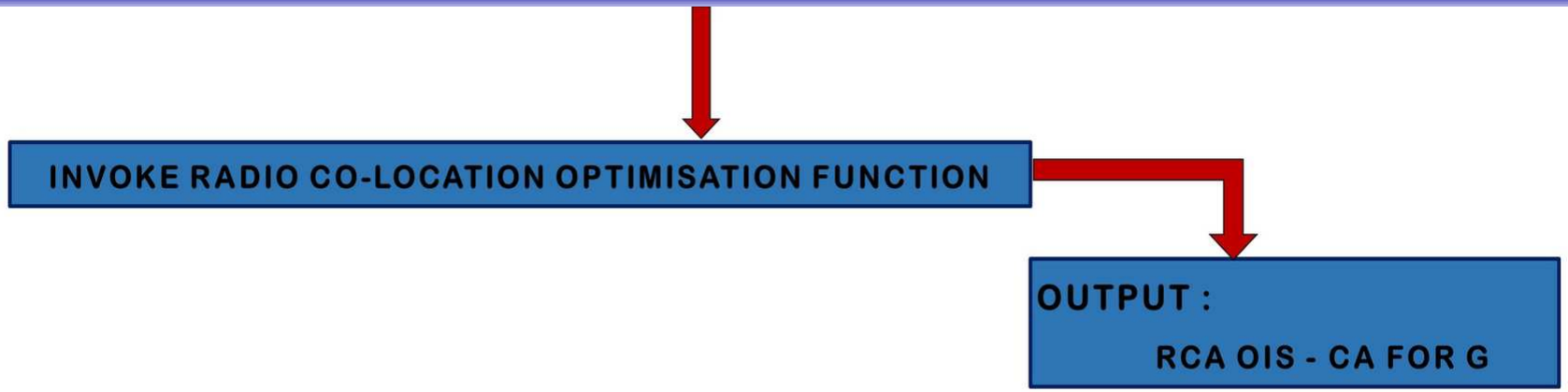
RCA Optimized Independent Set CA

OIS Algorithm



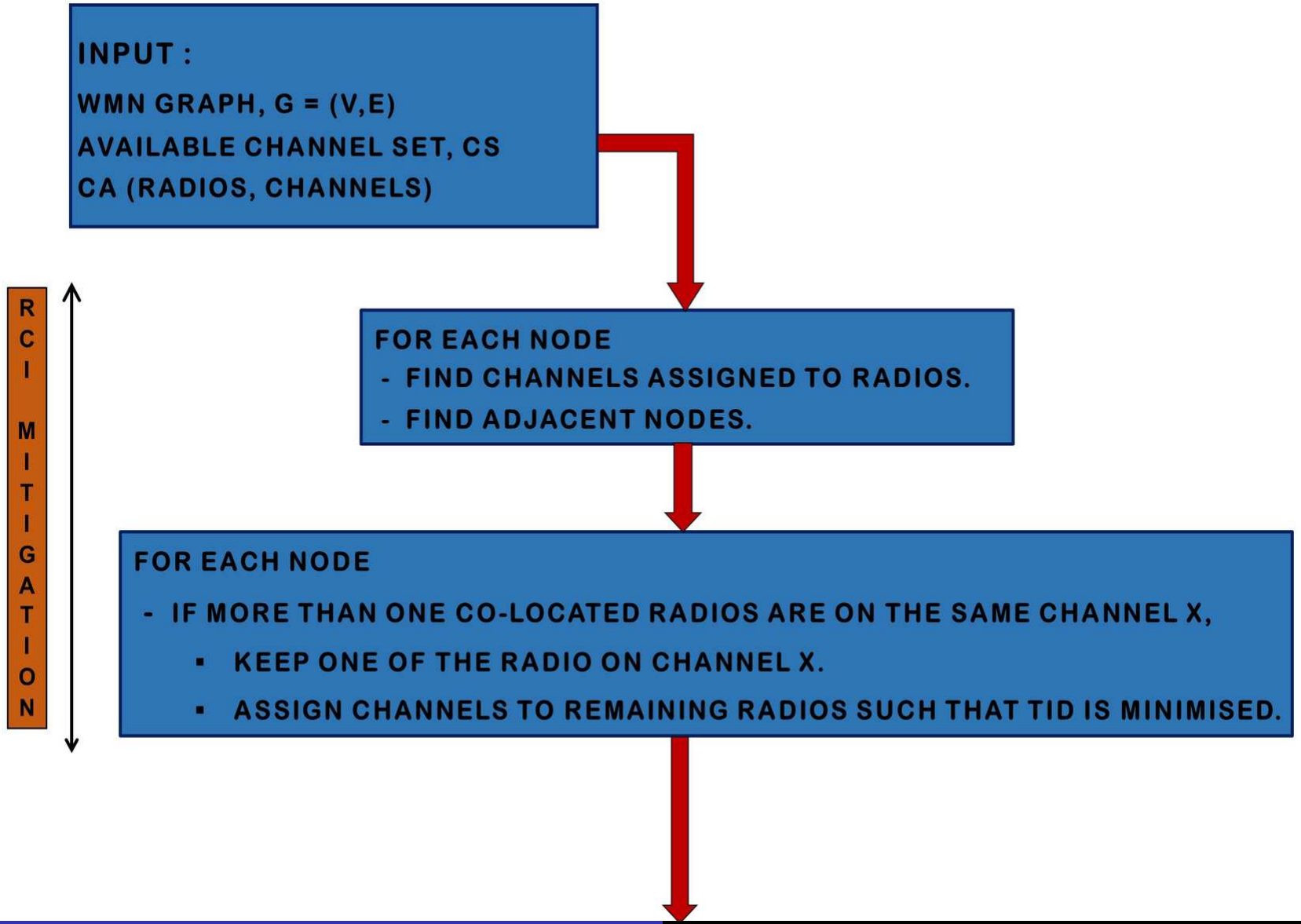
RCA Optimized Independent Set CA

OIS Algorithm



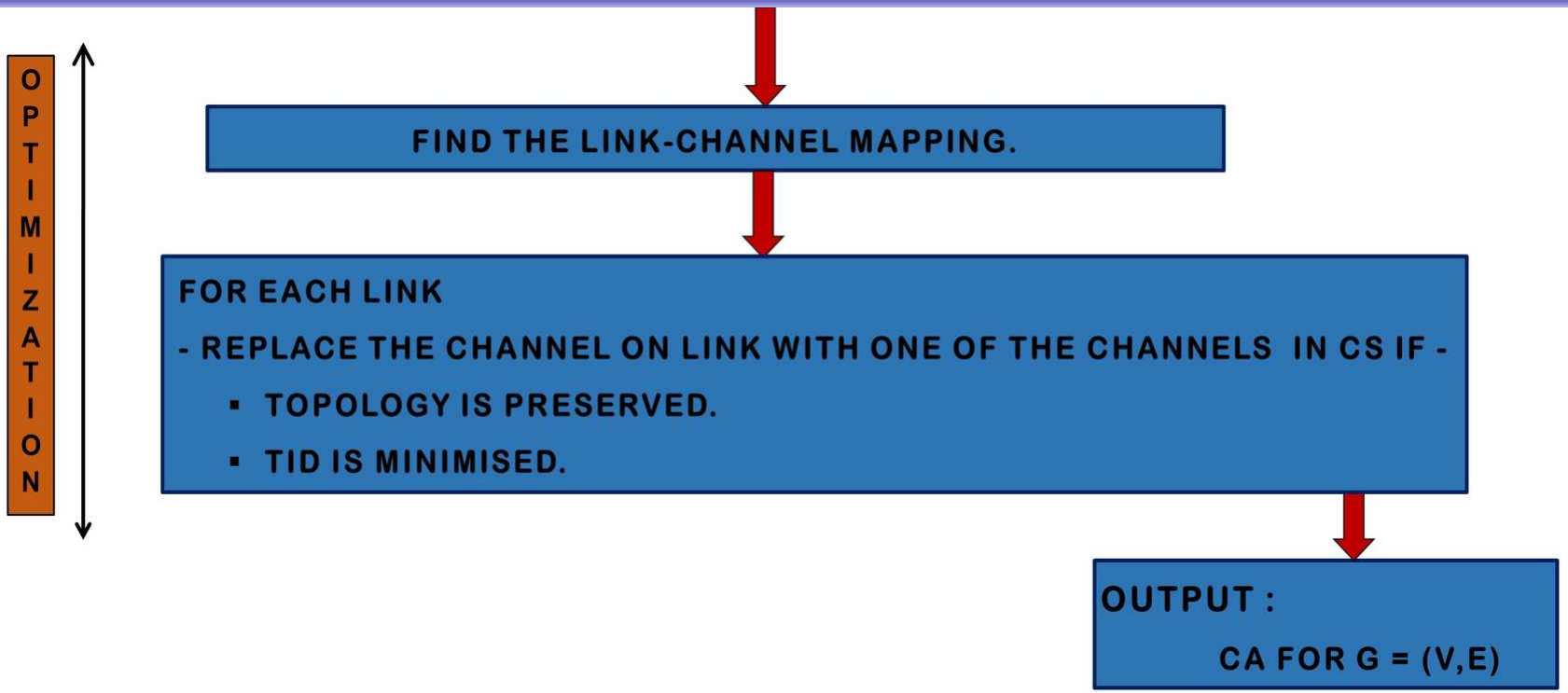
Radio Co-location Optimization

RCO Algorithm



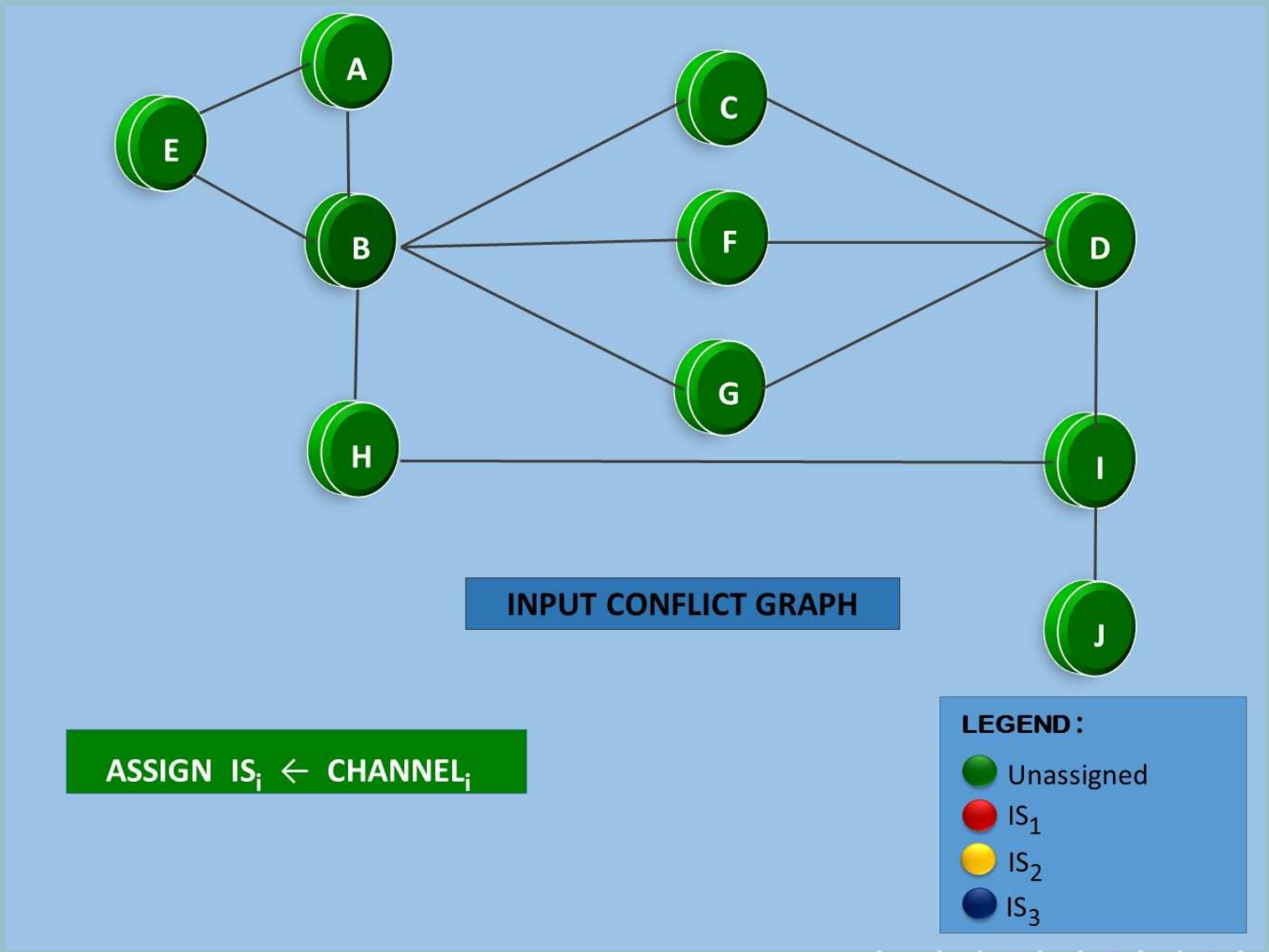
Radio Co-location Optimization

RCO Algorithm



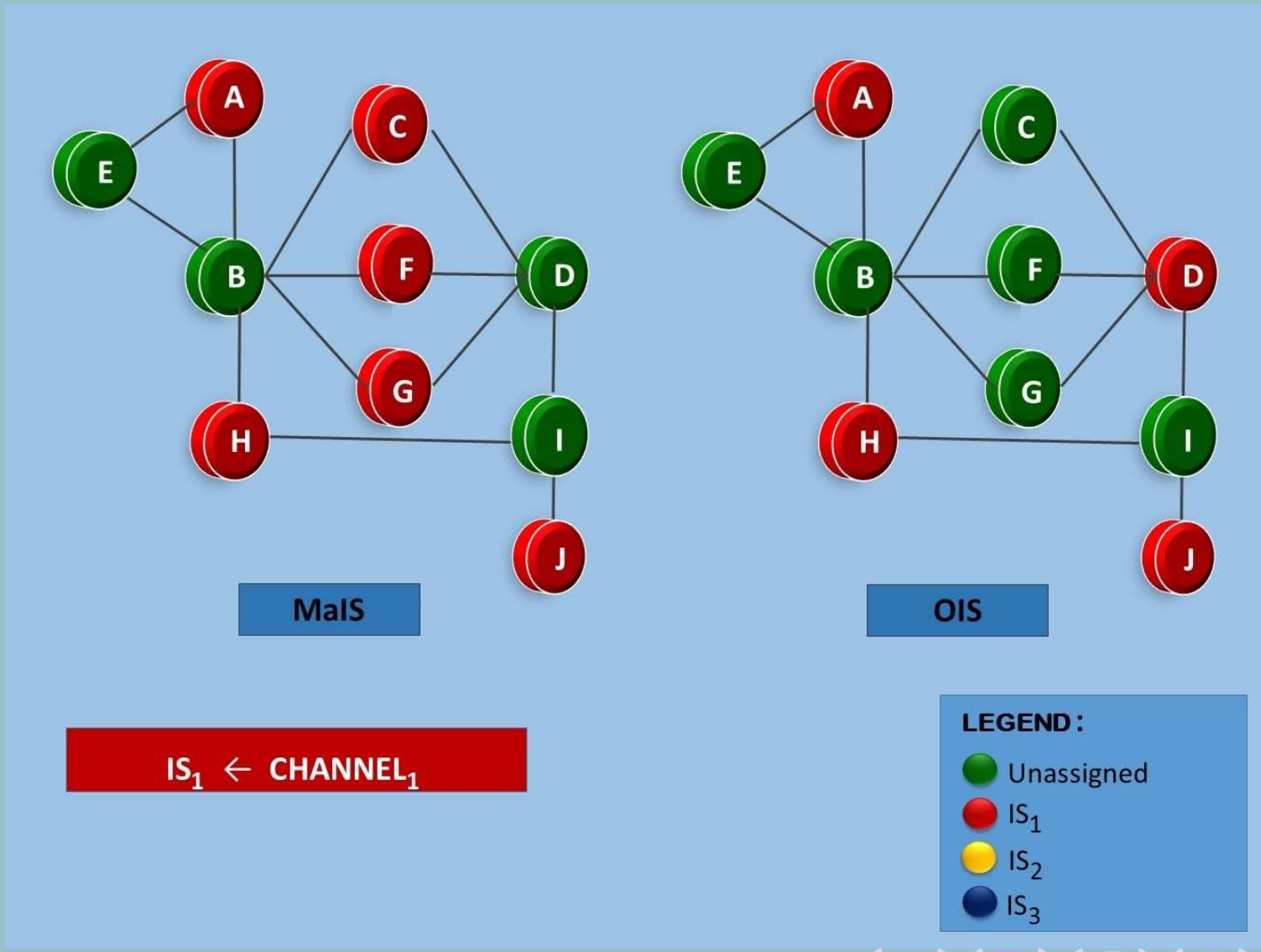
OIS vs MaIS : Independent Set Selection

Input Conflict Graph



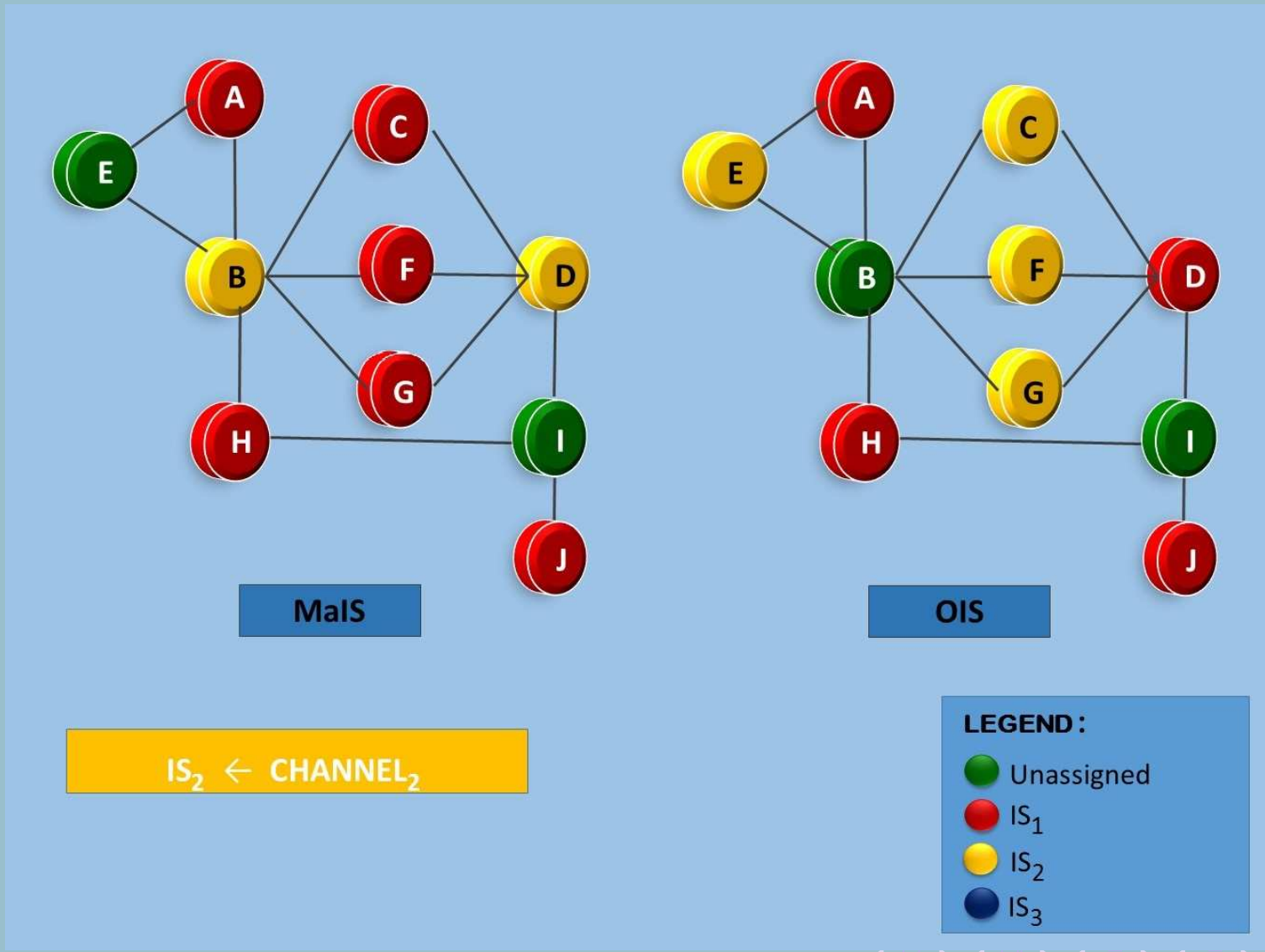
OIS vs MaIS : Independent Set Selection

Independent Set 1



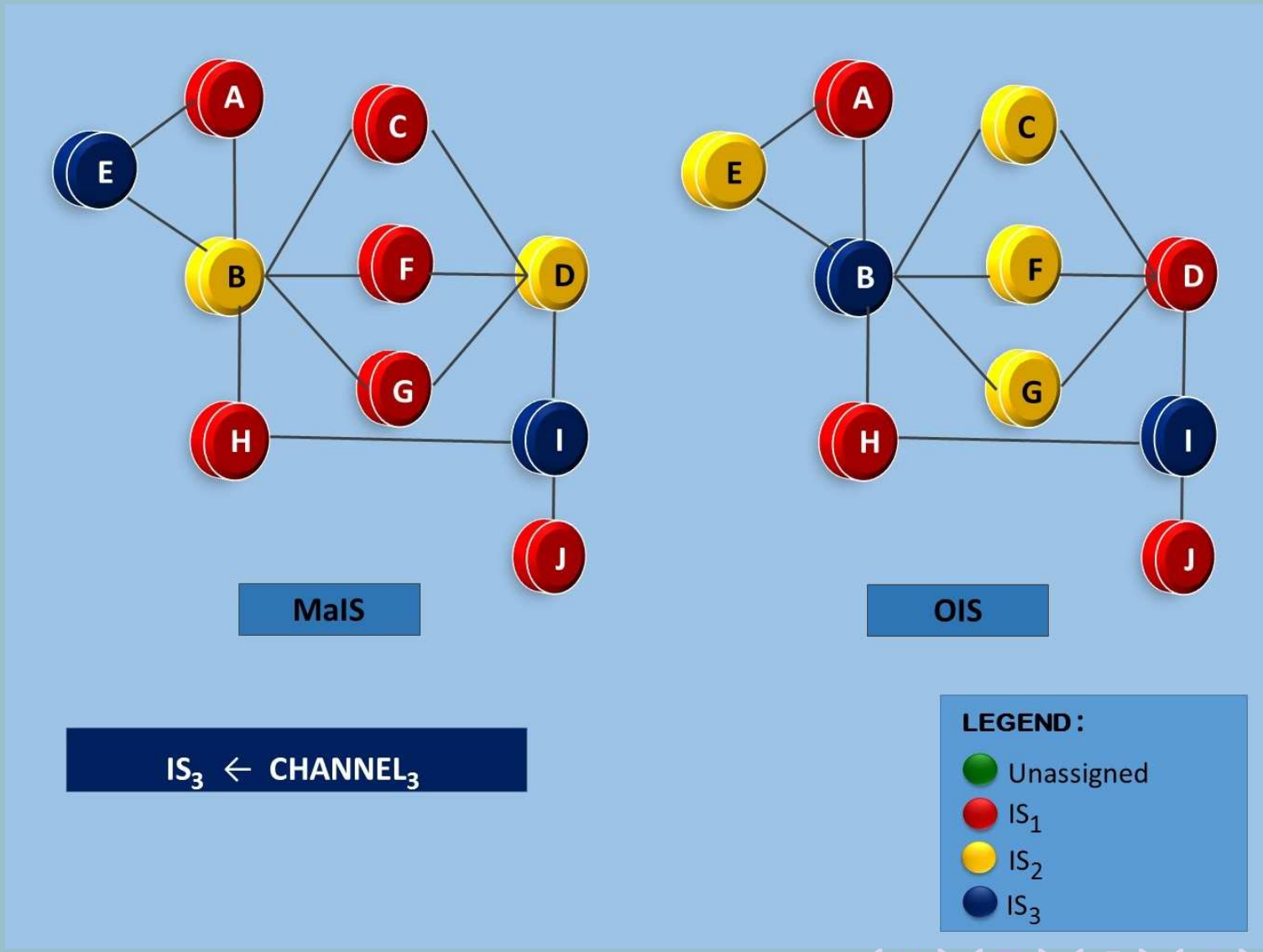
OIS vs MaIS : Independent Set Selection

Independent Set 2



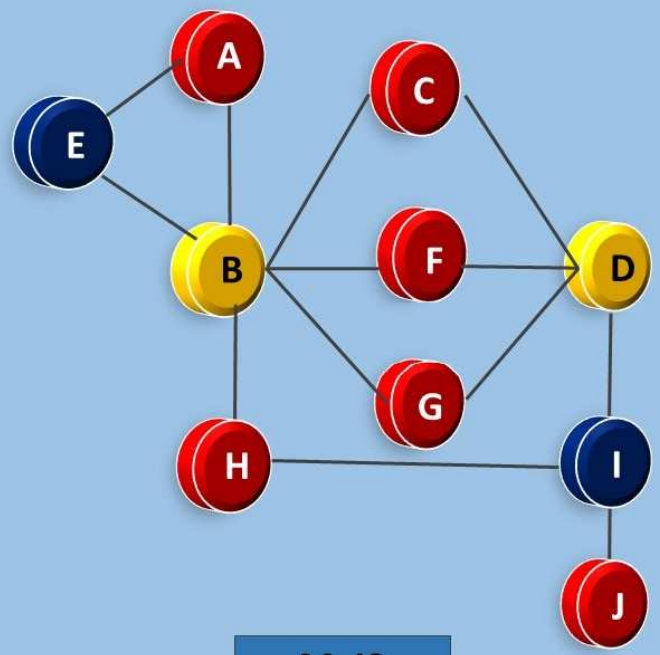
OIS vs MaIS : Independent Set Selection

Independent Set 3



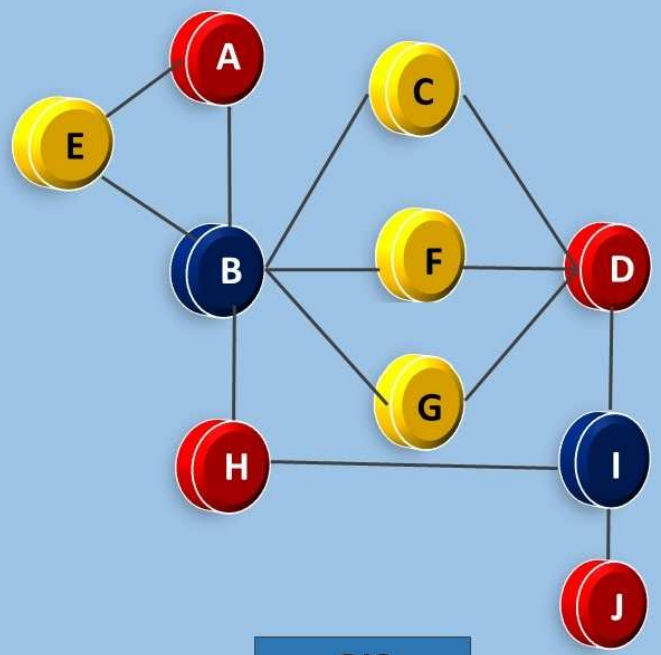
OIS vs MaIS : Independent Set Selection

Measuring Statistical Evenness



MaIS

- $IS_1 : IS_2 : IS_3 \rightarrow 6 : 2 : 2$
- Standard Deviation = 1.89



OIS

- $IS_1 : IS_2 : IS_3 \rightarrow 4 : 4 : 2$
- Standard Deviation = 0.94

OIS vs MaIS : Independent Set Selection

Is Channel Distribution Equitable ?

Ratio of Channel Distribution across Radios

Grid Size	Num of Radios	$R_{C1} : R_{C2} : R_{C3}$	
		MaIS	OIS
5×5	50	1.00 : 1.63 : 1.94	1.00 : 1.06 : 1.06
6×6	72	1.00 : 1.33 : 1.66	1.00 : 1.09 : 1.33
7×7	98	1.00 : 1.56 : 1.69	1.00 : 1.00 : 1.16
8×8	128	1.00 : 1.48 : 1.64	1.00 : 1.00 : 1.28
9×9	162	1.00 : 1.58 : 1.57	1.08 : 1.00 : 1.29

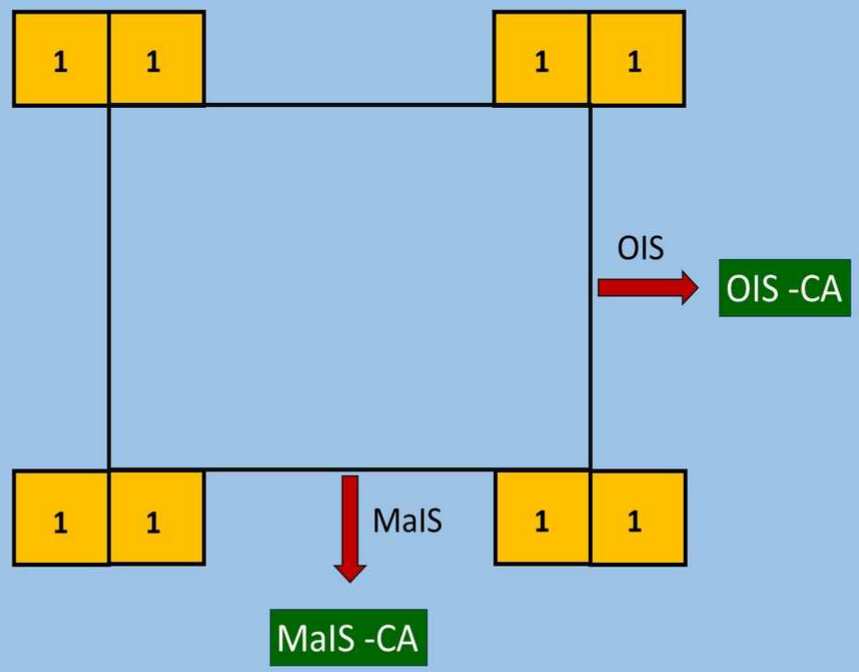
- 2 radios/node, 3 orthogonal channels C_1, C_2 & C_3
- Statistical Evenness of a CA $\rightarrow R_{C1} : R_{C2} : R_{C3}$.
  - $R_{Ch} \rightarrow$ Number of radios operating on channel Ch
  - Ratio normalized by smallest value.
- MaIS $\rightarrow$ Skewed distribution of channels.

Statistical Evenness $\rightarrow$ OIS $>$ MaIS

OIS vs MaIS : A Theoretical Illustration

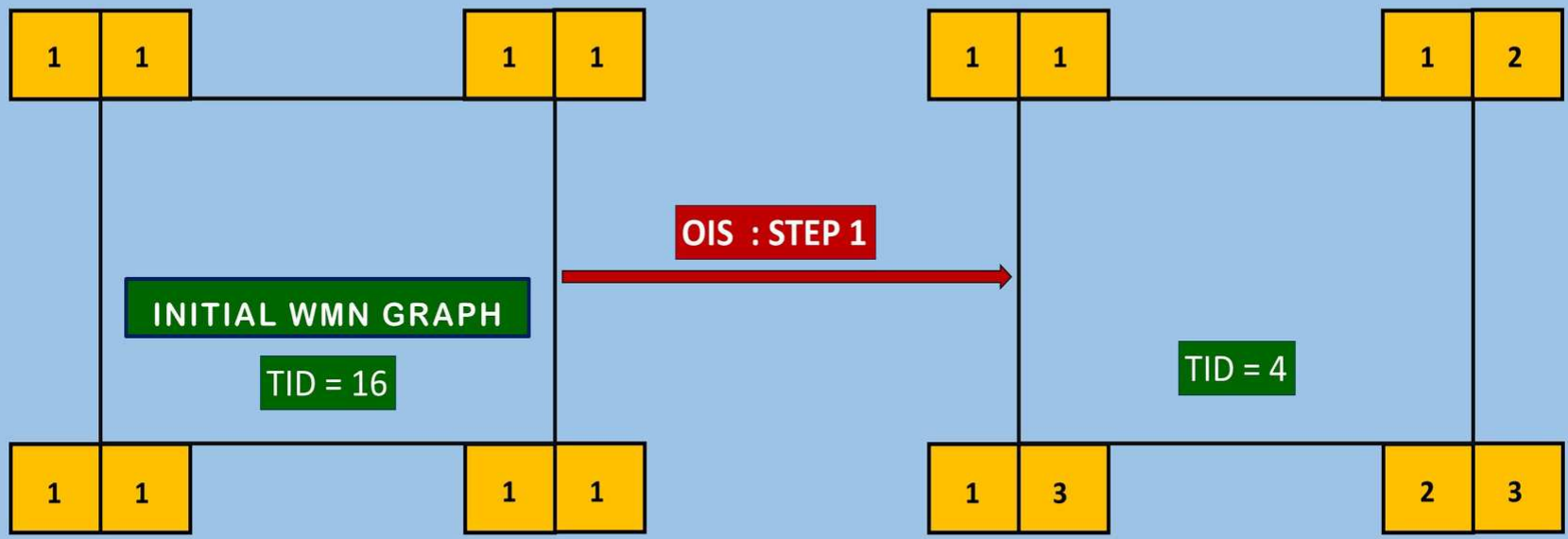
Sample WMN

INITIAL WMN GRAPH
- 4 NODES
- 2 RADIOS / NODE
- 3 CHANNELS AVAILABLE
- INITIALLY ALL NODES ON CHANNEL$_1$



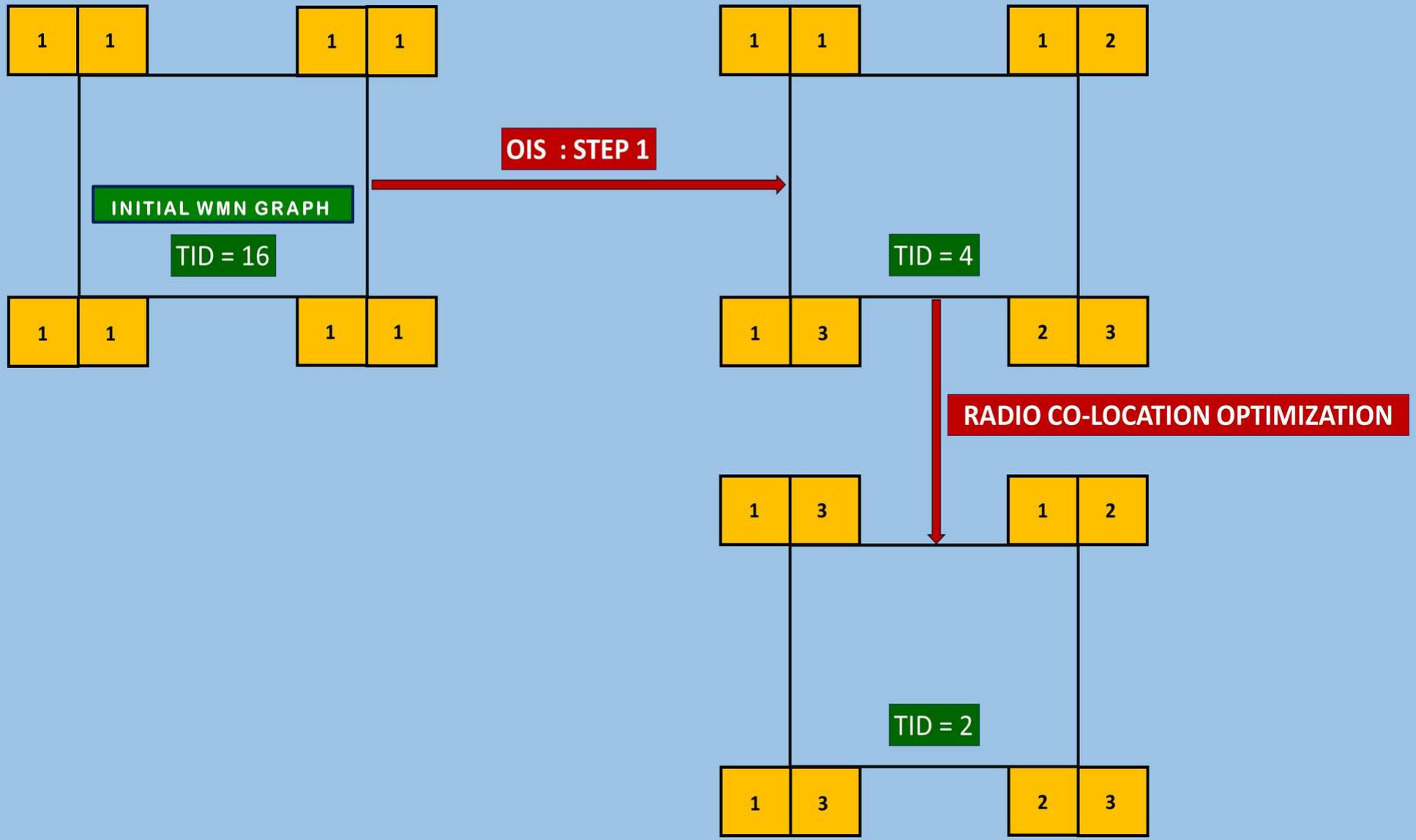
OIS vs MaIS : A Theoretical Illustration

OIS Step 1



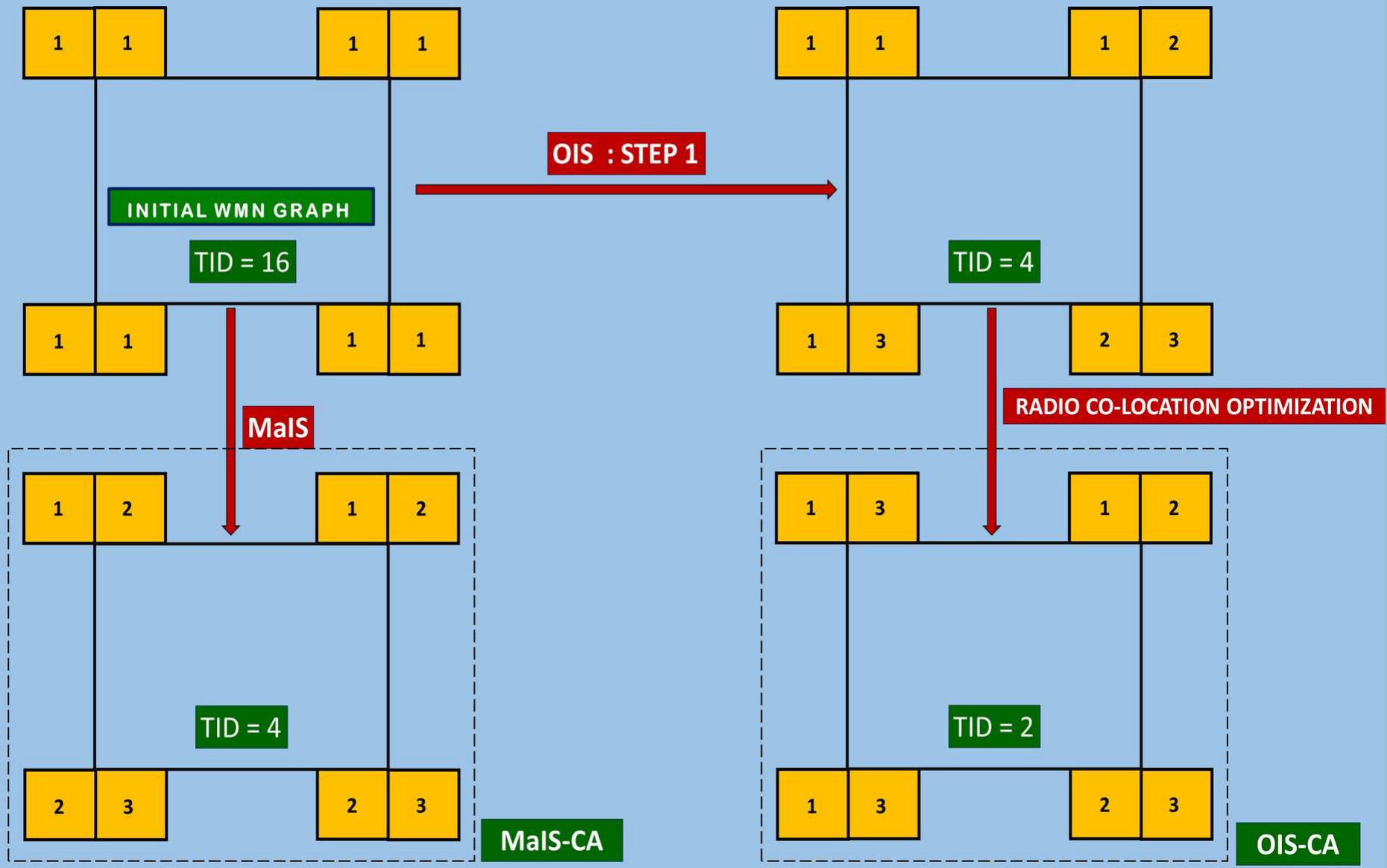
OIS vs MaIS : A Theoretical Illustration

Radio Co-location Optimization



OIS vs MaIS : A Theoretical Illustration

Channel Assignment Comparison



Simulation Setup
WMN Topologies & CA Schemes

WMN Topologies

- 5×5 grid WMN (GWMN).
- Random WMN (RWMN) of 50 nodes spread across an area of $1500m \times 1500m$.

CA Schemes Considered

- BFS-CA $\rightarrow$ A Breadth First Search based CA.
- MaIS-CA $\rightarrow$ A Maximum Independent Set based CA.
- OIS-CA $\rightarrow$ RCA Optimized Independent Set based CA.
- OIS-N-CA $\rightarrow$ Non-RCA version of OIS.

Simulation Setup
Data Traffic Characteristics

Flow Types

- Grid WMN.
  - 4-Hop Flows & 8-Hop Flows.
- Random WMN.
  - 3-Hop Flows to 10-Hop Flows.

Transport Layer Protocols

- TCP $\rightarrow$ ns-3 BulkSendApplication.
- UDP $\rightarrow$ ns-3 UdpClientServer.

Network Metrics Observed

- Network Aggregate Throughput (Throughput).
- Packet Loss Ratio (PLR).
- Mean Delay (MD).

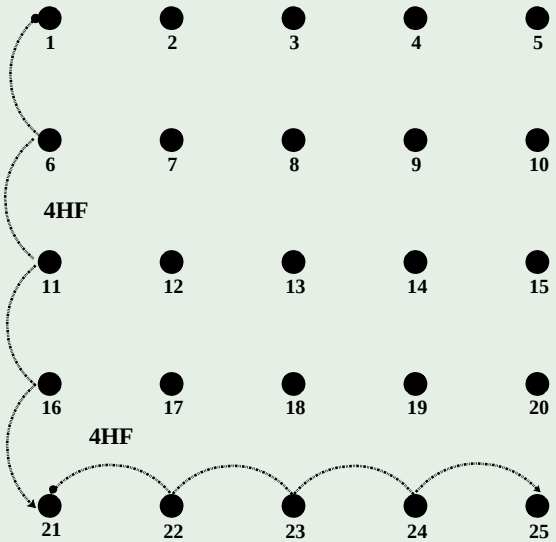
Simulation Setup

Test Scenarios

Grid WMN Test Cases

1. D2 → Two concurrent 8-Hop flows.
2. H5 → Five concurrent 4-Hop flows (Rows).
3. V5 → Five concurrent 4-Hop flows (Columns).
4. H4V4 →Eight concurrent 4-Hop flows (Combinations).
5. H5V5 → Ten concurrent 4-Hop flows (H5 & V5).
6. H5V5D2 → Twelve concurrent flows. (D2, H5 & V5).

Grid WMN Layout



Simulation Setup
Test Scenarios

Random WMN Test Cases

Test Cases → Concurrent multi-hop flows of 3 to 10 hop counts.

1. TC4 → 4 concurrent multi-hop flows.
2. TC8 → 8 concurrent multi-hop flows.
3. TC12 → 12 concurrent multi-hop flows.
4. TC16 → 16 concurrent multi-hop flows.
5. TC20 → 20 concurrent multi-hop flows.

Simulation Setup

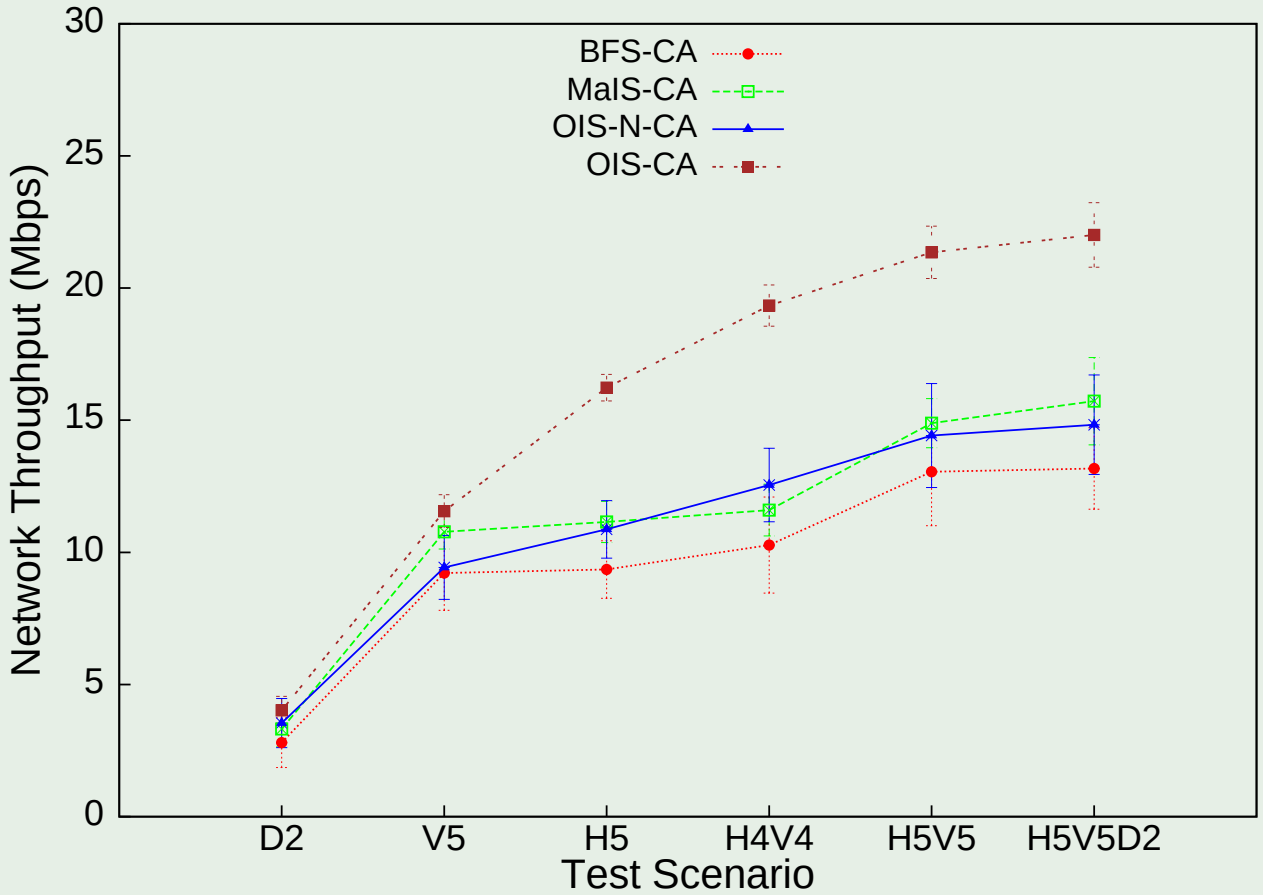
Simulation Parameters

ns-3 Simulation Parameters

Parameter	**Value**
Radios/Node	GWMN: 2, RWMN: 3
Range Of Radios	250 mts
IEEE Standard	GWMN: 802.11g RWMN: 802.11n
Available Orthogonal Channels	GWMN: 3 (2.4 GHz) RWMN: 4 (5 GHz)
Transmitted File Size	GWMN: 10 MB RWMN: 1 MB
Maximum 802.11g/n Phy Datarate	54 Mbps
Maximum Segment Size (TCP)	1 KB
Packet Size (UDP)	GWMN: 1 KB RWMN: 512 Bytes
MAC Fragmentation Threshold	2200 Bytes
RTS/CTS	Enabled
Packet Interval (UDP)	50ms
Routing Protocol Used	OLSR
Loss Model	Range Propagation
Rate Control	Constant Rate

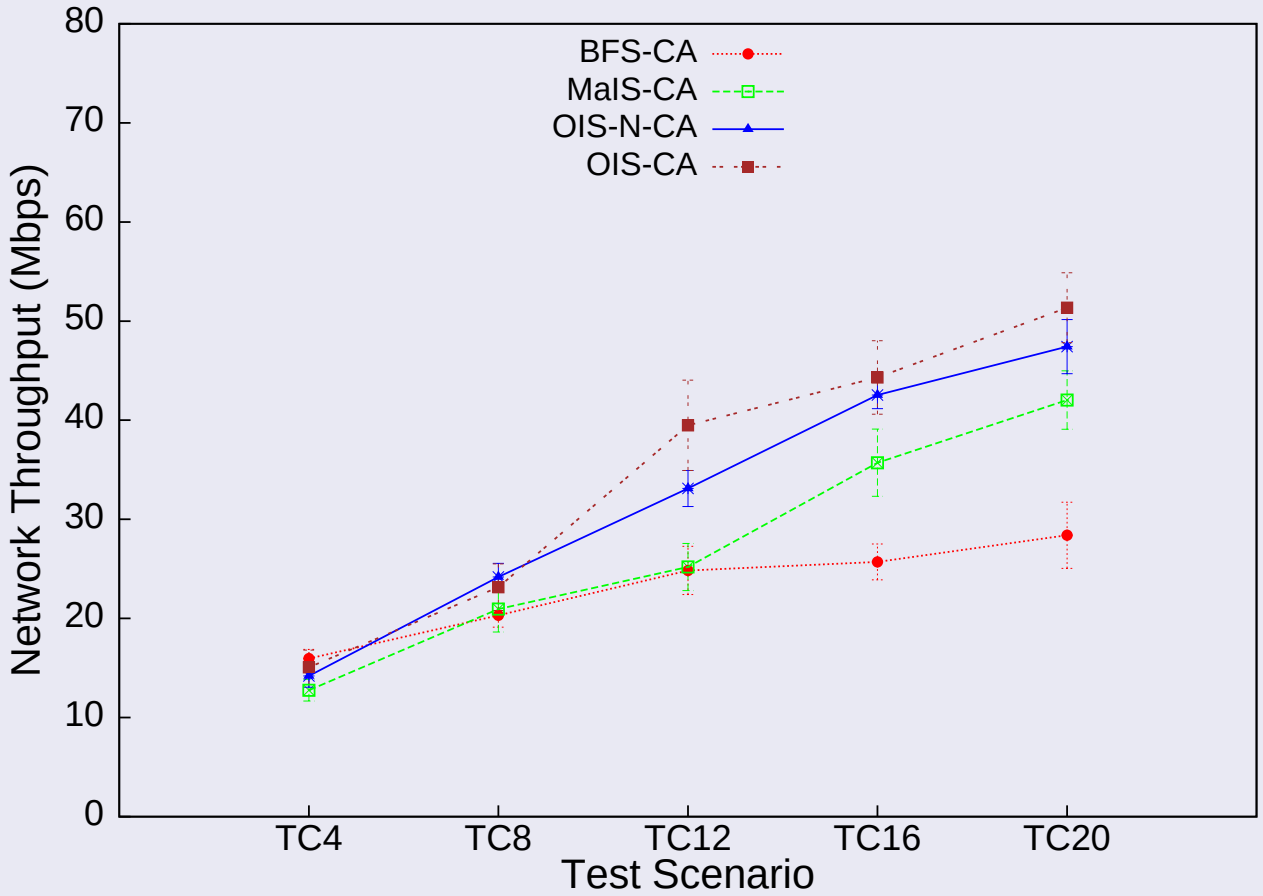
OIS Performance Evaluation

GWMN Throughput



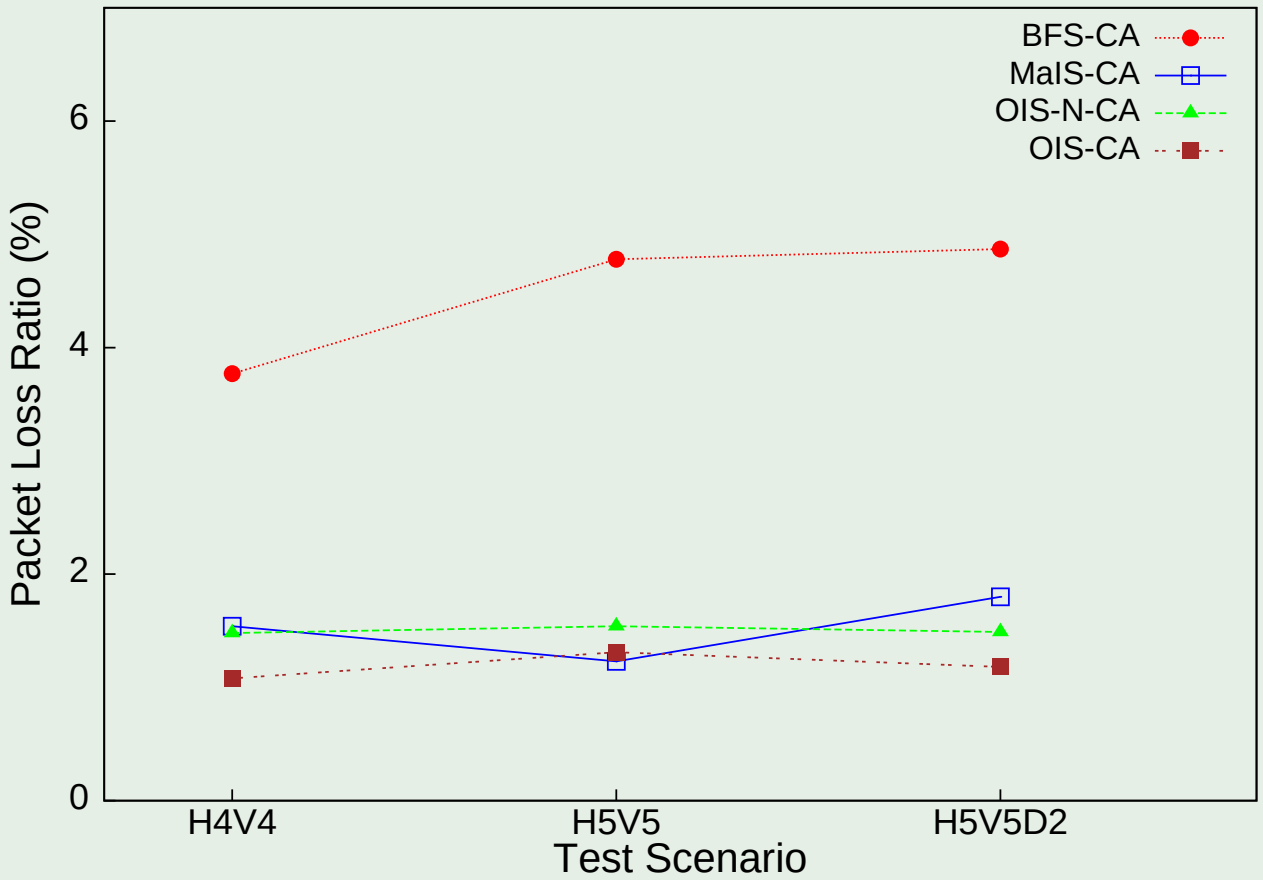
OIS Performance Evaluation

RWMN Throughput



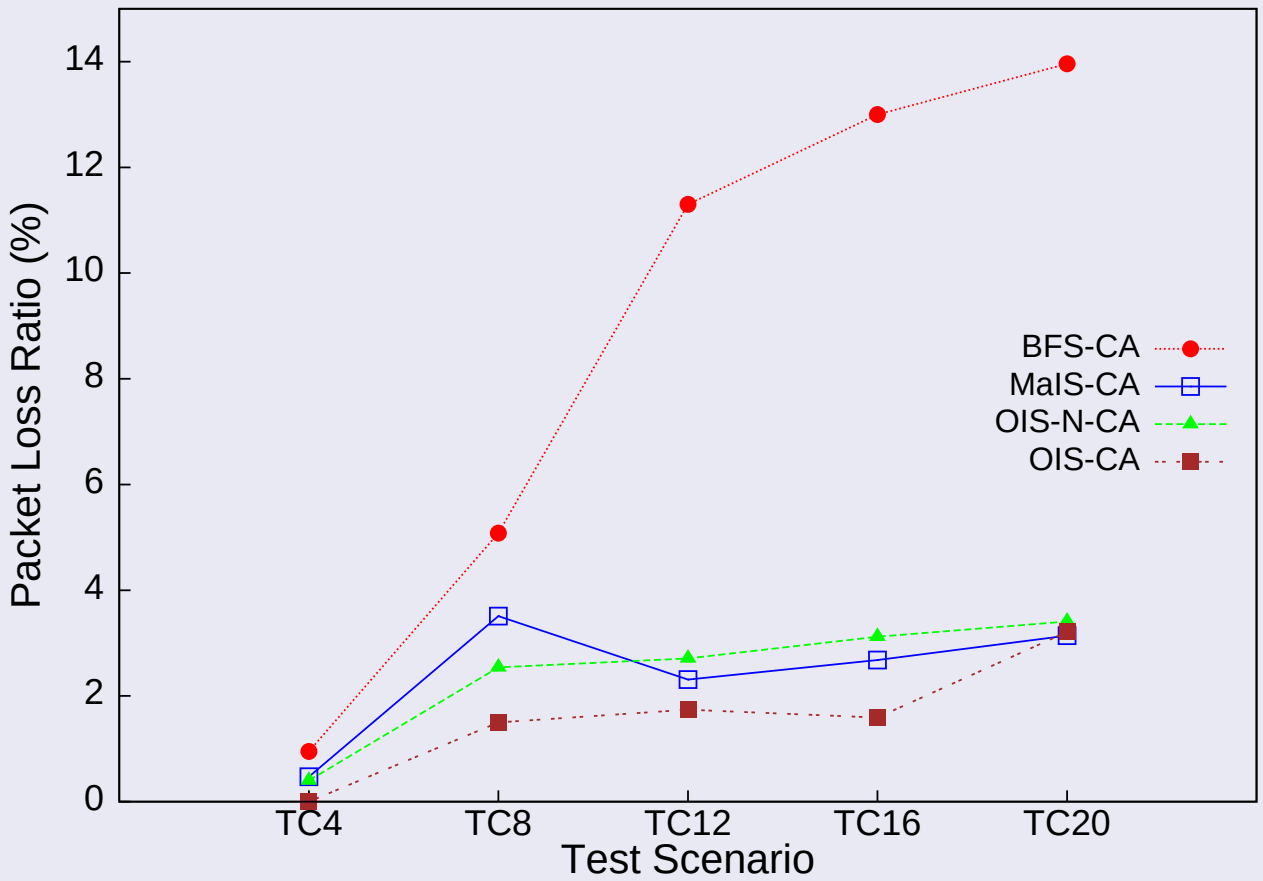
OIS Performance Evaluation

PLR in GWMN



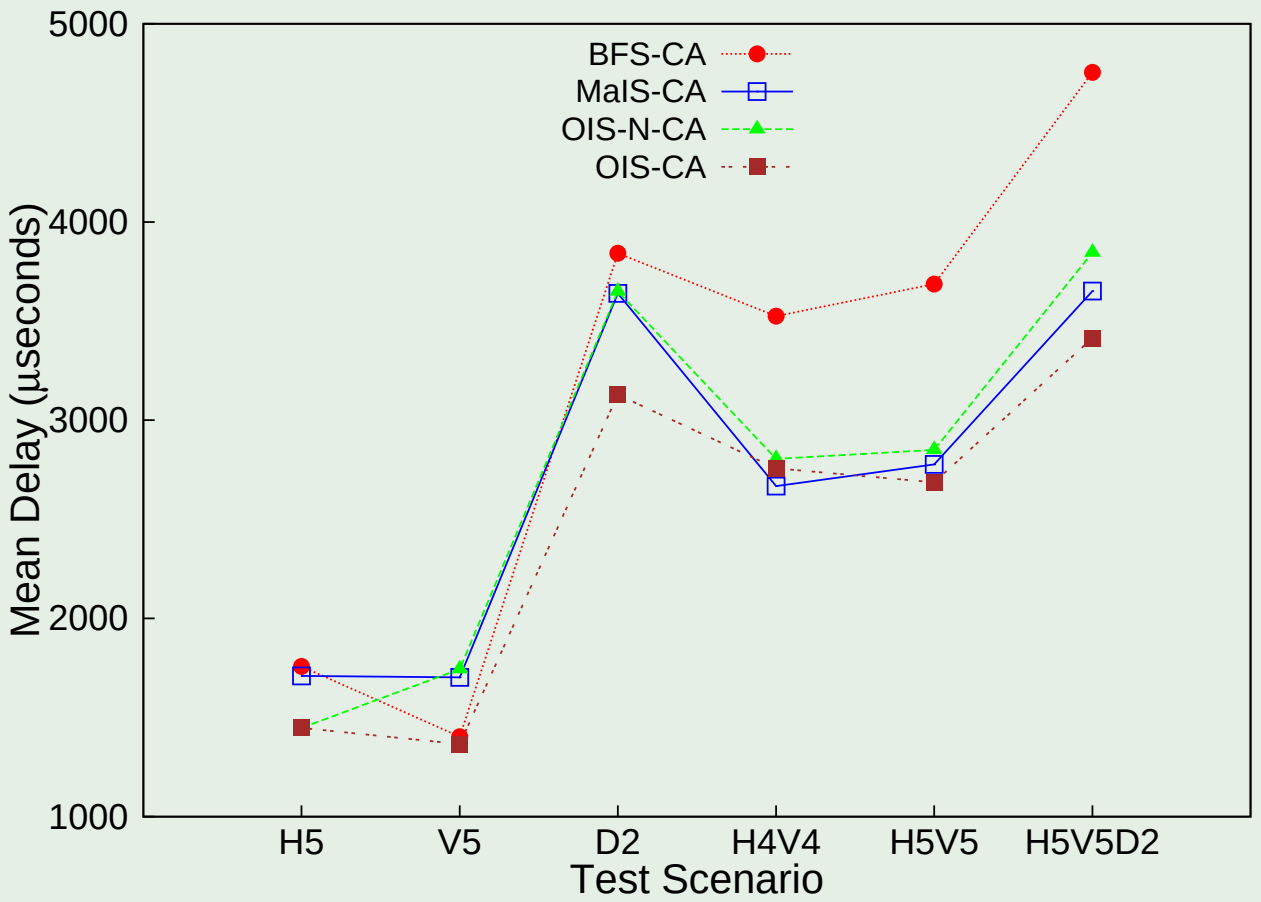
OIS Performance Evaluation

PLR in RWMN



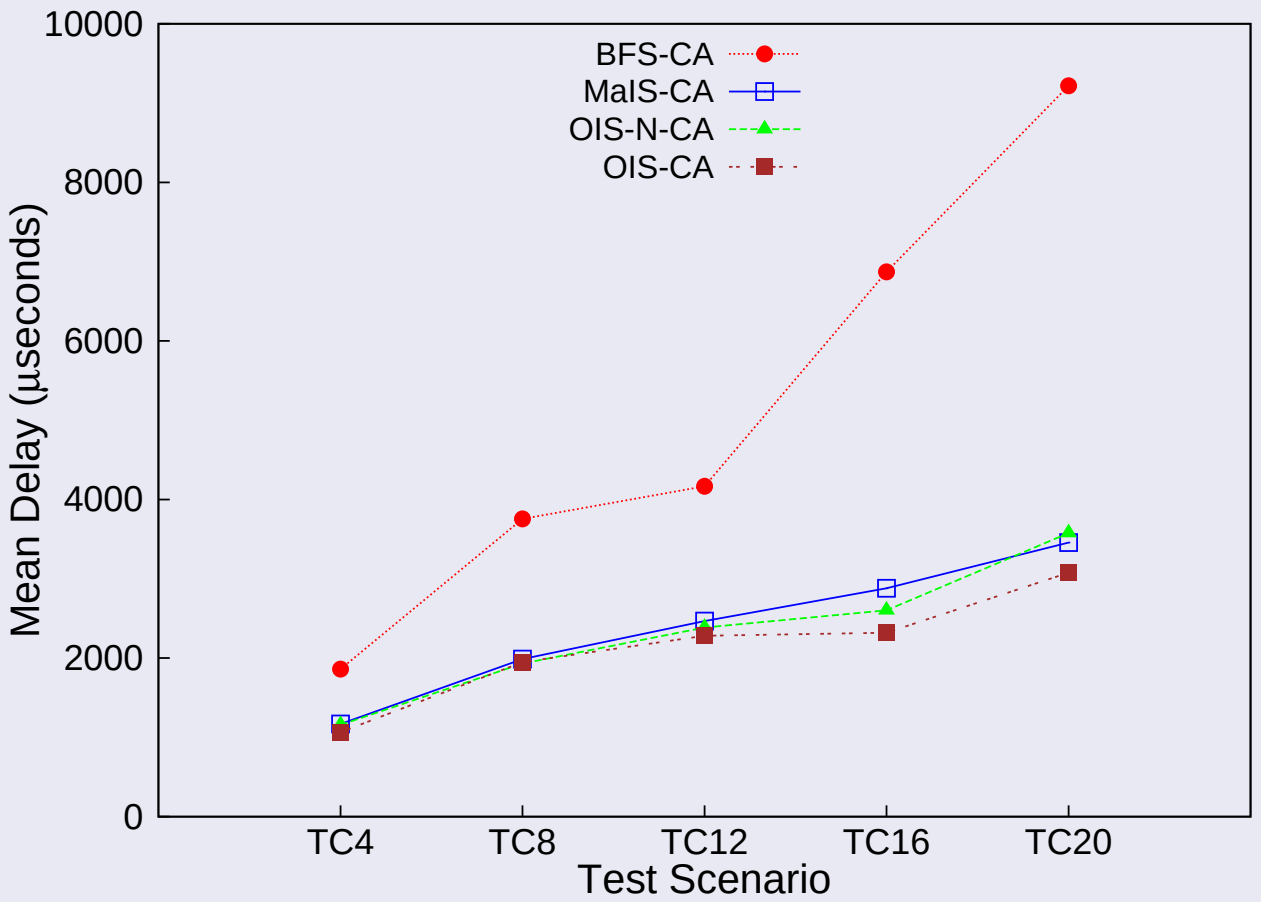
OIS Performance Evaluation

MD in GWMN



OIS Performance Evaluation

MD in RWMN



RCA Elevated Interference Zone Mitigation CA

Motivation

Factors Contributing To Idea Development

- Impact of interference varies within a wireless network.
- SINR levels at different locations differ.
- Fluctuating extreme SINR $<_{WMNPerformance}$ Uniform average SINR.

The Driving Idea

- Localized pockets of high interference $\rightarrow$ Performance bottlenecks.
  - Named $\rightarrow$ Elevated Interference Zones (EIZ)
  - Interference alleviation at EIZ $\rightarrow$ Enhanced performance.
- Emphasis on RCI mitigation

Features of EIZM CA

Spatio-statistical Design

Spatial Features

Focuses on localized Elevated Interference Zones.

- Identifies EIZ in a WMN through its Conflict Graph.
- Assigns channels to EIZ based on severity of interference.
- Correlates TID with SINR.

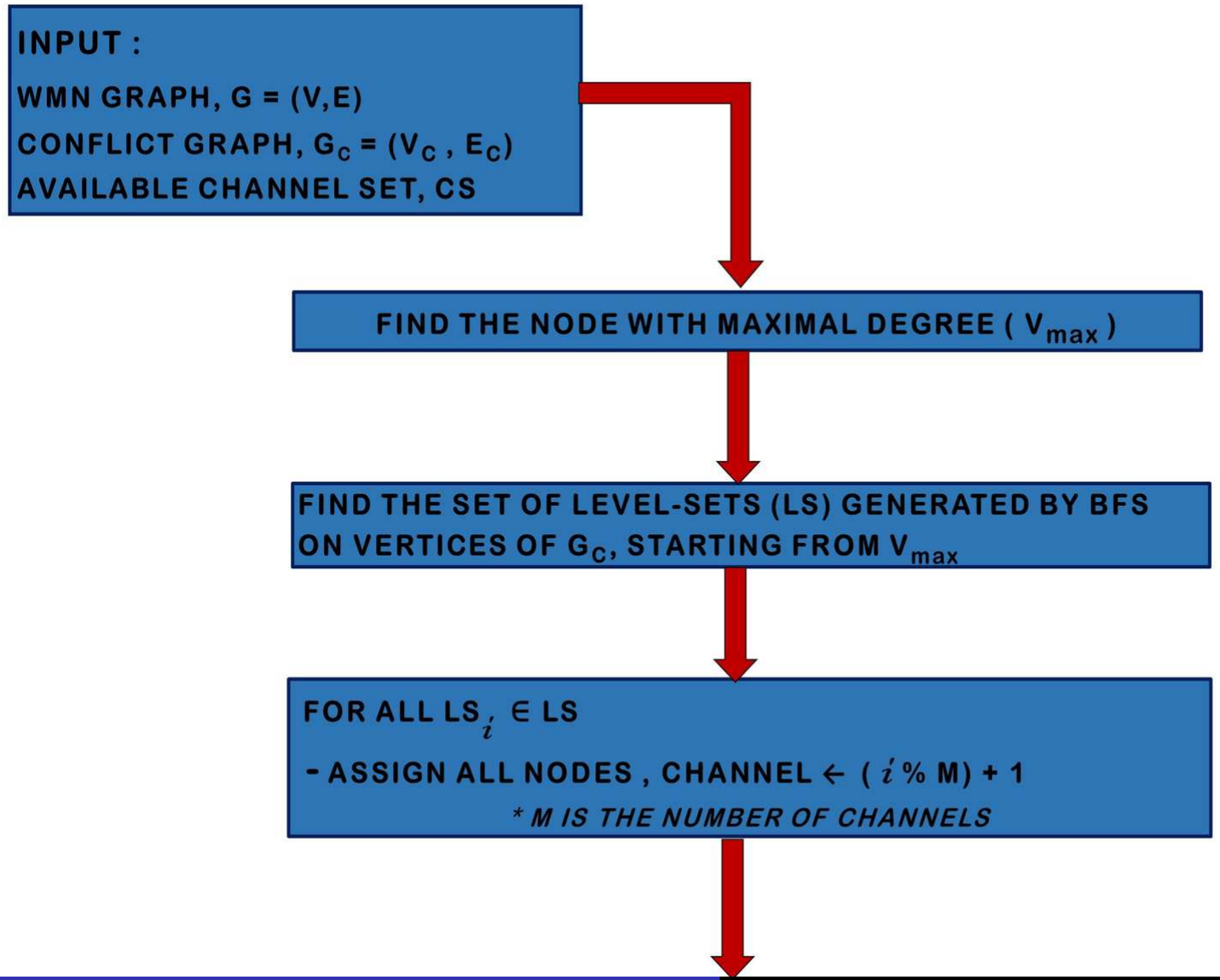
Statistical Evenness

Aimed at equitable distribution of channels across radios.

- Most CA schemes start with a default channel assignment.
- Causes overuse of default channel $\rightarrow$ Skewed distribution.
  - eg. MaIS-CA, BFS-CA, CEN-CA, CLQ-CA etc.
- EIZM-CA divides MMCG nodes into level Sets (BFS traversal).
  - Adjacent Level Set nodes $\rightarrow$ Orthogonal channels.
  - Improved distribution of channels.

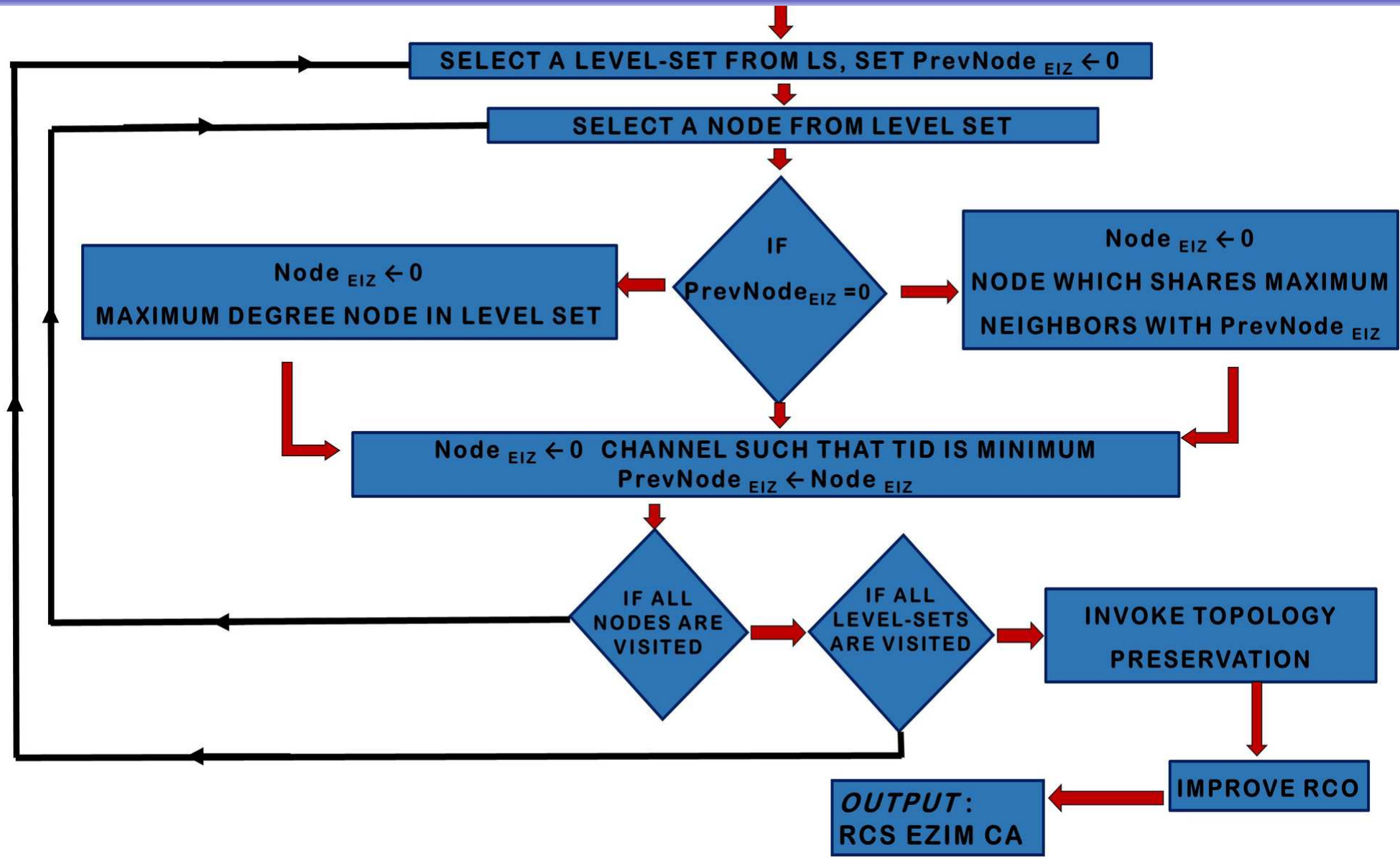
RCA Elevated Interference Zone Mitigation CA

EIZM Algorithm



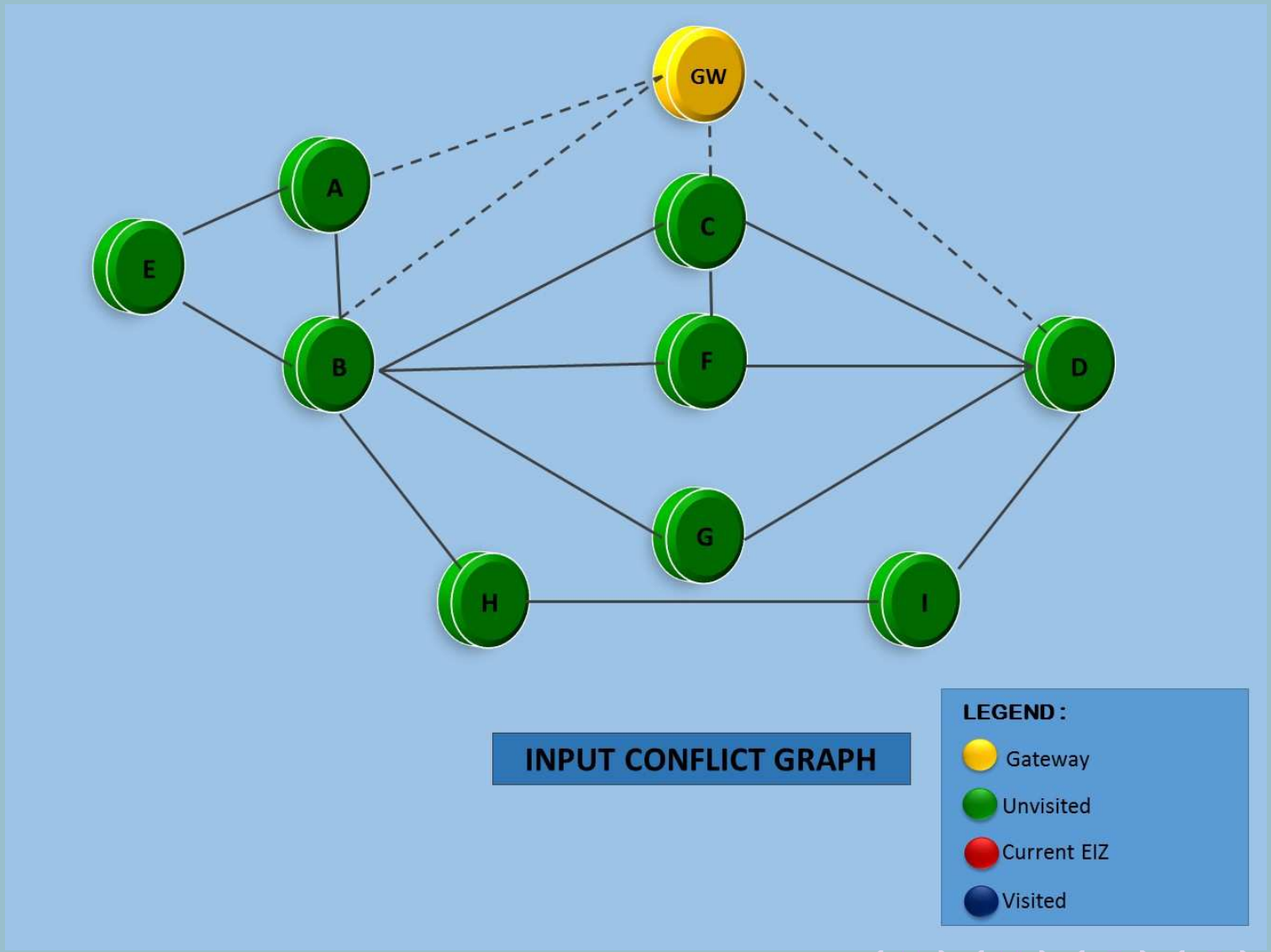
RCA Elevated Interference Zone Mitigation CA

EIZM Algorithm



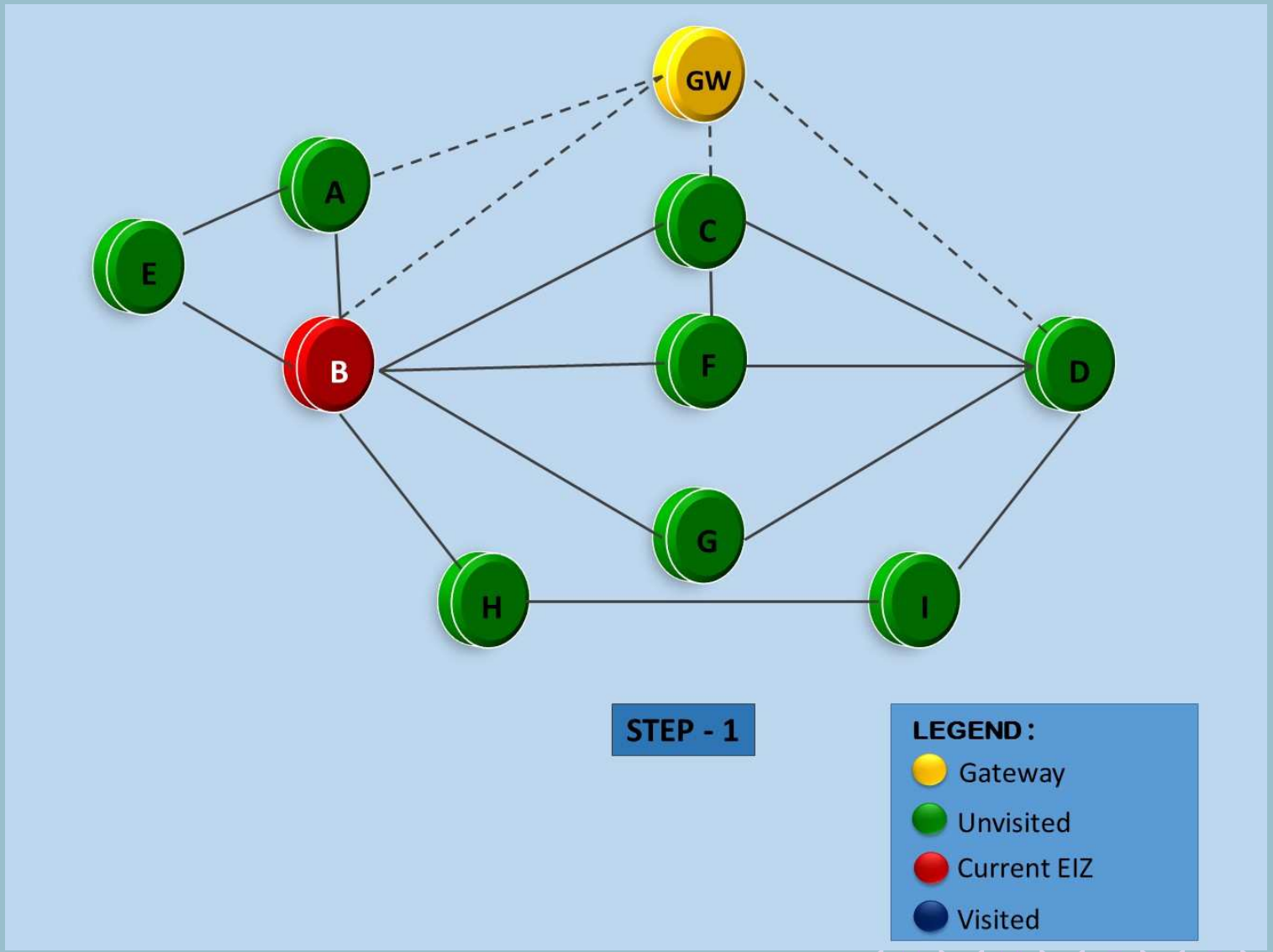
EIZ Selection Sequence

Input Conflict Graph



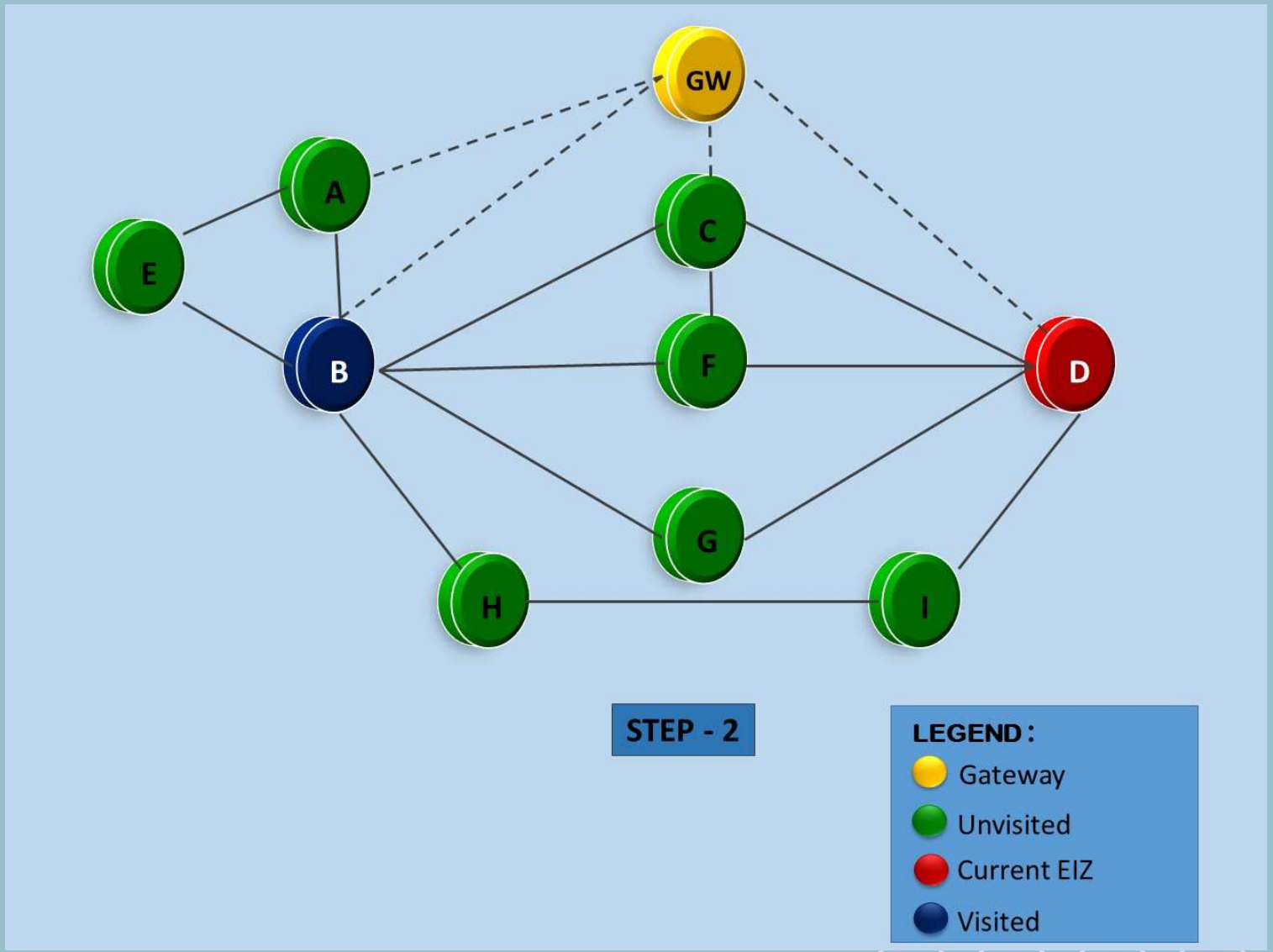
EIZ Selection Sequence

Step 1



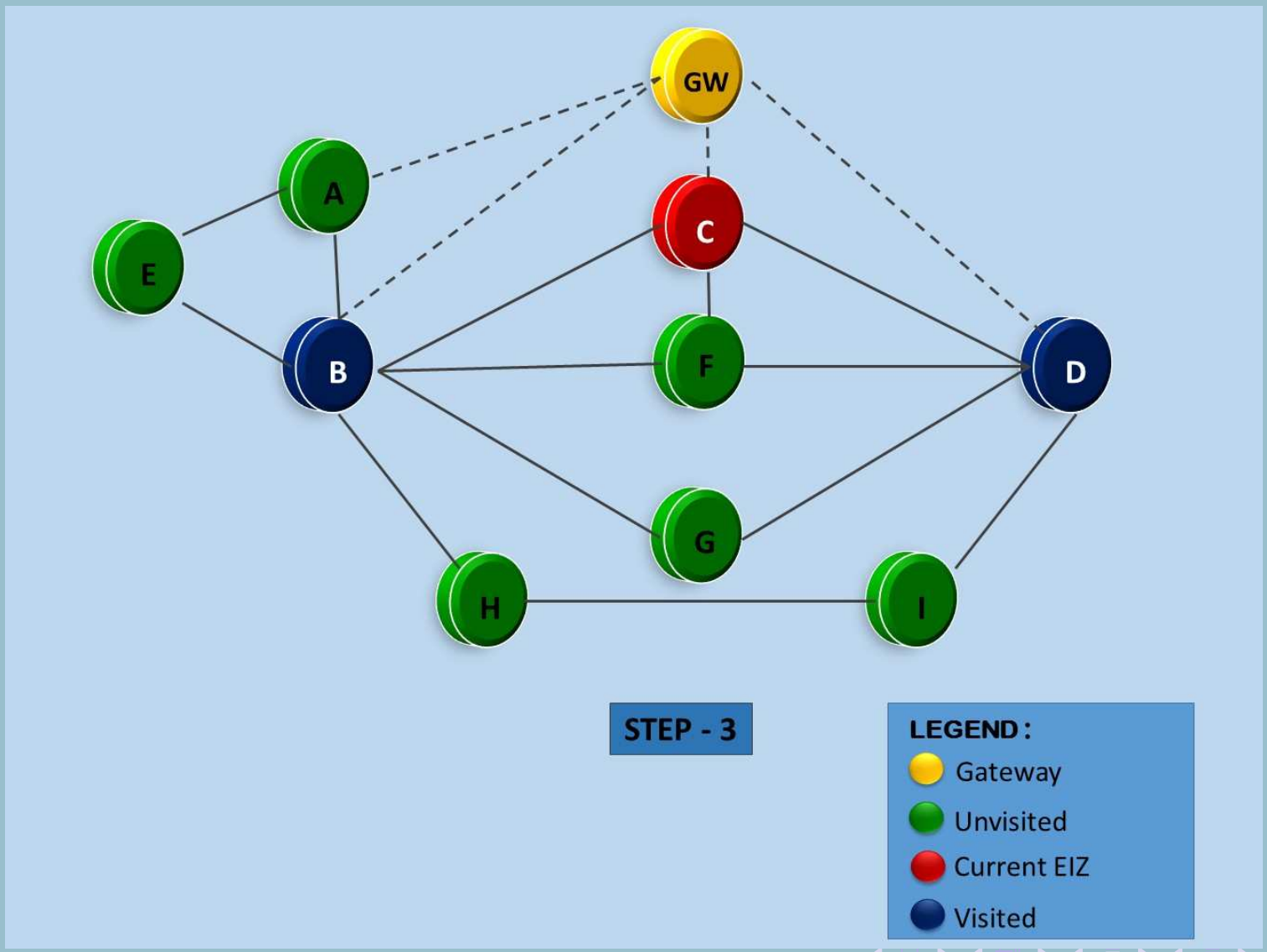
EIZ Selection Sequence

Step 2



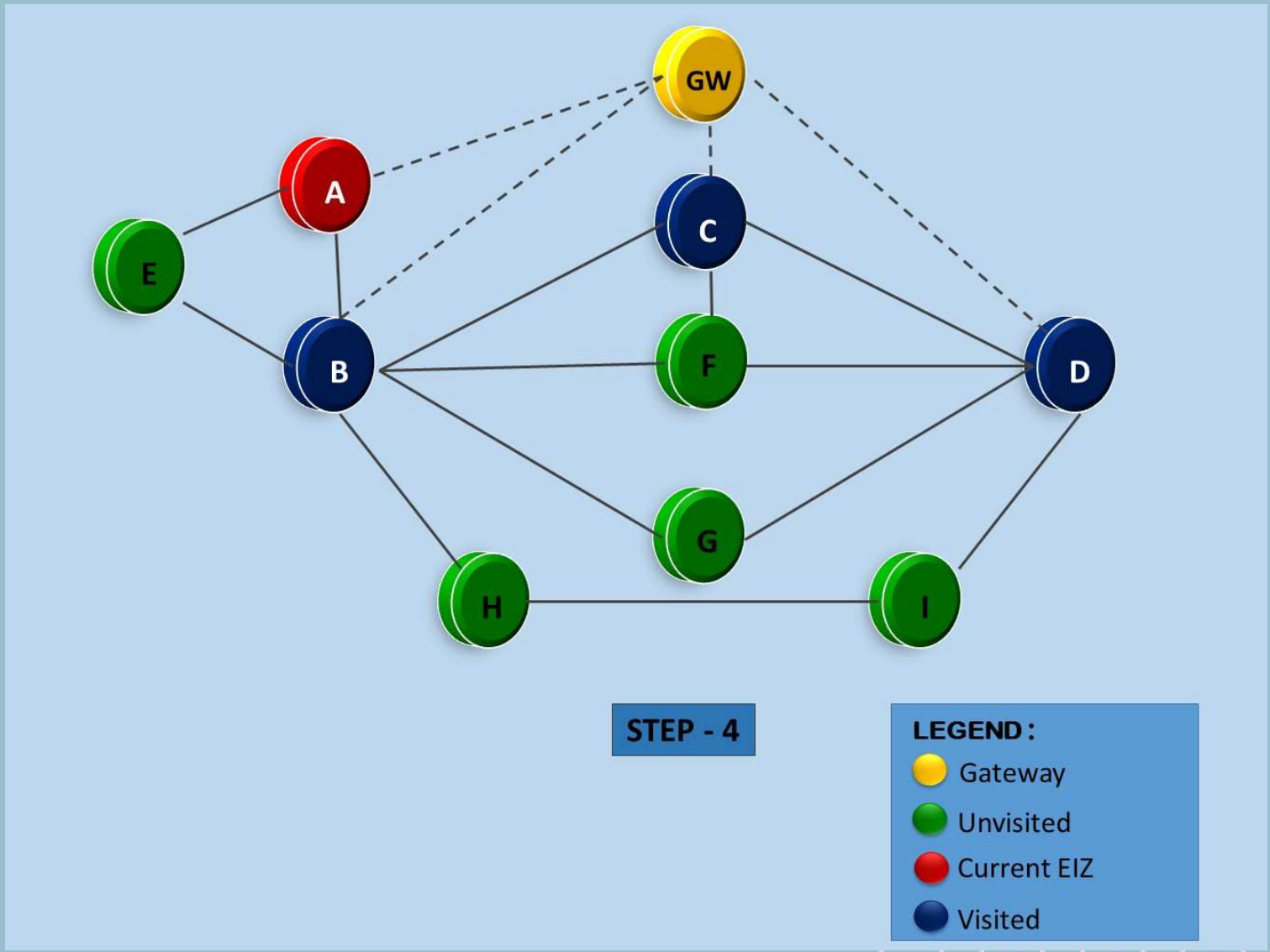
EIZ Selection Sequence

Step 3



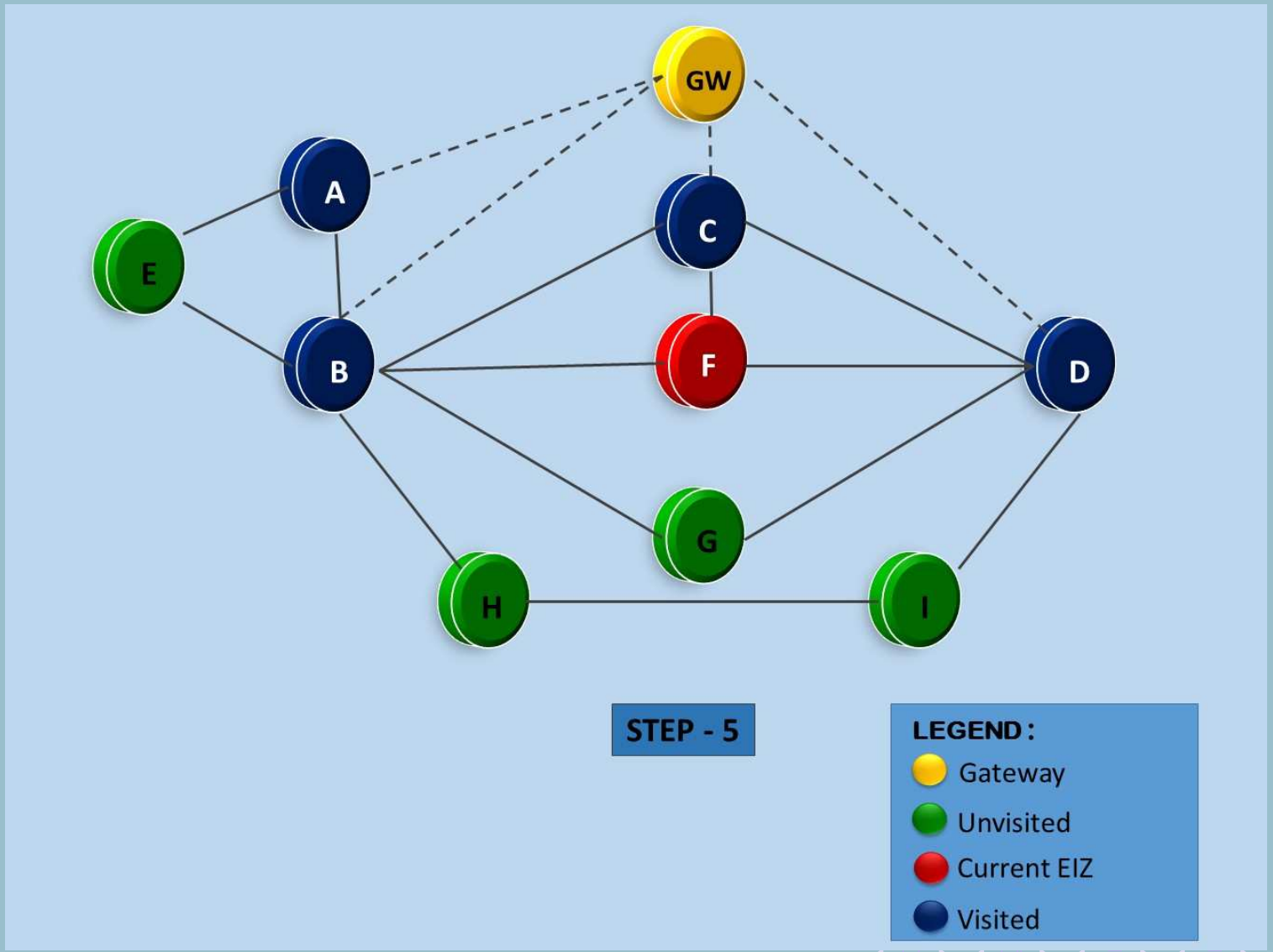
EIZ Selection Sequence

Step 4



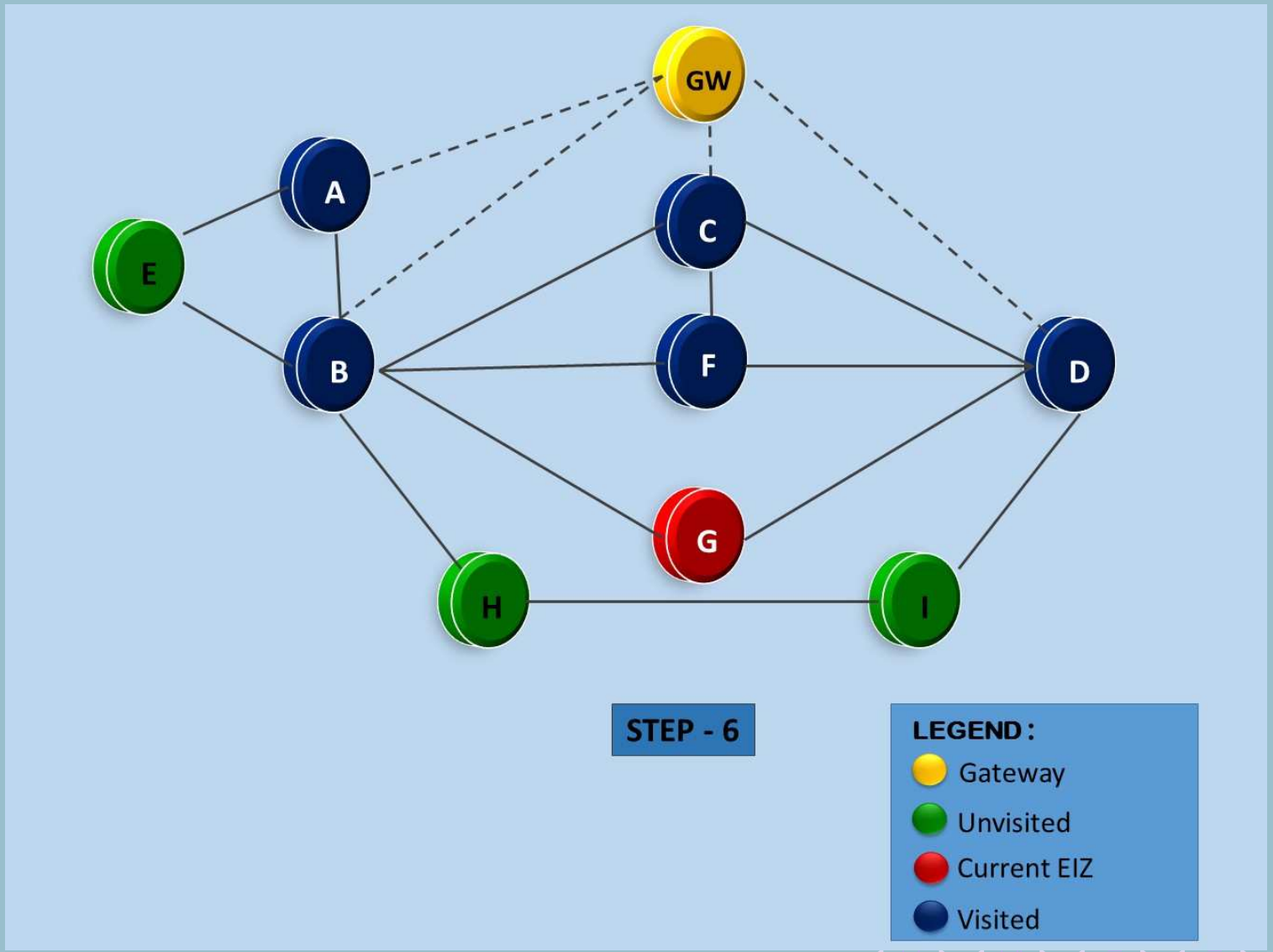
EIZ Selection Sequence

Step 5



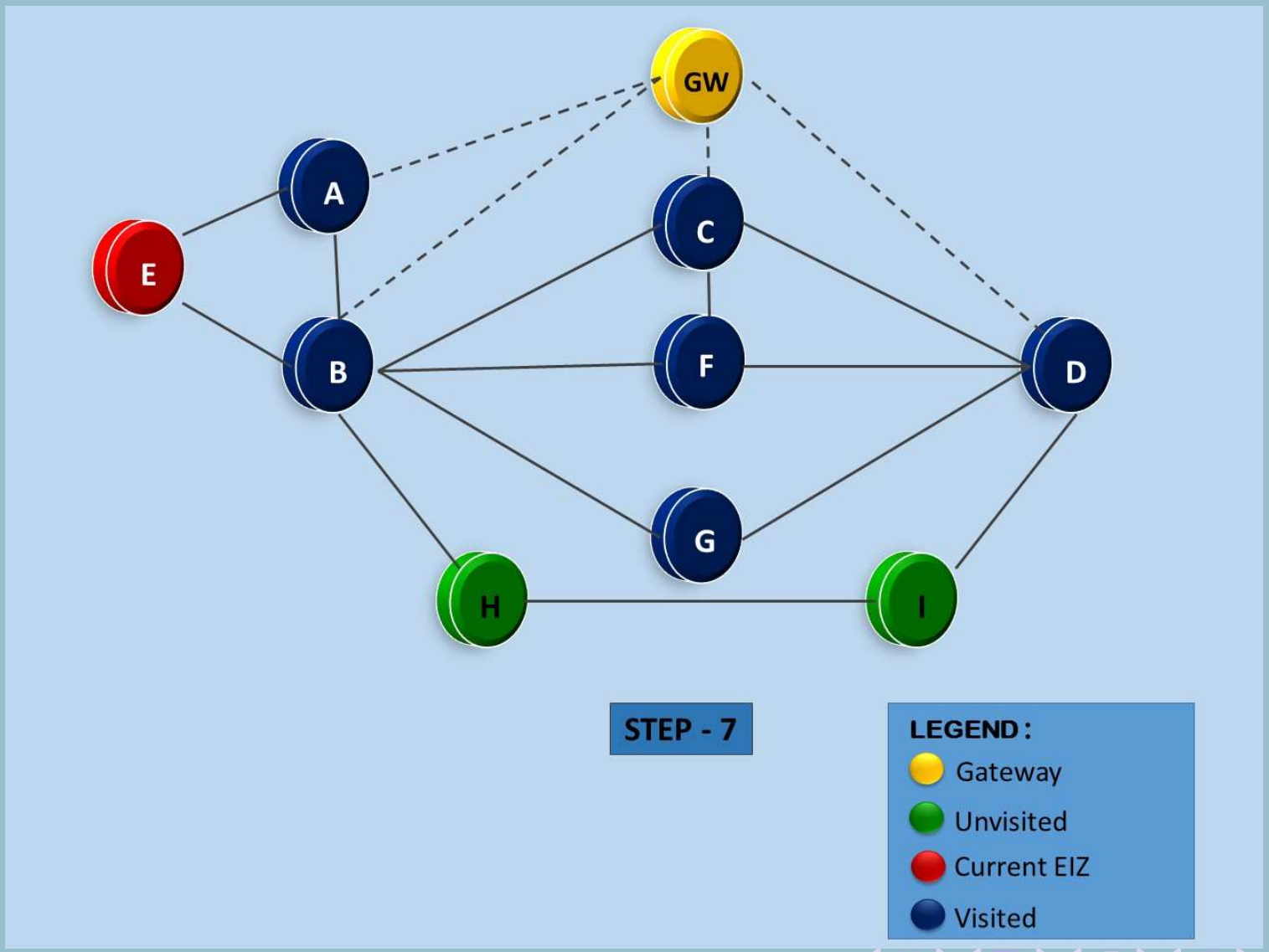
EIZ Selection Sequence

Step 6



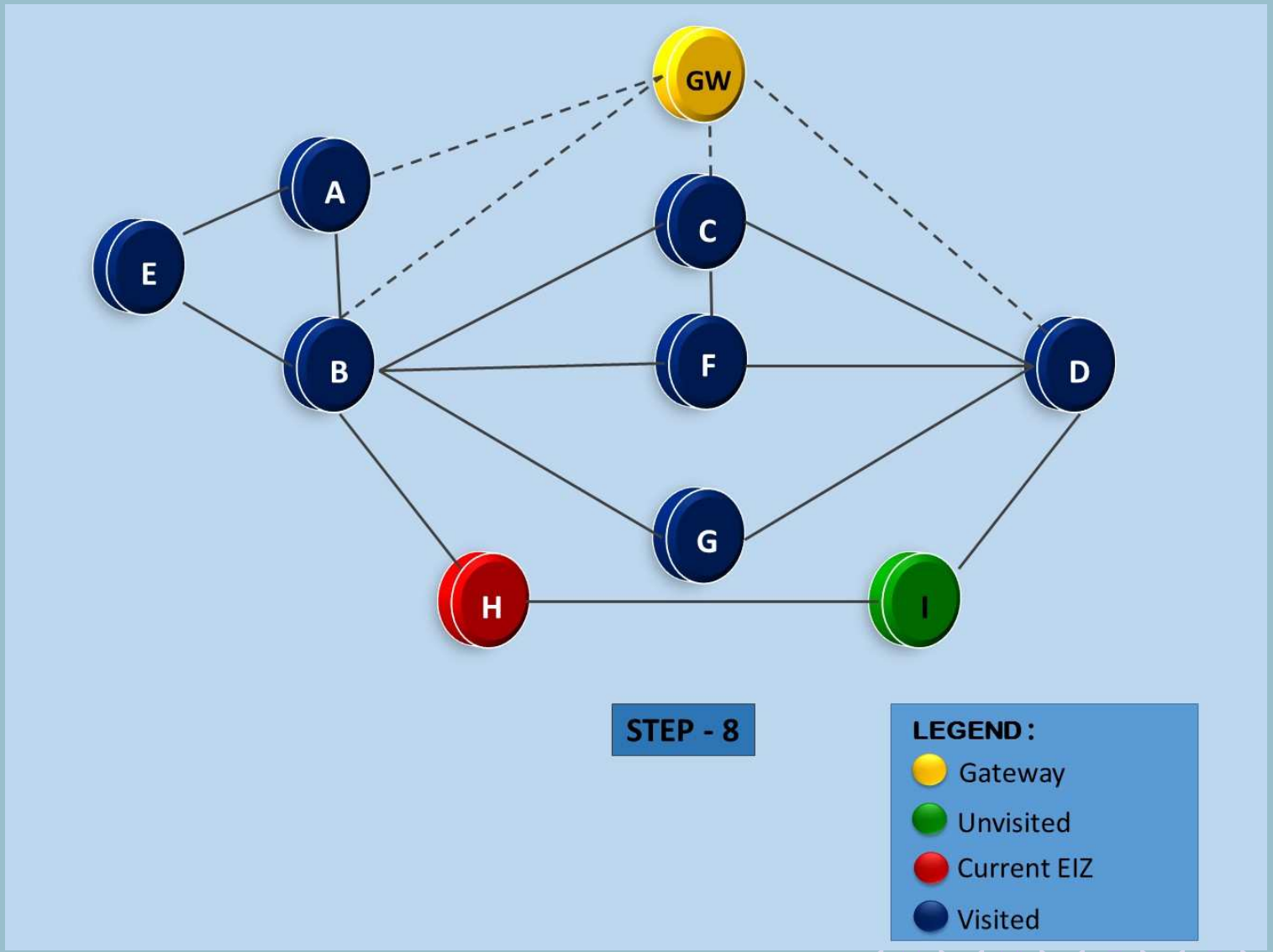
EIZ Selection Sequence

Step 7



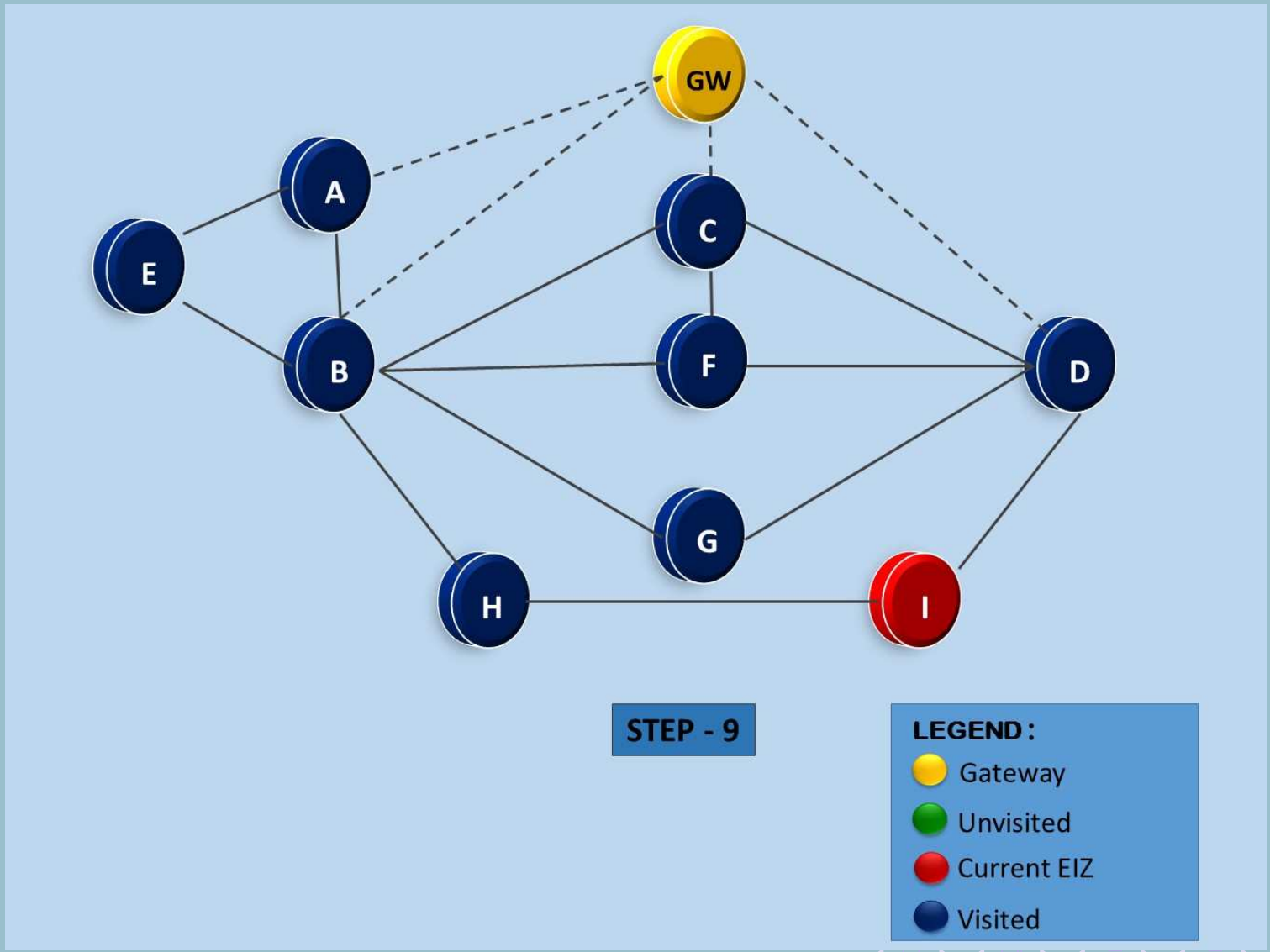
EIZ Selection Sequence

Step 8



EIZ Selection Sequence

Step 9

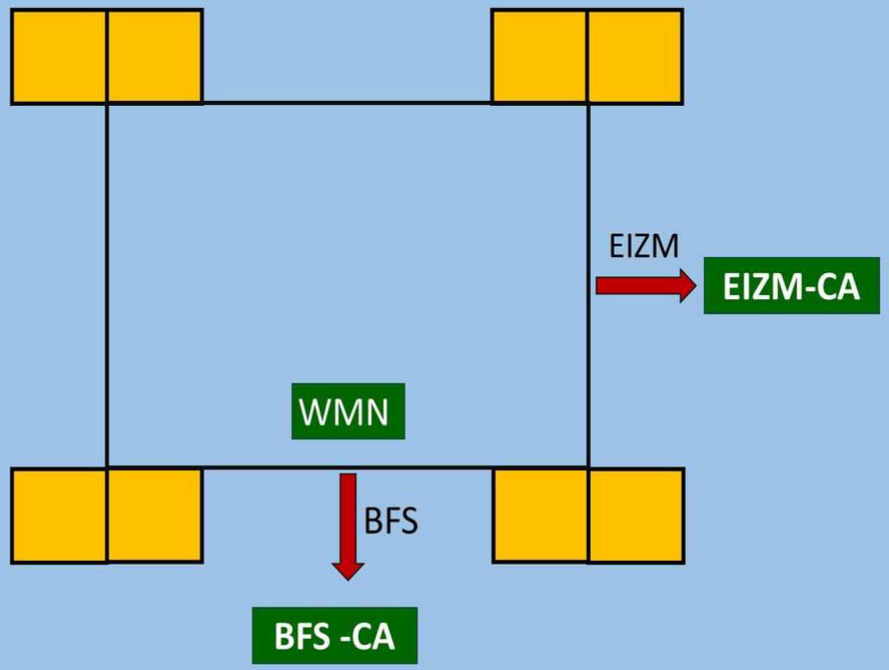


EIZM : A Theoretical Illustration

Sample WMN

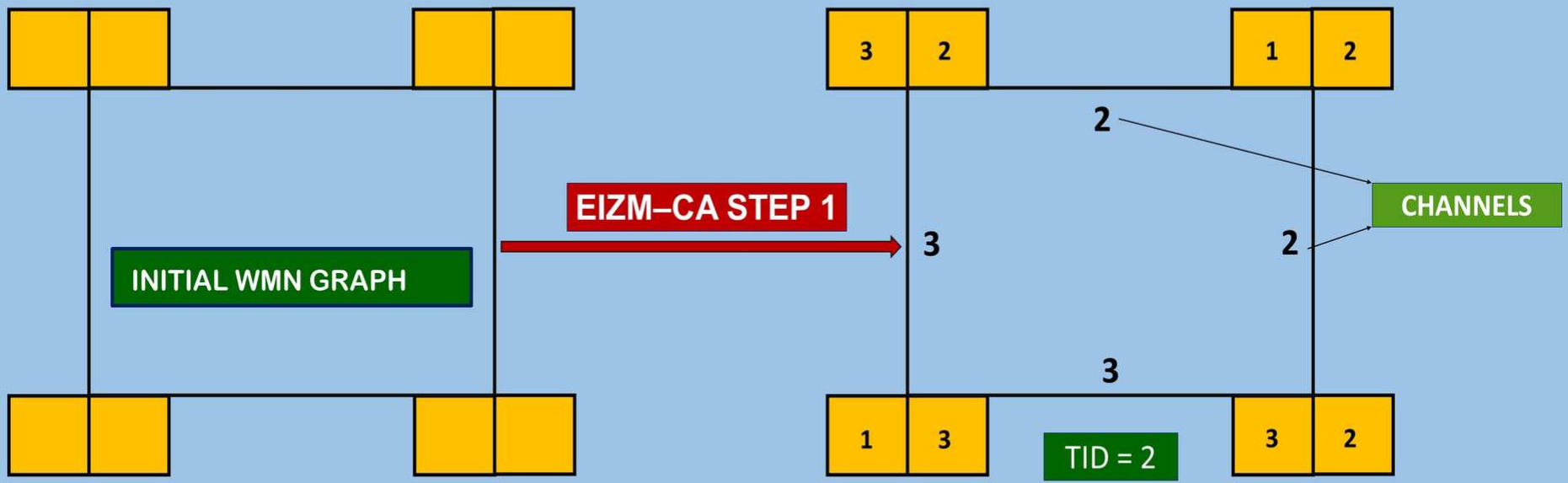
INITIAL WMN GRAPH

- 4 NODES
- 2 RADIOS / NODE
- 3 CHANNELS AVAILABLE
- NO INITIAL CHANNEL ASSIGNMENT TO RADIOS



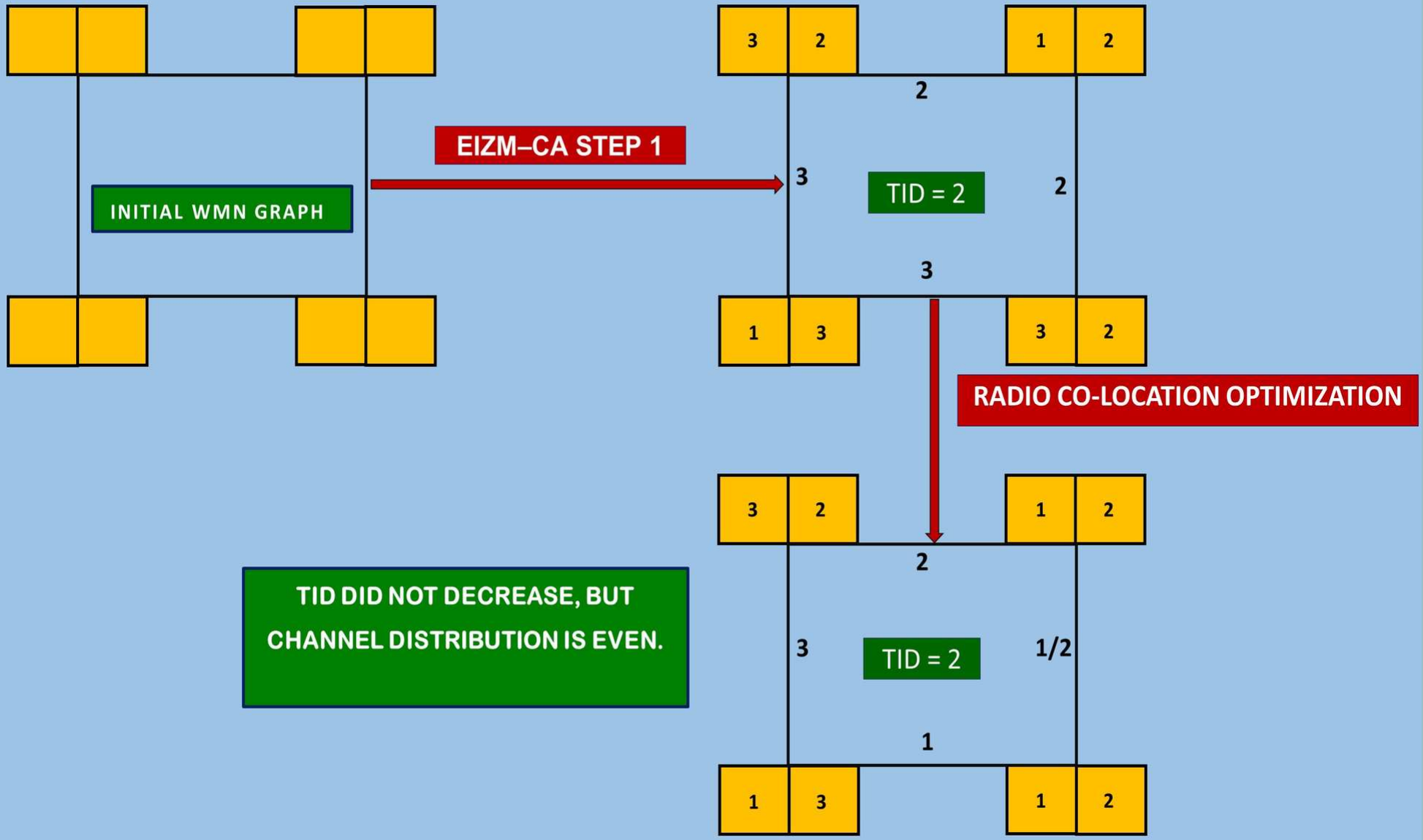
EIZM : A Theoretical Illustration

EIZM Step 1



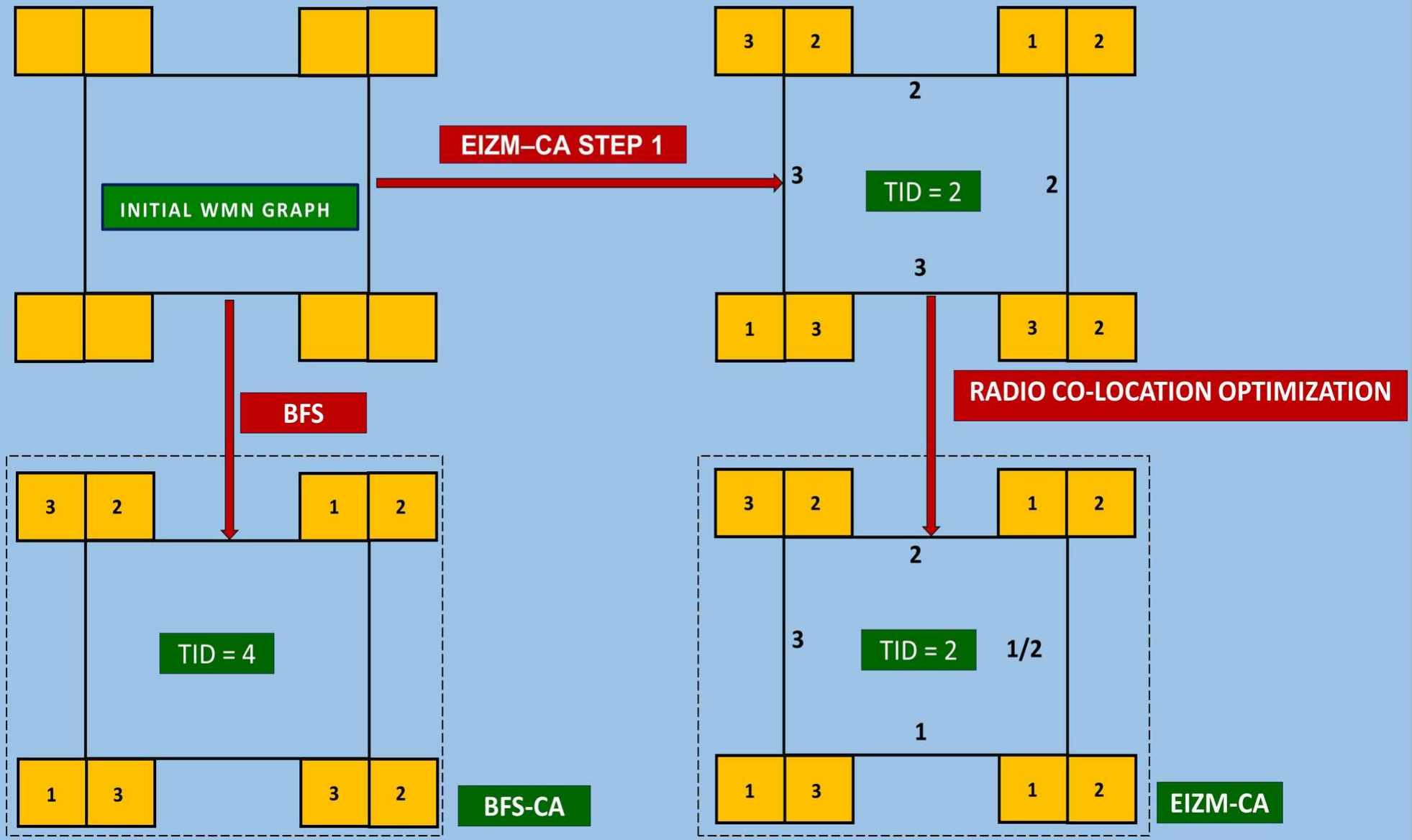
EIZM : A Theoretical Illustration

Radio Co-location Optimization



EIZM : A Theoretical Illustration

Channel Assignment Comparison : BFS-CA



Simulation Setup

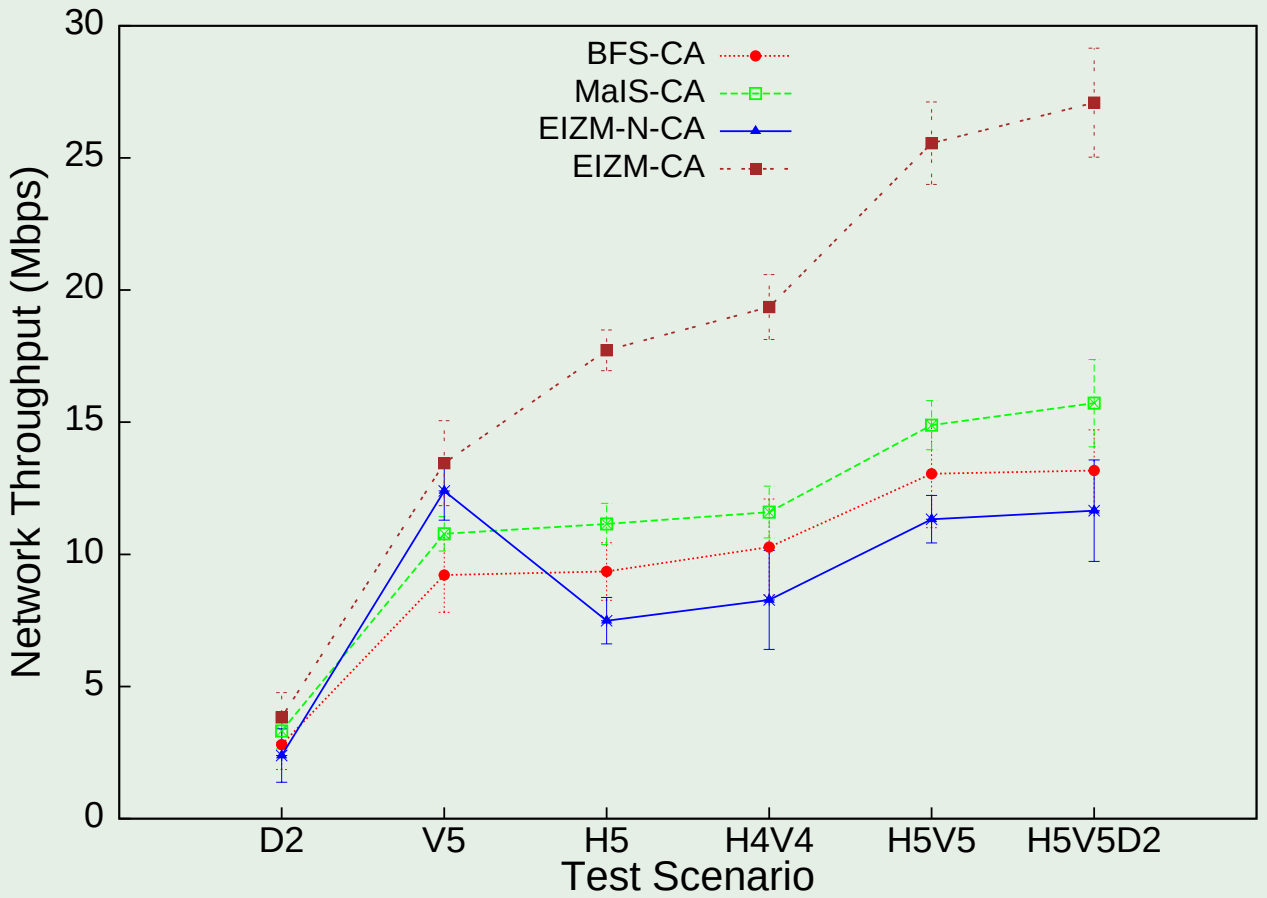
Simulation Setup → Similar to OIS Simulations

CA Schemes Considered

- BFS-CA → A Breadth First Search based CA.
- MaIS-CA → A Maximum Independent Set based CA.
- EIZM-CA → RCA EIZ based CA.
- EIZM-N-CA → Non-RCA version of EIZM.

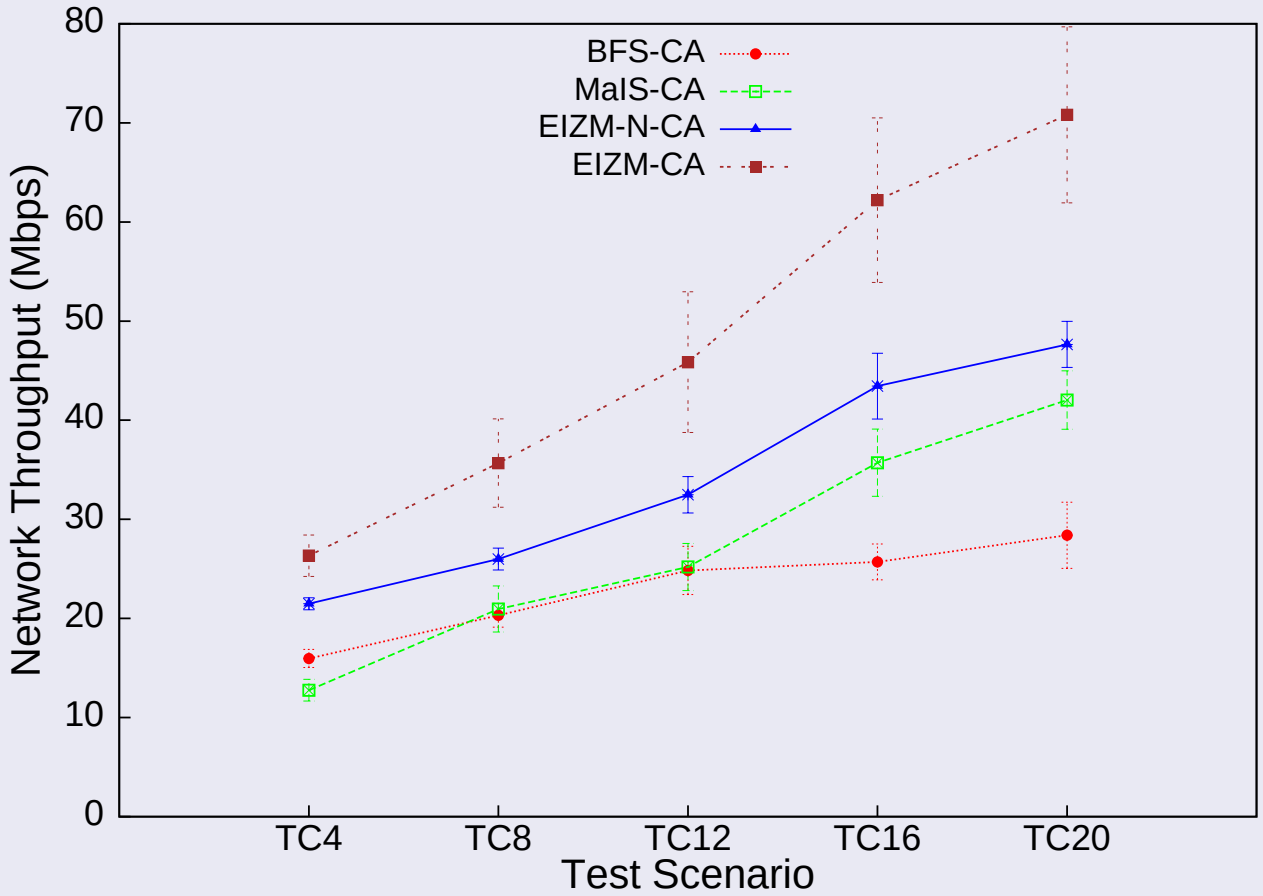
EIZM Performance Evaluation

GWMN Throughput



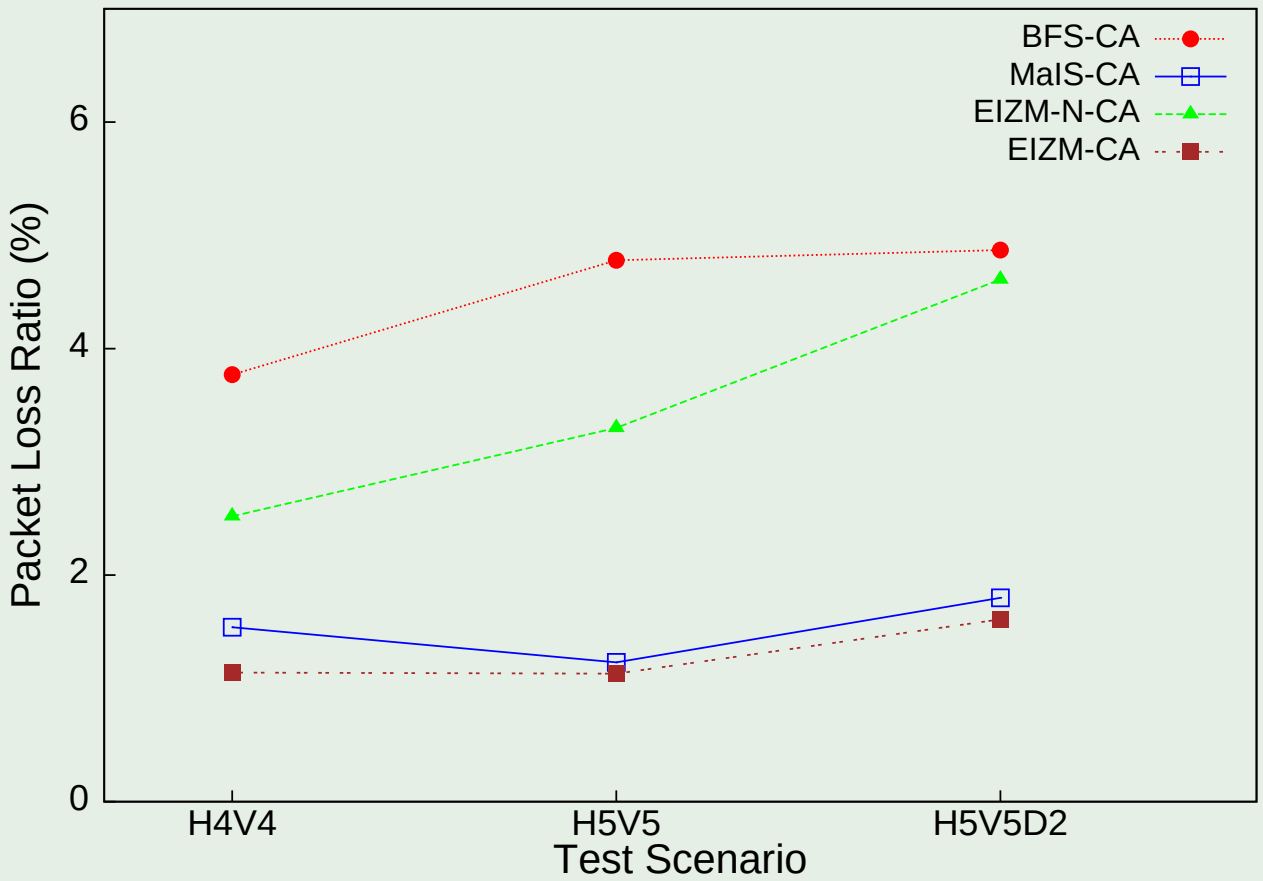
EIZM Performance Evaluation

RWMN Throughput



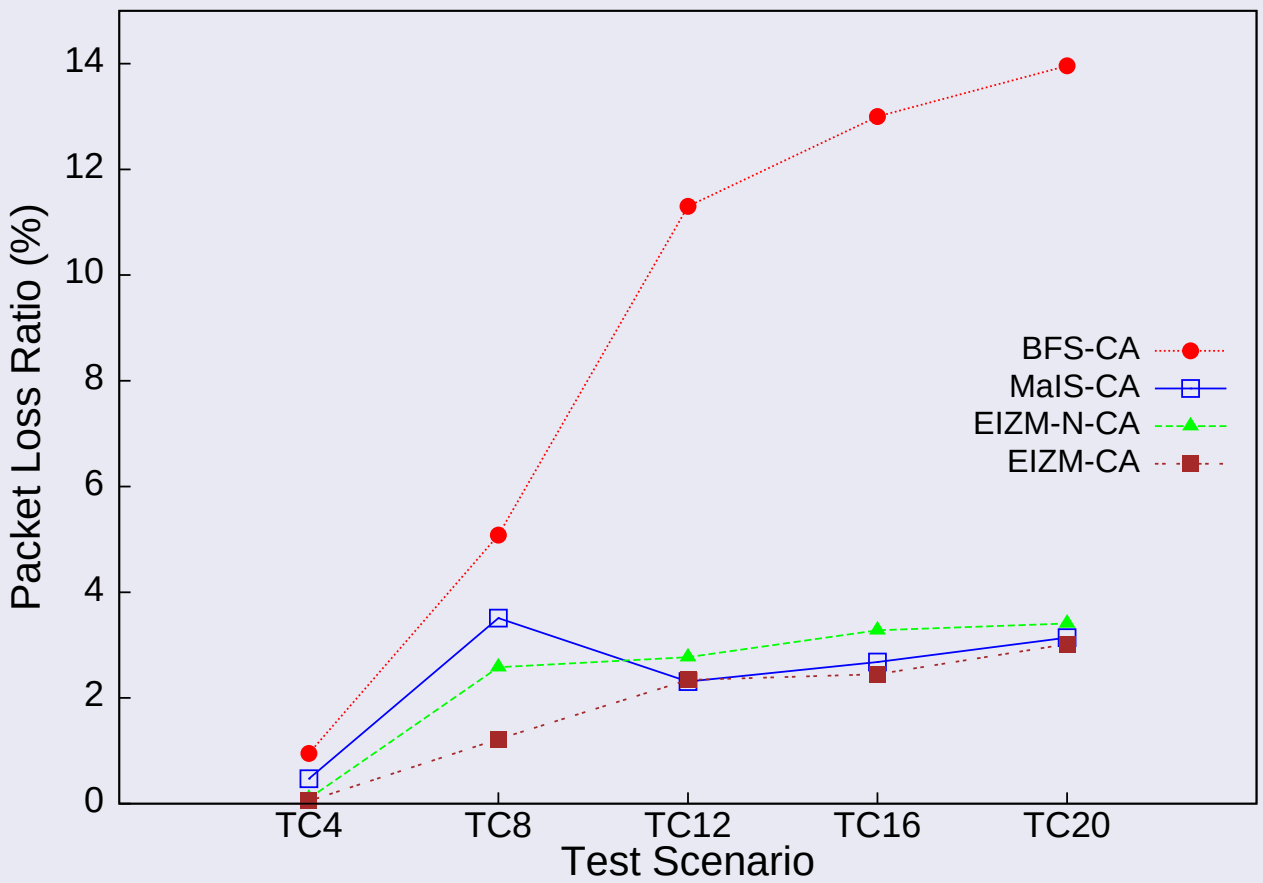
EIZM Performance Evaluation

PLR in GWMN



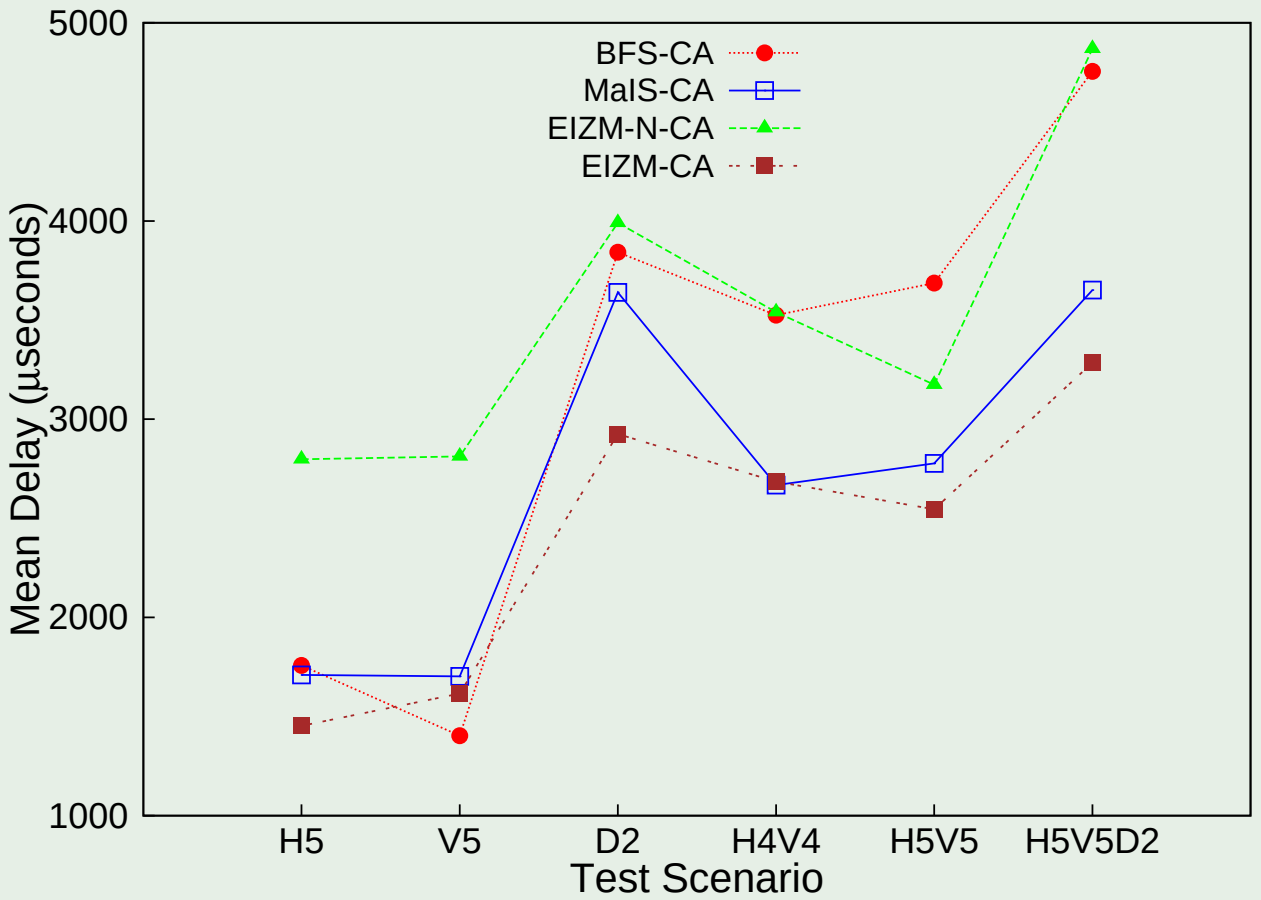
EIZM Performance Evaluation

PLR in RWMN



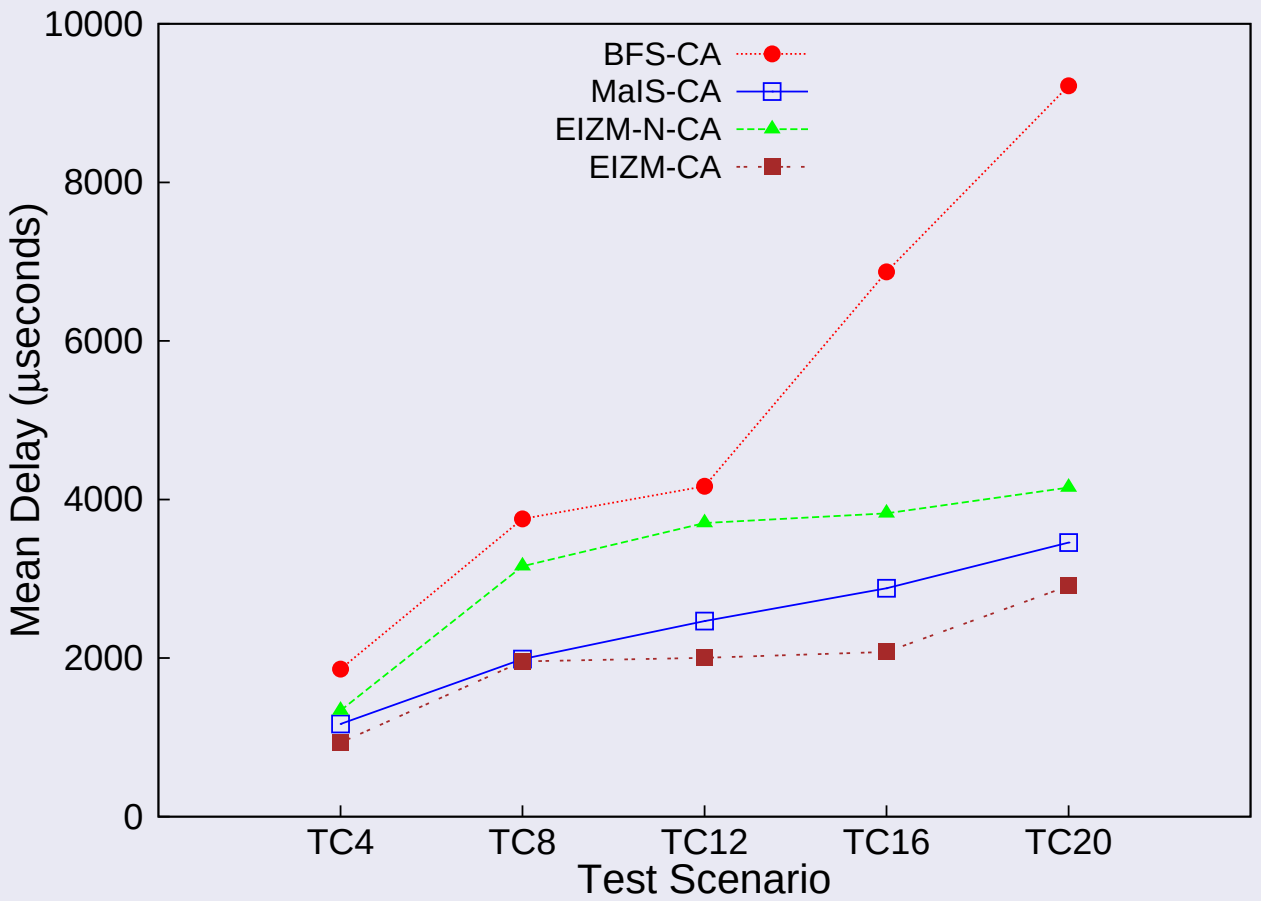
EIZM Performance Evaluation

MD in GWMN



EIZM Performance Evaluation

MD in RWMN



Quantitative Analysis of Results

Maximum Increase in Throughput

- EIZM-CA over MaIS-CA $\rightarrow 72\%$
- EIZM-CA over BFS-CA $\rightarrow 149\%$
- OIS-CA over MaIS-CA $\rightarrow 43\%$
- OIS-CA over BFS-CA $\rightarrow 81\%$

Maximum Decrease in MD

- EIZM-CA over MaIS-CA $\rightarrow 68\%$
- EIZM-CA over BFS-CA $\rightarrow 28\%$
- OIS-CA over MaIS-CA $\rightarrow 41\%$
- OIS-CA over BFS-CA $\rightarrow 19\%$

Maximum Decrease in PLR

- EIZM-CA over MaIS-CA $\rightarrow 11\%$
- EIZM-CA over BFS-CA $\rightarrow 81\%$
- OIS-CA over MaIS-CA $\rightarrow 41\%$
- OIS-CA over BFS-CA $\rightarrow 88\%$

EIZM-CA vs OIS-CA

- Throughput $\rightarrow$ EIZM-CA $>$ OIS-CA
- PLR $\rightarrow$ EIZM-CA $\approx$ OIS-CA
- MD $\rightarrow$ EIZM-CA $\approx$ OIS-CA

Conclusions

Radio Co-location Aware Channel Assignments

- EIZM-CA & OIS-CA significantly outperform reference CAs.
  - Radio Co-location Optimization.
  - Equitable distribution of channels across radios.
- EIZM-CA performs better than OIS-CA.
  - Spatio-statistical CA design $>$ Purely statistical CA design.

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Thank You

Queries ?