Network Laboratory – Wireless Research Group

Routing and Channel Assignment in Multi-Hop, Multi-Channel, and Multi-Radio Wireless Mesh Networks

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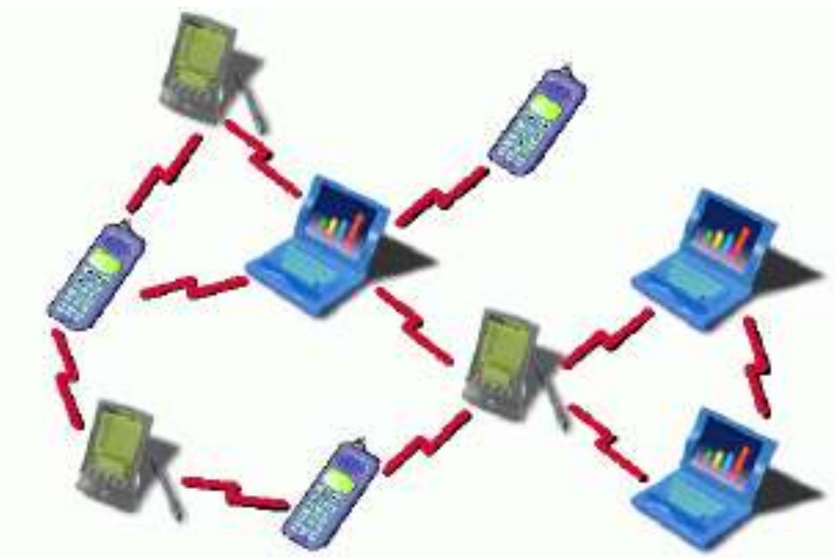
Outlines

- Chapter 1: Introduction.
- Chapter 2: A Survey on Routing Algorithms for Wireless Networks (submitted to IEEE Communications Surveys & Tutorials).
- Chapter 3: Heuristic Model: A Location-Aware Routing Metric (ALARM) for Multi-Channel, Multi-Radio WMN (published in WCNC 2008).
- Chapter 4: Analytical Model: Interference-Aware Routing in WMN.
- Chapter 5: Ongoing and Future Research.

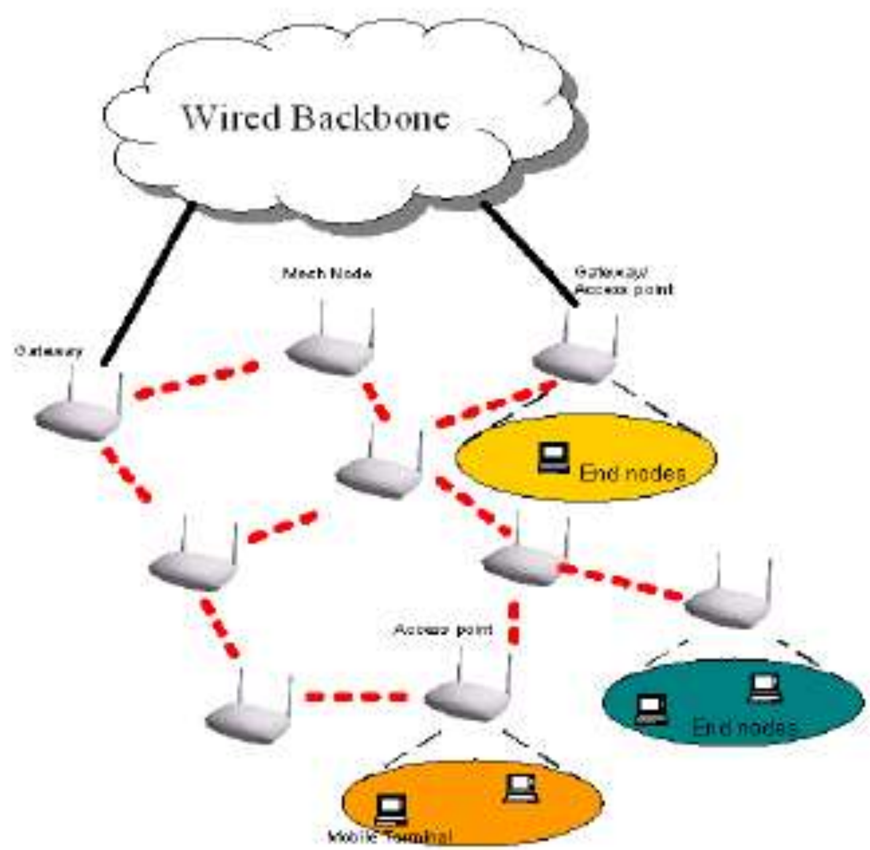
Introduction

Wireless Networks (WN)

- Ad-Hoc WN

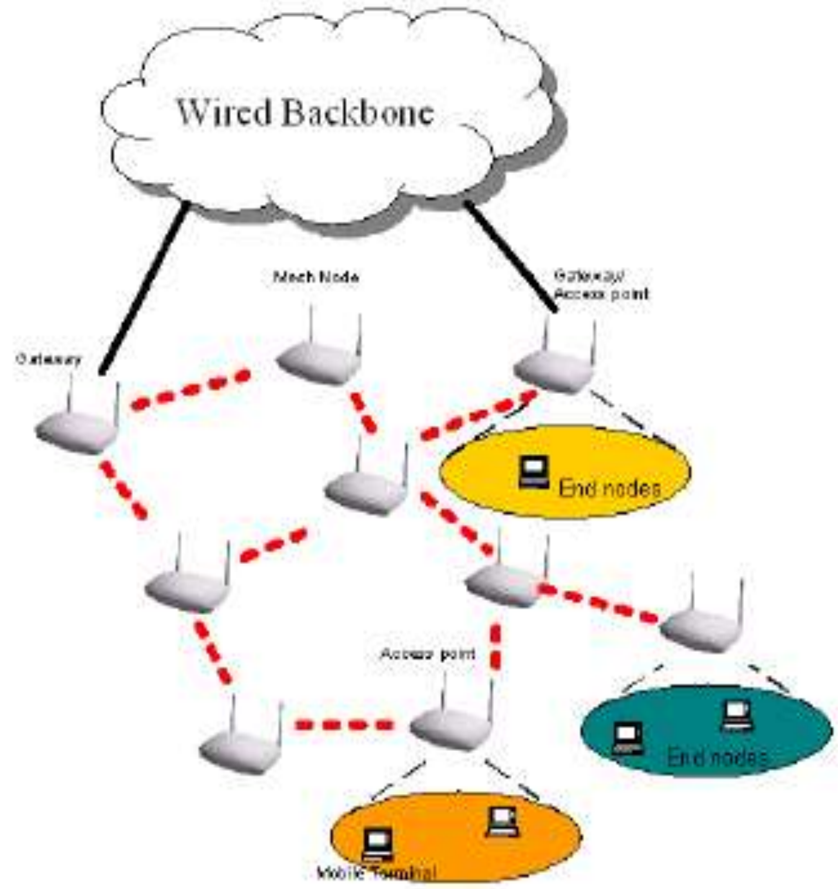


- Infrastructure-Based WN



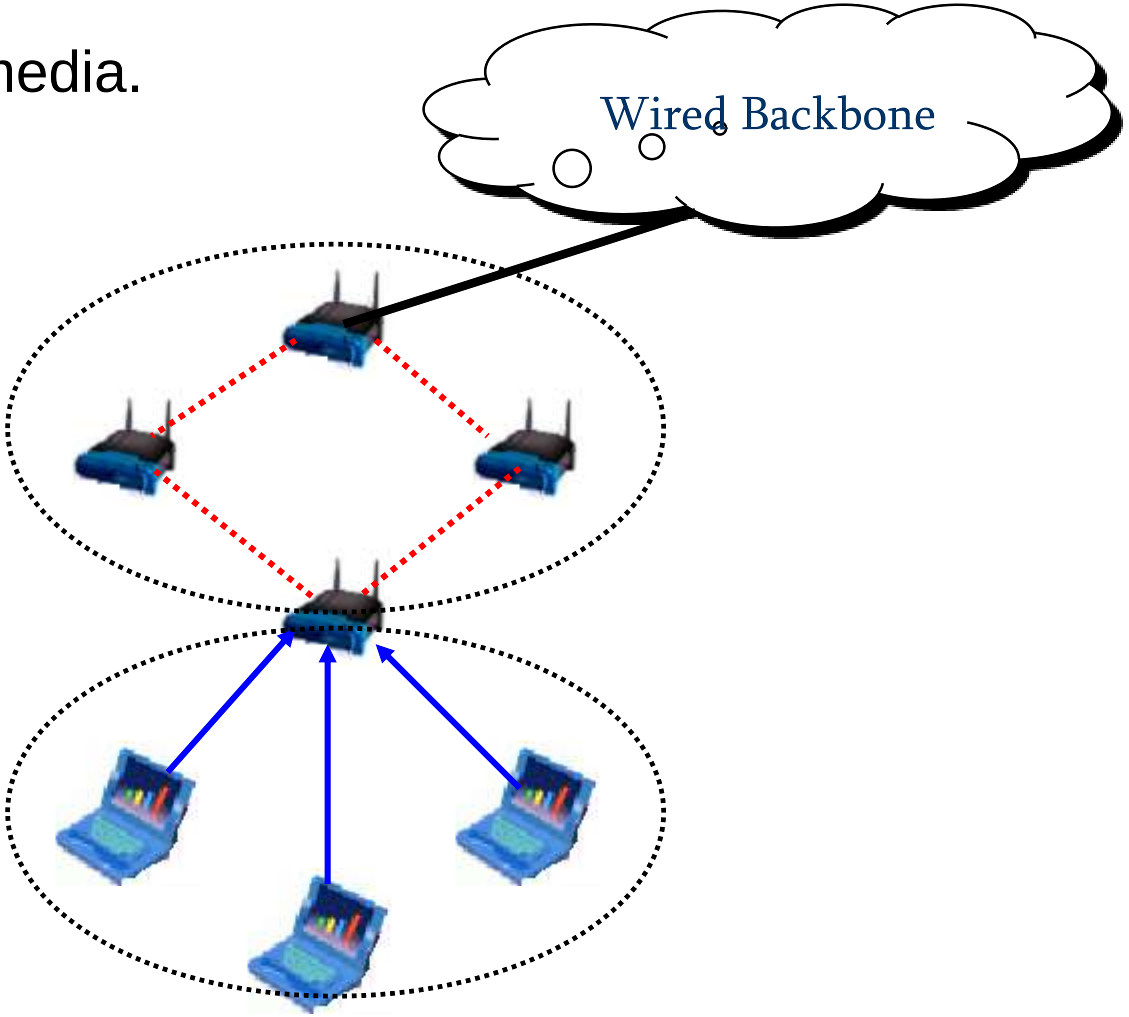
Wireless Mesh Network (WMN)

- Static wireless Mesh Nodes (MN) (like Gateways/Routers/Access Points) & end mobile users.
- MNs equipped with single or multi-radio.
- Links in WMN: single-channel or multi-channel.
- WMN is Multi-hop network.



Wireless Mesh Network (WMN)

- **Wireless Mesh Networks has special characteristics:**
  1. Fixed nodes.
  2. Shared wireless media.



Motivation

- Long term goal: Establish an enhanced comprehensive practical solution for WMN.

  - Routing
  - Channel Assignment (CA)
  - Network Management (NM)

“Geographical-Based Network Management Solution for WMN”

Routing in WMN

- Routing Algorithm (RA).
- Routing Metric (RM).
- Design balance routing solution.
  - ✓ Simple RM + advanced RA
  - ✓ Intelligent (link- aware) RM + Simple RA

- ***Shortest path*** routing without considering the channel characteristics is ***not efficient*** in WMN.

  Because:

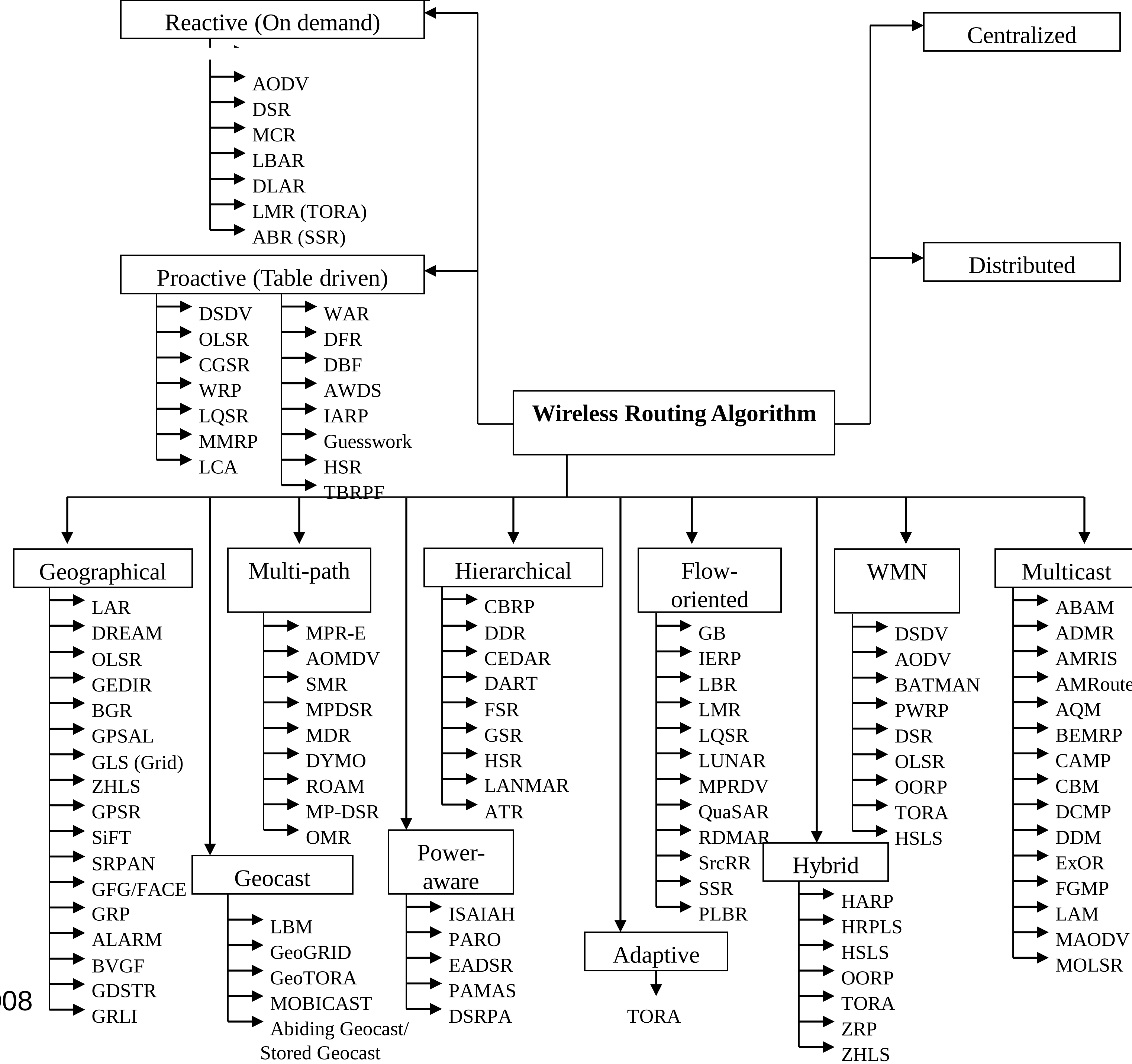
  1. It can not exploit the available channel diversity.
  2. It does not account the impact of interference.

A Survey on Routing Algorithms for Wireless Networks

Requirements & Tradeoffs

- **Requirements**
  - Decentralized
  - Self-organized
  - Self-healing (dynamic network topology)

- **Constraints/Tradeoffs**
  - Bandwidth
  - Energy consumption
  - Security



Wireless Routing Algorithm
Reactive (On demand)
AODV
DSR
MCR
LBAR
DLAR
LMR (TORA)
ABR (SSR)
Proactive (Table driven)
DSDV
OLSR
CGSR
WRP
LQSR
MMRP
LCA
WAR
DFR
DBF
AWDS
IARP
Guesswork
HSR
TBRPF
Centralized
Distributed
Geographical
LAR
DREAM
OLSR
GEDIR
BGR
GPSAL
GLS (Grid)
ZHLS
GPSR
SiFT
SRPAN
GFG/FACE
GRP
ALARM
BVGF
GDSTR
GRLI
Multi-path
MPR-E
AOMDV
SMR
MPDSR
MDR
DYMO
ROAM
MP-DSR
OMR
Geocast
LBM
GeoGRID
GeoTORA
MOBICAST
Abiding Geocast/
Stored Geocast
Hierarchical
CBRP
DDR
CEDAR
DART
FSR
GSR
HSR
LANMAR
ATR
Power-
aware
ISAIAH
PARO
EADSR
PAMAS
DSRPA
Adaptive
TORA
Flow-
oriented
GB
IERP
LBR
LMR
LQSR
LUNAR
MPRDV
QuaSAR
RDMAR
SrcRR
SSR
PLBR
Hybrid
HARP
HRPLS
HSLS
OORP
TORA
ZRP
ZHLS
WMN
DSDV
AODV
BATMAN
PWRP
DSR
OLSR
OORP
TORA
HSLS
Multicast
ABAM
ADMR
AMRIS
AMRoute
AQM
BEMRP
CAMP
CBM
DCMP
DDM
ExOR
FGMP
LAM
MAODV
MOLSR

Routing Categories

- Geographical
- Geo-Cast
- Multi-Path
- Hierarchal
- Hybrid
- Adaptive

Geographical Routing

- Global Positioning System (GPS) provides location information.
- Uses geographic location of the destination instead of IPs.
- Each node can determine its ***own location*** and the source is aware of the ***destination location.***
- There are various approaches, such as ***Flooding-Based, Planarity*** (face routing) and ***Greedy Forwarding*** (GF).

Geo-Cast Routing

- Merges Multicasting and Geographical approaches.

- Deliver information to ***a group*** of destinations identified by their geographical locations.

Multi-Path Routing

- Allows building and use of multiple paths for routing between a source-destination pair.
- Exploits the resource redundancy and diversity in the underlying network.
- ***<u>There are four elements to a multi-path routing:</u>***
  - Path discovery
  - Path disjointedness
  - Traffic distribution strategy
  - Path maintenance

Hierarchal Routing

- A self-organization scheme is employed to group network nodes into clusters.
- Each cluster has one or more cluster heads.
- Gateway: can communicate with more than one cluster.
- Inter-cluster routing can be a proactive protocol, while intra-cluster routing can be reactive.
- Advantage depends on depth of nesting and addressing scheme.

Hybrid Routing

- Initially: Establishes routes *proactively.*
- Then: Serves the demand from additionally activated nodes through *reactive flooding*.

Adaptive Routing

- The routing alternatively switches between *proactive-based routing and reactive-based routing* as needed.

Advantages & Disadvantages

Routing	Advantages	Disadvantages
Geographical / Geo-cast	1. Improves routing performance in Ad-Hoc WN.	1. Location's accuracy. 2. Assume that the nodes know their positions.
Multi-Path	1. Fault tolerance, 2. Load balancing, 3. Bandwidth aggregation, 4. Reduced failure delay, 5. Secure.	1. The improvement depends on the availability of disjoint routes between S-D pair.
Hierarchal	1. Performs better when node density is high. 2. Supports Scalability.	1. Hierarchy maintenance compromise the performance of the routing protocol. 2. Cluster head may become a bottleneck.
Hybrid/Adaptive	1. Combines the advantages of proactive and of reactive routing.	1. Depends on the amount of traffic and number of active nodes.

Heuristic Model:

A Location-Aware Routing Metric (ALARM) for Multi-Channel, Multi-Radio WMN

Background

- In 802.11 protocol, based on CSMA/CA, the interference can be partially avoided using one of the two carrier sensing techniques:

  1- Physical Carrier Sensing (PCS) using Clear Channel Assessment (CCA) threshold, or

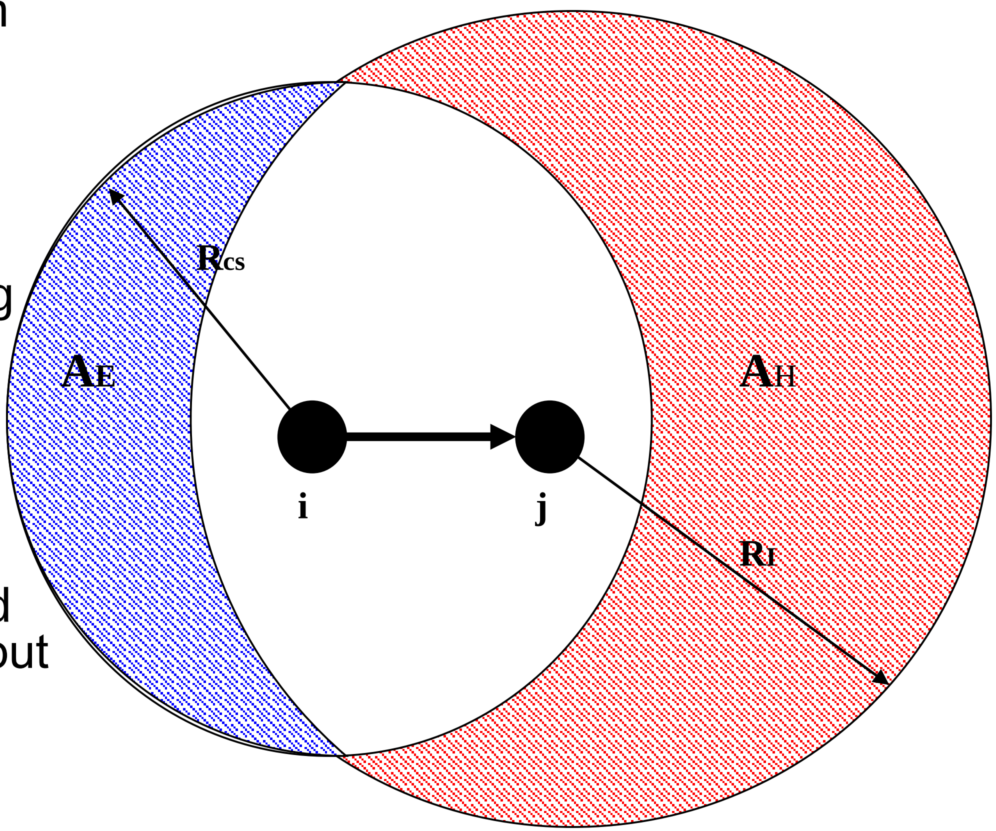
  2- Virtual Carrier Sensing (VCS) using RTS/CTS handshake.

Background

- Using RTS/CTS in 802.11 can avoid interference (collisions caused by Hidden terminals) in the single-hop WMN.
- This is not true when we have multi-hop WMN ➔ Extended Hidden terminal problem.
- Therefore, 802.11 alone can't handle the multi-hop WMN.
- Hence, while using 802.11, an intelligent techniques in routing, channel assignments, etc, need to be deployed.

Background

- <u>Hidden terminals:</u>
  - Transmitters not within hearing range.
  - Transmitter of the interferer is within the interference range of the reference receiver.
- <u>Exposed terminals:</u>
  - Two transmitter within same hearing range.
  - Transmitter of the interferer is not within the interference range of the reference receiver.
- In 802.11, both hidden and exposed terminal's problems cause throughput degradation.



Definitions & Terminologies

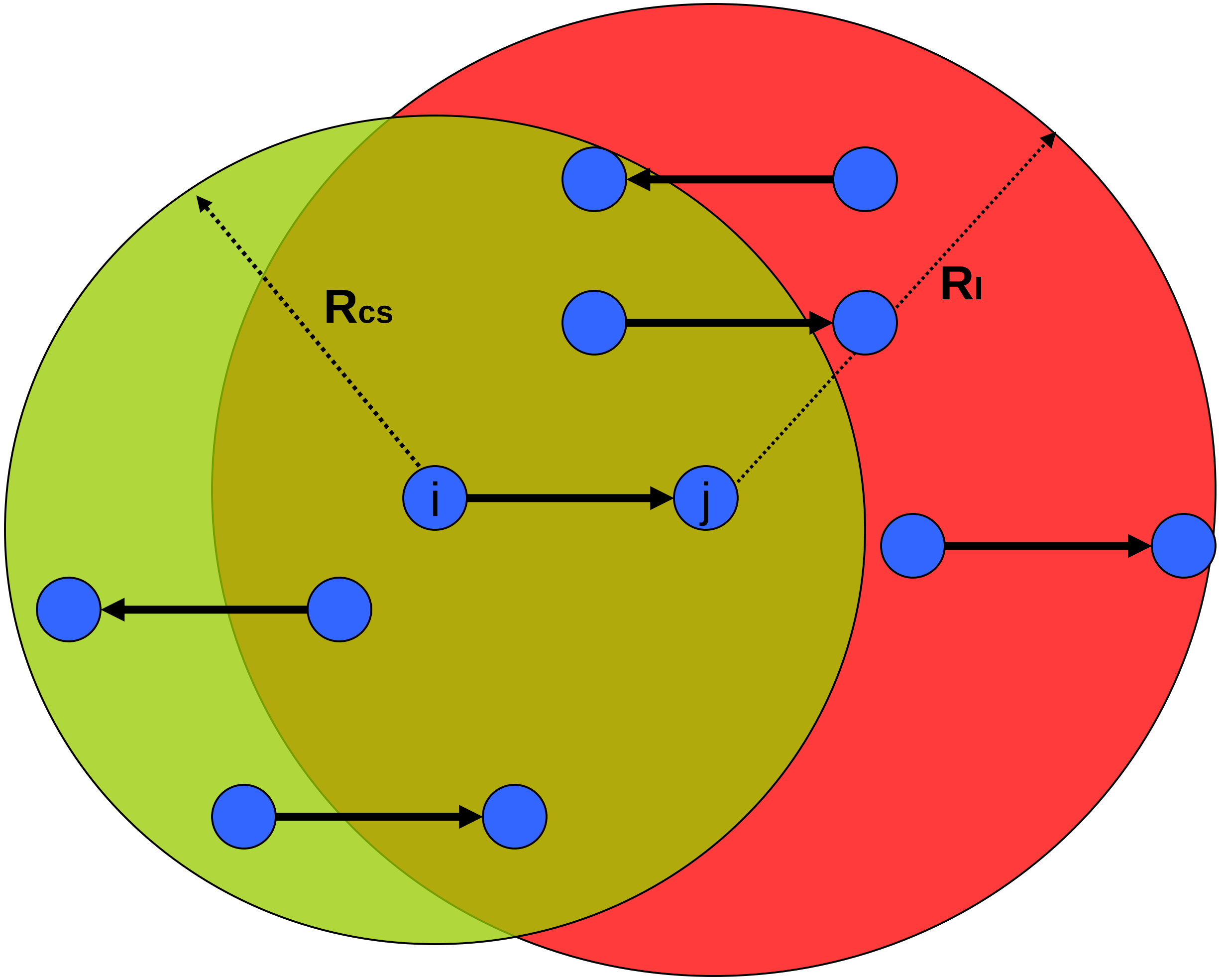
- **Transmission Range (R_{tx}):** the distance at which a node can receive (successfully decode) any packet from the transmitter with the presence of noise only.

- **Carrier-Sensing (Hearing) Range (R_{cs})**: a node will be able to detect an existing transmitter within that range via physical carrier sensing.

- **Interference Range (R_I)**: distance at which the signal-to-noise-and-Interference-ratio (SNIR) at the receiver is fallen below a certain threshold.

- **Transmission range ≤ Sensing range < Interference range.**

Definitions & Terminologies



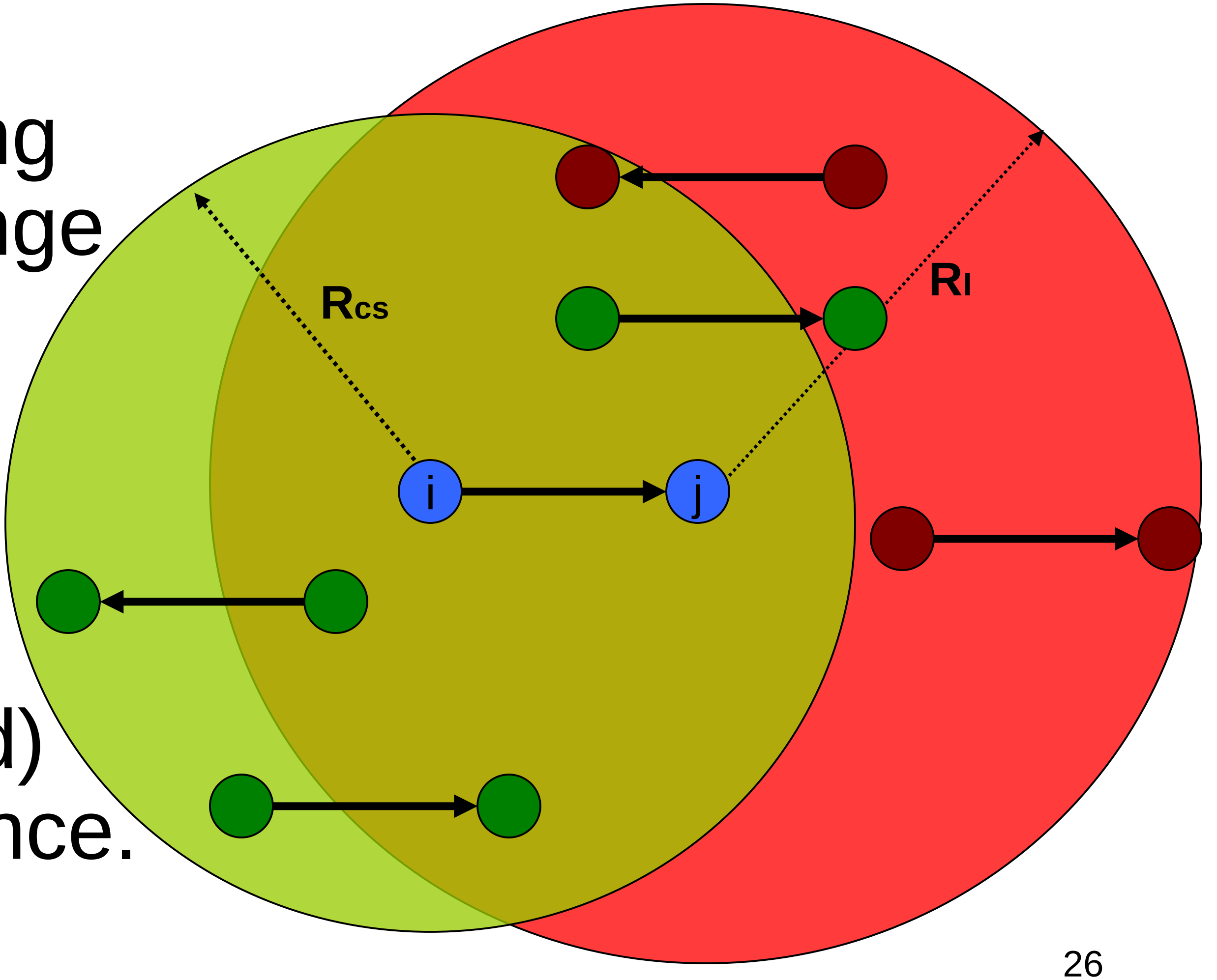
Interference Types

- <u>Type-1:</u>

  \- Carrier-sensing (or hearing) range interference.

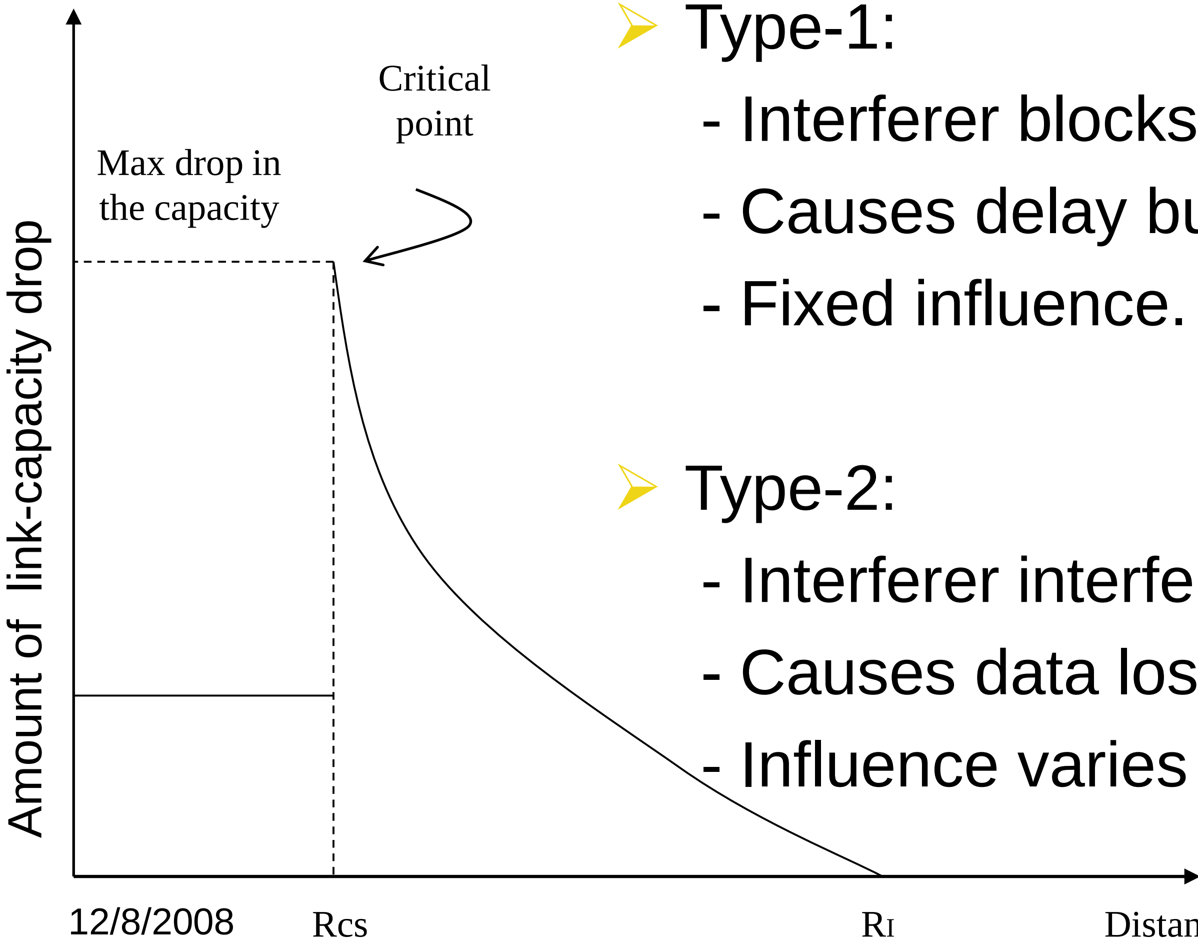
- <u>Type-2:</u>

  \- Interference (collision-based) range interference.



Interference Types

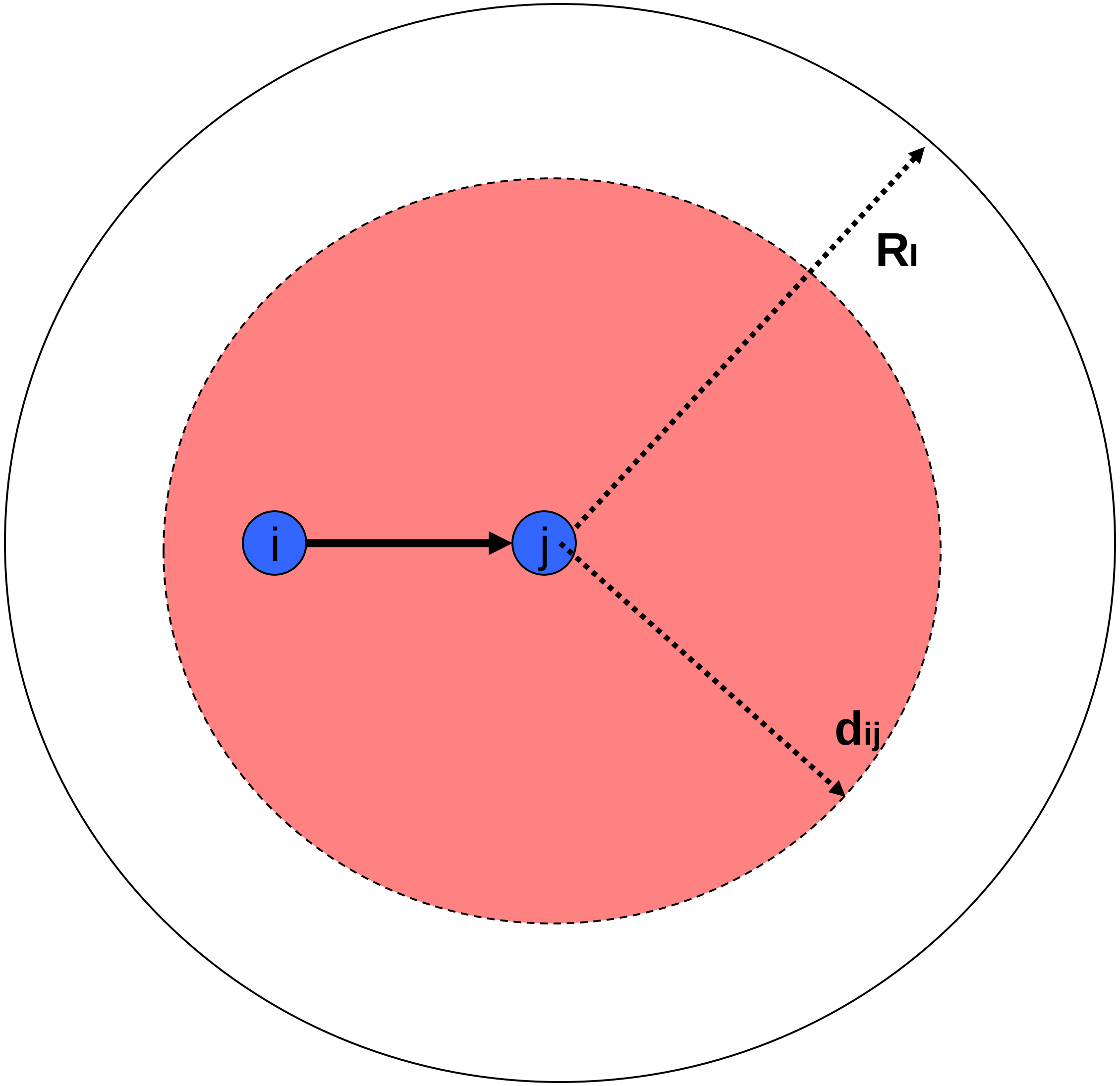
- What's the difference?



➢ Type-1:
- Interferer blocks L_{ij} transmission.
- Causes delay but not data loss.
- Fixed influence.

➢ Type-2:
- Interferer interferes the reception of L_{ij}.
- Causes data loss.
- Influence varies with distance.

Type-2 Interference



Routing in WMN

- **The criteria of a good routing metric:**
  1. Link-aware (cross layer solution).
  2. Considers co-channel links along the same path (Intra-flow interference).
  3. Captures the external interference from different simultaneous co-channel links off the path (Inter-flow interference).
  4. Channel spatial reuse.

Related Work

- Hop count
- Expected Transmission Count (ETX) - MIT(2003) [1]
- Expected Transmission Time (ETT) - Microsoft (2004) [2]
- Weighted Cumulative Expected Transmission Time (WCETT) - Microsoft (2004) [2]
- And others…

A Location-Aware Routing Metric

- Factors that affect the transmission at any link:

1. Interference from external sender.
2. Sensing other transmission.
3. Attenuation caused by S-D separation.
4. Link bandwidth.

ranges

1. Distances

2. Bandwidth

A Location-Aware Routing Metric

- ALARM doesn’t propose CA, but it builds the routing decision based on the different CA.
- ALARM is sensitive to CA.
- ALARM is very sensitive to the location of the interfering links (Type-1/Type-2).

A Location-Aware Routing Metric

Path cost metric:

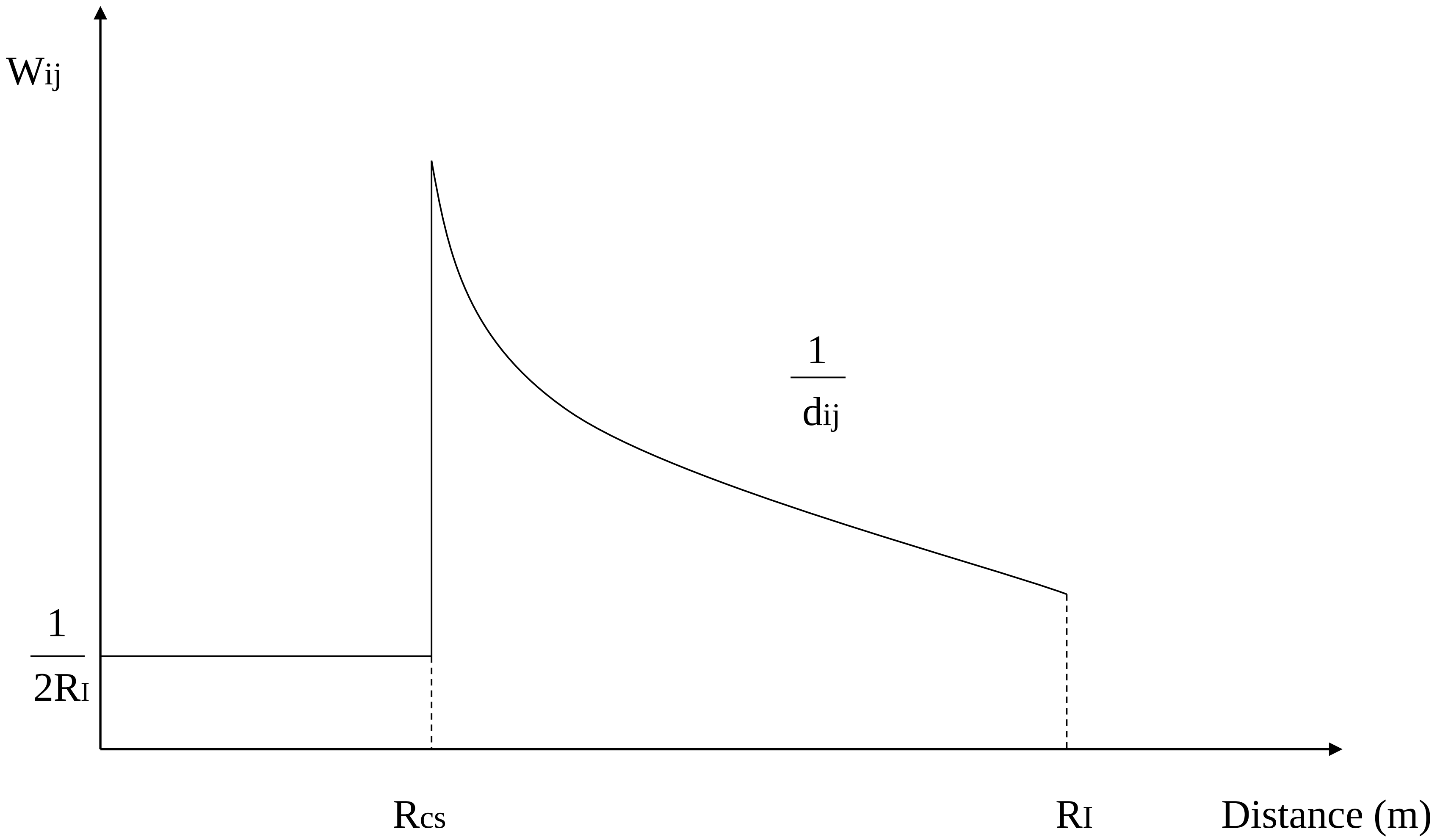
Location Factor

$$ALARM = (1-\alpha)\sum_{i\in p} ETT_i + \alpha \sum_{i\in p}\{N_i \sum_{j\in S_i} w_{ij}\}$$

$$w_{ij} = \begin{cases} \frac{1}{2R_I} & d_{ij} < R_{cs} \\ \frac{1}{d_{ij}} & R_{cs} < d_{ij} < R_I \\ 0 & R_I < d_{ij} \end{cases}$$

- **p is the set of all links along path p.**
- **S_i is the set of all co-channel links within carrier sensing or interference range of L_{ij}.**
- **N_i is the number of active co-channel links of L_{ij}, in other words, N_i is the size of set S_i.**
- **R_I is the Interference range.**
- **R_{cs} is the carrier-sensing range.**
- **d_{ij} is the distance between the receiver of L_{ij} and the sender of the interferer.**
- **$0 < \alpha < 1$.**

A Location-Aware Routing Metric



A Location-Aware Routing Metric

- w_{ij} is the pair-wise weight given to the interferers of L_{ij} based on the interferer's type and location.

- The value of w_{ij} is not symmetric ($w_{ij} \neq w_{ji}$)

- The value of w_{ij} when the links are within R_{cs} is constant because regardless of the location of the interferer it will block the transmission of other link.

- While this value depends on d_{ij} when the interferers are within R_I since the packet loss varies based on the value of this distance.

A Location-Aware Routing Metric

- ALARM as a path metric can be re-written link cost metric:

$$\text{ALARM} = \sum_{i \in p} \text{ALARM}_i$$

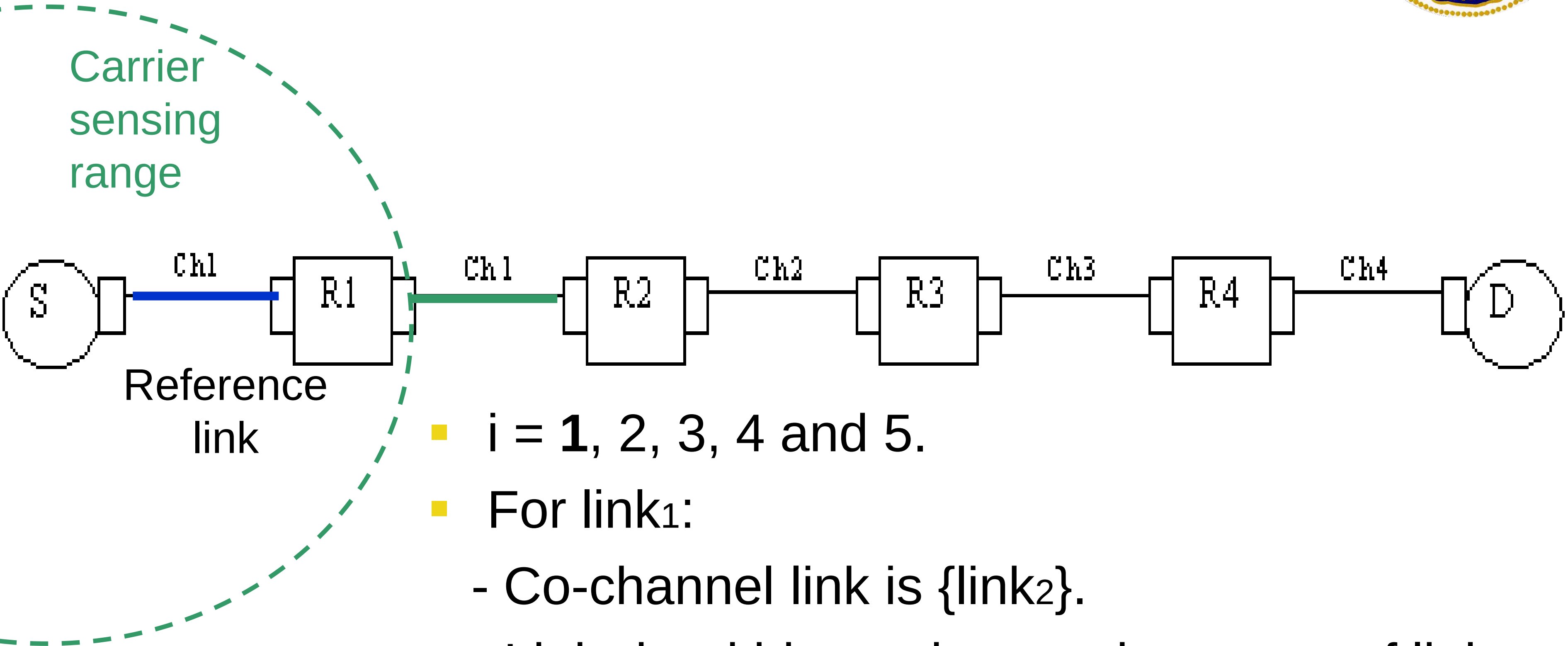
where

$$ALARM_i = (1-\alpha)ETT_i + \alpha N_i * \sum_{j \in S_i} w_{ij}$$

- This feature gives ALARM the ***flexibility*** that is missing in most of the current cross-layer routing metrics.

- The task of ***finding routing*** algorithm is much easier.

Example 1: Type-1 Interference



- i = **1**, 2, 3, 4 and 5.
- For $link_1$:

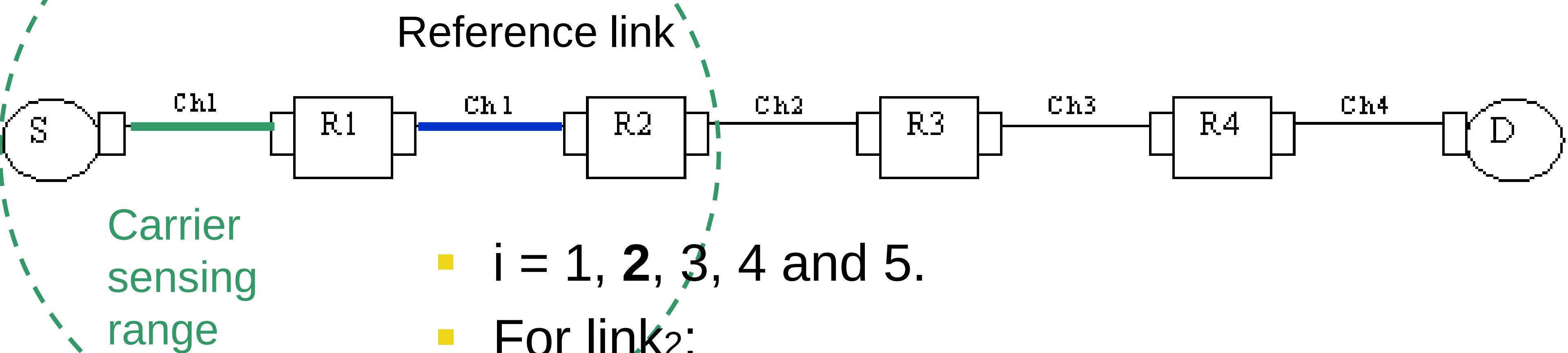
  - Co-channel link is {$link_2$}.

  - $Link_1$ is within carrier sensing range of $link_2$

  - S_1 = {$link_2$}, j = 1

  - R_I = 30m, N_1= $|S_1|$ = 1, $w_{11} = \dfrac{1}{30 * 2}$

Example 1: Type-1 Interference



- i = 1, **2**, 3, 4 and 5.
- For $link_2$:

  - Co-channel link is $\{link_1\}$.

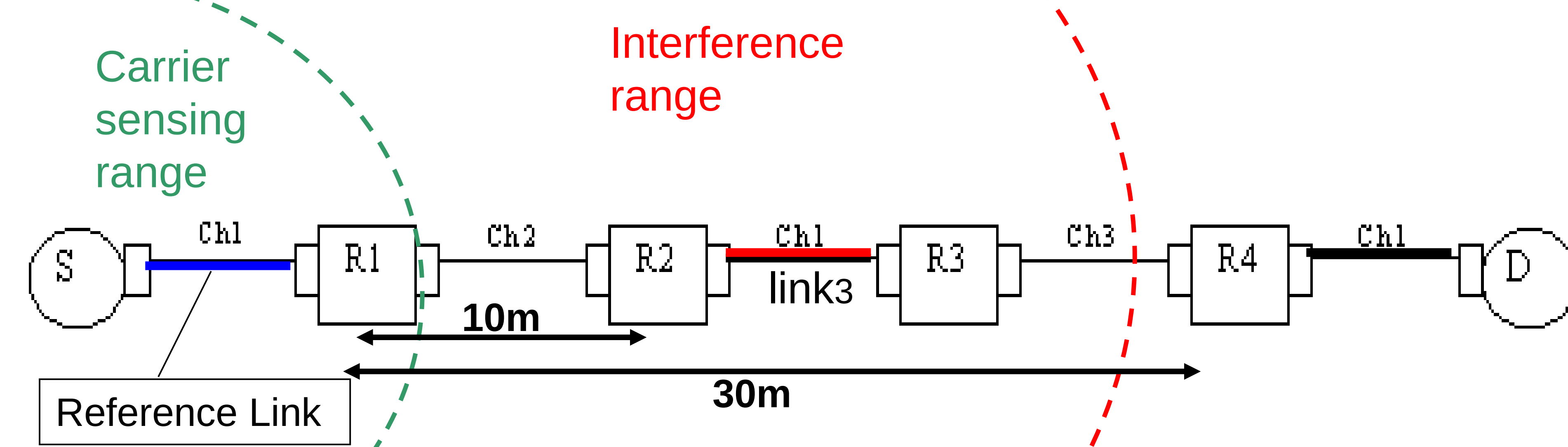
  - $Link_2$ is within carrier sensing range of $link_1$

  - $S_2 = \{link_1\}$, j = 1

  - R_I = 30m, $N_2 = |S_2| = 1$, $w_{21} = \frac{1}{30 * 2}$
- The result:

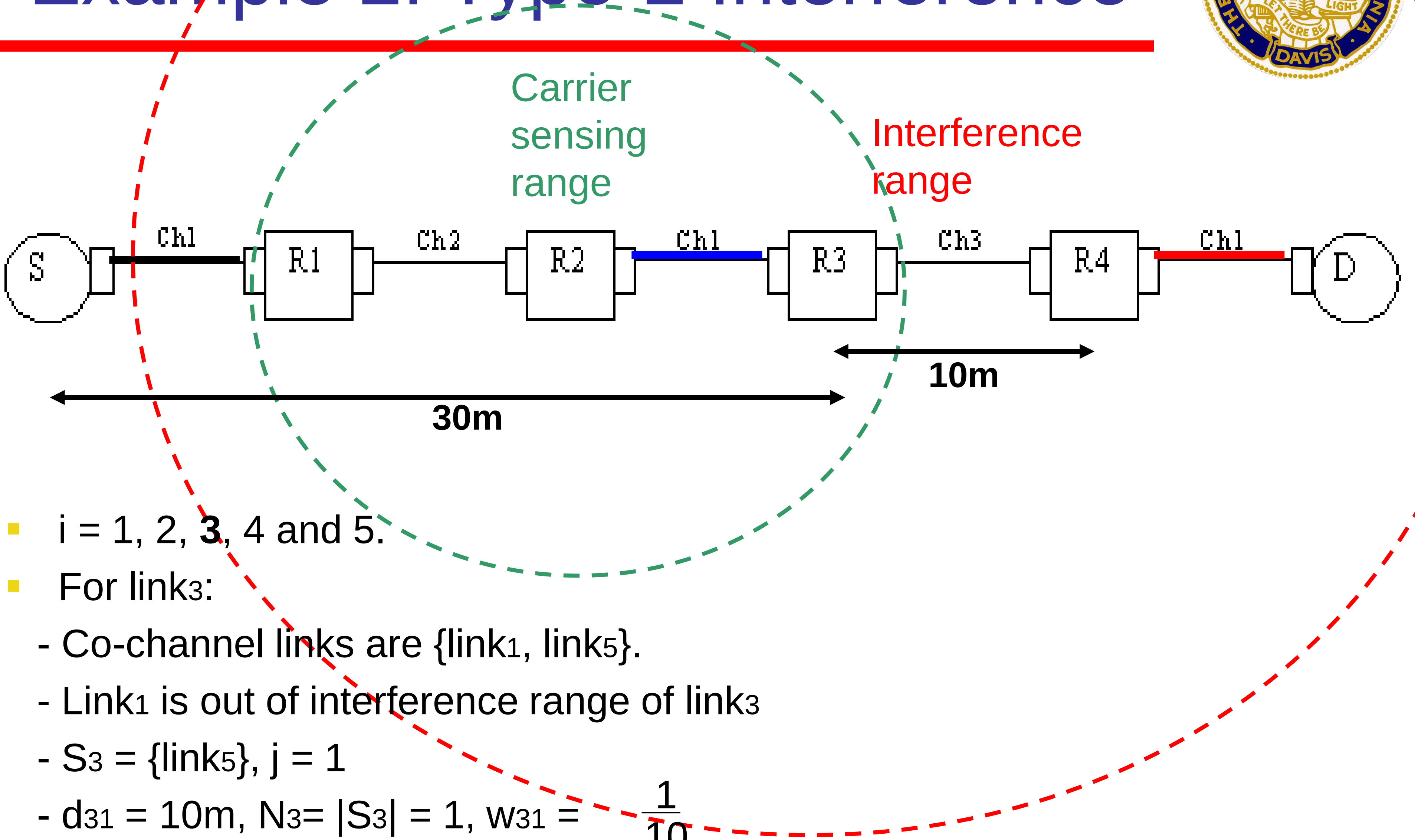
$$\sum_{i=1}^{5}\{N_i \sum_{j=1}^{1} w_{ij}\} = \frac{1}{30 * 2} + \frac{1}{30 * 2}$$

Example 2: Type-2 Interference



- $i = 1, 2, 3, 4$ and 5.
- For $link_1$:
  - Co-channel links are $\{link_3, link_5\}$.
  - $Links_5$ is out of interference range of $link_1$
  - $S_1 = \{link_3\}$, $j = 1$
  - $d_{11} = 10m$, $N_1 = |S_1| = 1$, $w_{11} = \dfrac{1}{10}$
- For $link_2$, $link_4$ there is no interferers
  - $S_2 = S_4 = \{\Phi\}$,
  - $N_2 = N_4 = 0$.

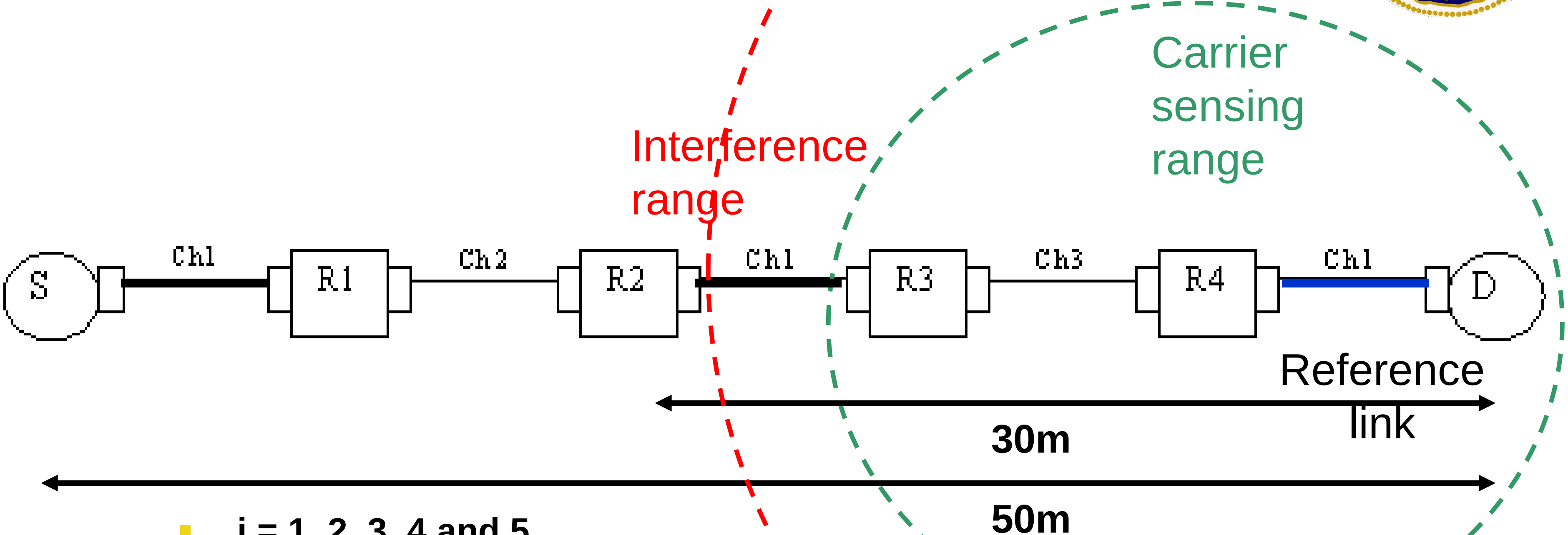
Example 2: Type-2 Interference



- i = 1, 2, **3**, 4 and 5.
- For $link_3$:

- Co-channel links are {$link_1$, $link_5$}.
- $Link_1$ is out of interference range of $link_3$
- S_3 = {$link_5$}, j = 1
- d_{31} = 10m, N_3= $|S_3|$ = 1, $w_{31} = \frac{1}{10}$

Example 2: Type-2 Interference



- i = 1, 2, 3, 4 and 5.
- For link$_5$:
  - Co-channel links are {link$_1$, link$_3$}.
  - Link$_1$ and link$_3$ are out of interference range of link$_5$
  - $S_5 = \{\Phi\}$, j = 0
  - $N_3 = 0$
  - $w_{31} = 0$
- The result: $\sum_{i=1}^{5}\{N_i \sum_{j=1}^{1} w_{ij}\} = 1 * (\frac{1}{10}) + 0 * (0) + 1 * (\frac{1}{10}) + 0 * (0) + 0 * (0).$

A Location-Aware Routing Metric

$$WCETT = (1-\beta)\sum_{i=1}^{n} ETT_i + \beta \max_{1 \le j \le k} X_j$$

- First term is equivalent at both ALARM and WCETT.
- ALARM is link-based metric, WCETT is a path-based metric.
- Because ALARM utilizes the ranges concept, it satisfies the following criteria:

1. Link-aware.
2. Considers the intra-flow interference.
3. <u>*Captures the inter-flow interference.*</u>
4. <u>*Considers channel spatial reuse.*</u>

Evaluation: Single & Double Chain Topology

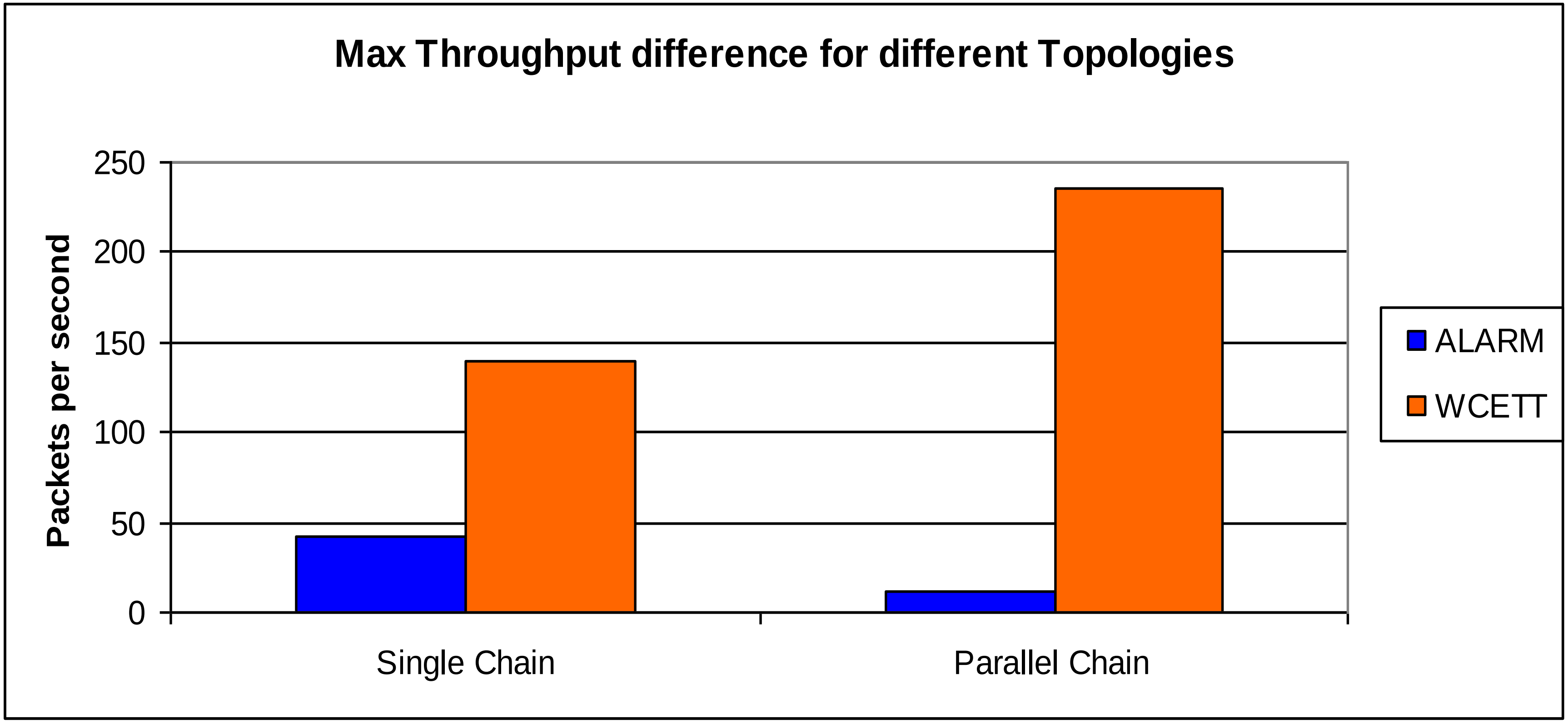
Simulation setup

- Different CA for each single-path multiple-hop chain network.

- Examine 122 different cases varies in:
    1. Channel assignment
    2. Link data rates
    3. Total number of channels
    4. Interference range
    5. Carrier-sensing range
    6. Number of paths running simultaneously

Evaluation: Single & Double Chain Topology

- Results:

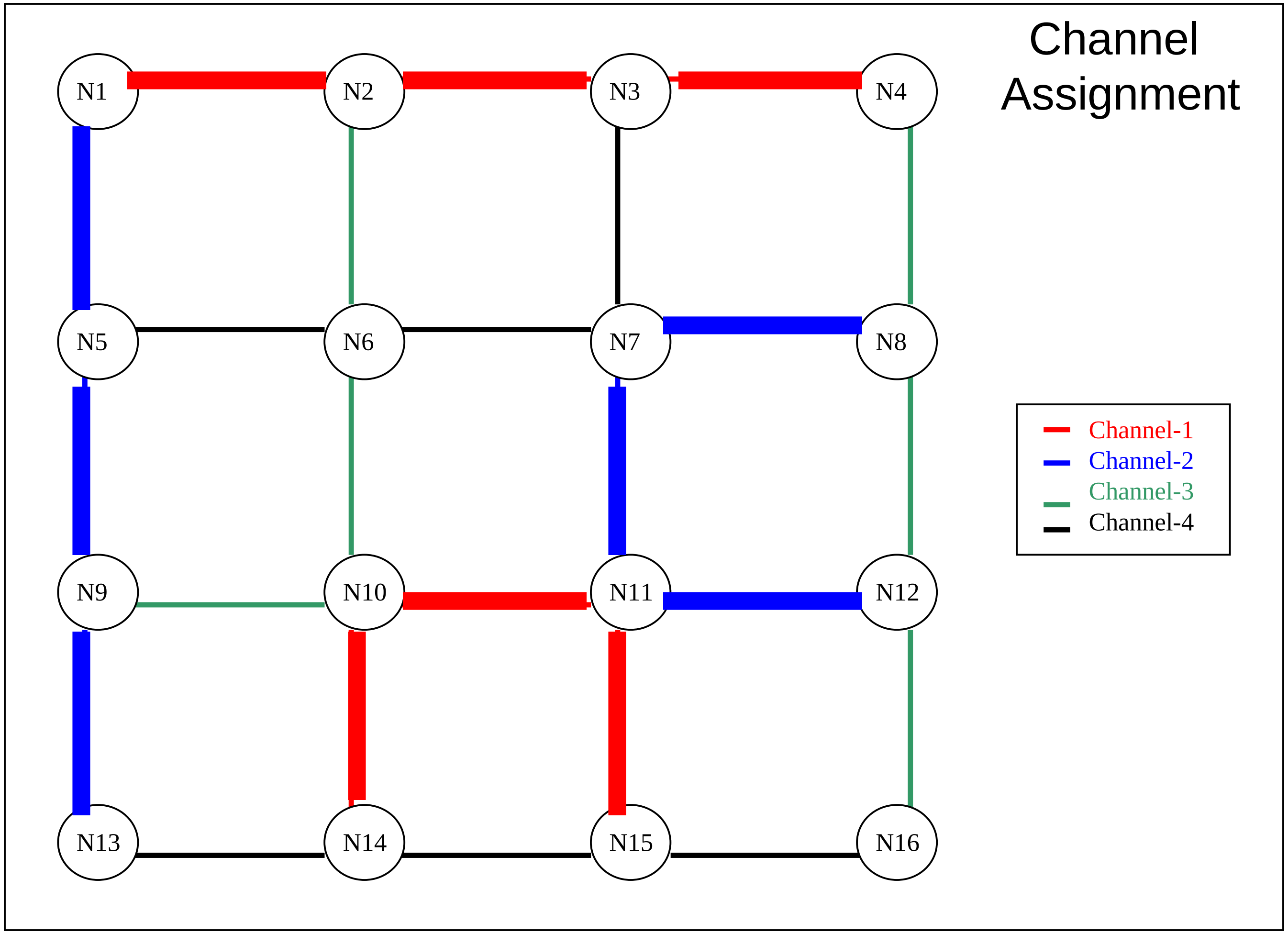


Evaluation: Single & Double Chain Topology

- ALARM of single chain topology has 6 non-best path selection (second best selection) out of 100 cases with 4% maximum difference.
- WCETT of single chain topology has 35 non-best path selection (good and worst selection) out of 100 cases with 23% maximum difference.
- ALARM errors happened when comparing similar CA, the location factor is constant.
- When the same CA is used, only ETT controls the method of path selection.

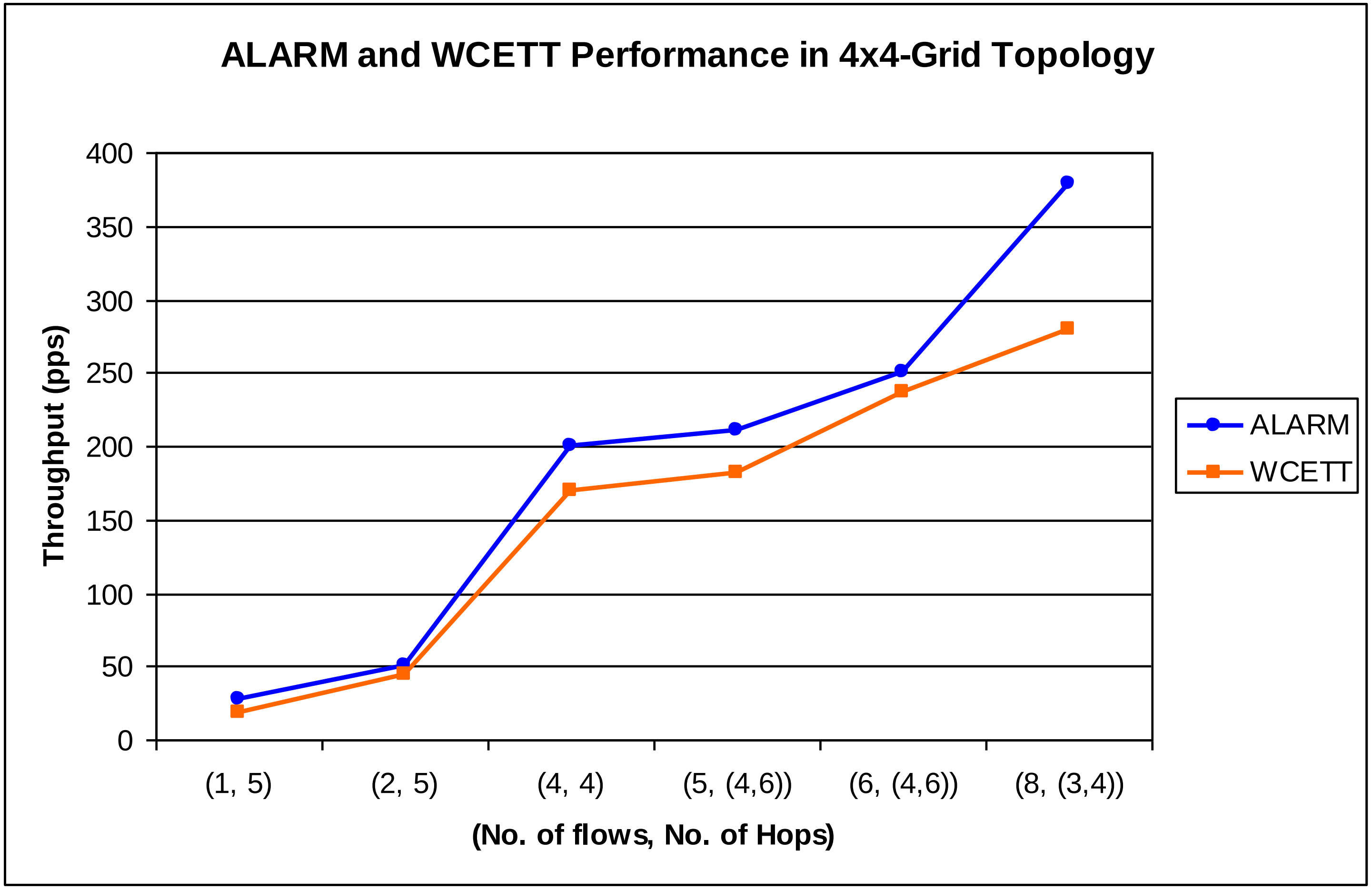
Evaluation: 4x4-Grid Topology

- 16 Nodes.
- 2 (802.11a) radios/node.
- 4 Channels.



Evaluation: 4x4-Grid Topology

- Results:



Analytical Model: Interference-Aware Routing in WMN

Background

- Routing performance is sensitive to the selection of the differential-capacity links:
  - Routing is challenging.
- In WMN, link capacity is influenced by the interference/traffic:
  - Link capacity is dynamic.
- Result: achieving optimal routing is very hard.

Related Work

- Modeling link capacity in 802.11 passed through different stages of development in the literature:

Consider interference:

→ Single interferer only [3].

→ Allow no interfering link to be active [4].

→ Consider one interference domain e.g. Sensing range (ignore hidden node problem) [5].

→ Consider one collision domain e.g. Interference range[6].

→ Consider two ranges (sensing/interference) based on physical details[7].

Modeling Approach

- PCS will be used instead of RTS/CTS because:
  - Can't avoid the multi-hop hidden nodes problem.
  - Adds more overhead traffic.
- Consider multiple interferers.
- Capture the different effects from carrier-sensing range and interference range.
- Using only high-level link-aware parameters (Location/Distance) to model the interference-aware link capacity.
- Consider Exposed/Hidden terminal problems.
- Multi-path routing.
- Solve the analytical model in MILP environment.

Analytical Model: Input

- Network topology, channel assignment, and load (traffic) matrix.

$\aleph$	set of all nodes in the network.
N	total number of nodes in the network ($N = \lvert\aleph\rvert$).
A_i	node n_i's adjacent set of nodes.
C_{ij}^{max}	is the maximum (initial) link capacity of link L_{ij}.
CS_{ij}	set of links $\in R_{cs}^{ij}$ of L_{ij} and assigned to the same channel of L_{ij}.
I_{ij}	set of links $\in R_I^{ij}$ of L_{ij} and assigned to the same channel of L_{ij}.
Dcs_{ij}^{xy}	(binary) = 1, when L_{xy} is within R_{cs}^{ij}.
DI_{ij}^{xy}	(binary) = 1, when L_{xy} is within R_I^{ij} and outside R_{cs}^{ij}.
d_{ij}	distance between node n_i and node n_j.
d_{ij}^{max}	maximum distance at which other co-channel links can not interfere with L_{ij} (= R_I^{ij}).
F^{sd}	traffic from source node n_s to destination node n_d.

Analytical Model: Variables

C_{ij}	link capacity of L_{ij}.
$\alpha_{ij}^{sd,f}$	(binary) = 1, when $L_{ij} \in path(p_{sd})$ and the f^{th} unit of F^{sd} is carried from n_s to n_d by L_{ij}.
β_{ij}^{xy}	(binary) = 1, when there is traffic carried on both links, L_{ij} and L_{xy} simultaneously.
S^{sd}	succeeded transmitted flow from node n_s to node n_d.

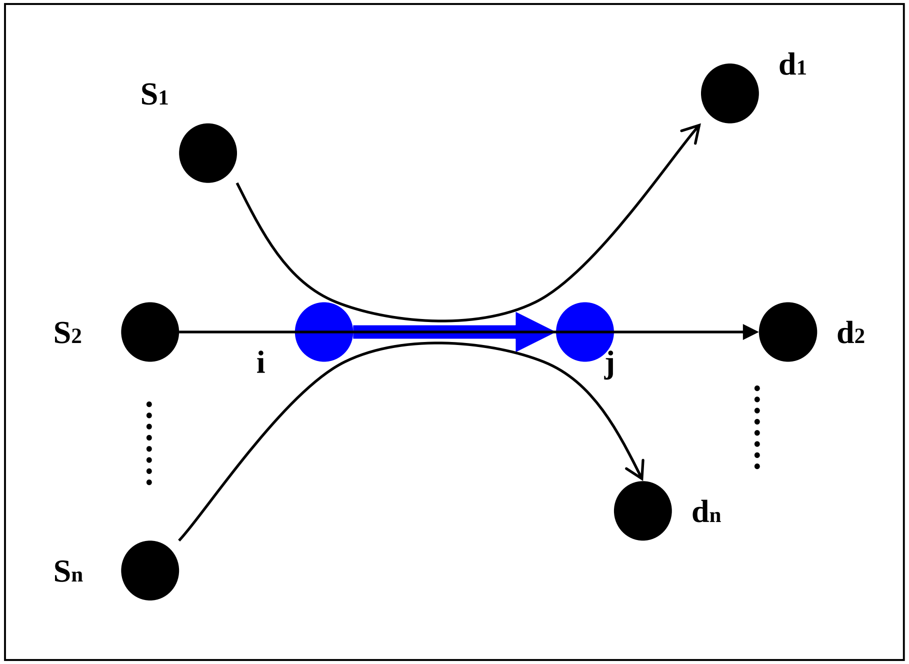
Analytical Model

Objective Function:

Maximize Throughput $\{ \text{Maximize } (\sum_{\forall(s,d)} S^{sd}). \}$

Traffic Constraint:

$$2 * \beta_{ij}^{xy} = \alpha_{ij}^{sd,f} + \alpha_{xy}^{zw,f}$$



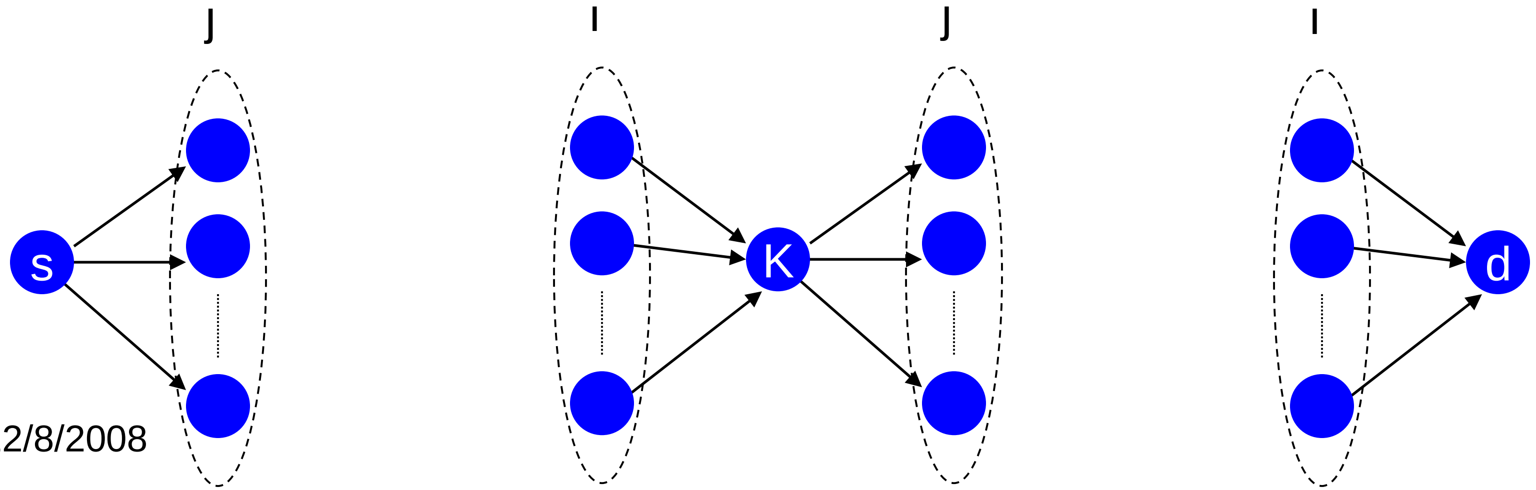
Analytical Model

Routing Constraints:

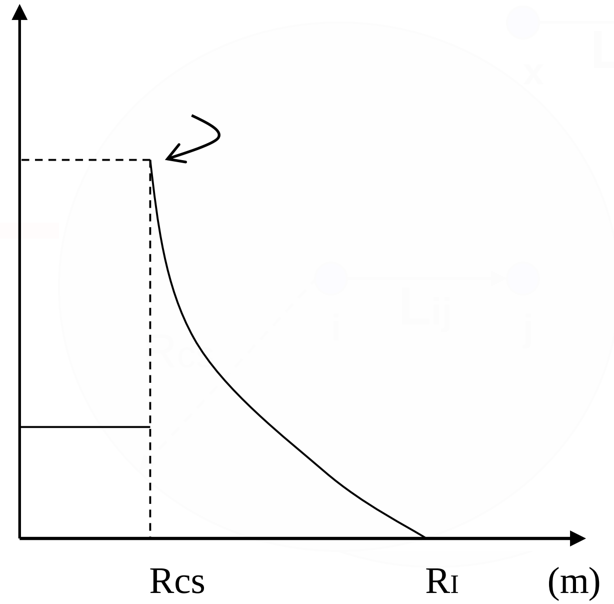
$$S^{sd} = \frac{PS}{T} * \sum_{\forall j \in A_s} (\sum_{\forall f} \alpha_{sj}^{sd,f}), \forall (s,d)$$

$$\sum_{\forall i \in A_k} (\sum_{\forall f} \alpha_{ik}^{sd,f}) = \sum_{\forall j \in A_k} (\sum_{\forall f} \alpha_{kj}^{sd,f}), \ \forall k \in \aleph, \forall (s,d)$$

$$S^{sd} = \frac{PS}{T} * \sum_{\forall i \in A_d} (\sum_{\forall f} \alpha_{id}^{sd,f}), \forall (s,d)$$



Analytical Model



Capacity Constraints:

$$\sum_{\forall(s,d)} \sum_{\forall t} \alpha_{ij}^{sd,t} \le C_{ij}, \forall L_{ij}.$$

→ Special case (at most single interferer exist):

$C_{ij} = \Big\{$

$\frac{1}{2}$ Type-1 Interferer

$\frac{d_{xj}}{d_{ij}^{max}}$ Type-2 Interferer

No Interferers

Analytical Model

<u>Capacity Constraints:</u>

→ General case (Multiple interferers exist):

$$C_{ij} = \begin{cases} \frac{1}{total-num-of-Type-1-interfers} * C_{ij}^{max} \\ \\ avg[\frac{d_{xj}}{d_{ij}^{max}}] * C_{ij}^{max} \\ \\ C_{ij}^{max} \end{cases}$$

Maximize $(\sum_{\forall(s,d)} S^{sd})$
subject to,

- Flow constraint:

$$2 * \beta_{ij}^{xy} \leq \alpha_{ij}^{sd,f} + \alpha_{xy}^{zw,f}, \forall L_{ij} \in \xi, \forall L_{xy} \in CS_{ij} \cup I_{ij}$$

- Loop-less constraint:

$$\alpha_{ij}^{sd,f} + \alpha_{ji}^{sd,f} \leq 1, \forall f$$

- Routing constraints:

$$S^{sd} = \frac{PS}{T} * \sum_{\forall j \in A_s}(\sum_{\forall f} \alpha_{sj}^{sd,f}), \forall(s,d)$$
$$\sum_{\forall i \in A_k}(\sum_{\forall f} \alpha_{ik}^{sd,f}) = \sum_{\forall j \in A_k}(\sum_{\forall f} \alpha_{kj}^{sd,f}), \forall k \in \aleph, \forall(s,d)$$
$$S^{sd} = \frac{PS}{T} * \sum_{\forall i \in A_d}(\sum_{\forall f} \alpha_{id}^{sd,f}), \forall(s,d)$$

- Capacity constraints:

$$\frac{PS}{T} * \sum_{\forall(s,d)} \sum_{\forall f} \alpha_{ij}^{sd,f} \leq C_{ij}, \forall L_{ij}, \forall(s,d)$$

$$C_{ij} = \left\{\frac{1}{1+|CS_{ij}|}\right\} * \left\{\frac{\epsilon + \sum_{\forall L_{xy} \in I_{ij}}(\frac{d_{xj}}{d_{ij}^{max}} * \beta_{ij}^{xy} + (1-\beta_{ij}^{xy}))}{\epsilon + |I_{ij}|}\right\} * C_{ij}^{max}$$

- Traffic constraint:

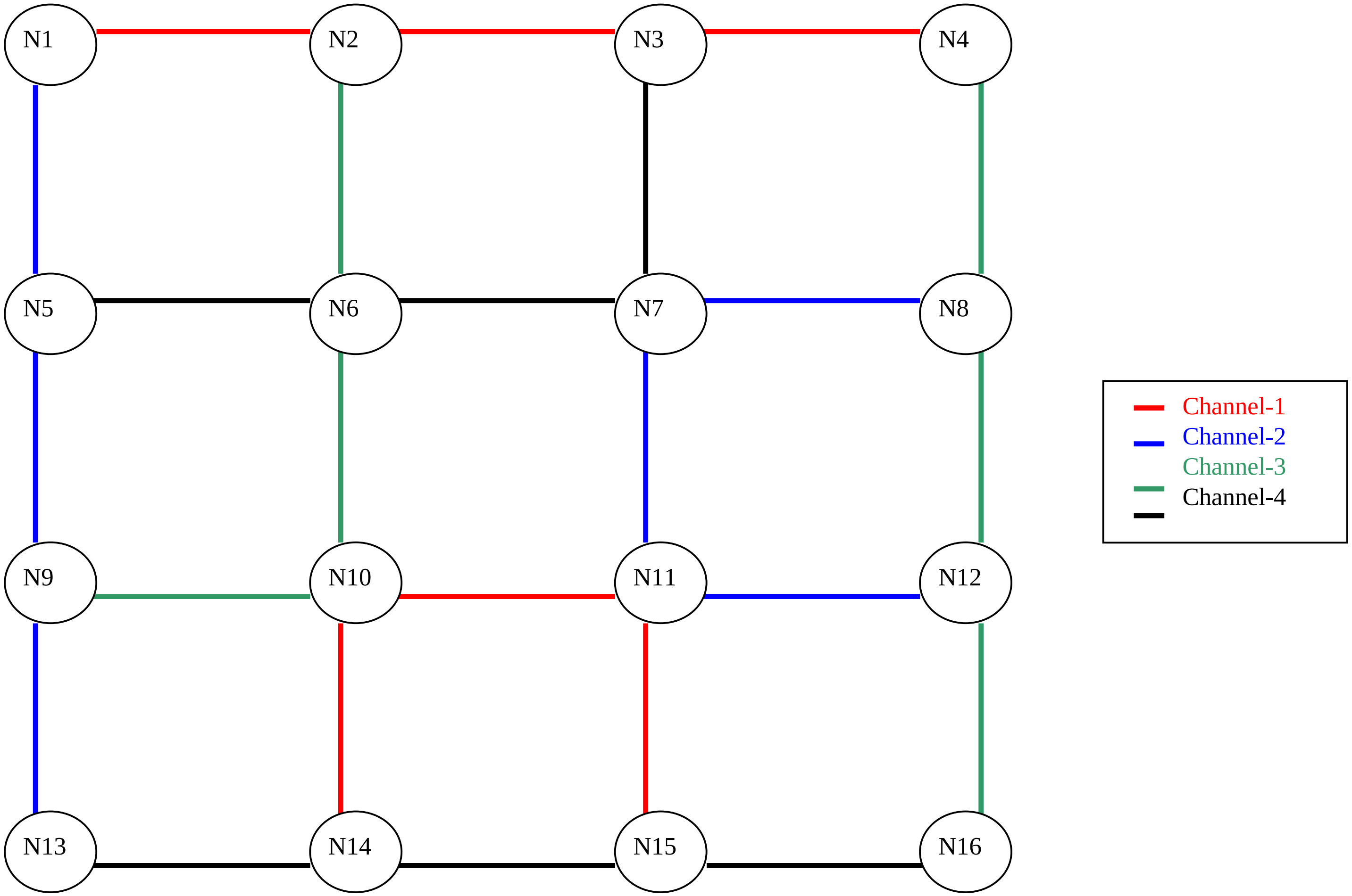
$$S^{sd} \leq F^{sd}, \forall(s,d)$$

Evaluation

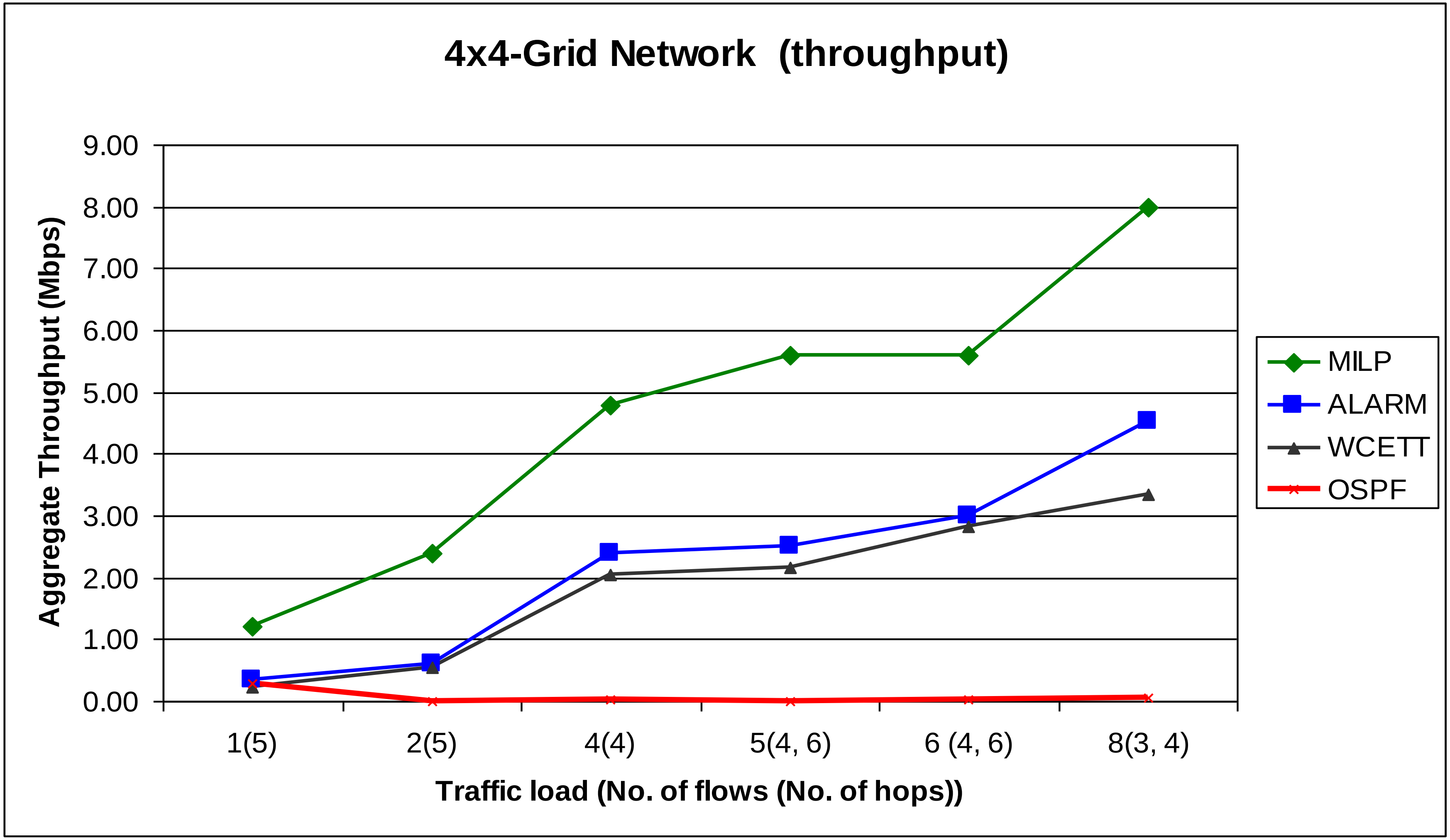
- 4x4-Grid WMN: (Multi-channel)
  - OSPF.
  - ALARM.
  - WCETT.

- Practical (Kemper Hall) WMN: (Single Channel)
  - OSPF.

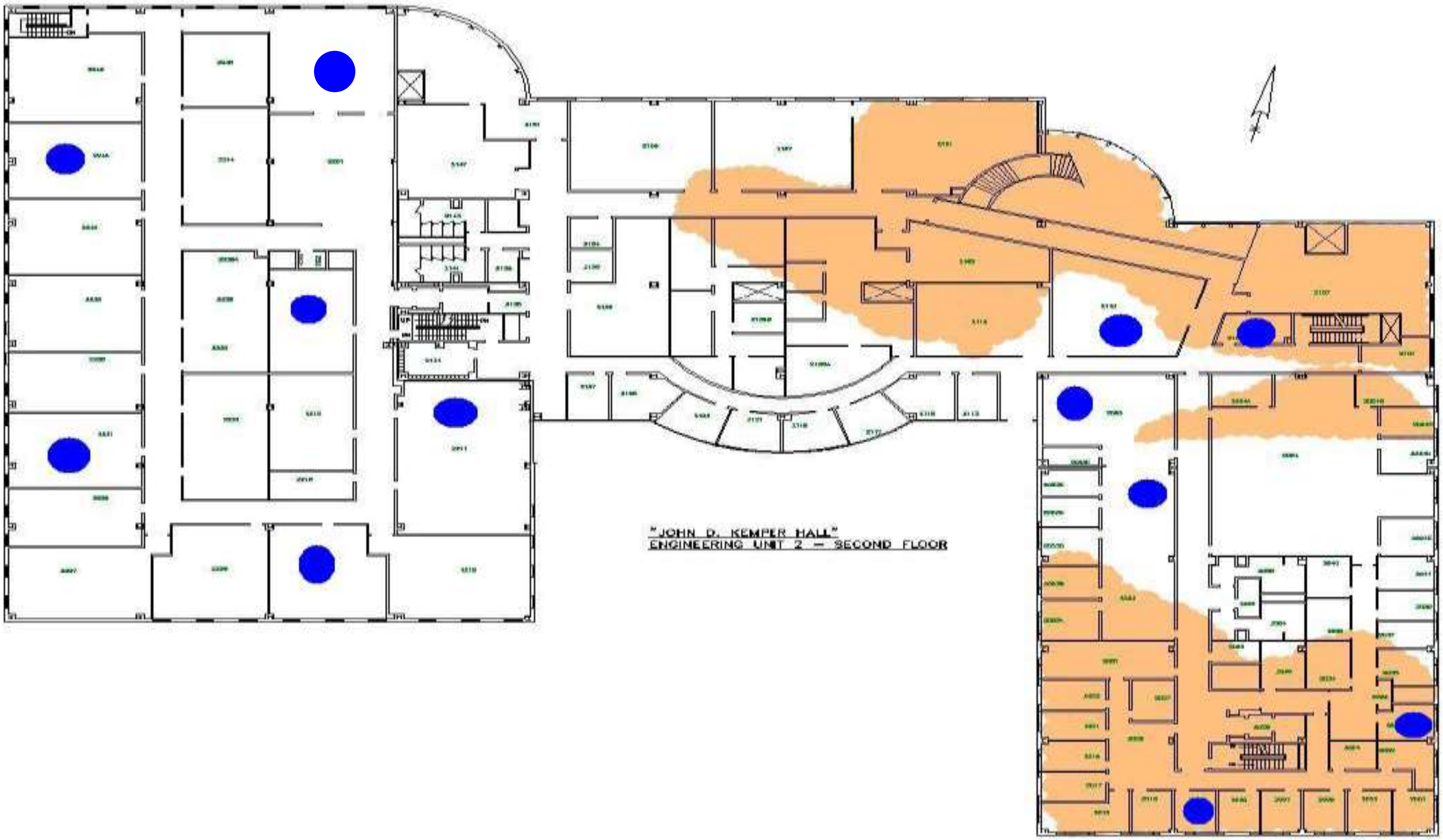
Example 1: 4x4-Grid WMN



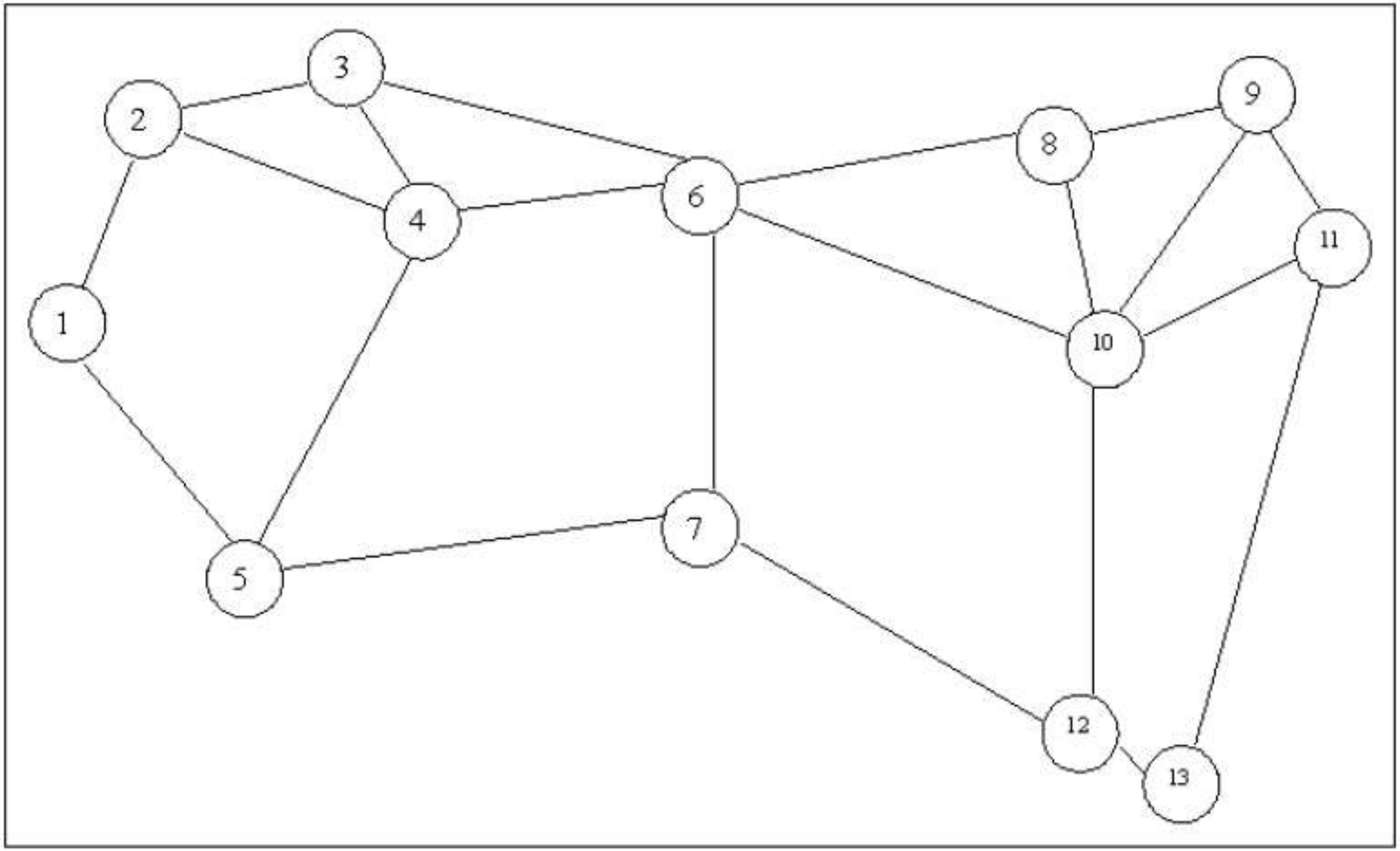
Example 1: 4x4-Grid WMN



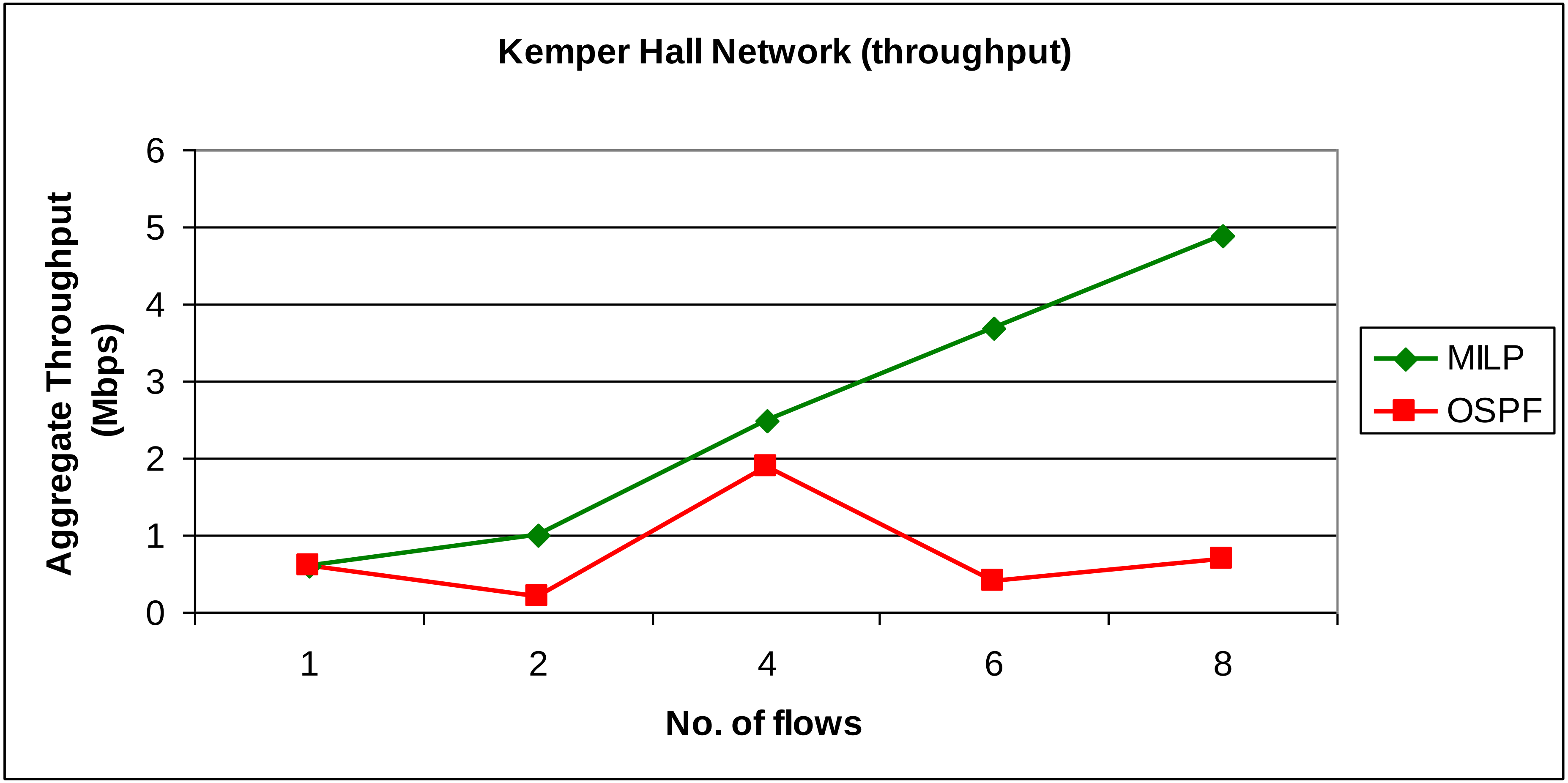
Example 2: Kemper Hall WMN



Example 2: Kemper Hall WMN



Example 2: Kemper Hall WMN

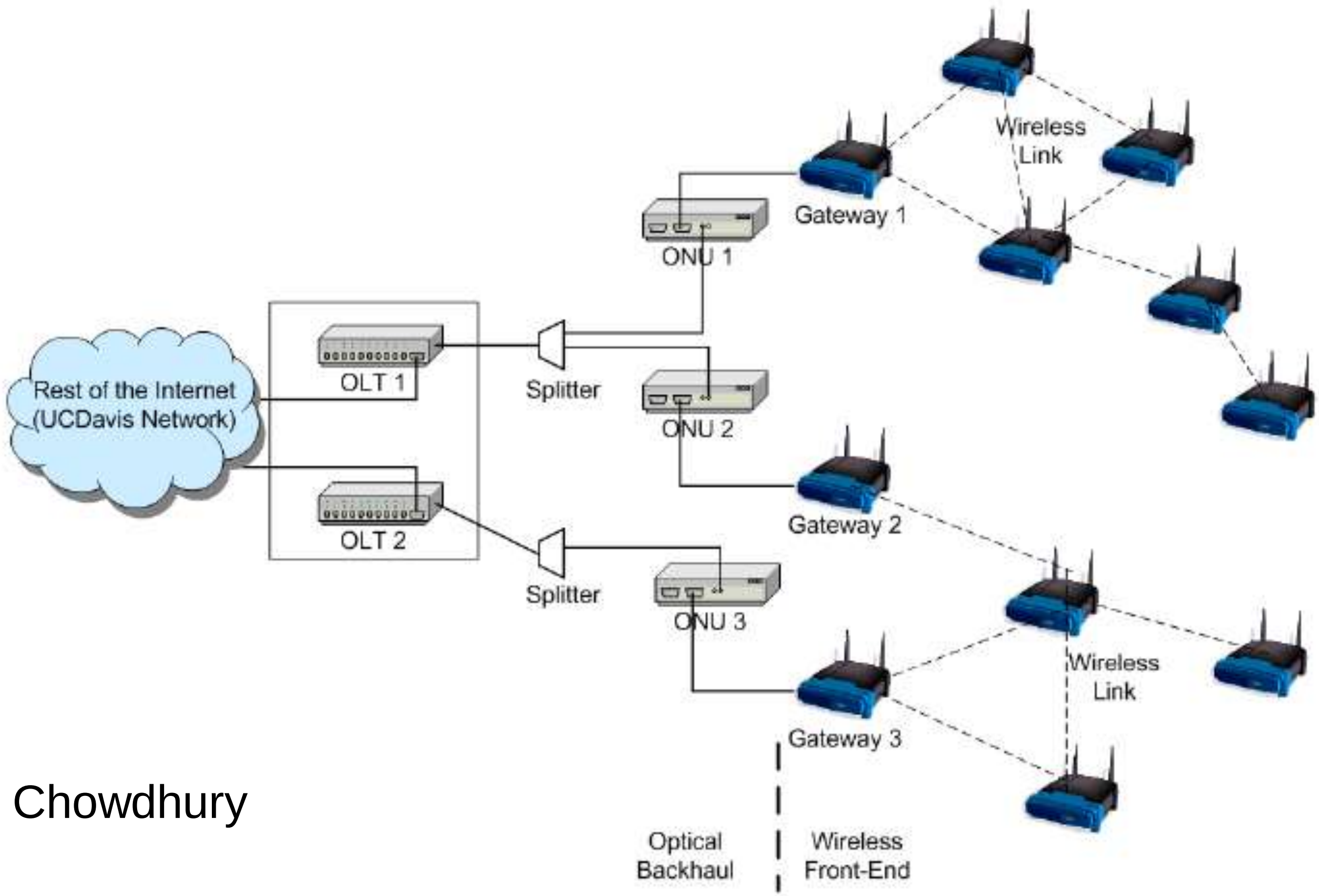


Conclusion

- This model captures the influence of different interferers in WMN by modeling the link capacity in the presence of any given number of interferer.
- There are mainly on two types of interferers:
  - Type-1: Interferers within the carrier-sensing range.
  - Type-2: Interferers within the interference range.
- Our analytical routing model performs better than the non-interference-aware (OSPF) in single channel as well as multi-channel wireless environment.
- Performance variance in multi-channel WMN is greater than the variance between the MILP performance and OSPF performance in single channel WMN.

Ongoing and Future Research

Evaluation using Test-Bed



Pulak Chowdhury

Channel Assignment

- Typical WMN (Single-radio/Single-channel). Interference.
- 802.11 support non-overlapping Multi-channel (Single-radio/Multi-channel). Dynamic switching overhead time.
- (Multi-radio/Multi-channel). Channel assignment issue.

Channel Assignment

- Static (Fixed) [8]/Dynamic [9] [10]/Hybrid [11] [12].
- Routing & CA: Independent or Jointly solved [11] [13].
- Interference-aware [11] / Traffic-aware [8].
- Geographical-based: Cellular Network and WLAN [14].

Network Management

- Topology Management.
- NM Architecture

Centralized	**De-centralized**
Deploy controller-based WLAN that handles mobility tasks.	Controller functions at the wireless AP's controllers or at the APs themselves.

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Q & A

Thank you.