Networks Laboratory – Wireless Research Group

Interference-Aware Topology, Capacity, and Flow Assignment in Wireless Mesh Networks

Eiman Alotaibi

Thanks to: Vishwanath, Massimo, Sayeem, Prof. Mukherjee

Department of Computer Science
University of California, Davis

Motivation

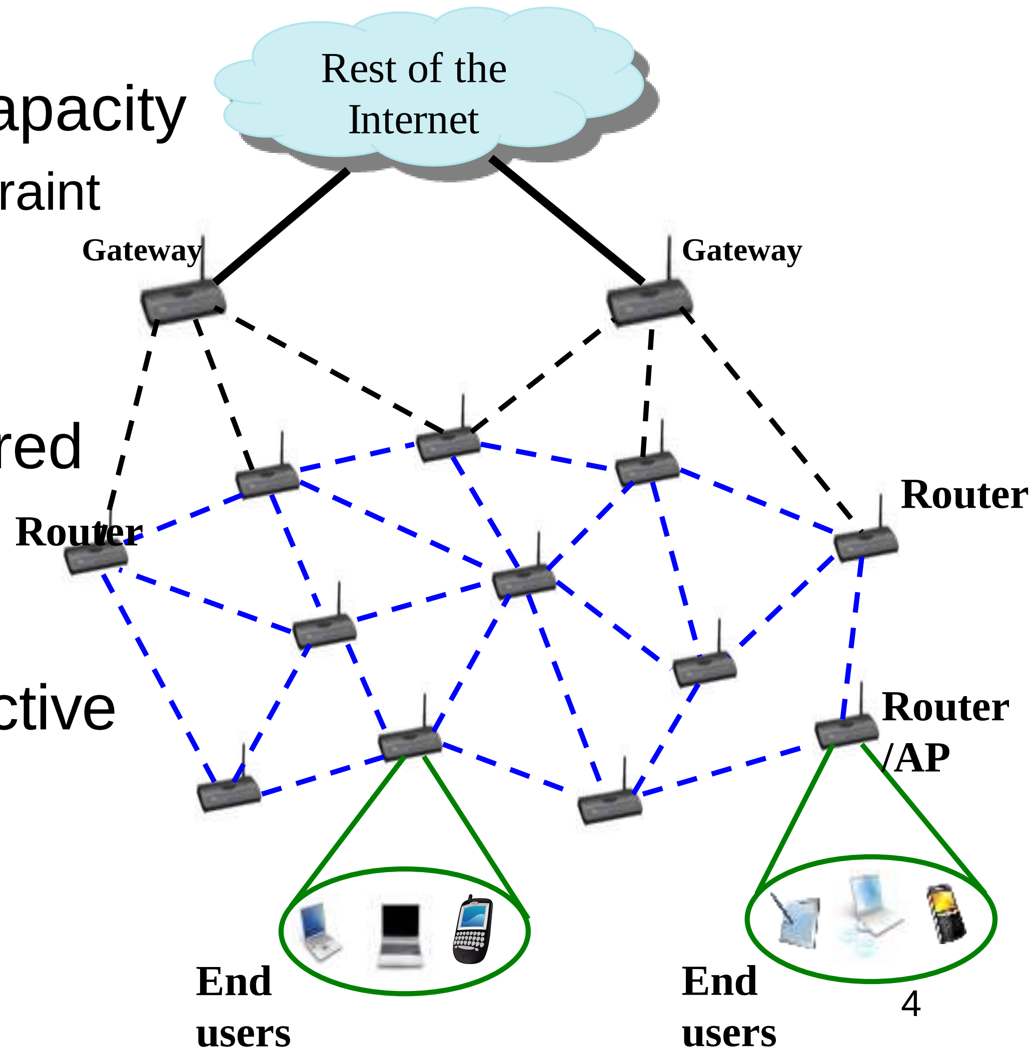
- Topology, Capacity, and Flow Assignment (TCFA) is a general network-design problem
- Design a cross-layer solution for TCFA That is:
    - Dynamically allocate resources
    - Self organized
- Design a realistic secondary-interference model

Why Topology Control?

- Wireless links are soft (no physical deployment is required)
- Network topology is not expected to be fixed for a long time
- A good topology design should follow the traffic demand and assign links as needed to serve as much users as possible within a short period of time
- Decreasing number of links on a topology ➔ decreases interference
- Decreasing number of links on a topology ➔ increases delay (increases number of hops)
- With minimum number of links, we can assign different channels to each links to achieve the best performance

In Wireless Mesh Network

- Each radio has a limited capacity
  - This can be used as a constraint instead of Cost Constraint
- Wireless Channel is a shared channel
- Interference limits the effective capacity

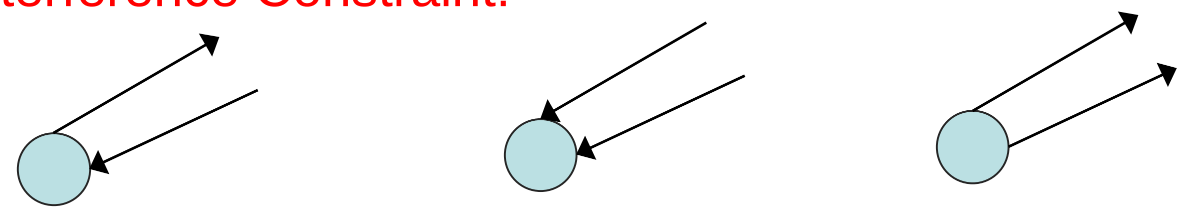


Why Topology CFA in WMN?

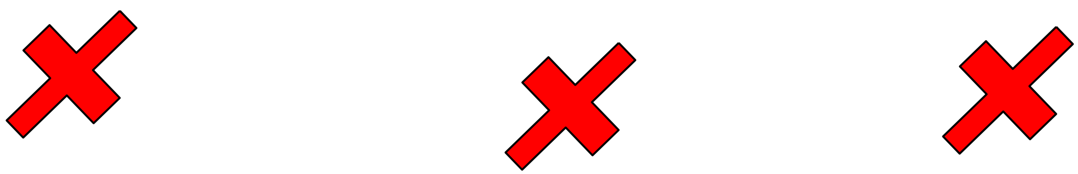
	Fully connected	Tree	Star
No. of links	high	low	low
Reliability	high	low	low
Interference	high	low	high
Power	high	low	high

Wireless Constraints

- Primary Interference Constraint:



Self Interference | Collision | Multicast



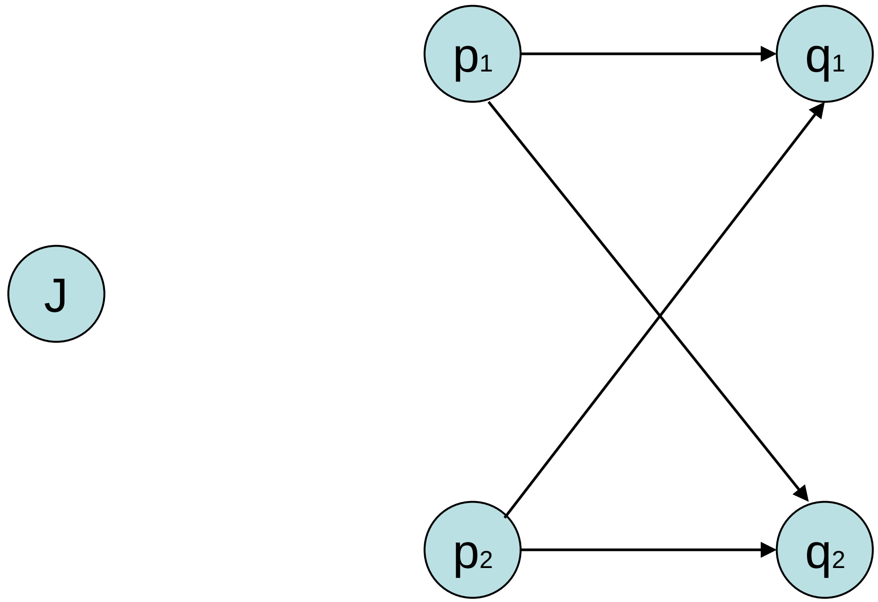
- Signal-to-Interference-and-Noise Ratio (SINR) Constraint:

$$\frac{G_{(i,j)}P_{(i,j)}}{N_o + \sum_{(p,q)\in L_t} I_{(p,q,i,j)}P_{(p,q)}} \geq \beta$$

Ref: Channel, Capacity, and Flow Assignment in Wireless Mesh Networks Presentation, by Vishwanath Ramamurthi

Wireless Constraints

- Secondary Interference Constraint:

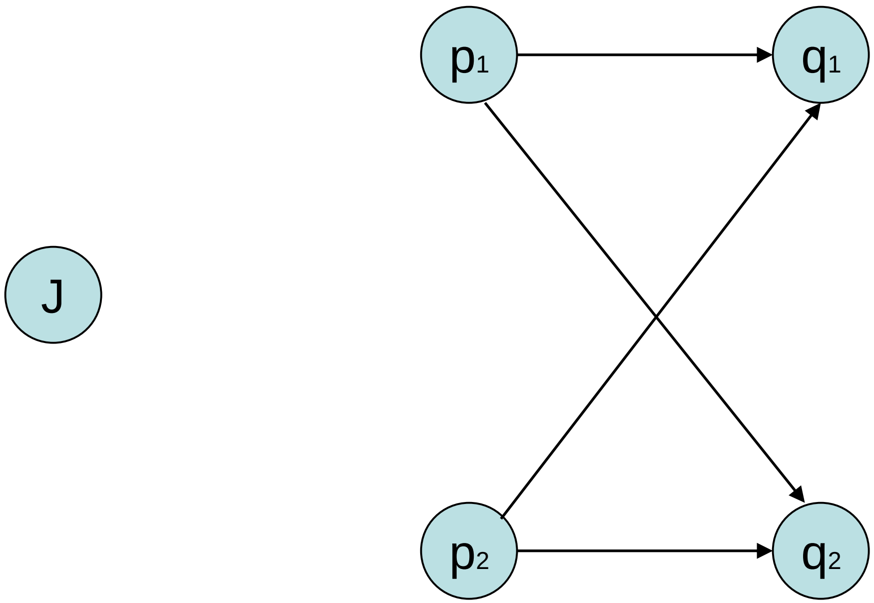


$$\text{Link\_I}(J) = \begin{array}{c c} & \begin{array}{cc} q_1 & q_2 \end{array} \\ \begin{array}{c} p_1 \\ p_2 \end{array} & \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \end{array}$$

Secondary-Interference Approaches

1. Combined Interfering-links Constraint (1eq)
2. Separate Interfering-links Constraint (Aeq)
3. Multiple Interfering-links Constraint (Meq)

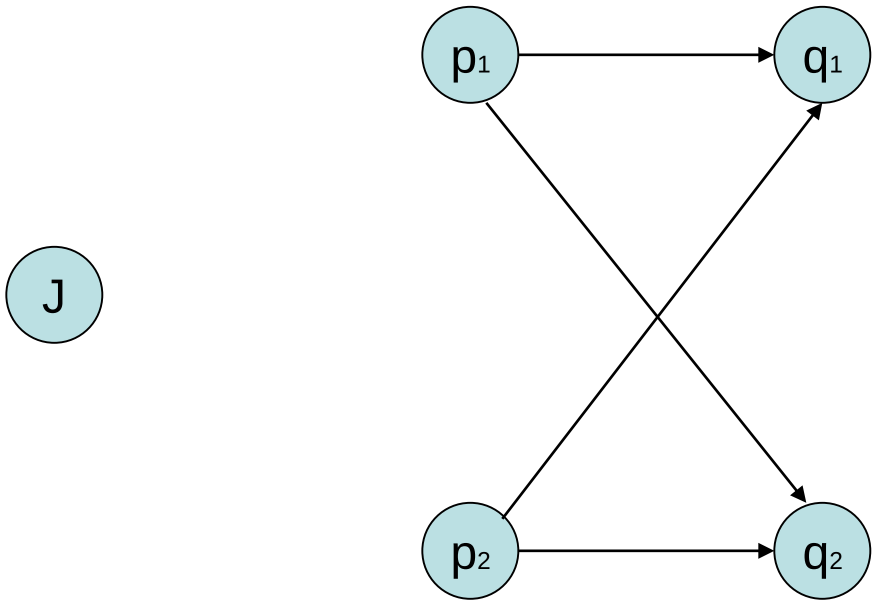
Combined Constraint



$$
\text{Link\_l(J)} = \begin{array}{c c} & \begin{array}{cc} q_1 & q_2 \end{array} \\ \begin{array}{c} p_1 \\ p_2 \end{array} & \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \end{array}
$$

$$C_j + C_{p_1q_1} + C_{p_1q_2} + C_{p_2q_1} + C_{p_2q_2} \le C$$

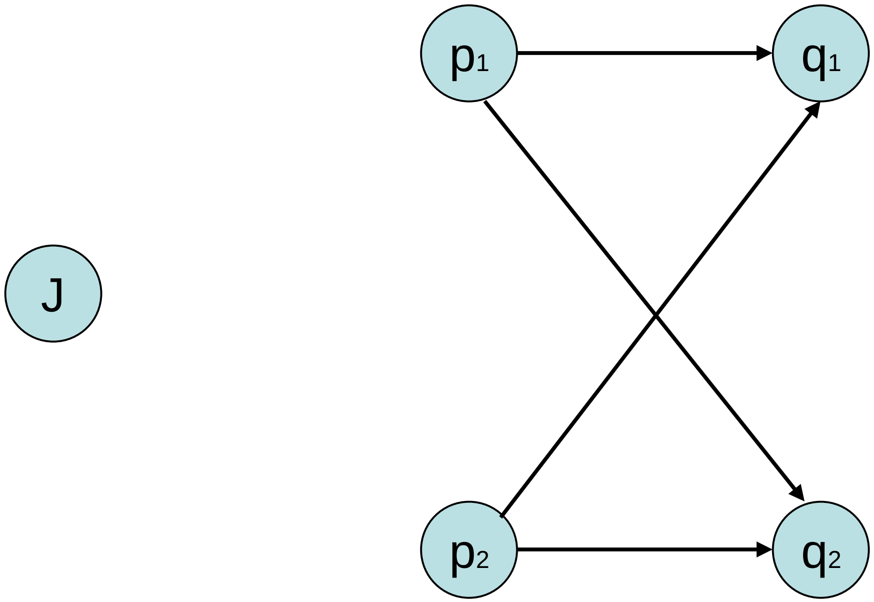
Separate Constraint



$$\text{Link\_I(J)} = \begin{array}{c} \\ p_1 \\ p_2 \end{array} \begin{array}{c} \begin{array}{cc} q_1 & q_2 \end{array} \\ \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \end{array}$$

$$\left.\begin{aligned} C_j + C_{p_1q_1} &\le C \\ C_j + C_{p_1q_2} &\le C \\ C_j + C_{p_2q_1} &\le C \\ C_j + C_{p_2q_2} &\le C \end{aligned}\right\} \Rightarrow \text{4 equations}$$

Multiple Constraint



$$\text{Link\_I(J)} = \begin{array}{c|cc} & q_1 & q_2 \\ \hline p_1 & 1 & 1 \\ p_2 & 1 & 1 \end{array}$$

$$S_1 = \{ L_{p_1q_1}, L_{p_2q_2} \}$$

$$S_2 = \{ L_{p_1q_2}, L_{p_2q_1} \}$$

$$\left.\begin{array}{l} C_j + C_{p_1q_1} + C_{p_2q_2} \leq C \\ C_j + C_{p_1q_2} + C_{p_2q_1} \leq C \end{array}\right\} \rightarrow \text{2 equations}$$

Secondary-Interference Approaches

- Our approach (Meq) provides more capacity compared to (1eq) approach (reduce Interference)
- Our approach reduces number of equations in the MILP compared to (Aeq) approach (increase processing speed)
- Meq is a More Realistic approach

TCFA Formulation

- Given:
  - Number of nodes and their locations
  - Number of interfaces per node
  - Source-destination traffic demands $D_{s,d}$
- Minimize: (# of links) + ε (delay)
  - With respect to: $\{C_{i,j}\}$ and $\{\lambda_{i,j}\}$
- Output:
  - Optimal Network Topology

Input Notations

N_A	Number of routers
N_G	Number of Gateways
N	$N_A + N_G$
C	Maximum radio capacity
D_{sd}	Traffic demand of a source-destination pair
F_j	Number of radio interfaces at node j
F_{jf}	Channel assigned to the f-th radio at node j
W	Number of channels available
E_{j,S_k}	Set of non-overlapping interfering links at node j
α	Minimum traffic parameter on any link
H_{max}	Maximum allowed number of hops along a single(s, d)flow
k	Maximum allowed congestion on any link

Variable Notations

$B_{ij,m}$	Capacity of L_{ij} over channel m
C_{ij}	aggregate link capacity of L_{ij} over all channels
$Src_{i,sd}$	Up/downstream traffic sourced from node i and issued by (s, d) source-destination flow
Snk_{isd}	Up/downstream traffic sunk at node i and issued by (s, d) source-destination flow
r_i	Total up/downstream traffic that is sourced or sunk at node i
$\lambda_{ij,sd}$	Amount of traffic on L_{ij} and belongs to (s, d) flow
λ_{ij}	Total up/downstream flow on L_{ij} over all (s, d) pairs
λ	Total traffic on all links
γ_{ij}	(binary) = 1, when L_{ij} carries traffic
γ	Number of links selected to represent the new topology
$h_{ij,sd}$	(binary) = 1, when L_{ij} is selected to carry traffic along (s, d) flow

TCFA Model

- <u>Demand constraints at routers</u>

$$\left\{\begin{array}{ll} \text{Source node} & s = i, \quad and \quad d = RI \\ \text{Destination node} & s = RI, \quad and \quad d = i \\ \\ \text{Intermediate node} & s \neq i, \quad and \quad d \neq i \end{array}\right\} \quad \forall i, \forall (s,d) \quad pairs$$

TCFA Model

- Total flow at a node

Throughput calculation $\quad \forall i$

- Flow-conservation constraints

Routing $\quad \forall i, \forall (s,d) \quad pairs$

TCFA Model

- Link-flow constraints

$$\lambda_{ij} = \sum\nolimits_{\forall(s,d)} \lambda_{ij}^{sd} \quad \forall(i,j)$$

- Delay constraints ✦

$$\lambda = \sum_{\forall(i,j)\in E} \lambda_{ij}$$

TCFA Model

- Capacity constraints

$$C_{ij} = \sum_{w=1}^{W} B_{ij}^{w} \quad \forall (i,j)$$

- Primary-interference constraints

$$\sum_{\forall links \in E} B_{ij}^{F_j^f} + \sum_{\forall links \in E} B_{ji}^{F_j^f} \leq C \quad \forall j, \forall f$$

- Secondary-interference constraints

$$\sum_{\forall i \in A_j} B_{ij}^{w} + \sum_{\forall p,q \in E_j^{S_k}} B_{pq}^{w} \leq C \quad \forall j, \quad \forall S_k$$

TCFA Model

- Link constraints $\gamma_{ij} \geq \frac{\lambda_{ij}}{G} \quad \forall(i,j)$
- Topology constraints $\gamma = \sum_{\forall(i,j)\in E} \gamma_{ij}$
- Hops constraints

$$h_{ij}^{sd} \geq \frac{\lambda_{ij}^{sd}}{G} \quad \forall(i,j), \forall(s,d) \quad pairs$$

$$\sum\nolimits_{\forall(i,j)\in E} h_{ij}^{sd} \leq H_{max} \quad \forall(s,d) \quad pairs$$

Performance Evaluation: Assumptions

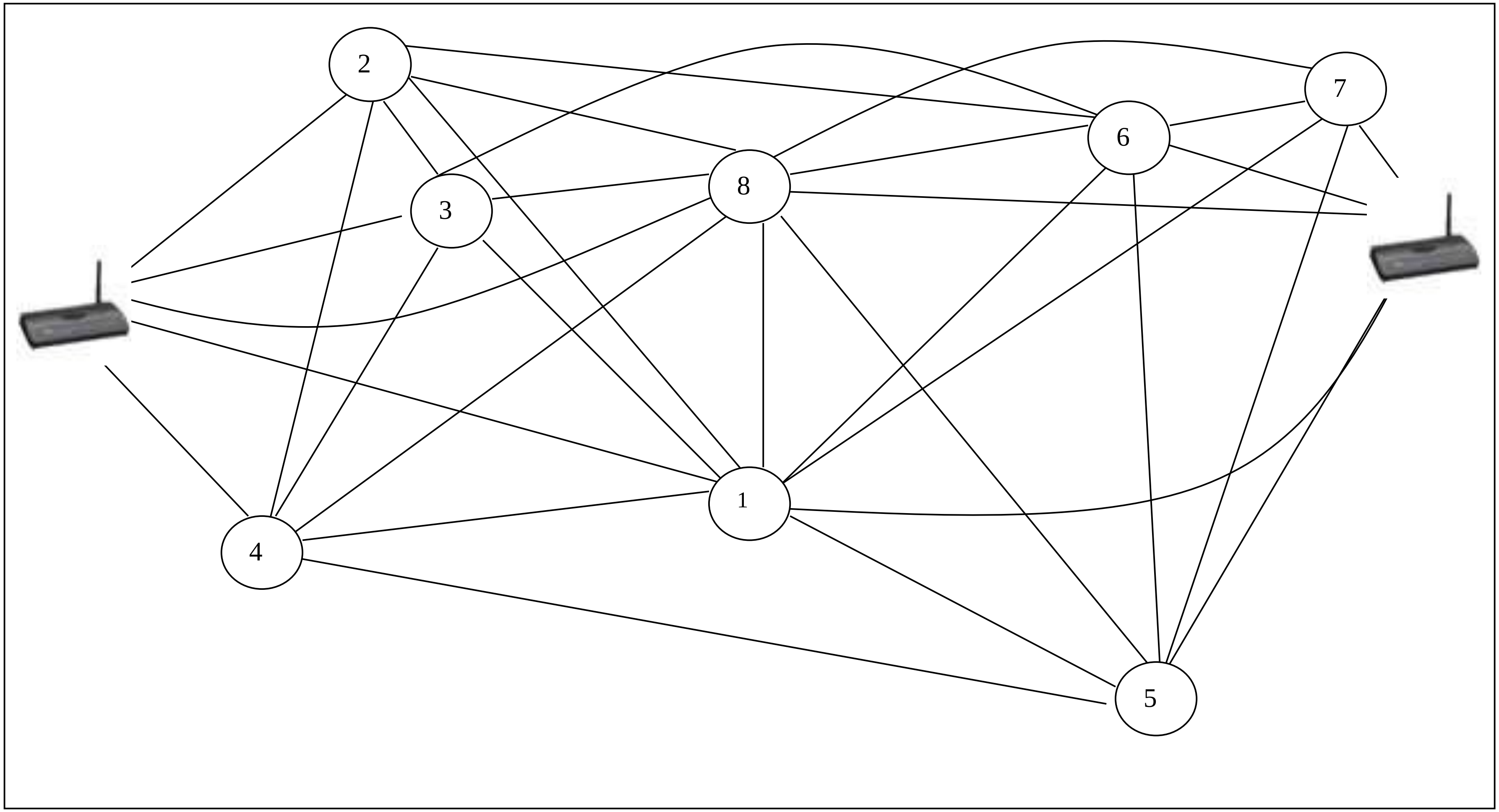
- Single channel
- Single radio per node
- Upstream Traffic (40%)
- Downstream Traffic (60%)
- At least ½ of the traffic served (feasible solution $\alpha = 0.5$)

Performance Evaluation

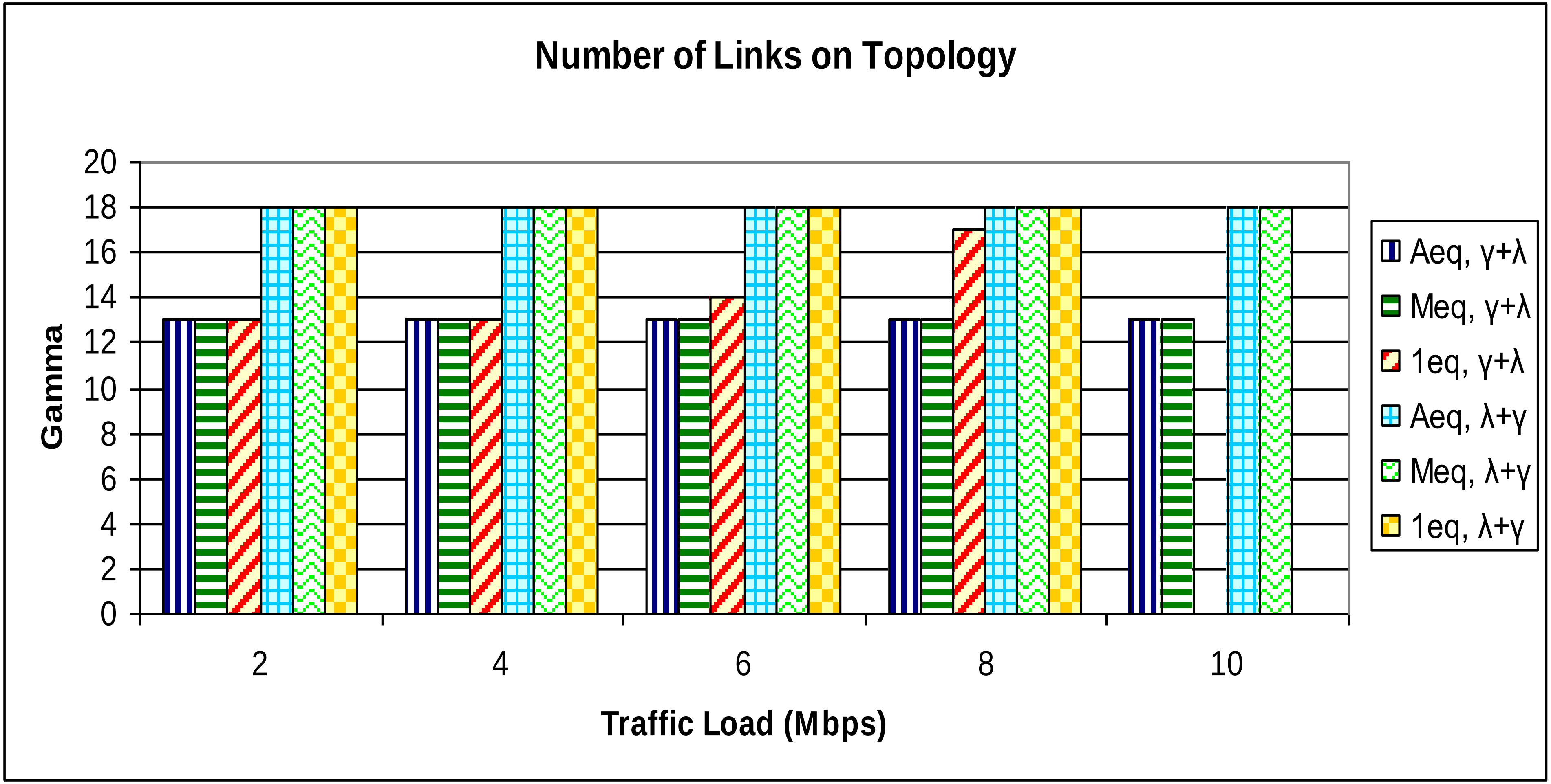
- We study different cases

- We vary:
  - Number of hops
  - Number of gateways
  - Traffic load (per router)
  - Two objective functions
  - The value of α (Min traffic on each link)

Input Topology (mesh)



Result: Interference approaches



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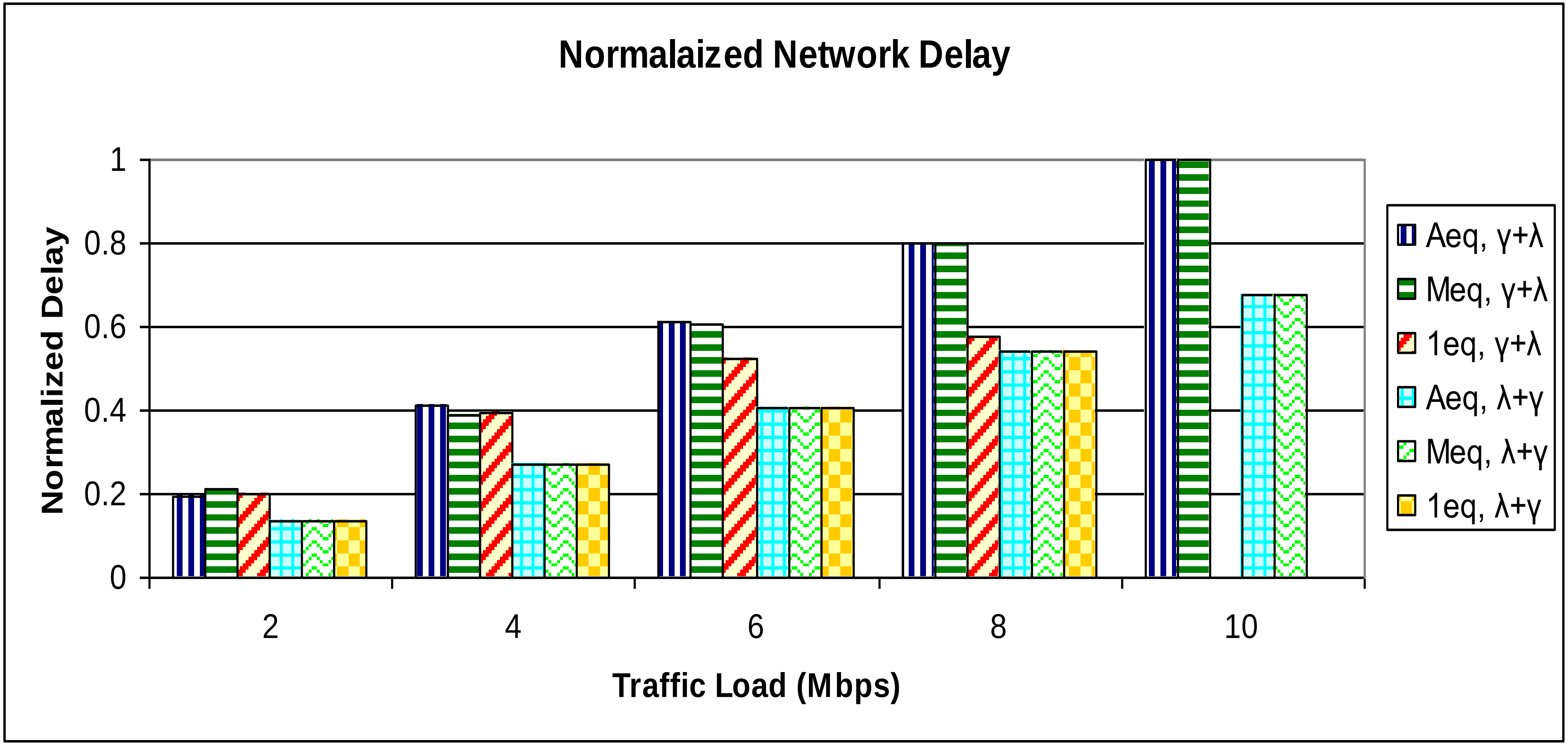
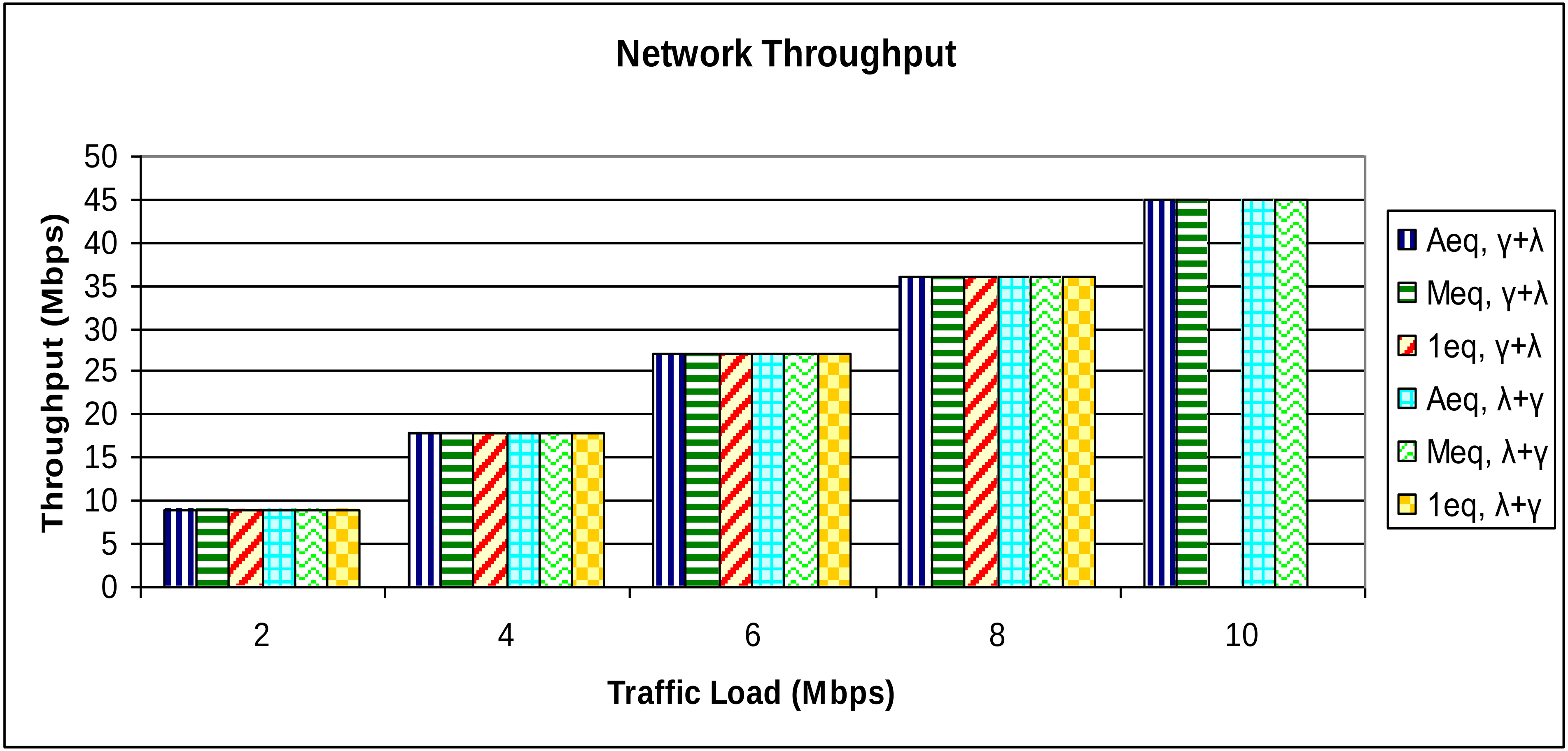
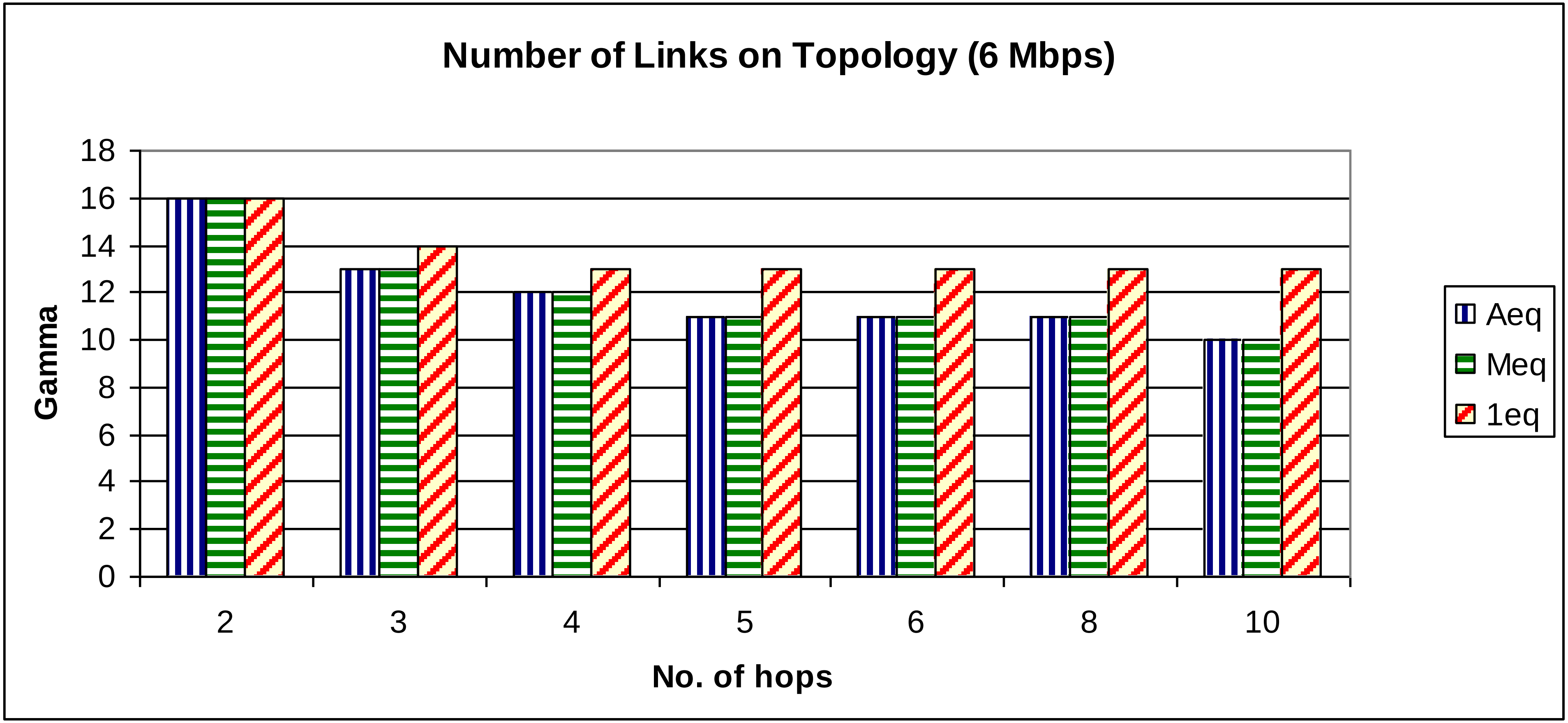


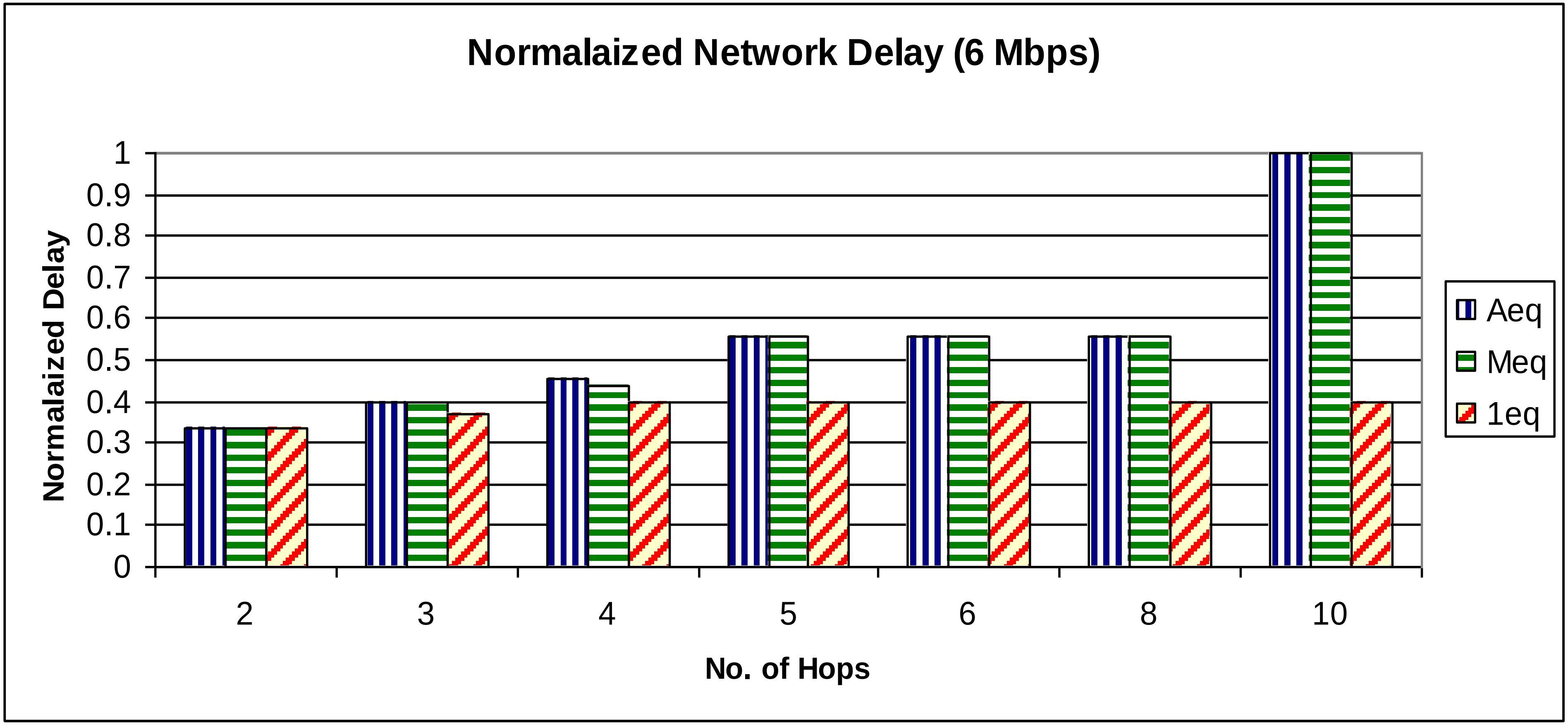
Result: Interference approaches



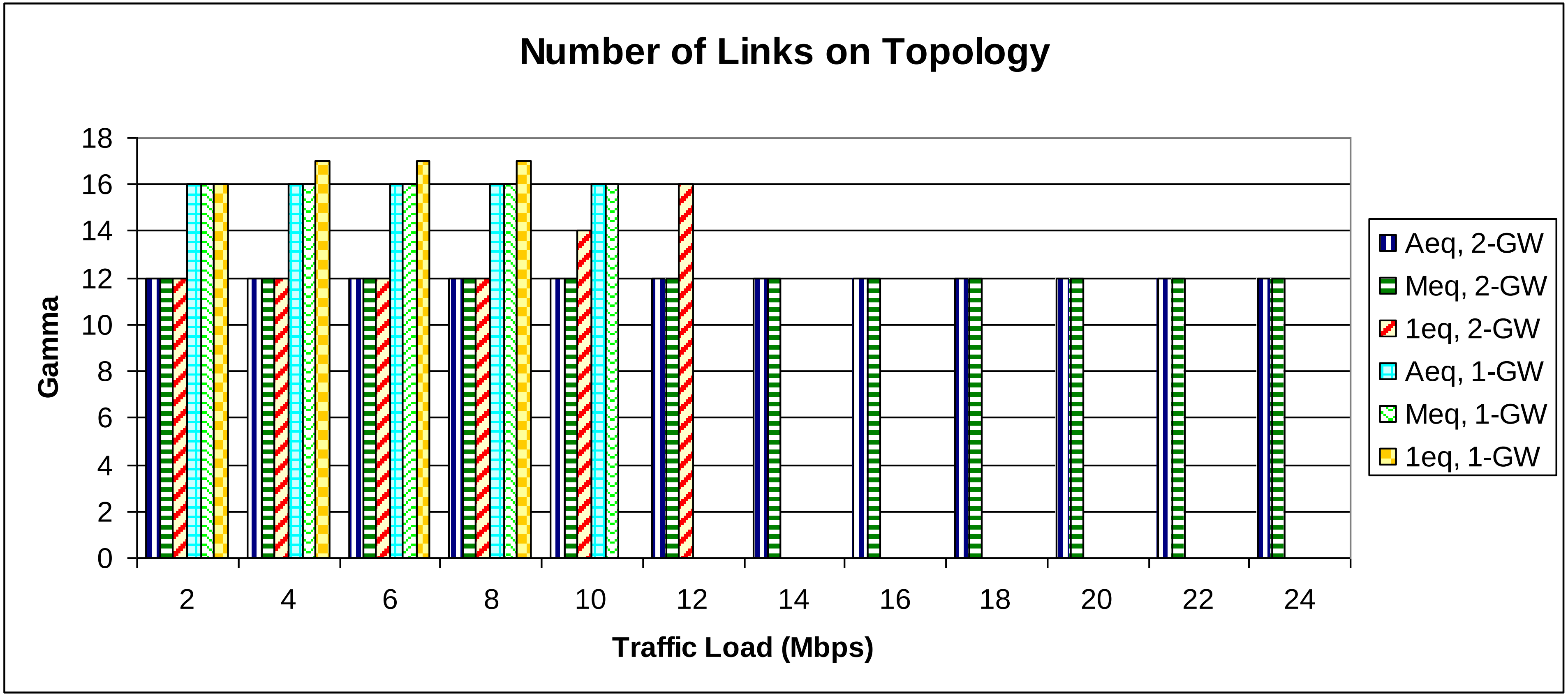
Result: Multi-hop



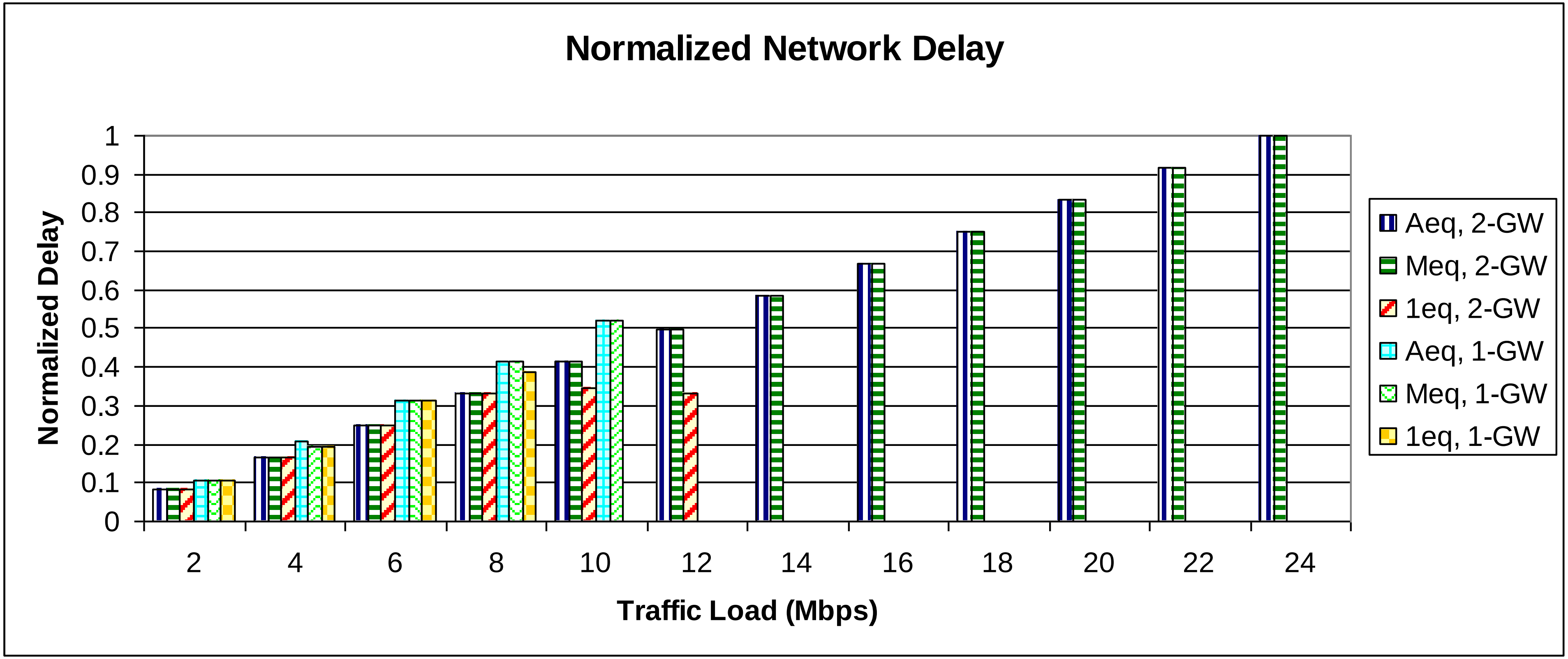
Result: Multi-hop



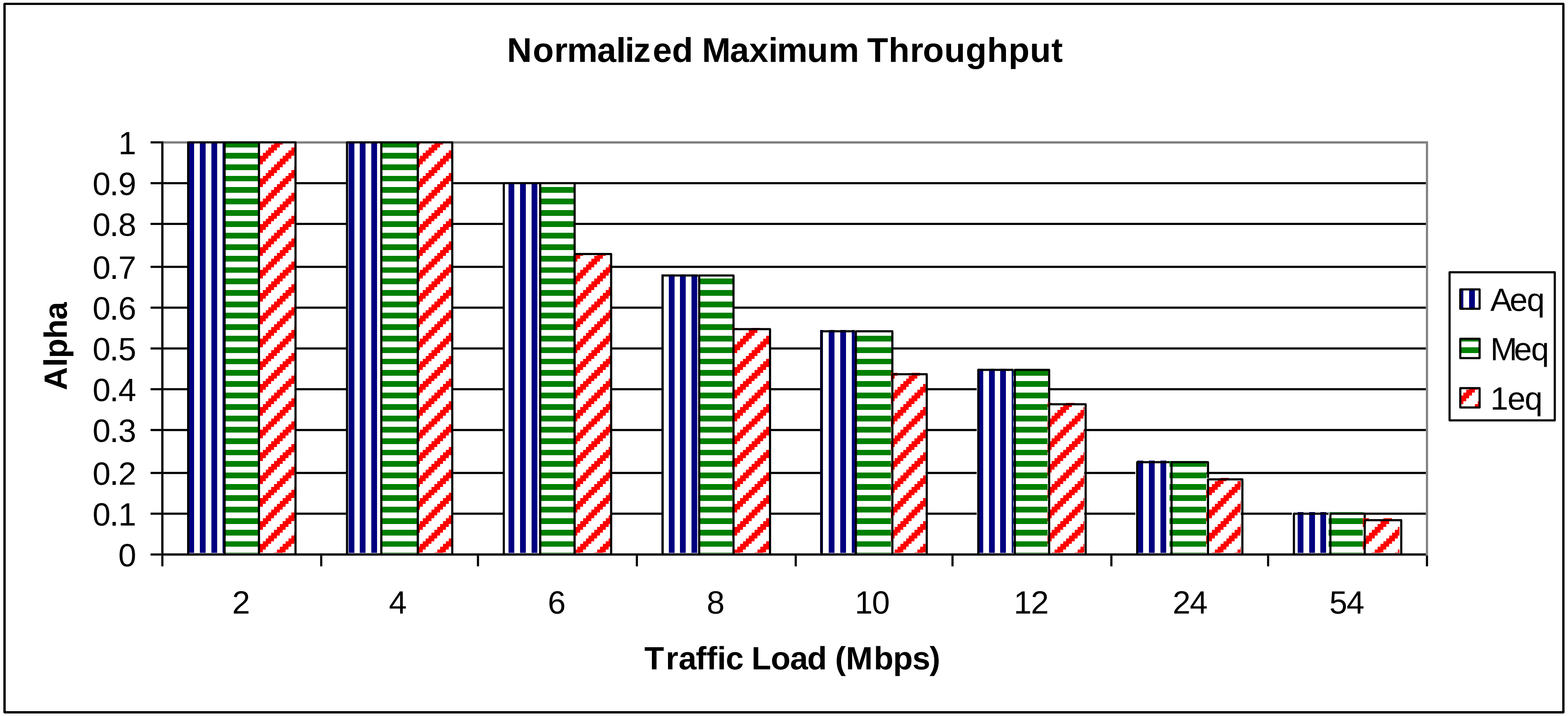
Result: Multi-GW



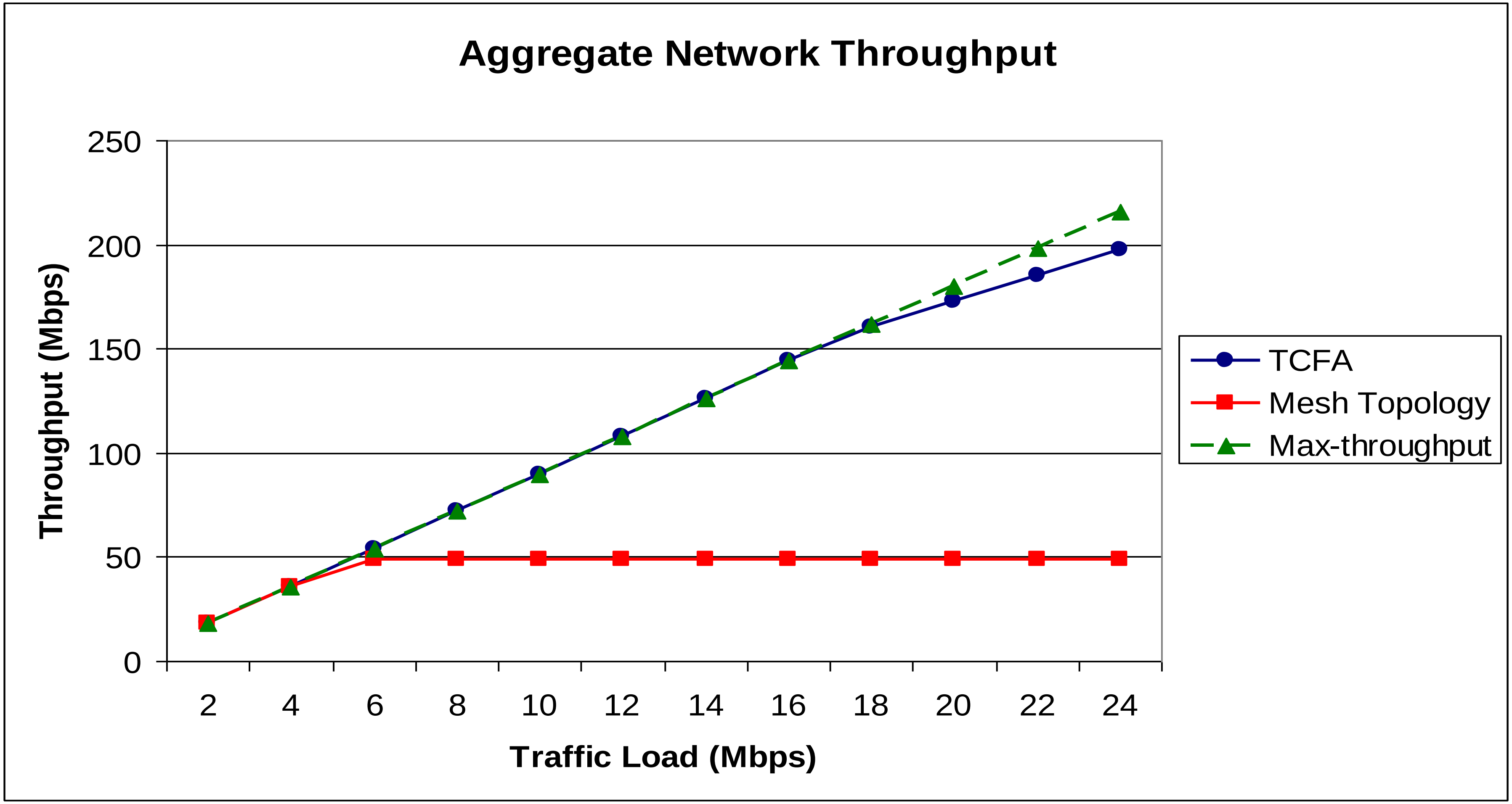
Result: Multi-GW



Result: The value of (α)



Result: TCFA Efficiency



Conclusion

- Design a Dynamic and self organize TCFA solution for WMN
- Deploy realistically the impact of the interference on the link capacity
- TCFA dramatically improves the performance of WMN
- The selection of no. of hops is essential

Q&A

Thank you

Backup Slides

Cross-Layer Design

Transport
"Flow Control"

Network
"Routing"

PHY/MAC
"Resource Allocation"
"Scheduling"
"Tx-Rx"
"Interference"

- CA in wireless network should also take into account Interference
- Interference depends on
  - Topology
  - PHY Layer technology
  - Antenna Beam pattern

- Benefits of Cross Layer Design
  - PHY layer limitations are considered
  - Network resources are utilized to the best possible extent

Ref: Channel, Capacity, and Flow Assignment in Wireless Mesh Networks Presentation, by Vishwanath Ramamurthi

Network Design Problems

Complexity

Problem	Given	Minimize	w.r.t	s.t
CA	τ, $\lambda_{i,j}$	T	$C_{i,j}$	D
FA	τ, $C_{i,j}$	T	$\lambda_{i,j}$	$0 \leq \lambda_{i,j} \leq \mu C_{i,j}$
CFA	τ	T	$C_{i,j}$, $\lambda_{i,j}$	D
TCFA	-	T	τ, $C_{i,j}$, $\lambda_{i,j}$	D

- τ = Network Topology
- $\lambda_{i,j}$ = flow on link (i,j)
- μ = average packet size
- $C_{i,j}$ = capacity of link (i,j)
- T = Average System Delay
- D = Maximum cost

$$\sum_{(i,j)\in E} d_{i,j}\left(C_{i,j}\right) = D$$

Ref: Channel, Capacity, and Flow Assignment in Wireless Mesh Networks Presentation, by Vishwanath Ramamurthi

Channel, Capacity, and Flow Assignment (CCFA)

- Given:
  - Network Topology, source-destination demands $\gamma_{s,d}$
  - Number of non-overlapping channels K
  - Number of Network Interface Cards (NICs) on each node q_i
- Minimize: T
- With respect to: $\{C_{i,j}\}$, $\{\lambda_{i,j}\}$, and $H_{i,j} \in \{1,\ldots,K\}$

Ref: Channel, Capacity, and Flow Assignment in Wireless Mesh Networks Presentation, by Vishwanath Ramamurthi

Network Utility

- Efficiency of a WMN

$$\eta = \frac{\text{Total Throughput}}{\text{Total Demand}} = \frac{\gamma}{D} = \frac{\sum \gamma_{s,d}}{\sum D_{s,d}}$$

- Utility U is defined to include both throughput and delay

$$U = \frac{\eta^{Em}}{T}$$

- Em = " Throughput emphasis factor "

  - How much is throughput emphasized over delay
- Generalized version of Kleinrock's "Power" of a network

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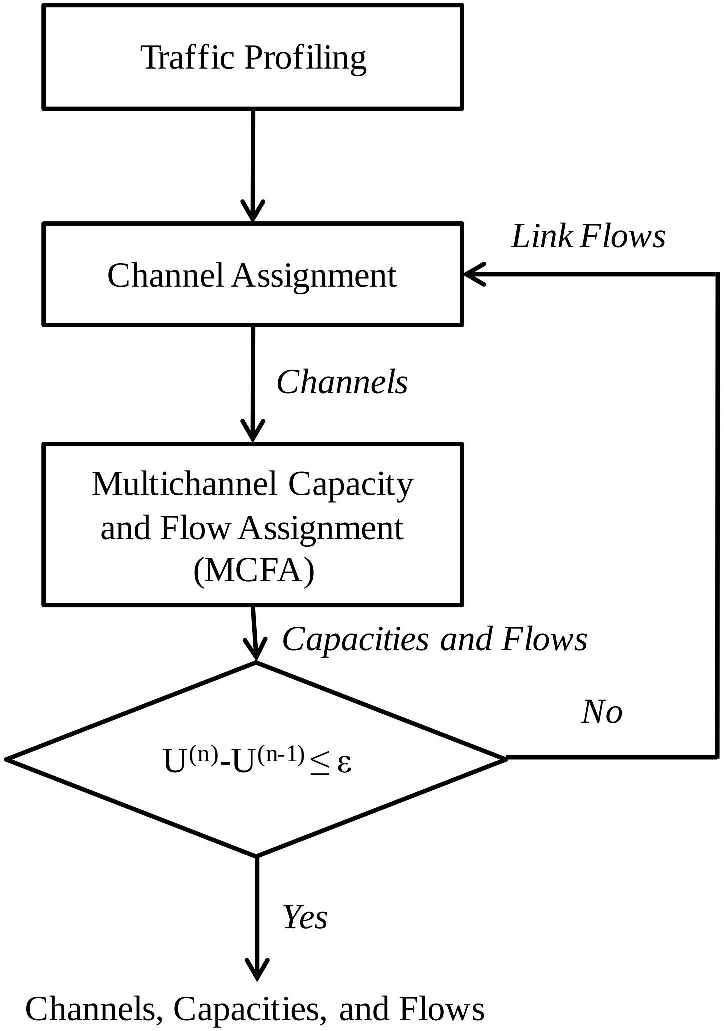
Overall CCFA Algorithm



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