A Green Framework for Energy Efficient Management in TDMA-based Wireless Mesh Networks

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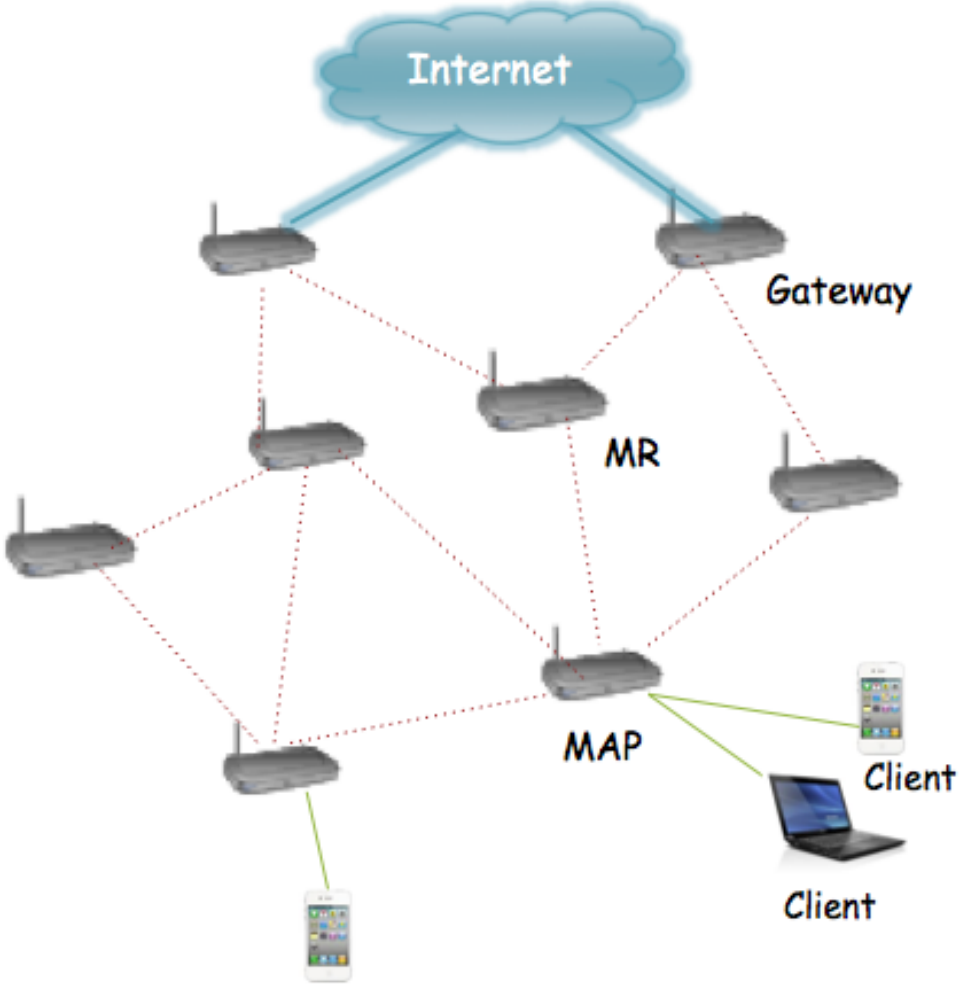
Outline

Outline

Wireless Mesh Networks



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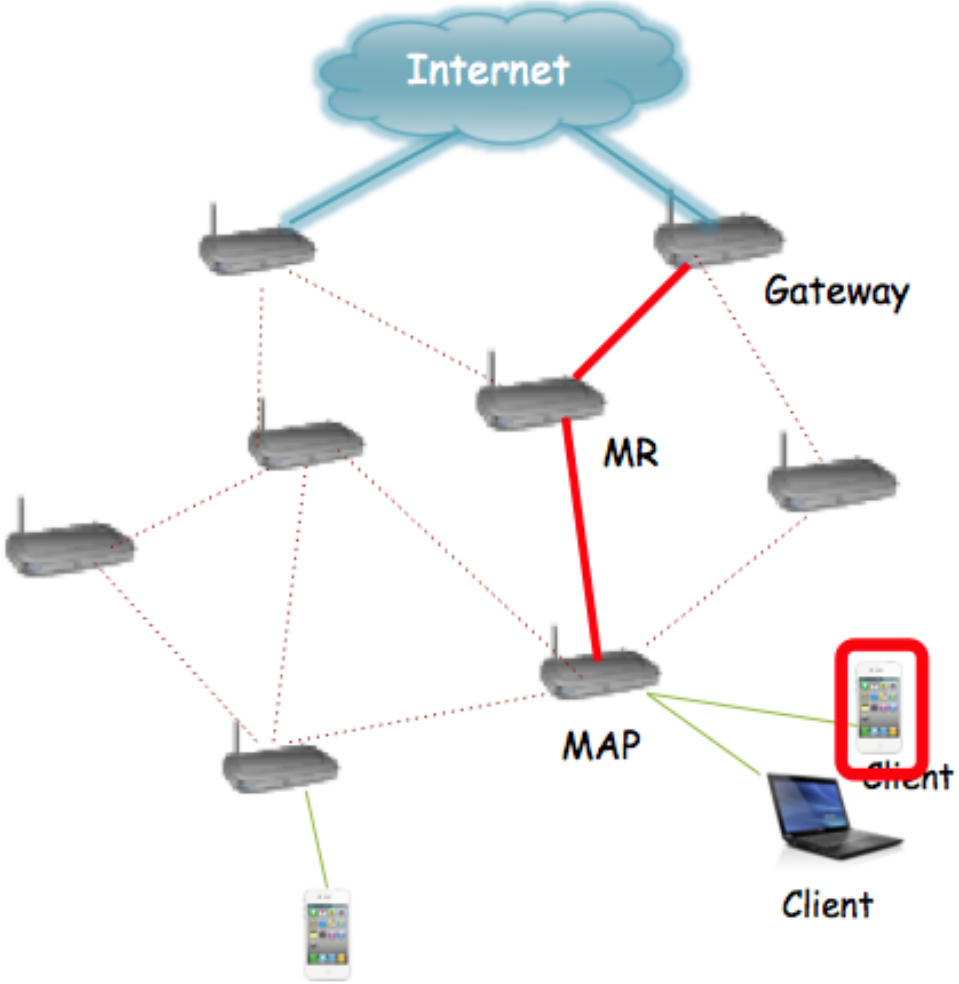

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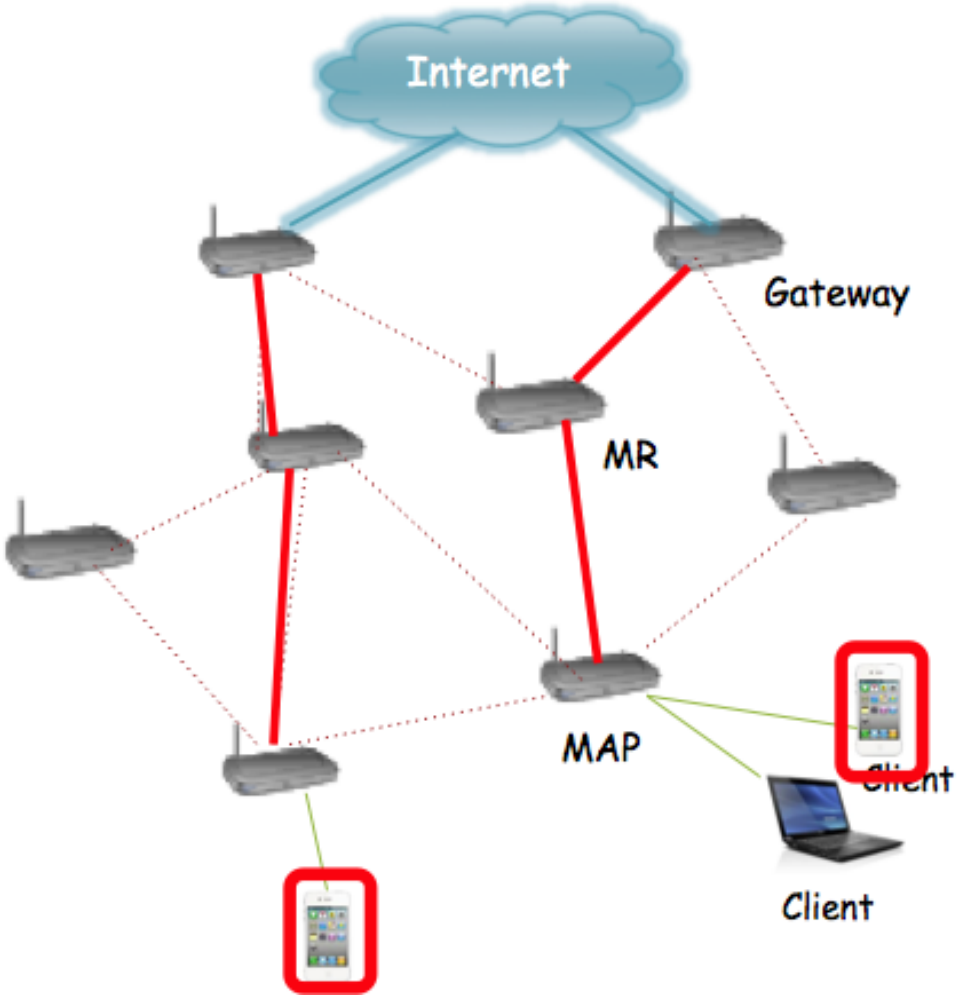

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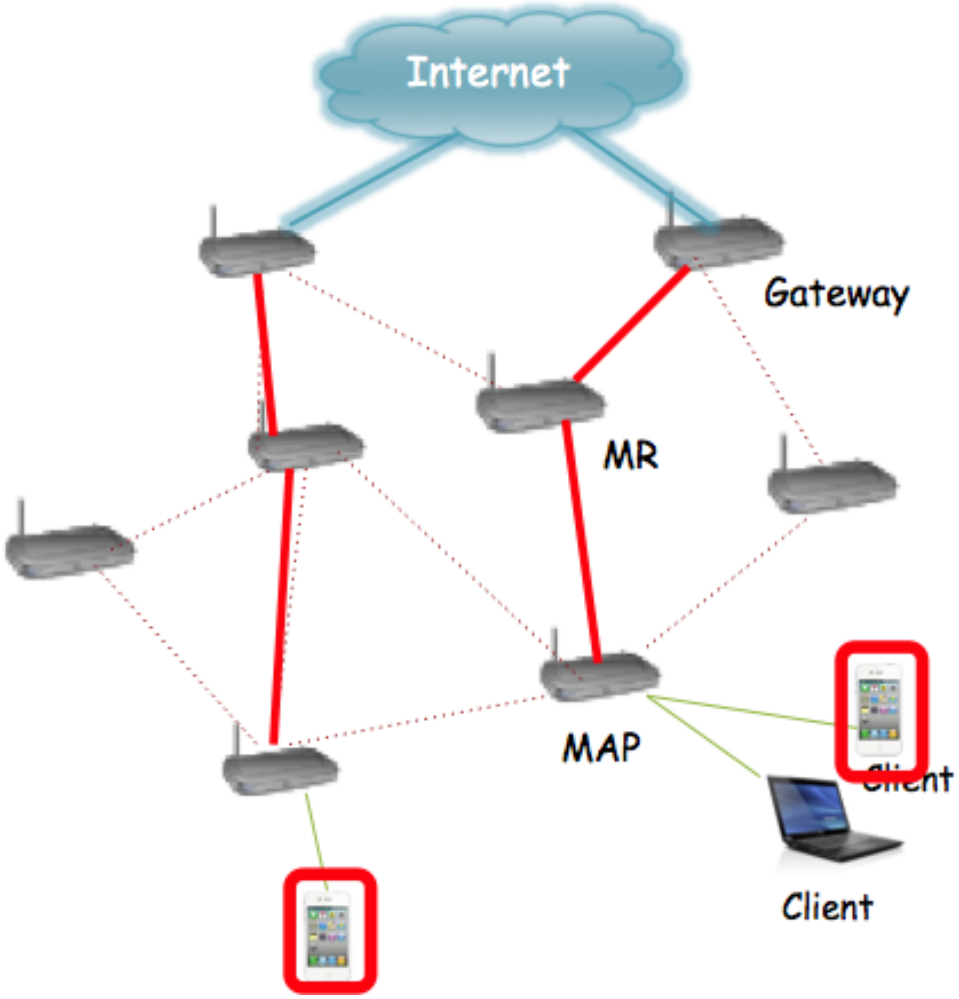

- Energy efficient Wireless Mesh Network

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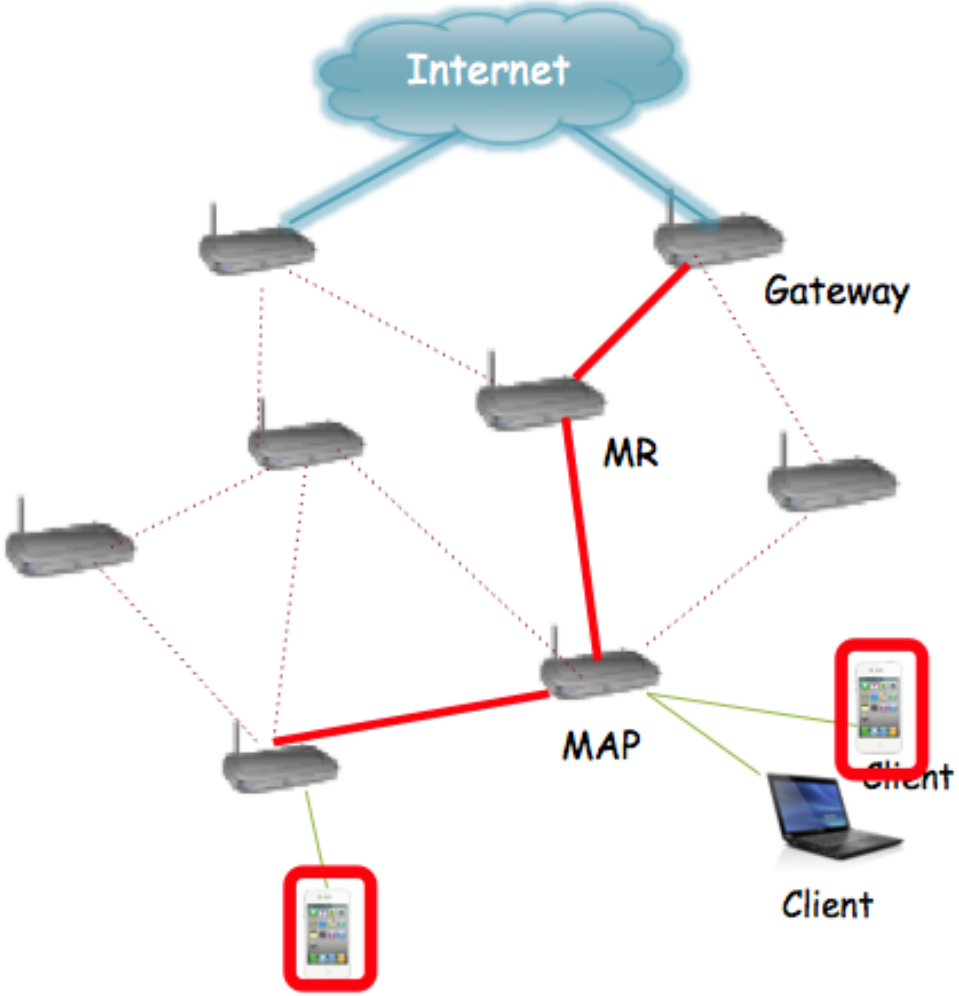

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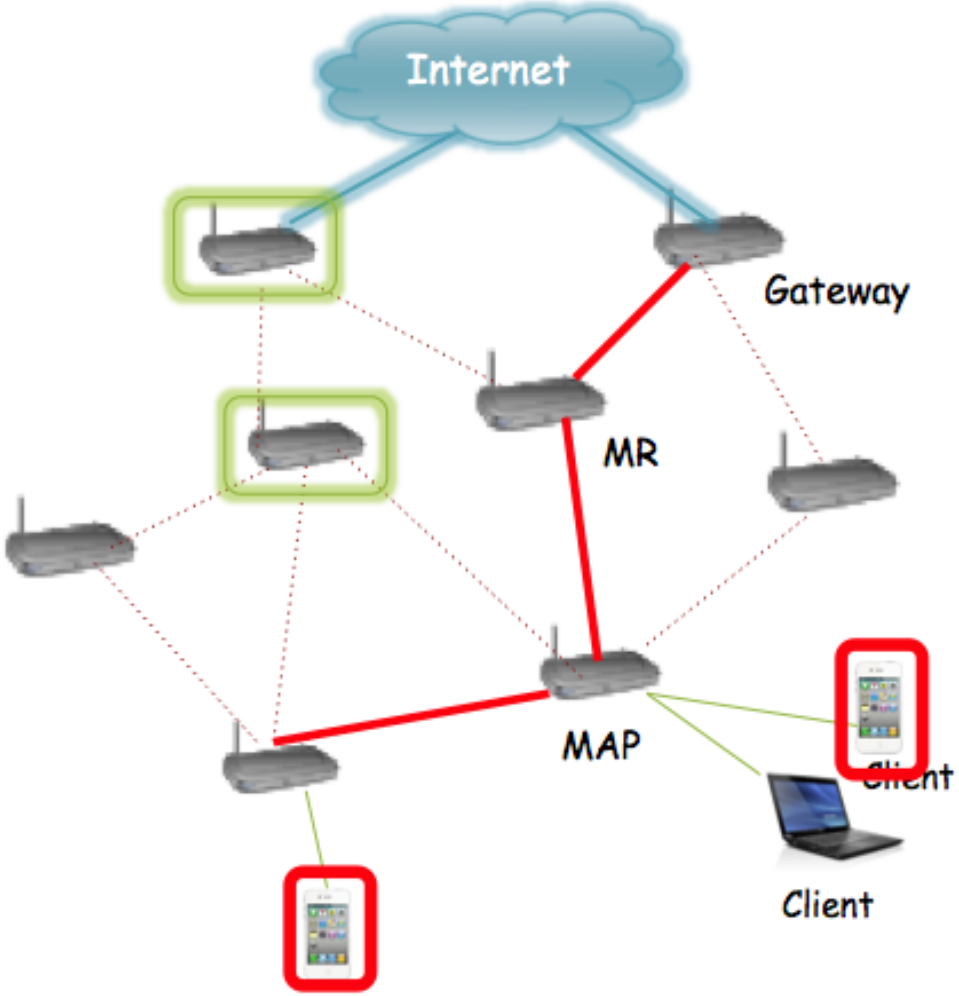


- Energy efficient Wireless Mesh Network

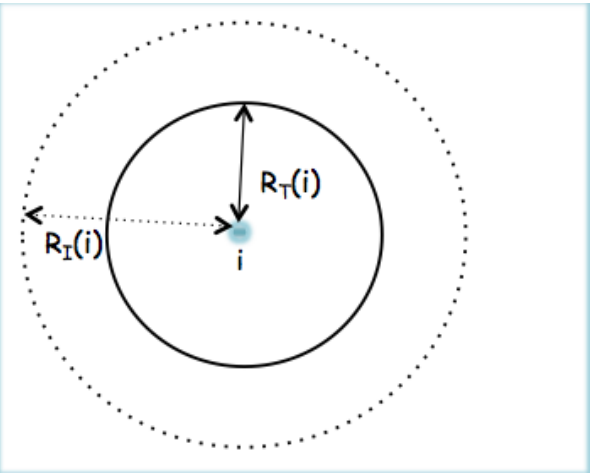
Outline

Network Topology

- The network is seen as a directed graph $G(V, E)$
- $V = \{v_1, ..., v_n\}$: set of all the nodes
  - $S = \{s_1, ..., s_m\} = \{v_{n-m+1}, ..., v_n\}$: set of nodes with internet connection $\Rightarrow$ *Gateways*
- $E = \{(i, j)/i, j \in \{1, ..., n\}, i \neq j\}$
- Connectivity Matrix M:

$$M_{i,j} = \begin{cases} 1 & \text{If there is a direct link between } v_i \text{ and } v_j \\ 0 & \text{Else} \end{cases}$$

Interference Model



- Each node i: Transmission Range and Interference Range
- A link (i, j) interferes with $(p, q))$ if:
  - $j \neq q$
  - $d_{i,q} \leq R_I(i)$
- Interference Matrix I

$$I_{(i,j),(p,q)} = \begin{cases} 1 & \text{If the link } (i,j) \text{ interferes with the link } (p,q) \\ 0 & \text{Otherwise} \end{cases}$$

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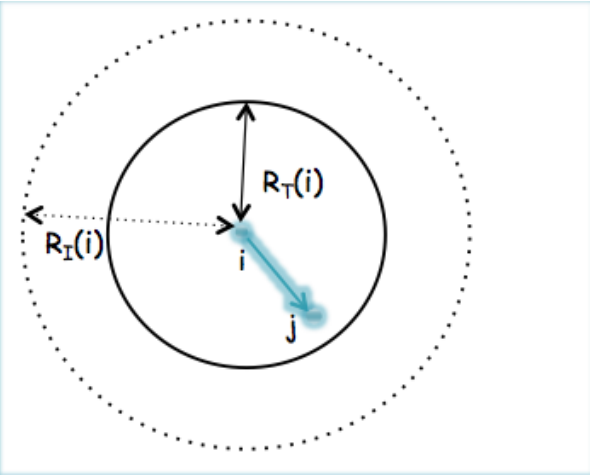

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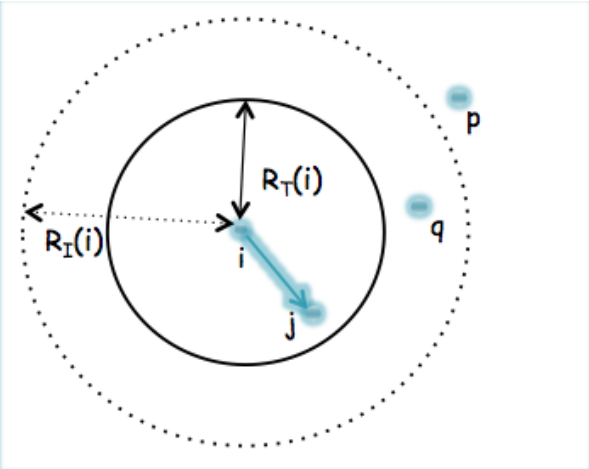

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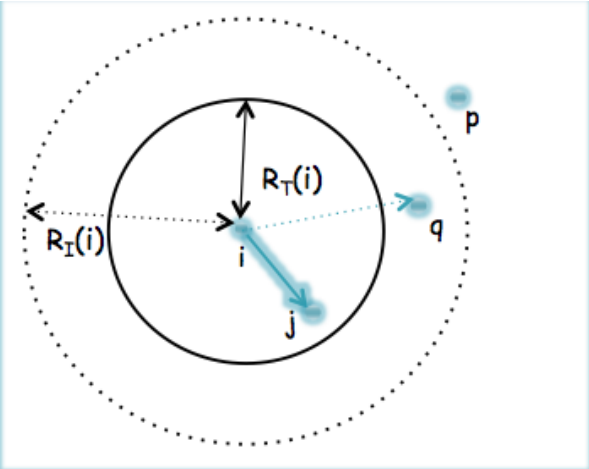

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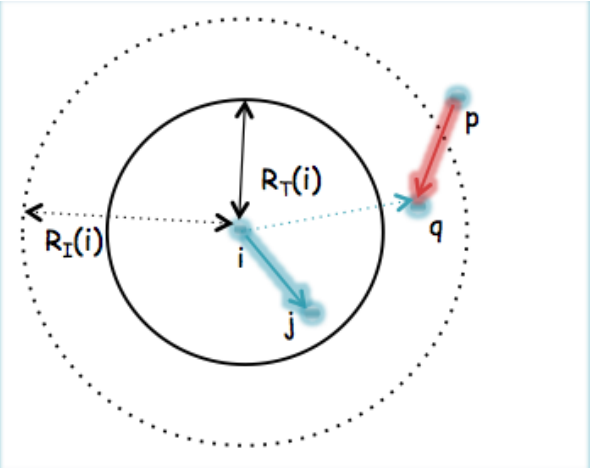

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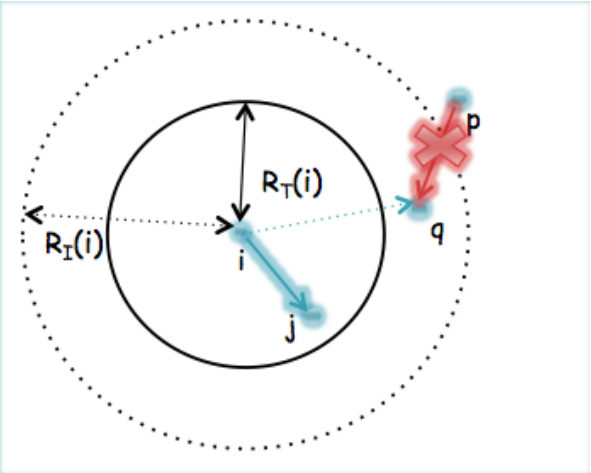

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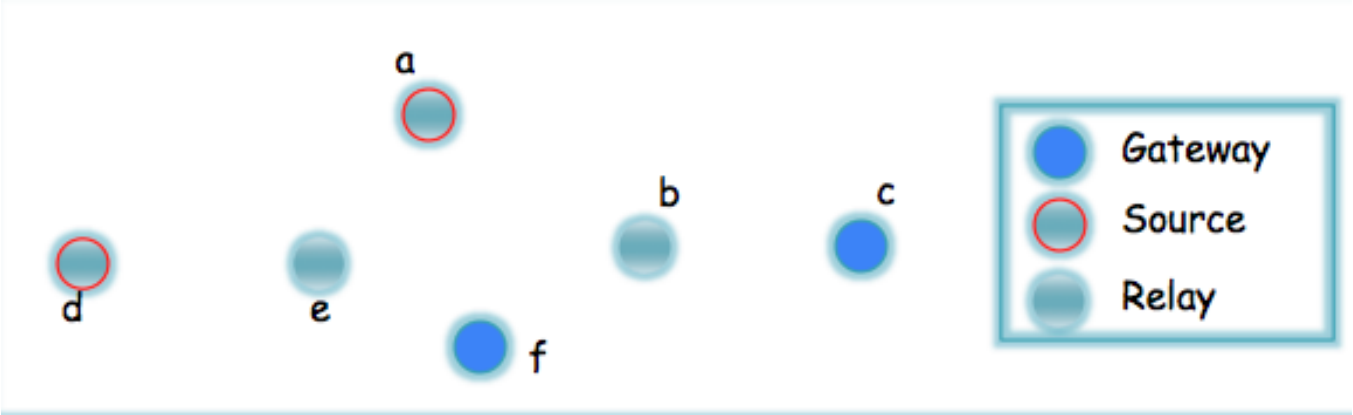
Traffic model & Routing and Link Scheduling

- The Traffic: A set of flows L
- In TDMA: Time is divided into periods of T units of time, each period $= \{1..T\}$ slots



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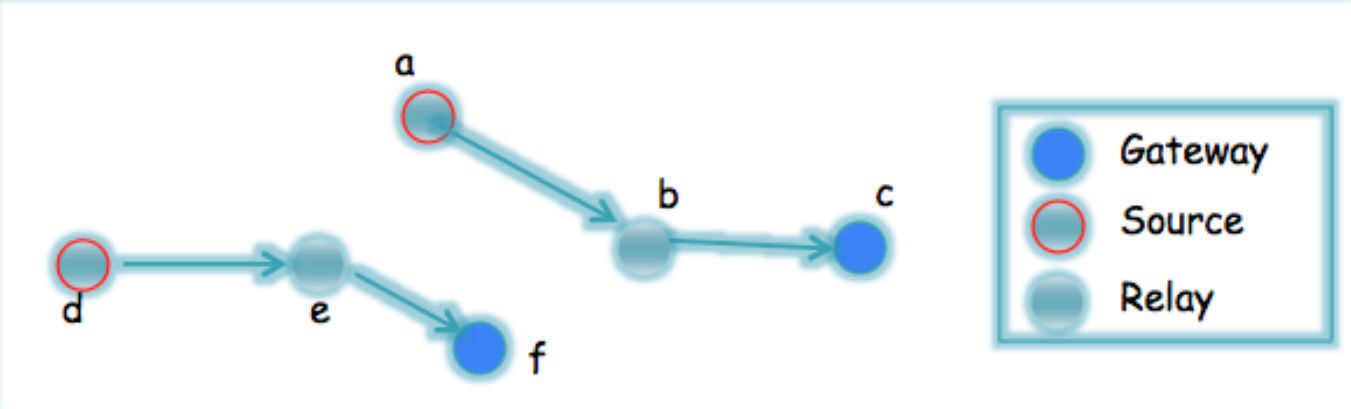

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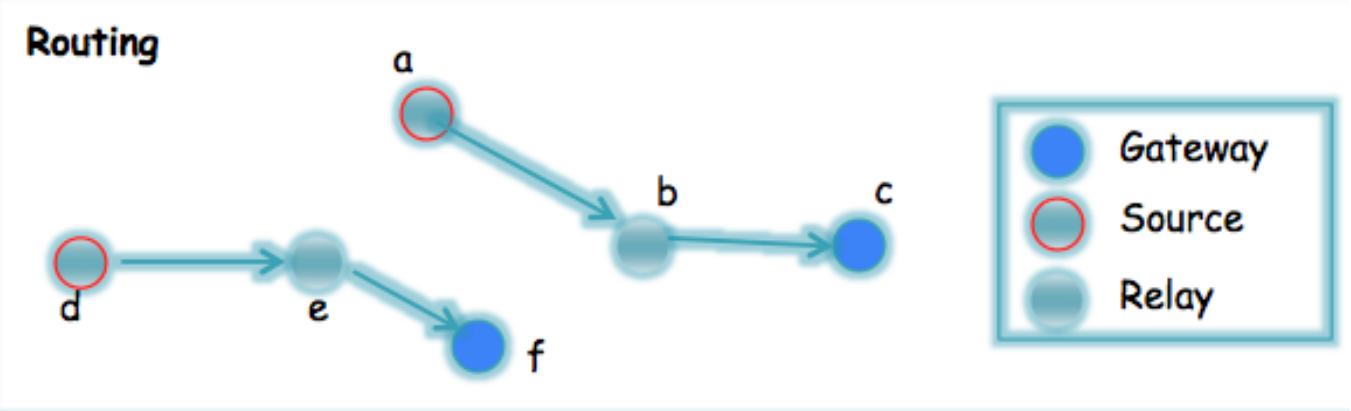

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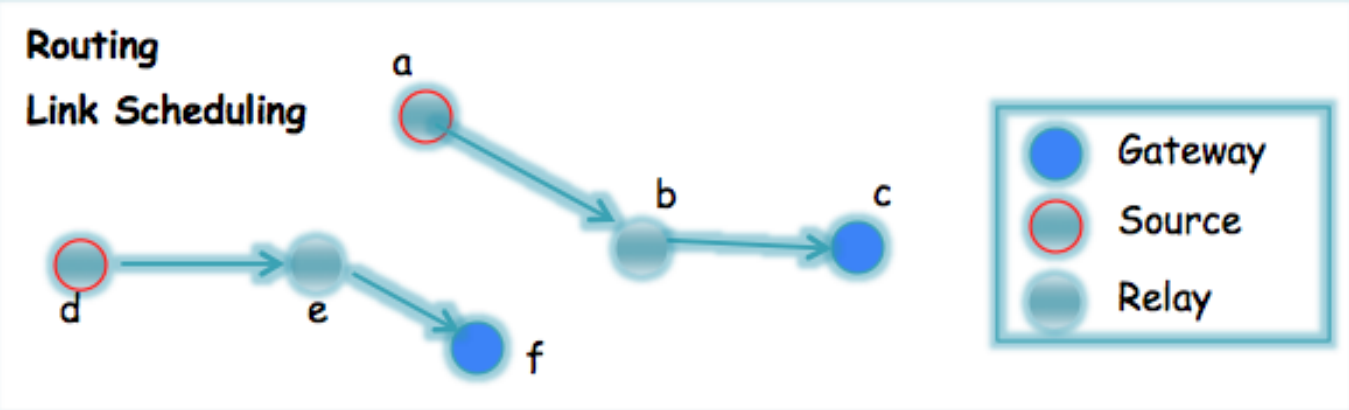

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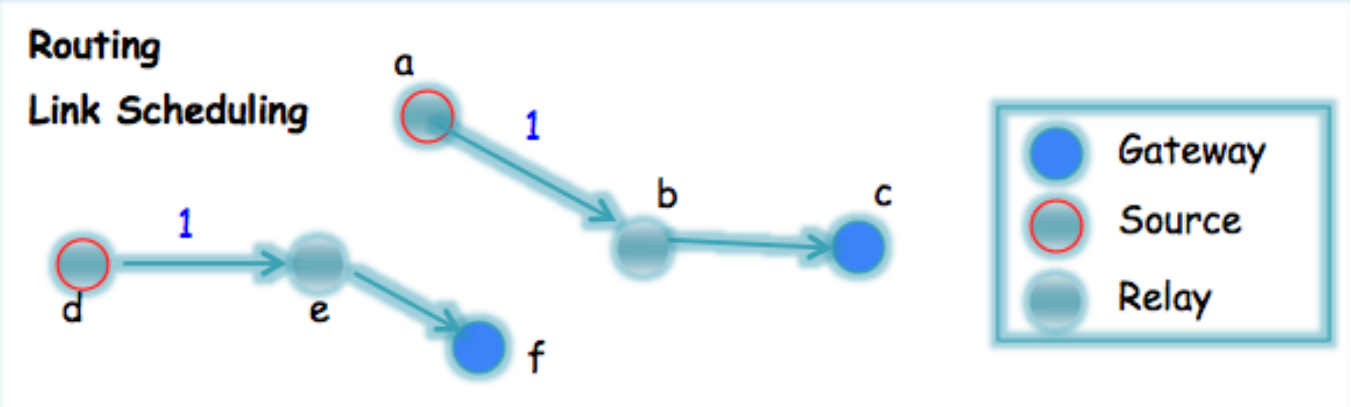

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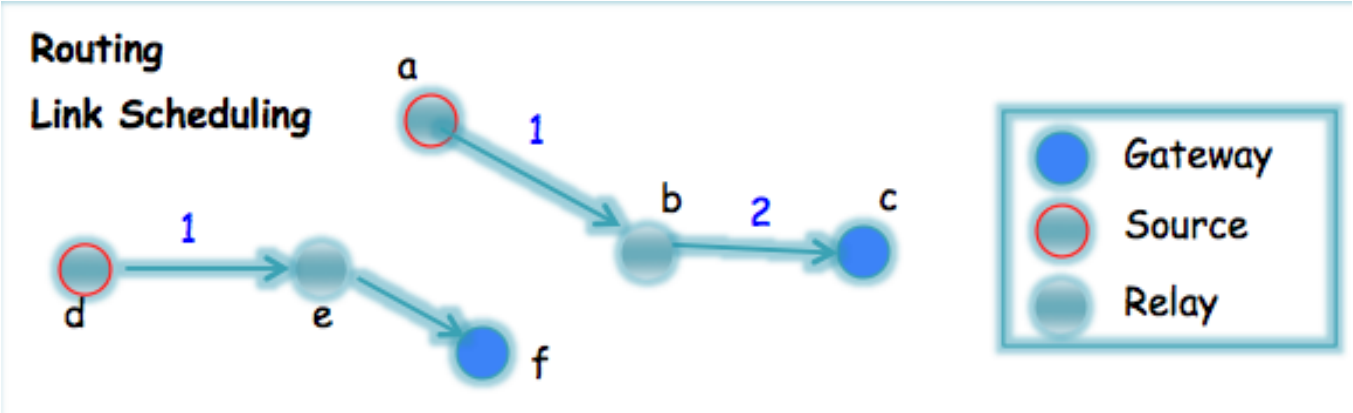

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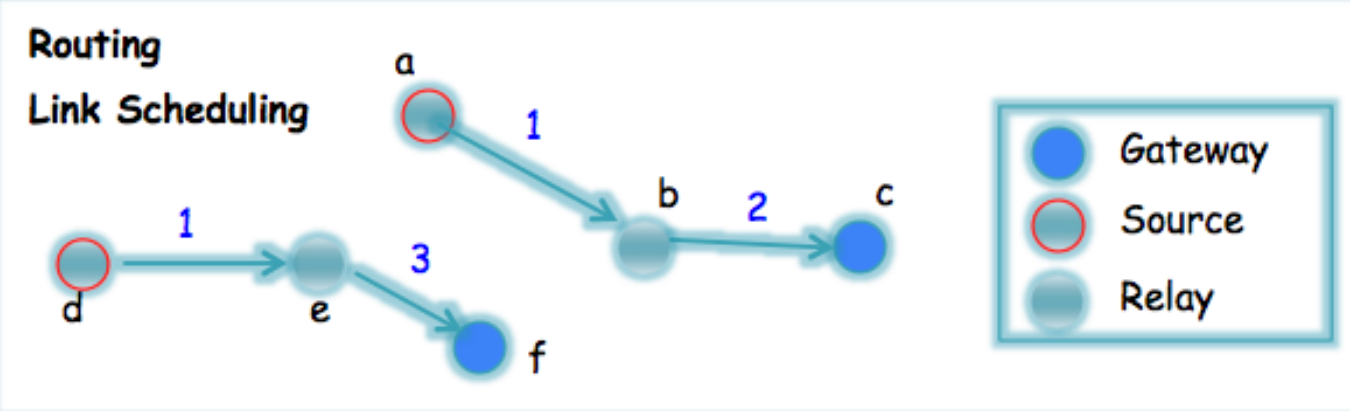

Energy Efficiency & Throughput

- Energy Efficiency = Reduced number of used nodes (ON/OFF model)

- Higher throughput (Routed Traffic / Used slots) = Reduced number of used slots during T

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  Used node definition:

$$y_i = \begin{cases} 0 & \text{If} \sum_{t \in \{1,..,T\}} \sum_{l \in L} \sum_{j=1}^{n} x_{ij}^{(t)}(l) + x_{ji}^{(t)}(l) = 0 \\ 1 & \text{Otherwise} \end{cases}$$

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$$z_t = \begin{cases} 0 & \text{If } \sum_{l\in L} \sum_{i,j=1}^{n} x_{ij}^{(t)}(l) = 0 \ \ \forall t \in \{1,..,T\} \\ 1 & \text{Otherwise} \end{cases}$$

Problem

GIVEN:

- A physical topology $G(V, E)$, connectivity and interference matrices M and I
- A set of m gateways
- A list L of flows

FIND:

- The optimal routing and link scheduling of the L flows
- Best tradeoff between network throughput and energy consumption

Outline

The ILP

$$Minimize\left(\alpha\sum_{i=1}^{n} y_i + (1-\alpha)\sum_{t\in\{1,..,T\}} z_t\right),\ \alpha\in[0,1]$$

subject to:
No transmission over a non existing link:

$$x_{ij}^{(t)}(l) \leq M_{i,j} \qquad \forall i,j\in\{1,...,n\}, \forall t\in\{1,..,T\}$$

Two interfering links are not scheduled during the same slot:

$$x_{ij}^{(t)}(l)+x_{pq}^{(t)}(l')I_{(i,j),(p,q)} \leq 1 \qquad \forall i,j,p,q\in\{1,...,n\}, \forall t\in\{1,..,T\}$$

The ILP

Flow conservation:

$$\sum_{l \in L} \sum_{t \in \{1,..,T\}} \sum_{j=1}^{n} x_{ij}^{(t)}(l) = \sum_{l \in L} \sum_{t \in \{1,...,T\}} \sum_{k=1}^{n} x_{ki}^{(t)}(l) +$$

$$\sum_{l \in L, s(l)=i} \left(\sum_{t \in \{1,..,T\}} \sum_{j=1}^{n} x_{ij}^{(t)}(l) \right) \quad \forall i \in \{1, ..., n-m\}$$

All flows have to be routed:

$$Success(l) = 1 \quad \forall l \in L$$

Solving methods

- Optimal-based method: Optimal Green Routing and Link Scheduling (O-GRLS)
  - Both Routing an link scheduling
  - Optimal solution using a solver

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- Optimal-based method: Optimal Green Routing and Link Scheduling (O-GRLS)
  - Both Routing an link scheduling
  - Optimal solution using a solver
- Meta-heuristic-based method: Ant Colony Green Routing and Link Scheduling (AC-GRLS)
  - Based on Ant Colony meta-heuristic
  - Near optimal solution
  - Reduced computational complexity
  - Path Formulation

AC-GRLS

- Path formulation:
  - Reduces the complexity of link formulation
  - Each flow (among L flows) is provided with K different paths toward a gateway
  - A solution: One path for each flow $\Rightarrow K^{|L|}$ possible solutions
  - Ant Colony meta-heuristic for efficient exploration of solution space
- Scheduling is done using a proposed Greedy Link Scheduling algorithm

Outline

Test Settings

- The objective function:

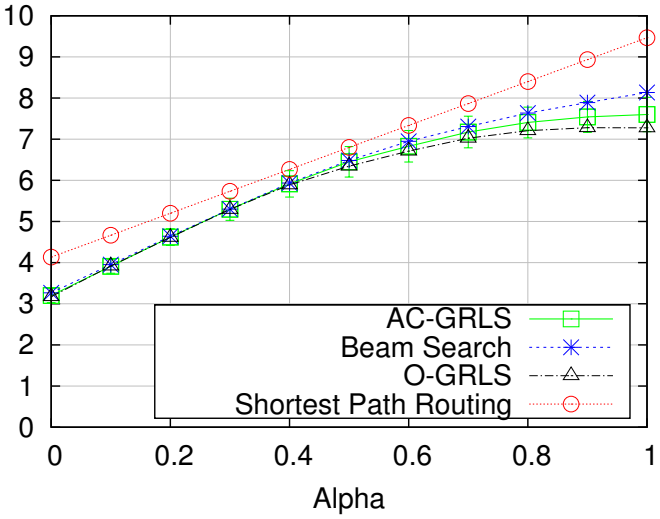
$$Minimize\left(\alpha\sum_{i=1}^{n} y_i + (1-\alpha)\sum_{t\in\{1,..,T\}} z_t\right) \qquad \alpha \in [0,1]$$

- Performance metrics:
  - Objective Function Value
  - Proportion of non-source used nodes
  - Achieved throughput
  - Average path length
- Network settings:
  - Grid and Random Topologies
  - Uplink traffic

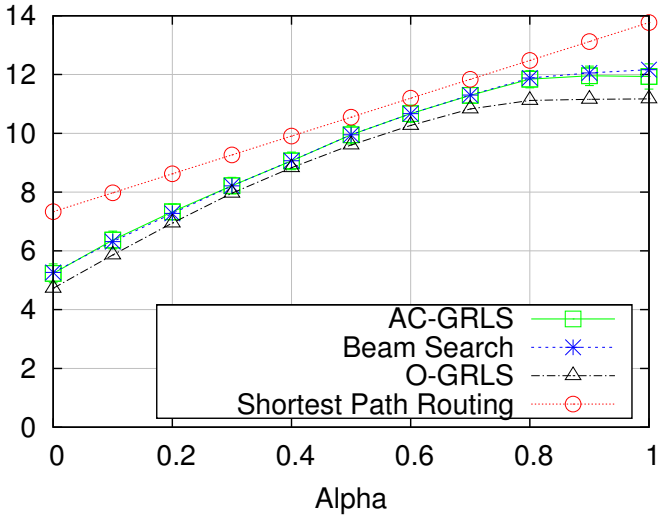
Scale	Nodes	Gateways	Load
Small	25	4	25%, 50% and 75%
Large	100	9	25%, 50% and 75%

Results: Small Scale Networks (25 nodes)

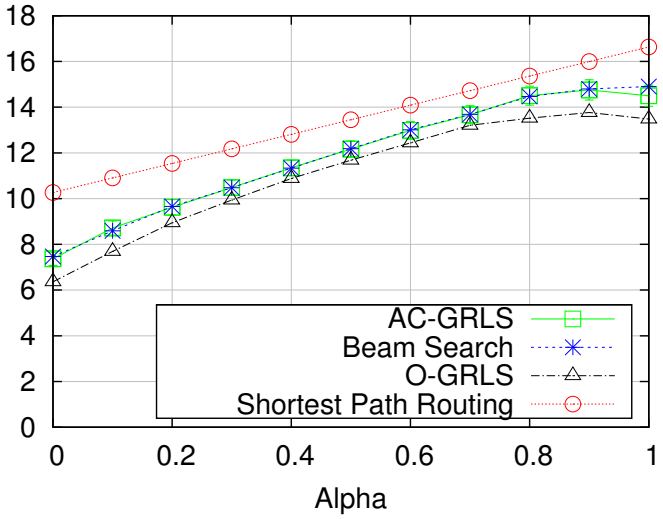
- AC-GRLS and O-GRLS Vs SP: Objective function value 30% better
- AC-GRLS Vs O-GRLS: Near optimal solution in a short computation time (0.5s Vs 550s)



25 % network load



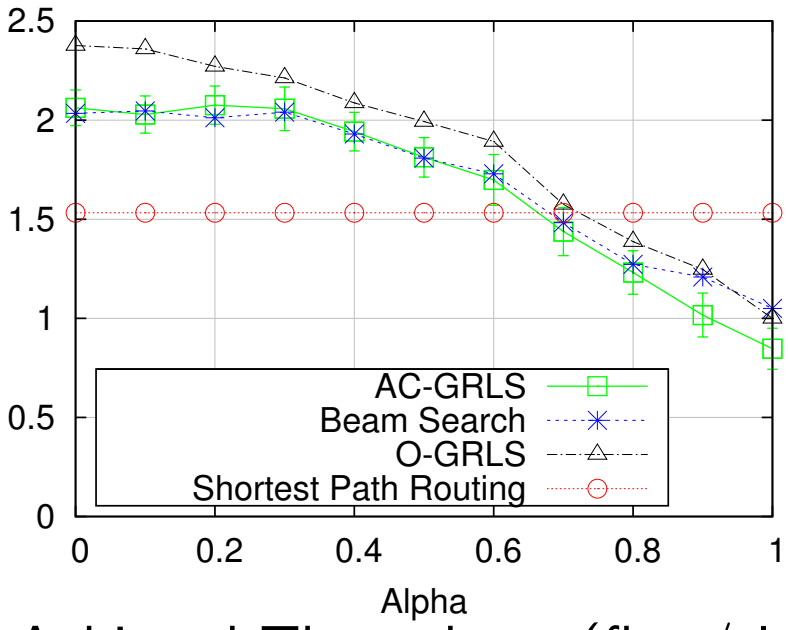
50 % network load



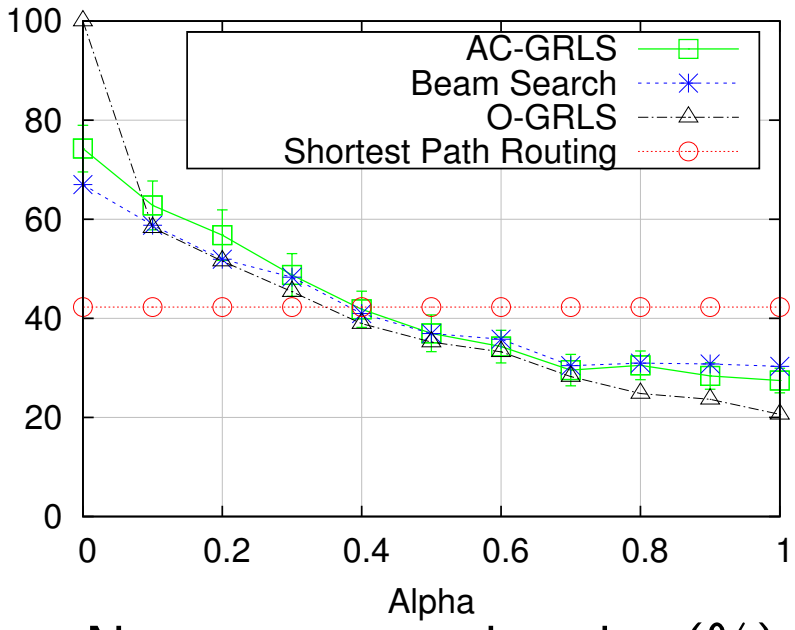
75 % network load

Results: Small Scale Networks (25 nodes), 75% load

- Achieved throughput and Energy consumption:
  - The same energy budget, achieved throughput is 30% better ($\alpha = 0.4$)
  - The same throughput with 30% fewer used nodes ($\alpha = 0.7$)



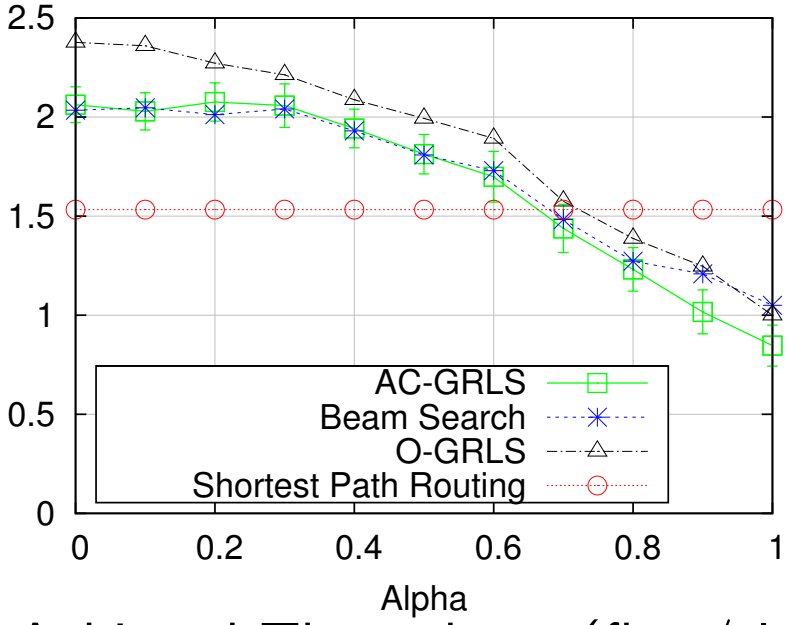
Achieved Throughput (flow/slot)



Non-source used nodes (%)

Results: Small Scale Networks (25 nodes), 75% load

- Tuning α :
  - A desired throughput $\Rightarrow$ a certain value of α Desired Throughput $= 1.8$ flow/slot $\Rightarrow \alpha = 0.5$



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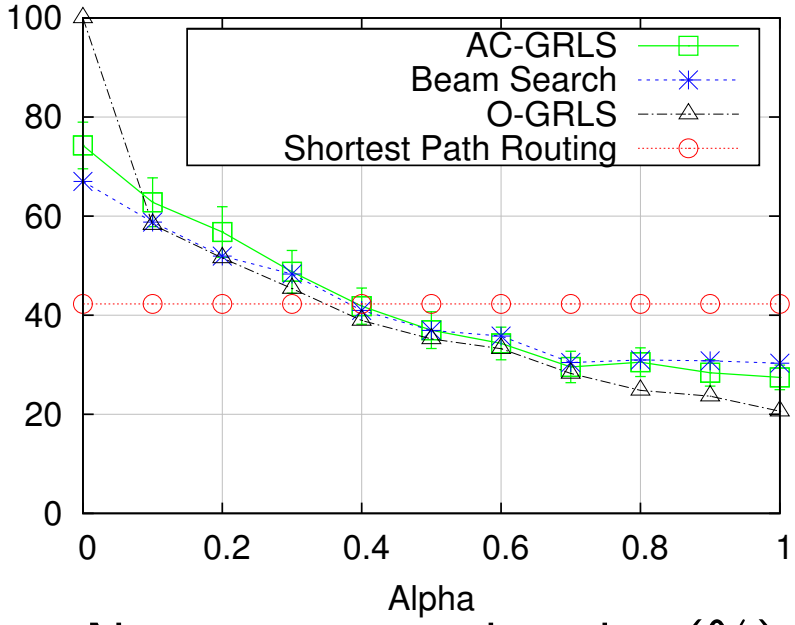
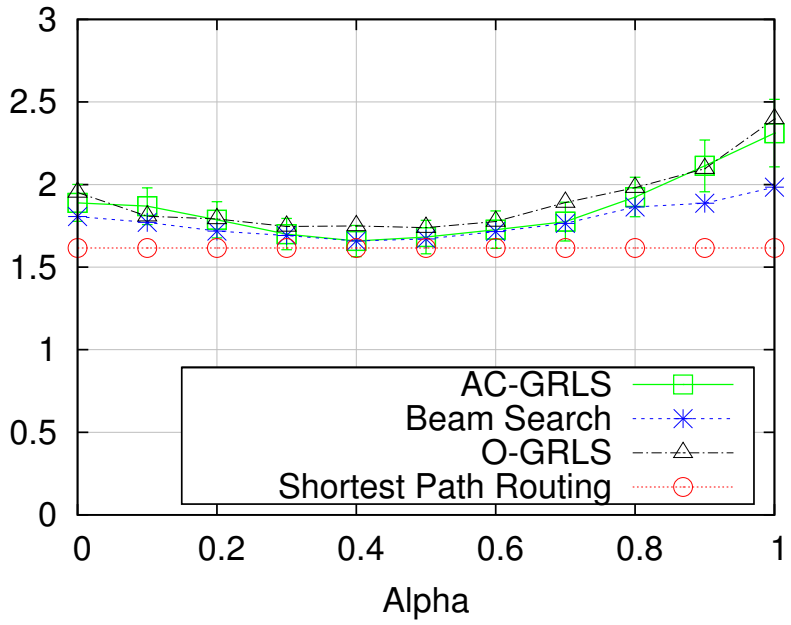


Non-source used nodes (%)

Results: Small Scale Networks (25 nodes), 75% load

- Average path length:
  - Relatively short paths ($\alpha \in [0.4, 0.7]$)



Outline

Conclusion

- Energy efficient management in TDMA-based WMNs
  - Routing and link scheduling
  - Optimal formulation and efficient approximation
  - Parametrized objective function: Energy-Thoughput tradeoff
  - Better than Shortest Path strategies
- Future work:
  - Fine-grain energy consumption model
  - Switch ON/OFF costs

The ILP

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subject to:
No transmission over a non existing link:

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Two interfering links are not scheduled during the same slot:

$$x_{ij}^{(t)}(l) + x_{pq}^{(t)}(l')I_{(i,j),(p,q)} \leq 1 \qquad \forall i,j,p,q \in \{1,...,n\}, \forall t \in [1,T]$$

The ILP

No routing when reaching a Gateway

$$x_{ij}^{(t)}(l) = 0 \qquad \forall i \in \{n-m+1, ..., n\}, j \in \{1, ..., n\}, \forall l \in L, \forall t \in [1, T]$$

No loops when routing

$$\sum_{t=1}^{T} \sum_{j=1}^{n} x_{ji}^{(t)}(l) \leq 1, \quad \sum_{t=1}^{T} \sum_{j=1}^{n} x_{ij}^{(t)}(l) \leq 1, \forall i \in \{1, ..., n\}, \forall l \in L$$

The ILP

Flow conservation:

$$\sum_{l \in L} \sum_{t=1}^{T} \sum_{j=1}^{n} x_{ij}^{(t)}(l) = \sum_{l \in L} \sum_{t \in \{1,\ldots,T\}} \sum_{k=1}^{n} x_{ki}^{(t)}(l) + \sum_{l \in L, s(l)=i} \left(\sum_{t=1}^{T} \sum_{j=1}^{n} x_{ij}^{(t)}(l) \right) \quad \forall i \in \{1, \ldots, n-m\}$$

All flows have to be routed:

$$Success(l) = 1 \quad \forall l \in L$$

AC-GRLS

Algorithm 1 AC-GRLS pseudo code

```
Set Parameters
Initialize pheromone trails
for i = 1 → Number of Iterations do
    Construct Ant Solutions
    for all Ants do
        Build a solution step by step
    end for
    Update Pheromones
end for
```

AC-GRLS

Building a solution step by step:

---

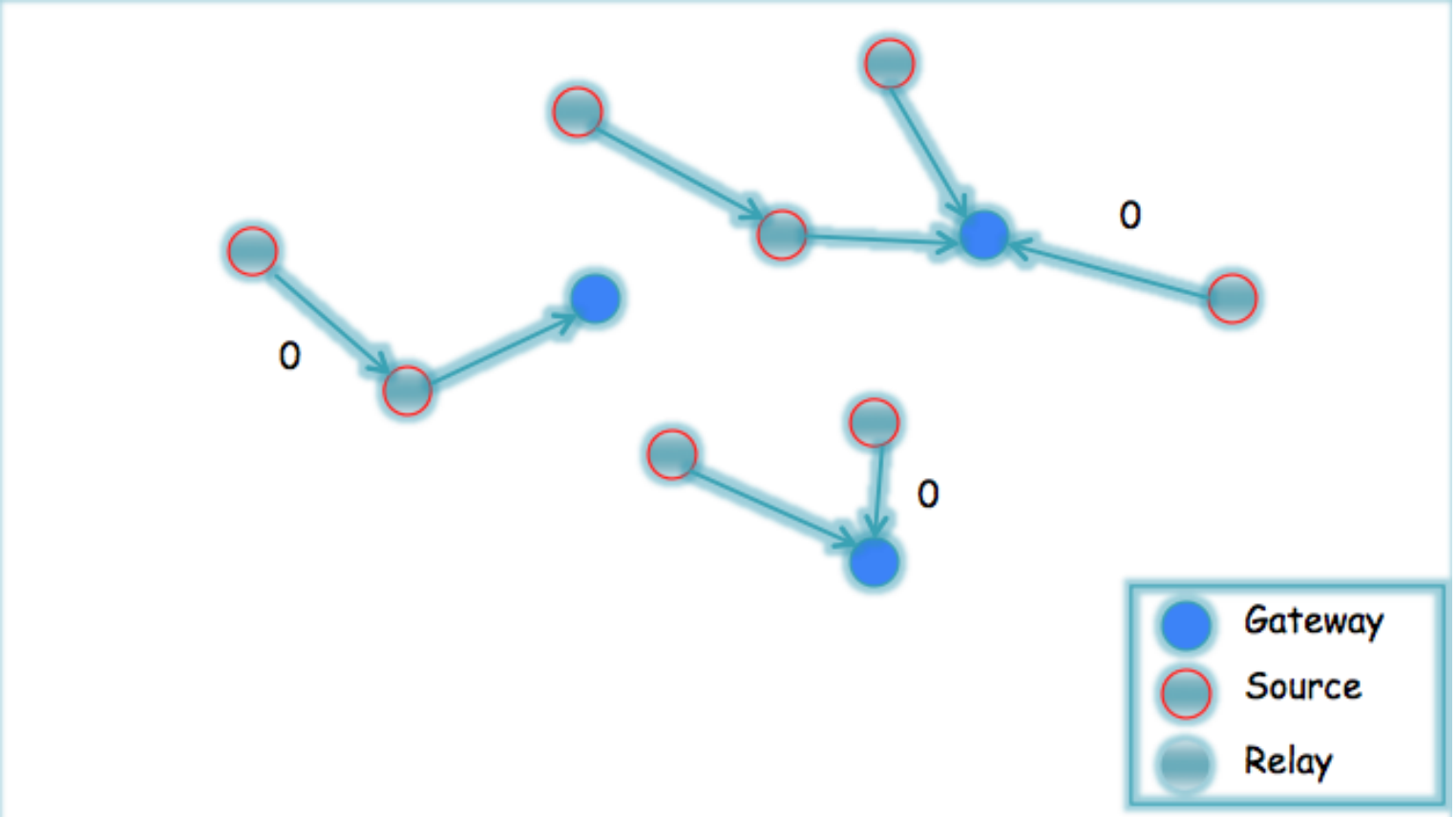
for $l = 1 \rightarrow$ Number of flows **do**
  $p \leftarrow Random(0..1)$
  if $p < q_0$ **then**
    Choose path j where $j = \mathrm{Argmax}_{k \in N_l} \left(\tau_{lk}^{\alpha_{ANT}} \times \eta_{lk}^{\beta_{ANT}} \right)$
  else
    Choose path j according to P_{lj} probability
    $P_{lj} = \frac{\tau_{lj}^{\alpha_{ANT}} \eta_{lj}^{\beta_{ANT}}}{\sum_{k \in N_i} \tau_{lk}^{\alpha_{ANT}} \eta_{lk}^{\beta_{ANT}}}$
  end if
  Add the jth path for flow l to current_solution
end for

AC-GRLS

Pheromone Trail Update:

```
//Update Pheromones for all flows l
for l = 1 → Number of flows do
    for j = 1 → K do
        τ_lj ← (1 − ρ)τ_lj //Evaporation
        if current_solution is the best solution for the current iteration And j^th path is selected for flow l then
            τ_lj ← τ_lj + Δ^best_lj //Reinforce the pheromone for the best solution of the current iteration
        end if
    end for
end for
```

Greedy Link Scheduling



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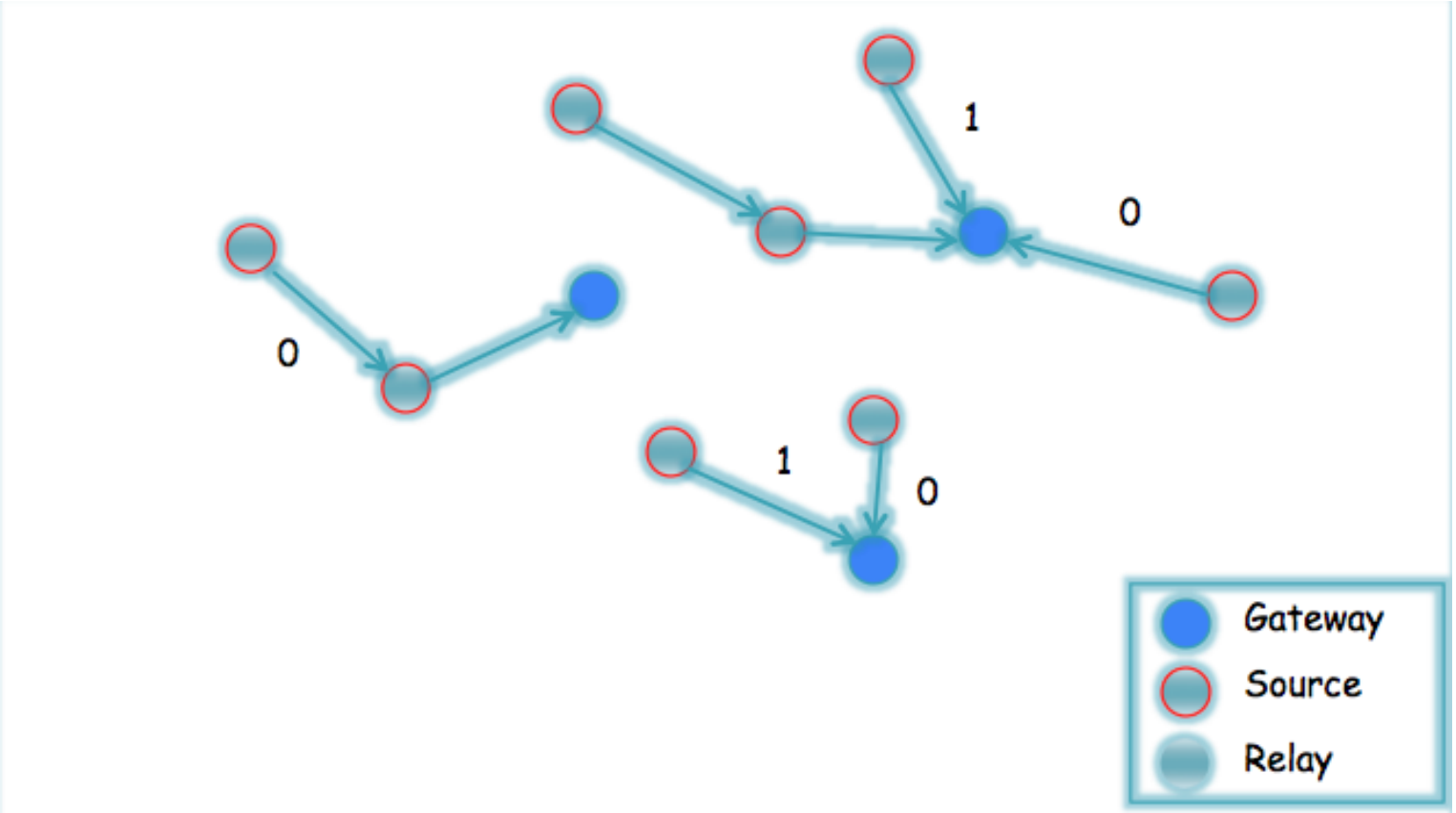

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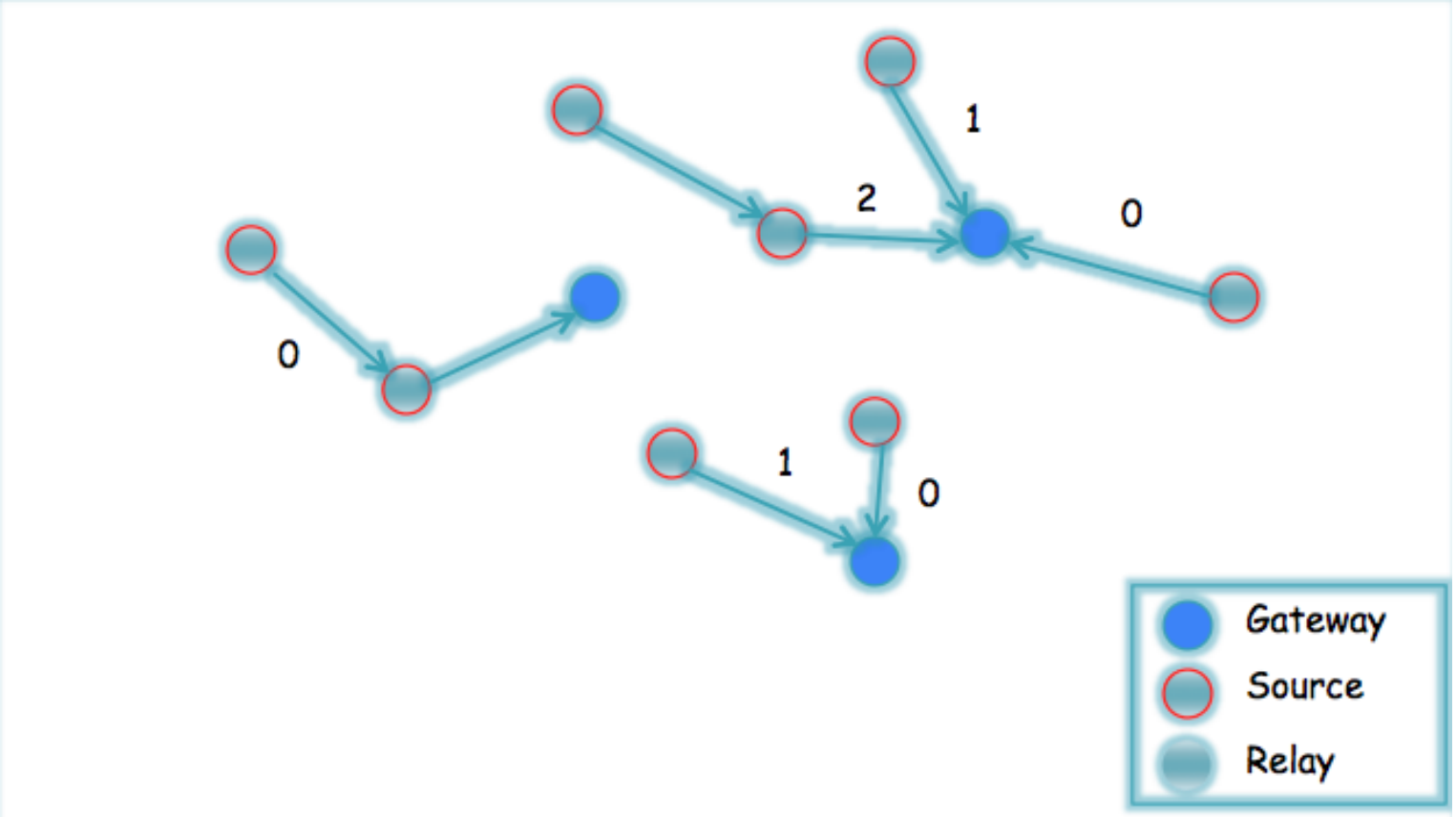

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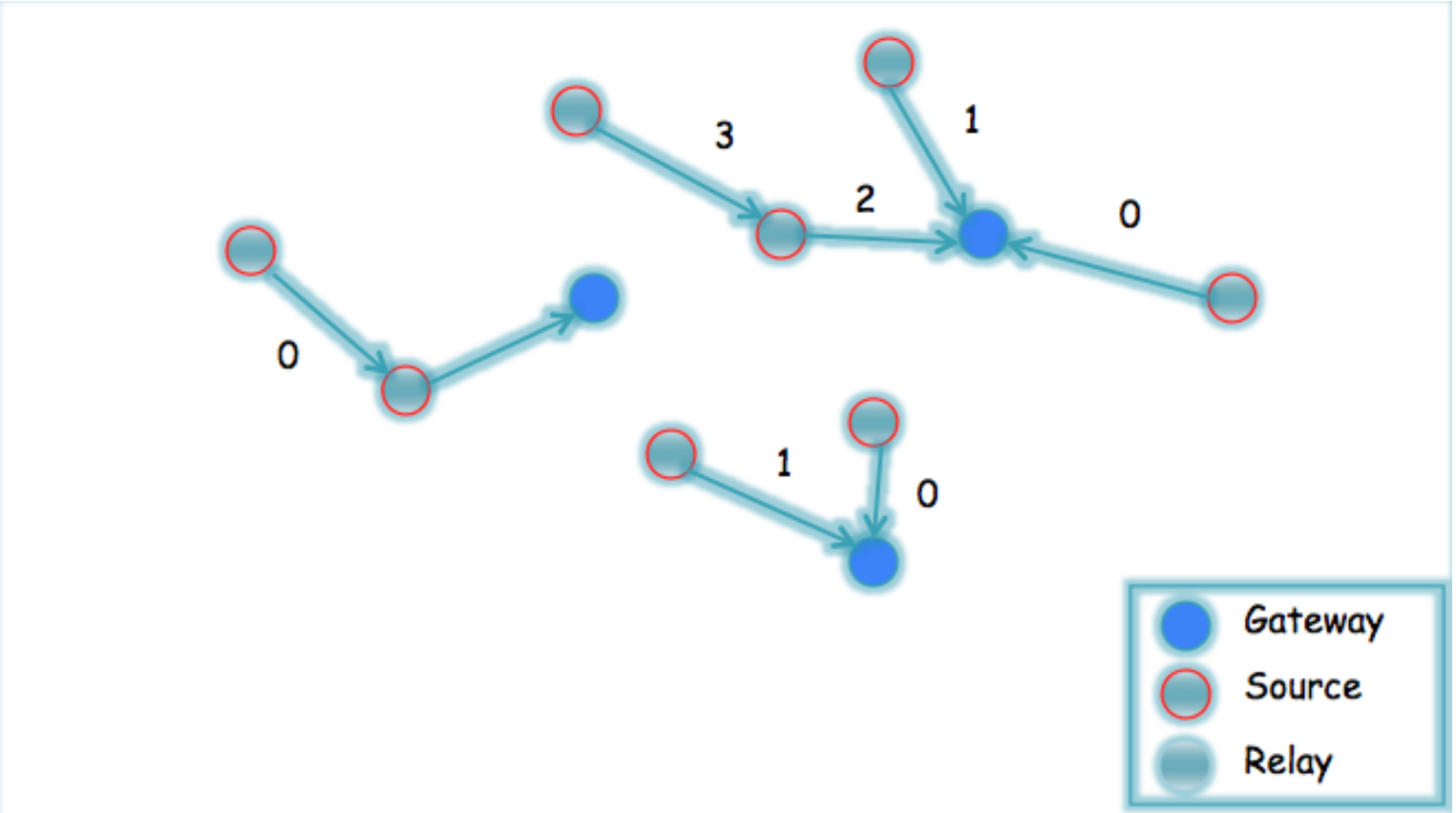
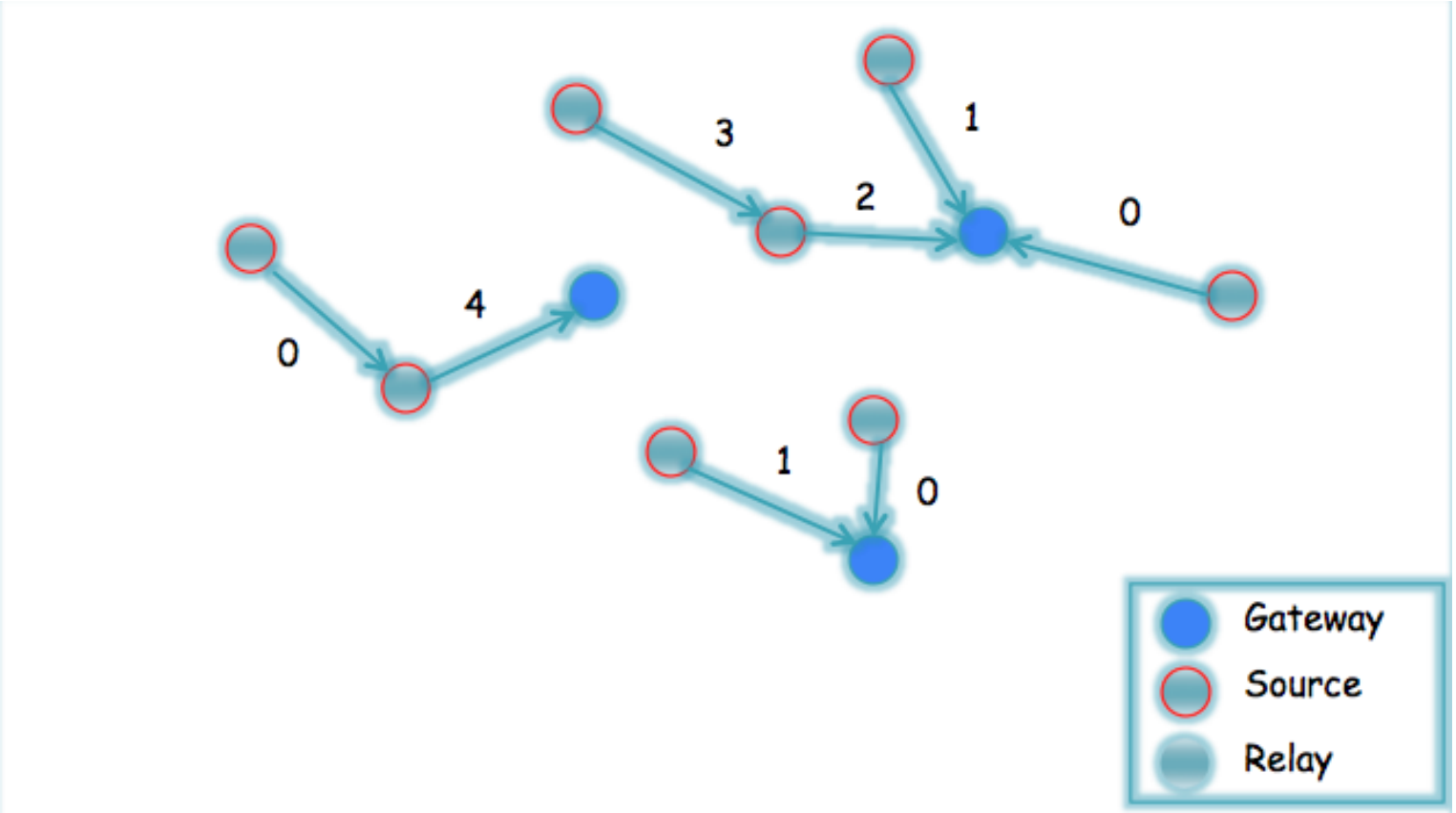


Greedy Link Scheduling



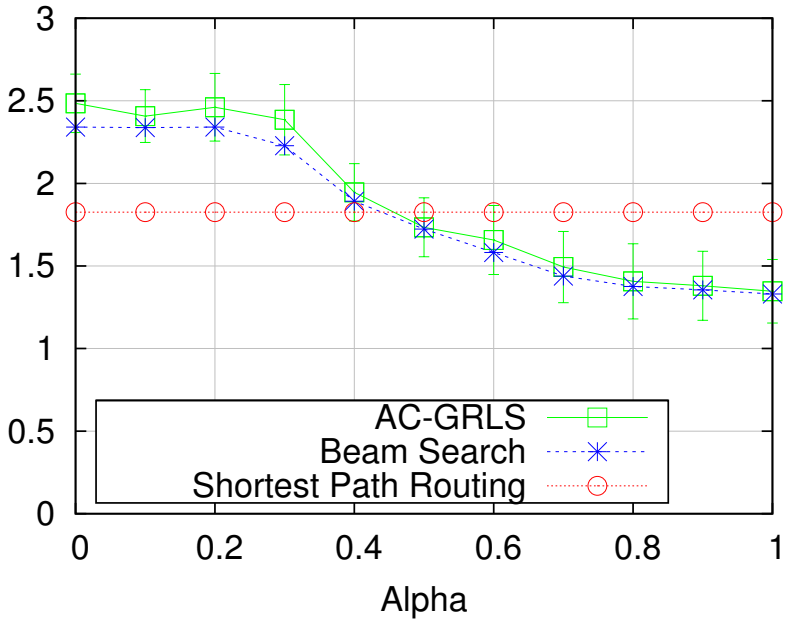
Greedy Link Scheduling

Algorithm 2 Greedy Link Scheduling

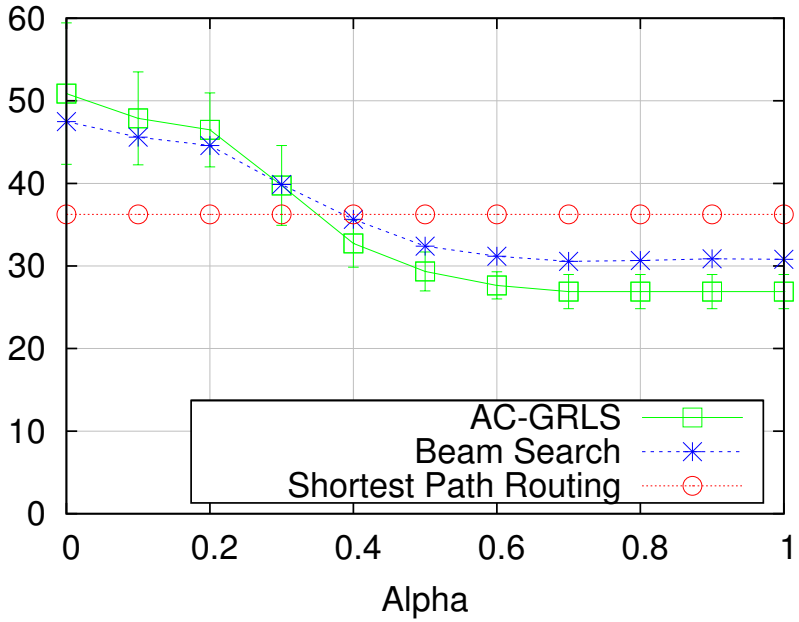
IN: LS: List of links to schedule, The conflict graph.
OUT: $Sched$: List of Slots with the corresponding scheduled links in each slot.
$Sched \leftarrow \{\}$; $i \leftarrow 0$ //i is the current slot
while $LS \neq \emptyset$ **do**
  //Extend $Sched$ by one slot
  $i \leftarrow i + 1$; $Sched[i] \leftarrow \{\}$
  for all $ls \in LS$ **do**
    if ls is not interfering with any link in $Sched[i]$ **then**
      $Sched[i] \leftarrow Sched[i] \cup \{ls\}$; Remove ls from LS
    end if
  end for
end while
Return $Sched$

Results

- Large Scale Networks (100 nodes), 75% network load



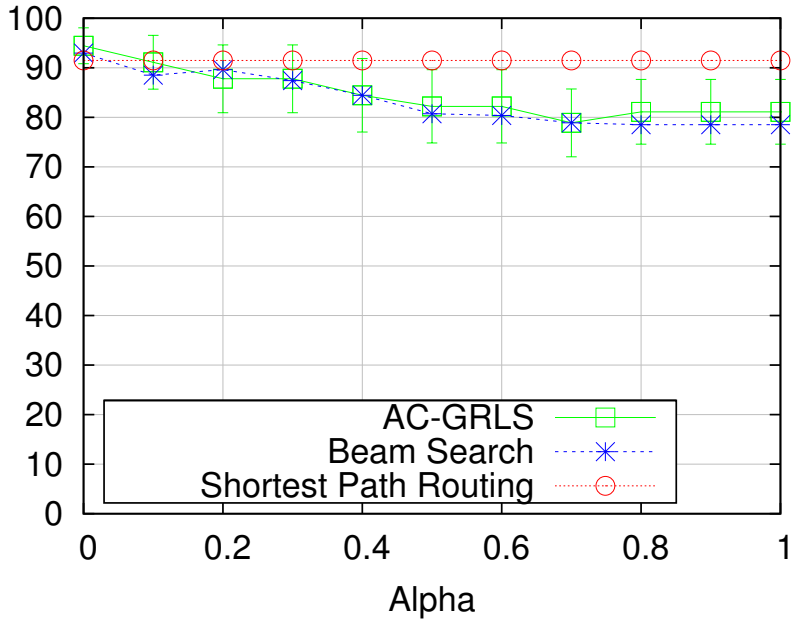
Achieved Throughput (flow/slot)



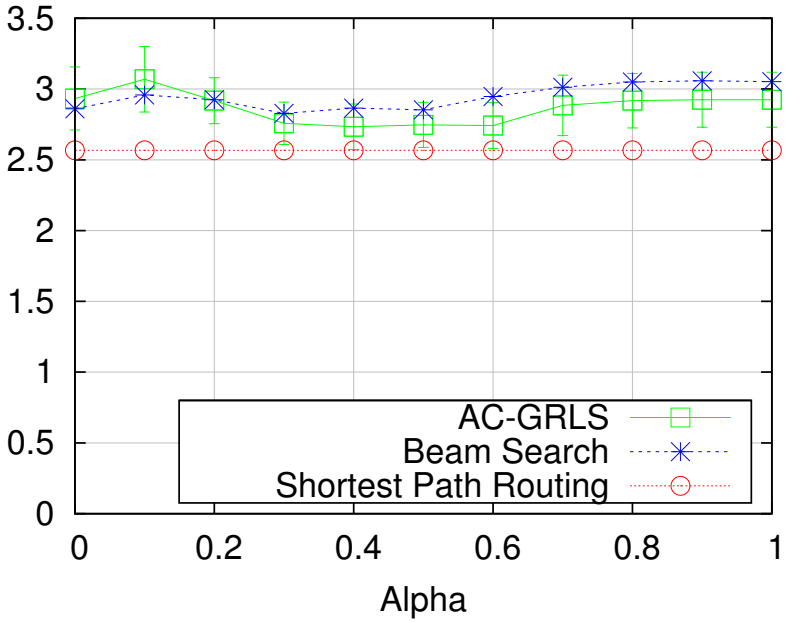
Non-source used nodes (%)

Results

- Large Scale Networks (100 nodes), 75% network load



Used gateways (%)



Average path Length

Energy Consumption & Traffic Model

- ON/OFF Energy consumption model model:
  - ON: node consumes energy
  - OFF: no energy consumed
- The Traffic: A set of flows L:
  - Each flow $l \in L$: from a source $s(l)$ toward a gateway $s \in S$
  - Multi-hop routing