Delay and Throughput in Random Access Wireless Mesh Networks

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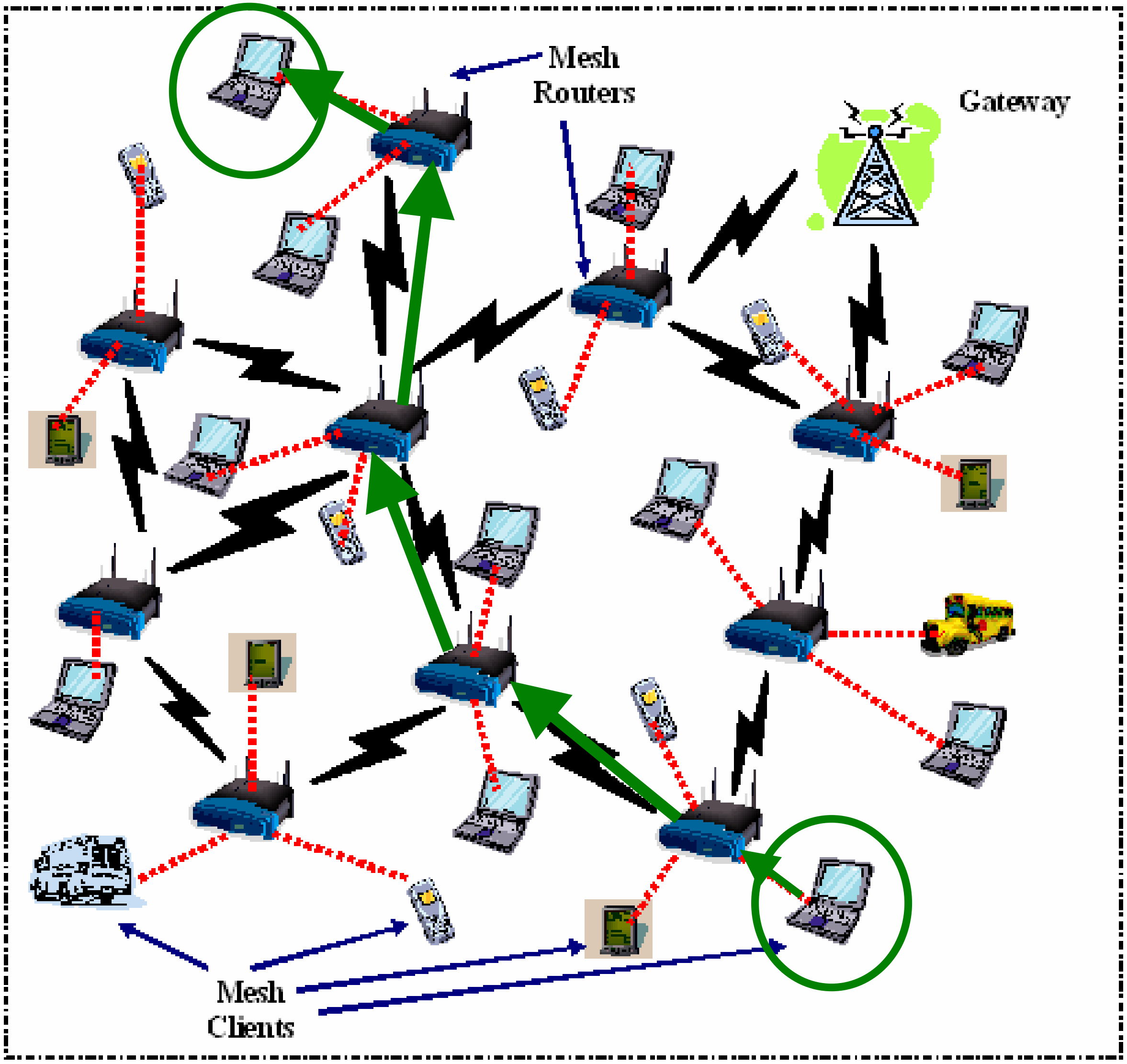
Wireless Mesh Networks (WMNs)

- WMNs are becoming increasingly popular for providing connectivity among communities
- Consists of mesh clients and mesh routers
  - Mesh clients: devices that require connectivity
  - Mesh routers: form backbone of WMN
- Compared to ad hoc networks, WMNs have infrastructure in form of mesh routers hence better performance is expected
- Examples: SeattleWireless, MIT Roofnet, Wireless Philadelphia, SoCalFreeNet

Mesh Routers

- Compared to mesh clients, the routers have enhanced features like larger transmission range, ability to communication on multiple channels
- When a mesh client needs to communicate with another client or gateway, it forwards the packet to its assigned mesh router
- Packet is then forwarded along the mesh router backbone until it reaches a router that is near the destination



A wireless mesh network

Motivation

- Design of WMN governed by
  - Mesh client density
  - Available budget
  - Required bit rate
  - Expected traffic pattern
- Size and budget of WMN may vary
  - MIT Roofnet – few clients, low budget
  - Wireless Philadelphia – thousands of clients, huge budget
- Attempt to answer questions like:
  - *What bit rate achievable if m routers with l available channels deployed to serve n clients?*
  - *How many clients can m routers with n available channels server so that desired bit rate is achievable?*
  - *What end-to-end delay to expect for a given implementation?*

Delay in WMNs

- Queuing delay depends on
  - ***Packet arrival process*** – How much traffic is handled by network?
  - ***Mesh router density*** – How many clients does a router serve?
  - ***MAC protocol*** – How the channel is shared among routers?
  - ***Traffic pattern*** – how many times a packet is forwarded over the router backbone before it reaches destination?
- End-to-end delay is sum of queuing and transmission delays at mesh routers
- Modeling all the factors is quite challenging

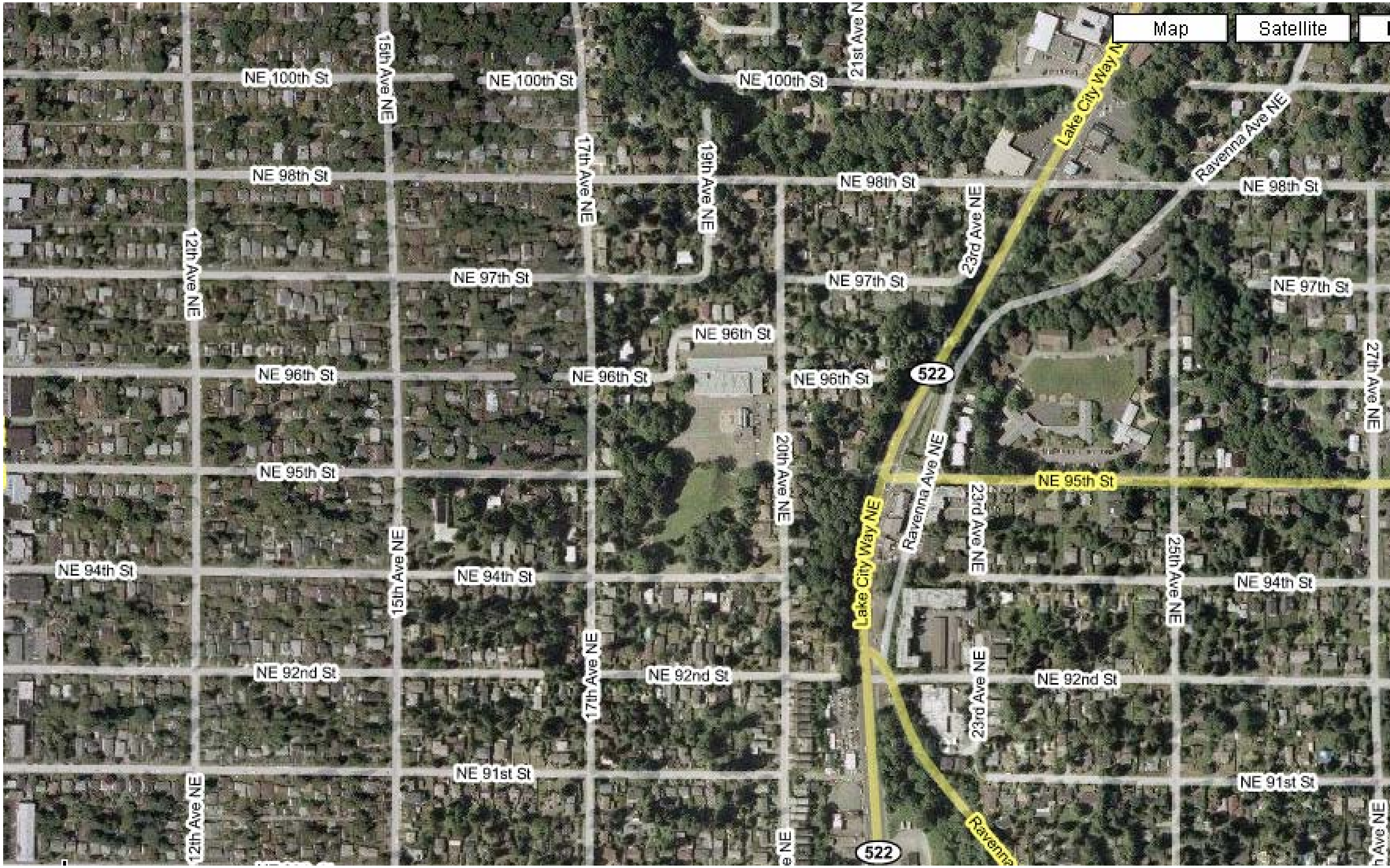
Throughput in WMNs

- *Maximum achievable per node throughput* of a WMN is the maximum rate at which the clients of the network may generate traffic while keeping delay finite
- Maximum achievable throughput is inversely proportional to
  - Average time a router takes to serve a packet
  - Average number of flows served by the routers

Our Approach

- Model multihop mesh networks as queueing networks
- Use Diffusion approximation method to evaluate closed form expressions of ***service time*** and ***end-to-end packet delay***
- Use the expressions of service time and delay to evaluate maximum achievable throughput

WMN Model



An urban neighborhood – Typical location for WMN deployment

WMN Model

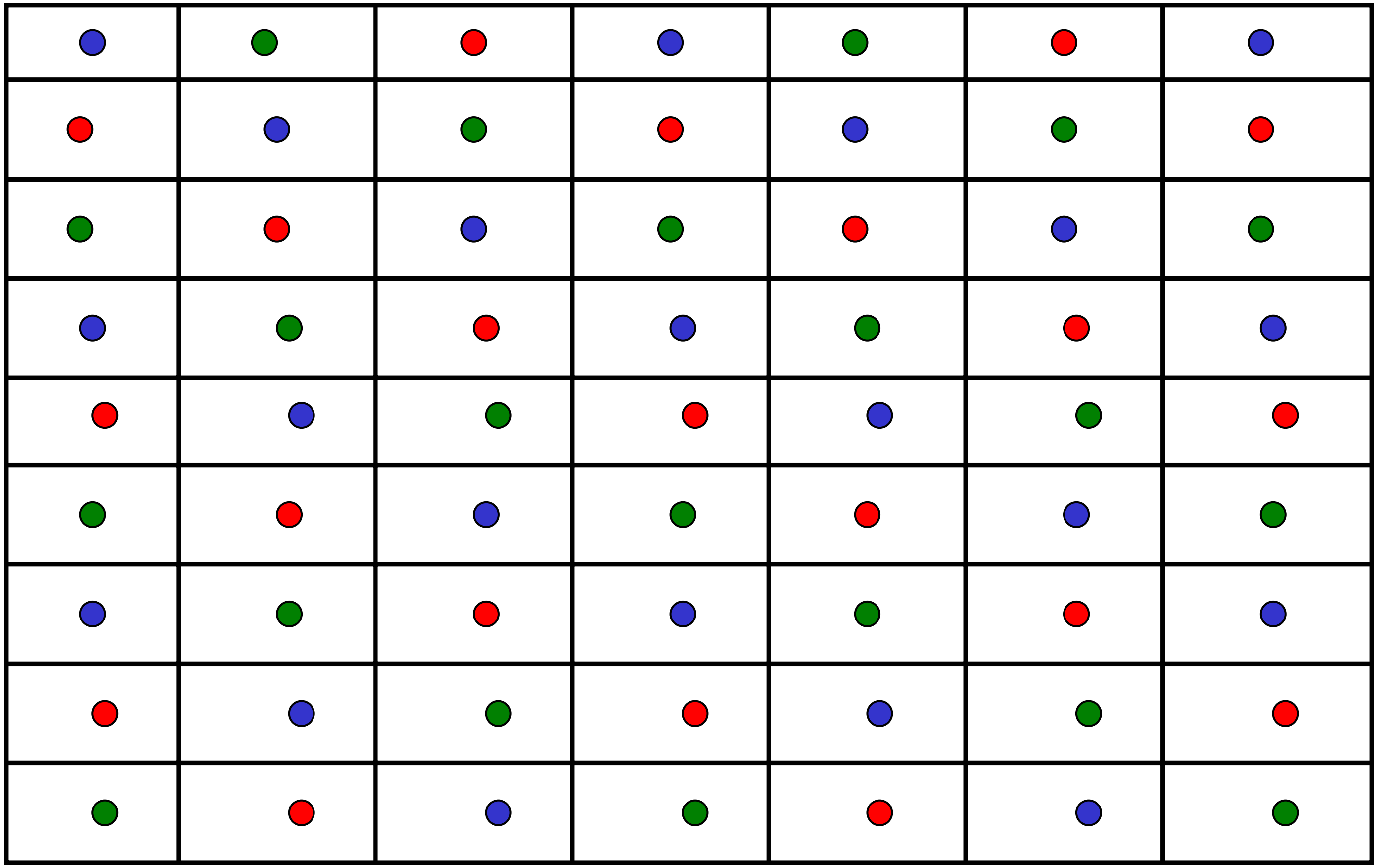
A common approach is to install one mesh router for each block

WMN Model

So a mesh network may be viewed as collection of disjoint cell, each having a mesh Router for serving clients within the cell

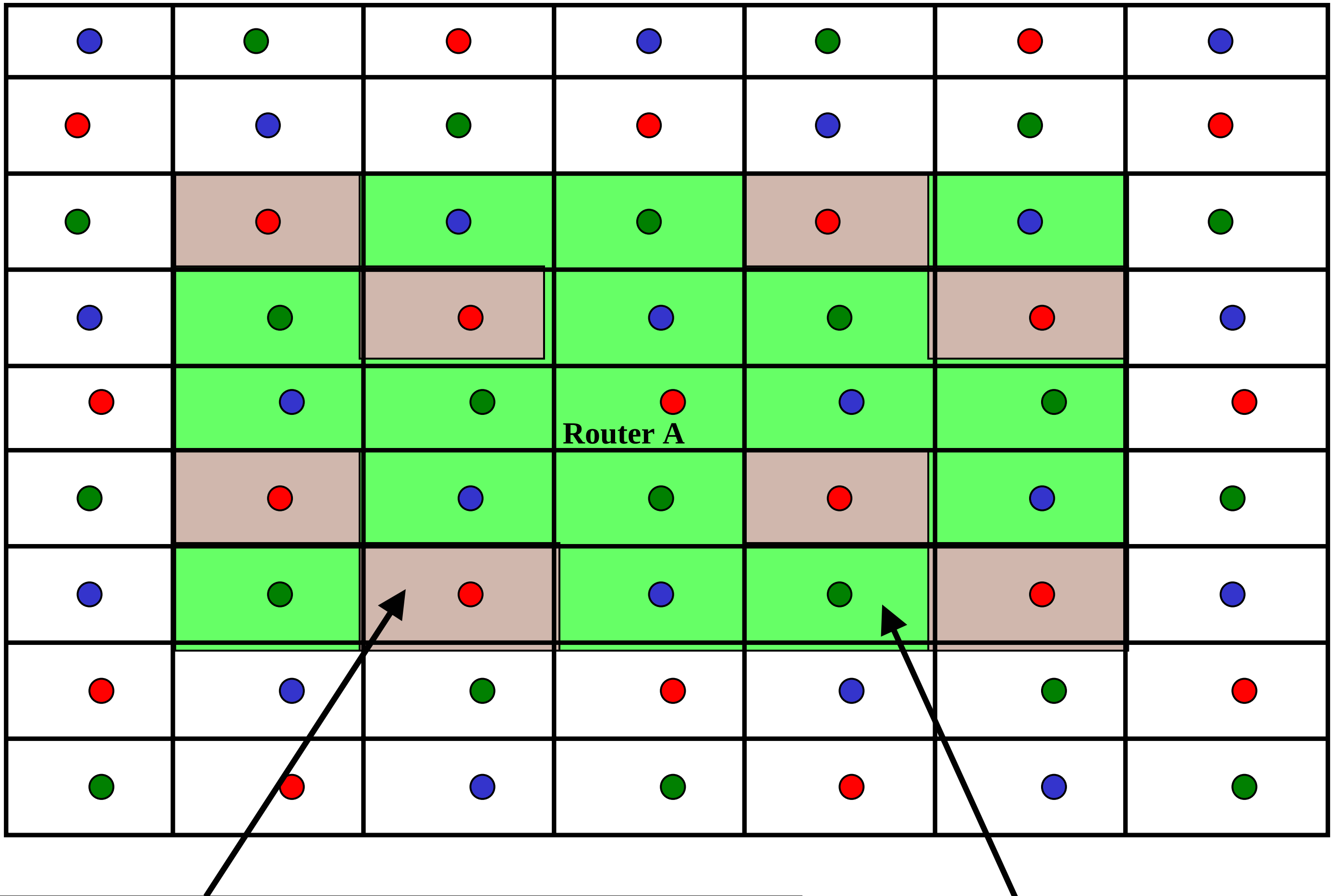
Mesh Model

- n mesh clients are uniformly and independently over a unit torus
- The torus is divided into disjoint identical cells of are $a(n)$ each, such that there are $m = 1/a(n)$ cells
- Each router can communicate with routers of neighboring cells
- Each mesh router can hear on all available channels (l channels), transmits on the particular channel allocated to it.
- All two hops neighbors transmitting on the **same channel** are ***interfering neighbors***



For example, IEEE 802.11 allows transmission on three orthogonal channels

- Routers transmitting on channel 1
- Routers transmitting on channel 2
- Routers transmitting on channel 3



Since routers transmit at different channels, ***number of interfering neighbors*** of Router A reduced to 8

Potential interferers of Router A = 24 Routers

Thus number of interfering neighbors (I) of a mesh router is a function of cell geometry and the number of available channels/interfaces

Traffic Model

- Each client produces packets of length L at rate λ packets/sec
- As soon as a packet arrives at a client, it is assumed to be transferred to the corresponding server) no delay at clients
- When a router receives a packet from a neighbors
  - The packet belongs to a clients within its cell with probability $p(n)$ (***absorption probability***)
  - The packet is forwarded to a randomly chosen neighbor with probability $1 - p(n)$
- That is, the fraction of packets received by a router that are destined to its cell equals $p(n)$

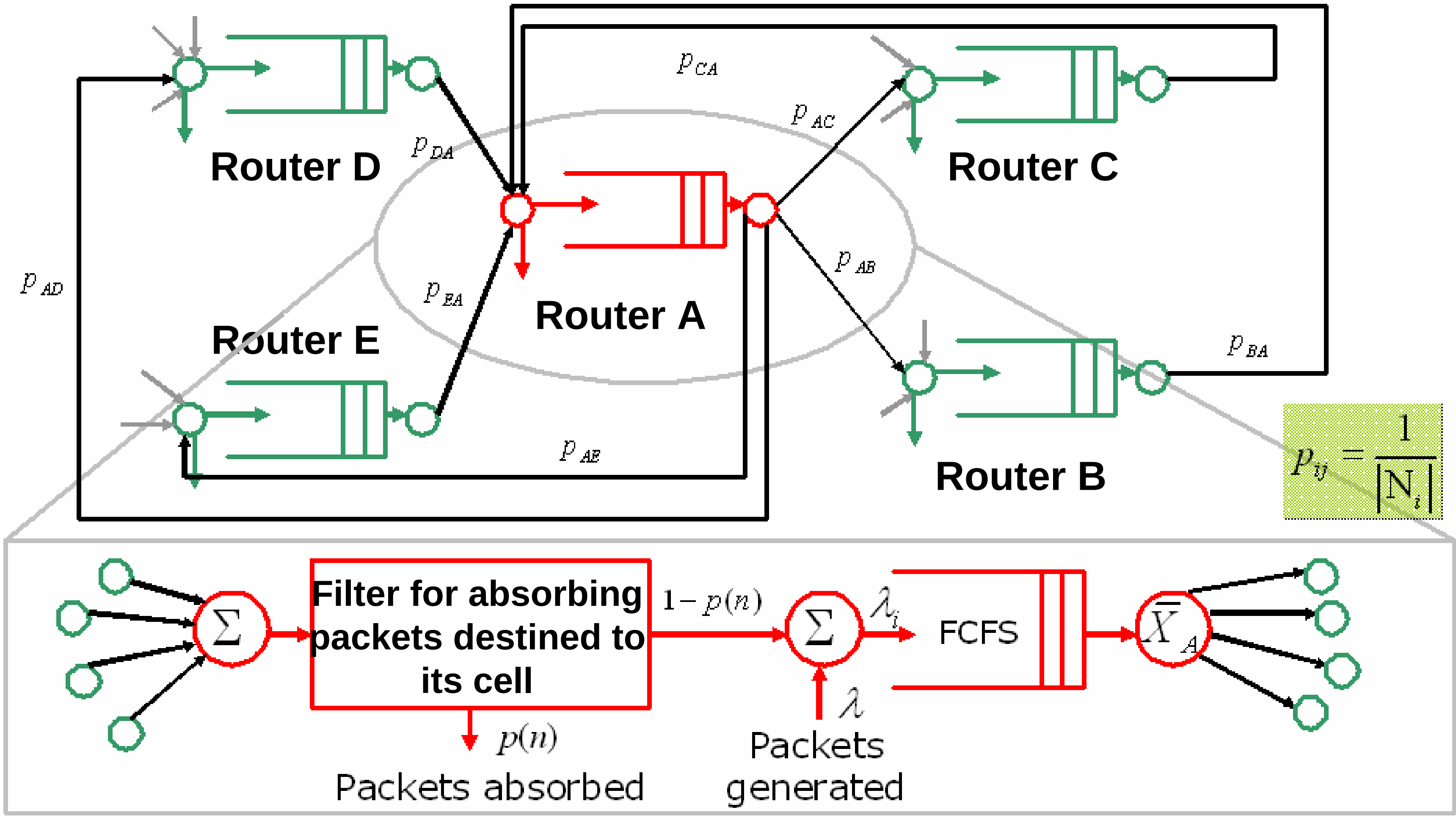
$p(n)$ characterizes the degree of locality of traffic – Low $p(n)$) average number of hops between a source destination pair is large

MAC Model

- Before transmitting a packet each router counts down a random timer
- The duration of the time is exponentially distributed with mean $1/\xi$
- Once the timer of a router expires it starts transmitting and at the same instant the timers of all interfering neighbors is frozen
- The frozen timers are resumed as soon as the current transmission finishes

The MAC model captures the collision avoidance mechanism of IEEE 802.11 and is still mathematically tractable

Queuing Model



G/G/1 queuing network

Each station of the queuing network represents a mesh router. Diffusion approximation is used to solve the queuing network

Service Time Result

- Average service time of a mesh router

$$\overline{X_i} = \frac{\frac{1}{\xi} + \frac{L}{W}}{1 - \lambda_i \mathcal{I}(L/W)}$$

Service time in absence of interference

Fraction of time the channel is busy

$\mathcal{I}$: Number of interfering mesh routers

$\lambda_i = \frac{na(n)\lambda}{p(n)}$: Overall packet arrival rate at a mesh router

$\frac{L}{W}$: Time required to transmit a packet

$\frac{1}{\xi}$: Mean backoff duration

Service Time Result

- Average end-to-end packet delay

$$\overline{D} = \frac{\rho}{na(n)\lambda(1-\hat{\rho})}$$

$\rho = \lambda_i \overline{X_i}$: Utilization factor of a mesh router

$\hat{\rho} = \exp\left(-\frac{2(1-\rho)}{c_A^2 \rho - c_B^2}\right)$

c_A^2: Squared coefficient of variance (SCV) of inter-arrival time

c_B^2: SCV of service time

Maximum Achievable Throughput

- Maximum Achievable throughput of a mesh client

$$\lambda_{max} = \frac{1}{\bar{s}na(n)\left(c+\frac{L}{W}\mathcal{I}\right)} \text{ or } \lambda_{max} = \Theta\left(\frac{1}{\bar{s}na(n)}\right)$$

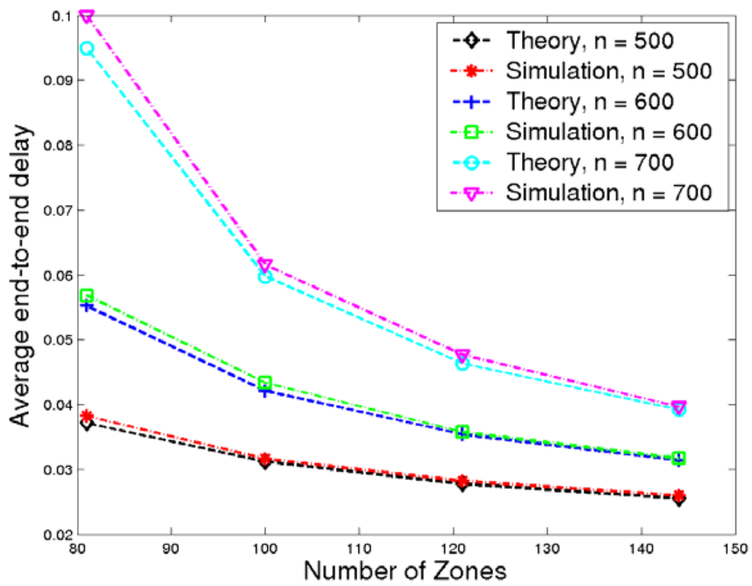
Where $\bar{s} = 1/p(n)$: Average number of hops traveresed by a packet

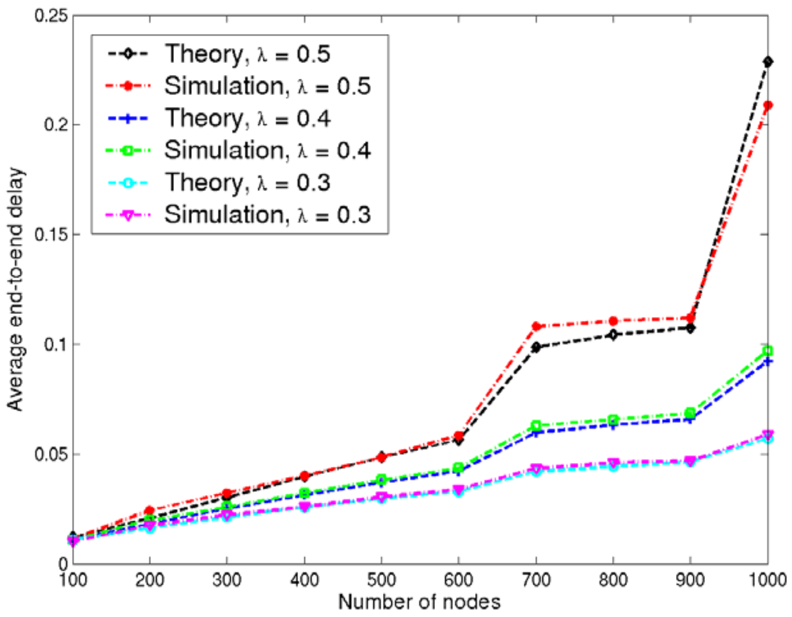
- For $p(n) = \sqrt{\frac{\log(n)}{n}}$ and $a(n) = \frac{\log(n)}{n}$ (parameters comparable to G-K model)

$$\lambda_{max} = \Theta\left(\frac{W}{\sqrt{n \log n}}\right)$$

Thus for random access WMN, G-K bound is asymptotically achievable although channel capacity is wasted by random access MAC. This is because the number of interfering neighbors is independent of *n* and thus the channel capacity wasted due to collision avoidance mechanism does not depend on *n*.

Simulation Results





The analytical results agree well with those obtained from simulation

Comparison of Maximum Achievable Throughput for Ad Hoc and Mesh Networks

$$\frac{\lambda_{max_{mesh}}}{\lambda_{max_{ad\ hoc}}} \approx \frac{\frac{1}{(\sqrt{A(n)/a(n)})n/m}\frac{1}{\xi} + \frac{L}{W}\left(\frac{1}{(\sqrt{A(n)/a(n)})n/m} + 4\sqrt{\frac{A(n)}{a(n)}}\right)}{\frac{1}{\xi} + (\mathcal{I}+1)\frac{L}{W}}$$

- This ratio depends on
  - Number of clients per cell $\left(\frac{n}{m}\right)$
  - Ratio of communication area to cell area $\left(\frac{A(n)}{a(n)}\right)$
  - Number of interfering neighbors in WMN $(\mathcal{I})$
- It is possible to choose values for above quantities such that the ratio is less than one – A badly designed mesh network may do worse than infrastructure-less ad hoc network

Conclusion

- Developed queuing network models for ad hoc and mesh networks
- Used diffusion approximation to solve them
- Obtained closed form expressions for delay and maximum achievable throughput
- Future Work: Develop and solve queuing networks for WMN with one or many gateways