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 communicate 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
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:

- **Red**: Routers transmitting on channel 1
- **Green**: Routers transmitting on channel 2
- **Blue**: Routers transmitting on channel 3
Router A

Potential interferers of Router A = 24 Routers

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

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 $\lambda$ 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 neighbor:
  - The packet belongs to a client 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 $p(n)$ implies 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 $\frac{1}{\xi}$.
- 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

\[ \overline{X}_i = \frac{1}{\xi} + \frac{L}{W} \left( 1 - \lambda_i I(L/W) \right) \]

- Service time in absence of interference
- Fraction of time the channel is busy

\( I \): Number of interfering mesh routers

\( \lambda_i = \frac{n a(n) \lambda}{p(n)} \): 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
  \[ \lambda_{max} = \frac{1}{\bar{s}na(n)\left(c + \frac{L}{W}I\right)} \]  
  or \[ \lambda_{max} = \Theta\left(\frac{1}{\bar{s}na(n)}\right) \]

  Where \( \bar{s} = 1/p(n) \): Average number of hops traversed 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

\[ \frac{\lambda_{\text{max, mesh}}}{\lambda_{\text{max, ad hoc}}} \approx \frac{1}{(\sqrt{A(n)/a(n)})n/m} \left( \frac{1}{(\sqrt{A(n)/a(n)})n/m} + \frac{L}{W} \right) \left( \frac{4 \sqrt{A(n)}}{a(n)} \right) \frac{1}{\xi + (\mathcal{I}+1) \frac{L}{W}} \]

- 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