Measurement Driven Deployment of a Two-Tier Urban Mesh Access Network

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Two-Tier Mesh Architecture

- Limited Gateway Nodes wired to Internet
- Mesh Nodes wirelessly forward bandwidth
- Backhaul Tier (Blue) - mesh node to mesh node
- Access Tier (Red) - mesh node to client node
City-wide Two-tier Mesh: Houston RFP

- Three tiers of access: public service, Internet access, safety
- 620 square miles, Coverage:
  - 95% Outside
  - 90% Inside (window)
- $1 million startup capital downtown, $100 million total
- 18k mesh nodes, 3k gateways, Over 1 million end nodes!
Technology For All/Rice Deployment

- TFA MISSION: “Empower low income communities through technology”

- Pilot neighborhood: Houston’s East End
  - Per capita income 1/3 national average ($10k), 37% of children below poverty
  - 64.2% of adults without GED

- 4.2 km² covering 40,000 residents

- Education and work-at-home (“Learn-and-Earn” and Job-Tech)
Outline

• TFA/Rice Background
• Objectives and Hardware
• Measurement Driven Deployment
  • Single Hop Measurements
  • Multihop Measurements
  • Computational Placement Model
• Related Work
• Conclusion
TFA Design Objectives

- Single wireline gateway (burstable to 100 Mb/sec)
- Coverage for entire 4 sq. km neighborhood (vs. only homes with mesh nodes)
- 1 Mb/sec minimum access rate
- $15k per square km
- Programmable platform for protocol design and measurement
Off-the-Shelf Hardware

- **Mesh Node**
  - 802.11b, 200mW, Linux OS
  - 1GHz x86, 4GB Flash
  - 15 dBi antennas at 10 m (serve both access and backhaul)

- **Client Node**
  - 802.11b, 200mW
  - Engenius CB-3 Ethernet Bridge (like DSL/Cable modem)
Methodology

- **Single Link Behavior** = pathloss ($\alpha$), throughput as a $f(SNR)$
- **Multihop Measurements** = traffic matrices ($\beta$)
  - Long-lived TCP flows, Static Rate Limited Flows, Web Traffic
- **Placement Study** = wire ratio ($w$), topology (regular grid, regular grid w/ perturbations, and random)
  - Average mesh node throughput
- **Network Reliability**
Single Hop Experiments

- Empirically measure importance of critical deployment factors
  - Accurate understanding of propagation environment (pathloss)
  - Accurate throughput to signal strength mapping
- Link Measurements
  - Backhaul and Access* Links

* Not shown here, see results in paper
Backhaul Link Measurements

- 235 Measurements (30 seconds)
- Concentrated measurements at distances > 175 meters
- Experiment Set-up
  - 10 m height for fixed node
  - 10 m height for portable node
  - UDP traffic
  - RTS/CTS enabled
  - PHY layer autorate enabled
Throughput (SNR)

- Need to find throughput as a function of signal strength for model
  - Manufacturer specification not sufficient (overly optimistic)
- Linear Approximation on logarithmic scale
- Target throughput for backhaul links 3 Mbps
  - -75 dBm signal strength
  - Access: -86 dBm for 1 Mbps (DSL speeds)
Pathloss

- Pathloss ($\alpha$) = 3.3
  - Theory - urban pathloss from 2 to 5
  - Increased pathloss (access links 3.7)
  - Increased height and better antenna
- Increased Shadowing, 5.9 where access links (4.1)
- 200-250 m range at -75 dBm for 3 Mbps
  - Access: 150-200 m range at -86 dBm for 1 Mbps
Deployment Findings

- Accurate propagation measurements critical (theory says 2 to 5)
  - Findings from placement model when we set internode spacing according to theory
    - 2 yields completely disconnected network
    - 3.5 yields overprovision factor of 55%
    - 4 yields overprovision factor of 330%
    - 5 yields 9 times overprovisioning (approx. $1 Billion vs. $100 million for Houston!)

- Accurate throughput-signal-strength function critical - manufacturers values overestimate link range 3X -> disconnected

- Requires only a few measurements
  - 15 random measurements = std. dev. 3% about average
  - 50 random measurements = std. dev. 1.5% about average
Multihop Experiments

- Issue: Spatial Bias
- Single Active Flow known
- Multiple active flow experiments measured
- Interflow and self-contention

- Experiments:
  - Long-lived TCP Flows (Upload, Download*, Bidirectional*)
  - Rate Limiting
  - Web traffic* (download)

* Not shown here, see results in paper
TCP Long-lived Upload

- Upload experiences severe spatial bias
- Packet loss (from contention/collision) exacerbates effect
- RTS/CTS overhead outweighs fairness improvement for starved nodes
Rate Limiting

- Experiment: statically rate limit all nodes to the same rate (x-axis)
- Expect fair rate to be 1/9 (444 kbps) of effective capacity (4 Mbps)
- Result: 450 kbps has fair per-node throughput
- Upload still has spatial bias at 450 kbps
Multihop Measurement Findings

• Imperative to consider contending flows
  • Single active flow measurements lead to large fraction of starving and disconnected nodes (comparing the $\beta$ values yields avg. throughput per mesh node of twice actual -- 2x overestimation)

• Starvation in fully backlogged upload
  • Compounding of MAC-induced loss & equal prioritization of intermediate node’s and forwarded traffic

• RTS/CTS overhead outweigh gains in starved nodes

• Proper limiting of flows alleviates starvation

• Web traffic allows statistical multiplexing to alleviate starvation (even without rate limiting)
Placement Study

- Results
  - Effect of Traffic Matrices
  - Effect of Perturbations
  - Reliability*
  - Grid vs. Grid w/ Perturbations vs. Random*
  - Case Study Network Deployment*

- Experimental Set-up
  - Square (Manhattan) Grid, add perturbations
  - Poisson placement for random topologies

* Not shown here, see results in paper
Effect of Traffic Matrices

- Rate limited flows achieve approx. 1/2 of long-lived flows
- Unfair traffic pattern
- Web traffic able to achieve both high throughput and fairness
- Employing dynamic rate limiting w/ web traffic would be ideal
Perturbations

- Increase in std. deviation as perturbation increase
- 6% increase in throughput up to 40 meters (1/6 of inter-node spacing)
- Not In My Backyard Scenario
  - Uniform perturbation distribution
  - 225 m spacing (grid)
Status of TFA Deployment

- 12 Nodes (Red) Deployed
- Approximately 2 square kilometers covered and growing
- 700+ users and rapidly growing
- New Devices (PDAs) and applications (health care)
Related Work

- MIT Roofnet Measurements
  - Strong line-of-sight component, Single Tier
  - Single active multihop flows

- Philadelphia Wireless Spectrum Analysis
  - Spectral scan of 49 points (135 mi.²)
  - Signal strength measurements of access links

- Optimizing the Placement of iTAPs (Microsoft)
  - Wired mesh node placement problem
  - Analytical optimization formulation
Conclusion

• Critical factors to consider in deploying mesh networks
  • Accurate knowledge of propagation environment
  • Accurate throughput-signal-strength function
  • Traffic characterization must include concurrently contending multihop flows
• Rate Limiting to avoid starvation of multihop flows
• Placement Study to explore mesh deployment factors
  • Random suitable for one-tier small scale but not large scale
Future Work

- Management of TFA Network
  - Traffic Management with QoS
    - Dynamic rate allocation scheme to instill fairness
  - Capacity Planning
    - From Coverage Limited to Capacity Limited: The evolution of a mesh network
  - Security, DDoS
    - Mesh traffic force single point of failure, security is critical
- Rice TAPs/WARP Platform Collaboration
Questions...?

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Web Traffic

- Expect load to saturate at 30 users, where the first link becomes saturated
- 80 users - similar spatial bias to fully backlogged case
- Web traffic acts as singly active flows on small-scale of time
- On average, only one flow active up to 25 users

Web-emulation script (C) - Two minute trials
5 to 80 constant users on nodes B through E
Download 30 kB webpage, 7 second “think” time, exponentially distributed
Assume gateway node is not the bottleneck