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A Measurement Study of Multiplicative Overhead Effects in Wireless Networks

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http://networks.rice.edu

System: Large-scale, Multi-tier Mesh Network

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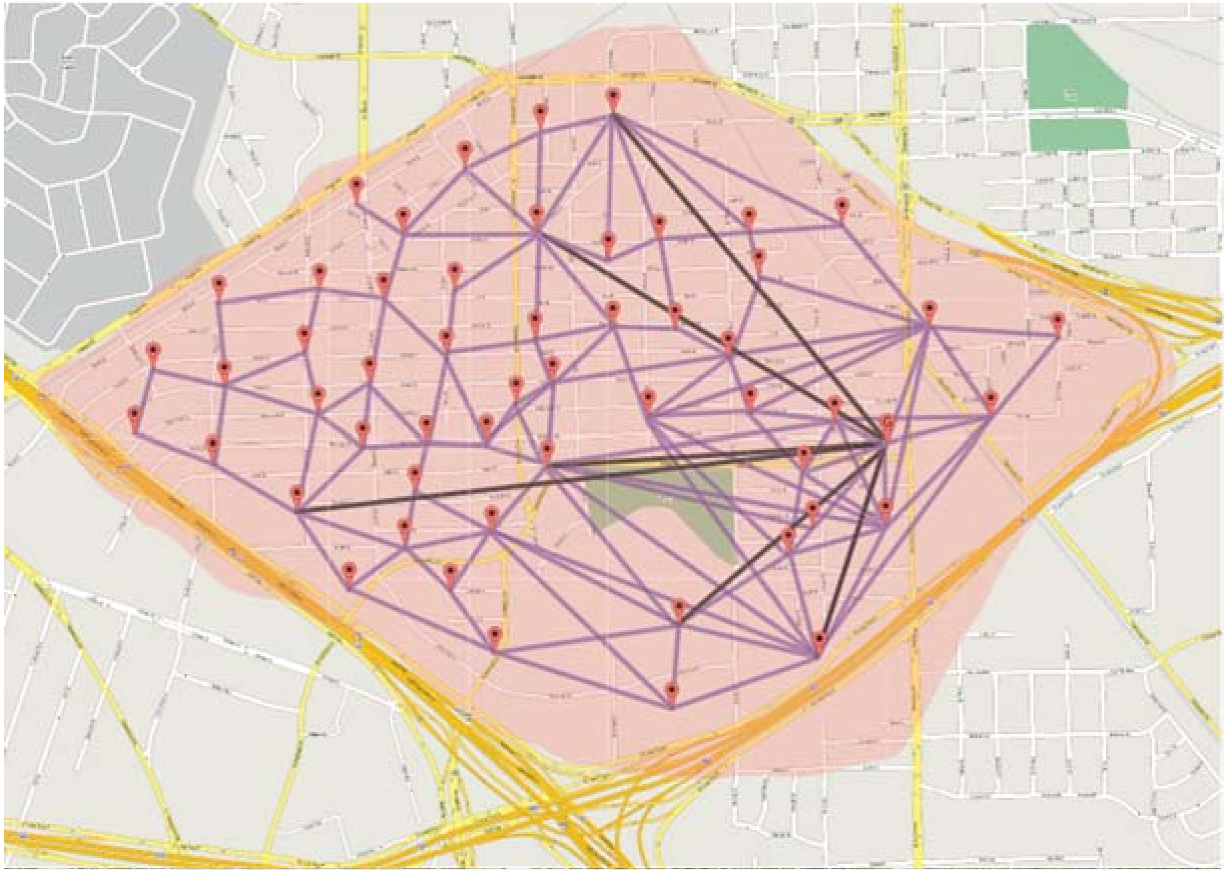

TFA-Rice Mesh Deployment
http://tfa.rice.edu

- Serving 4,000 users over 3 km^2
- 802.11b access and backhaul tiers
- 802.11a directional tier for capacity injection
- Multiple radios at gateway nodes, single radios elsewhere

Background

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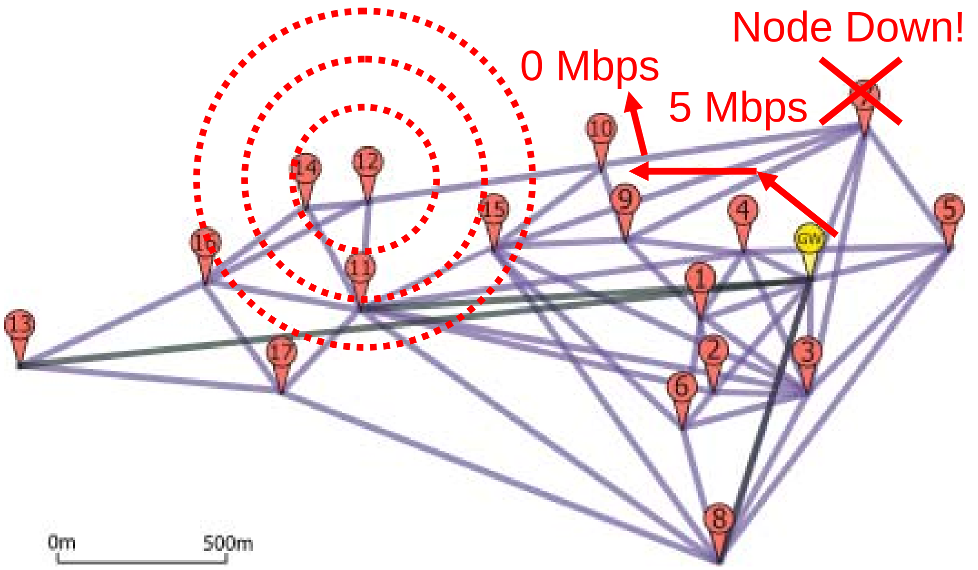
Two key components driving this study are present in all wireless networks, not just mesh networks (e.g., TFA):

1. Heterogeneous Connectivity Set
   a) Forwarding links (selected by routing protocol)
   b) Non-forwarding links (broadcast medium)

2. Data and Control Planes
   a) Large-sized data frames
   b) Small-sized control frames
      1) Link Establishment
      2) Routing
      3) Congestion Control
      4) Network Management



Contributions

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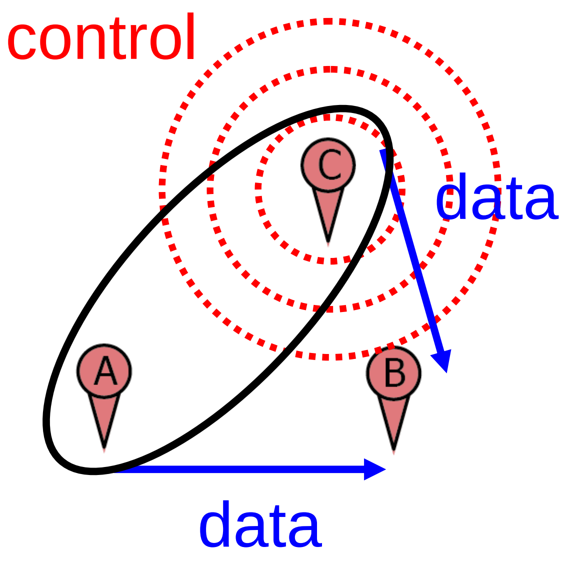
Heterogeneous connectivity matrix produces two key effects:

- Control frames force multiplicative degradation on data plane
  - Overhead traffic at rate r can reduce data throughput by up to 50 times r
  - Wireless Overhead Multiplier driven primarily by **non-forwarding** links



- Competing data flows have severe throughput imbalance and poor network utilization
  - RTS/CTS ineffectiveness coupled with heterogeneous links
  - Lower rate forces longer transmission time, decreasing success probability

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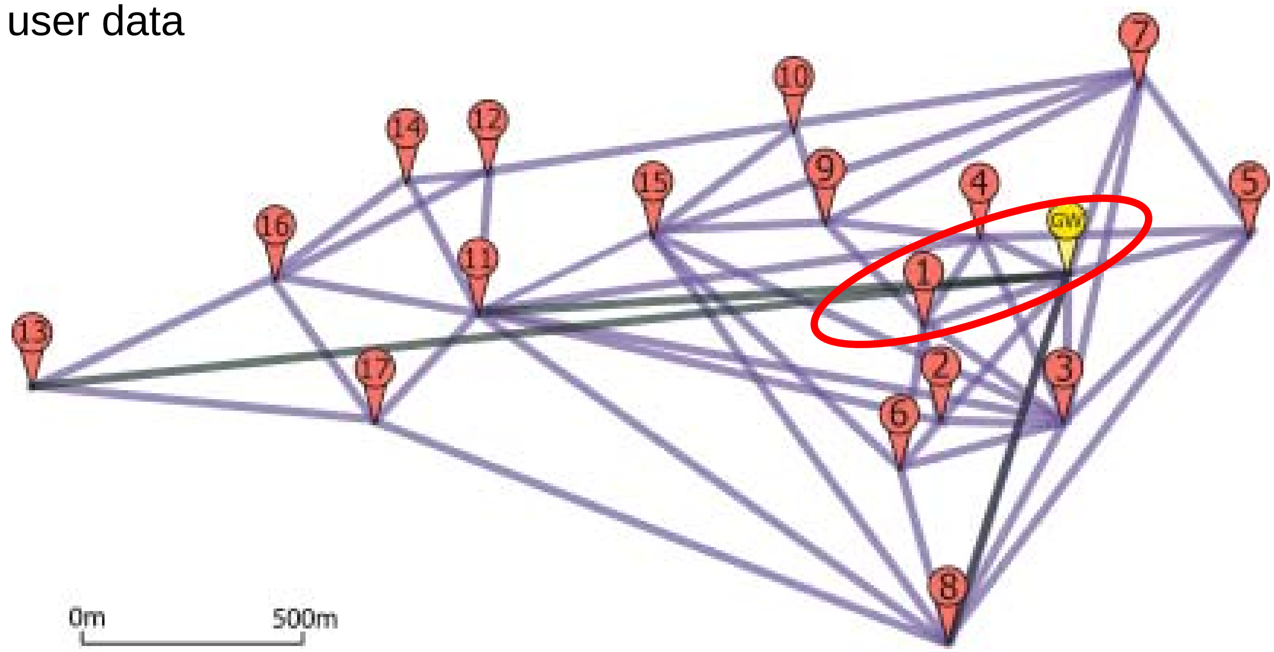
Impact of Overhead

- Without network overhead (small-sized packets including AODV, beacons):
  - Minimal control overhead from only TX and RX
- With network overhead:
  - All the overhead of the control protocols from all other nodes
- Experiment Details:
  - All one-hop nodes from gateway
  - UDP traffic (1500B)
  - No user data



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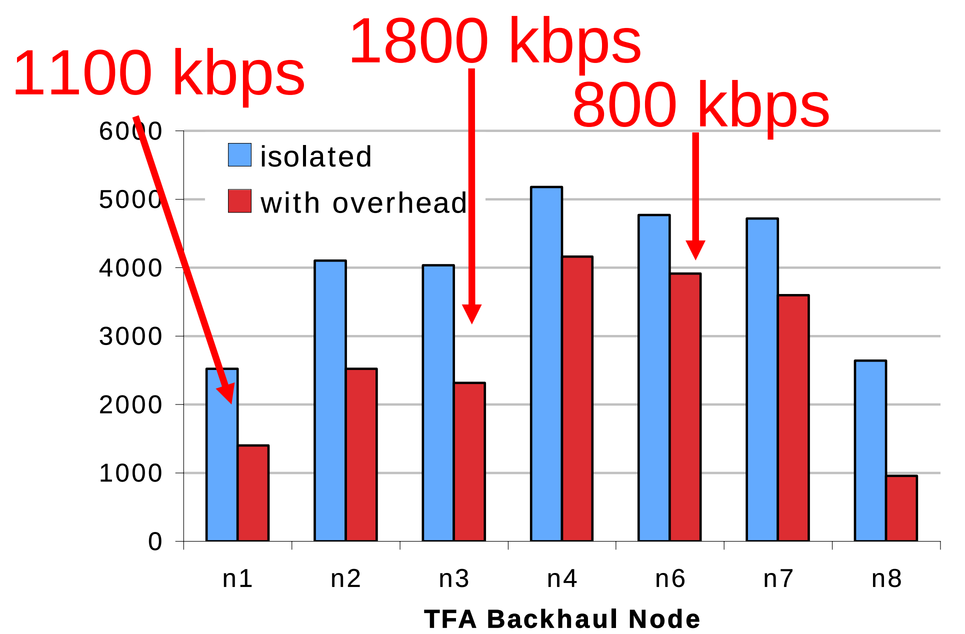
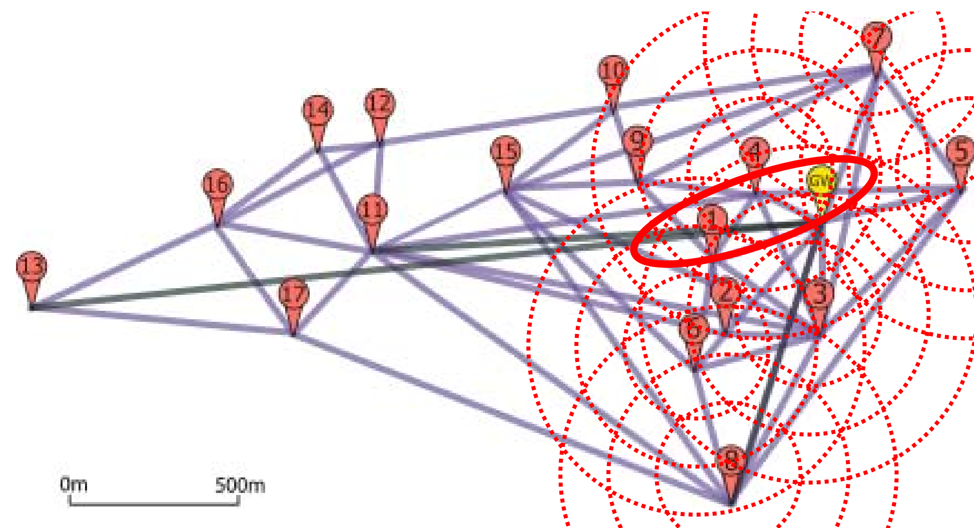
Diverse Overhead Effects

- Identical hardware platform
- Identical configuration
  - TX power 200 mW, RTS disabled, Autorate enabled
- Overhead of 80 kbps (approx. 10 kbps/node)
- Vastly different performance with and without overhead
  - 800 to 1800 kbps degradation
  - 10-20 times injected overhead





Wireless Overhead Multiplier Definition

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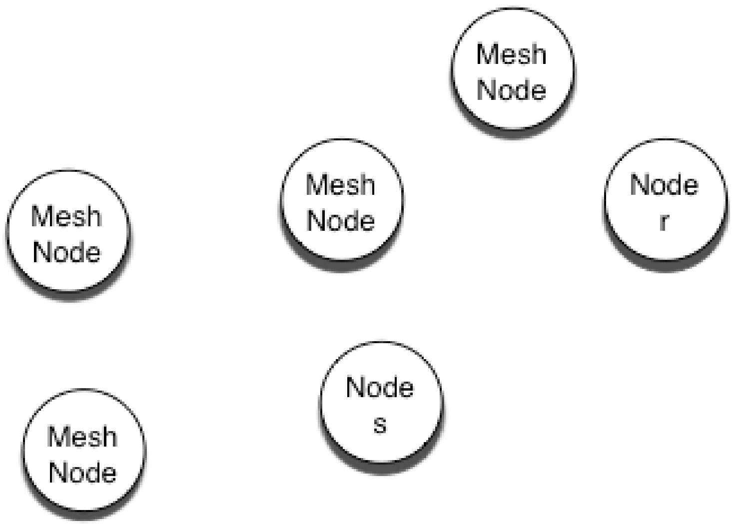
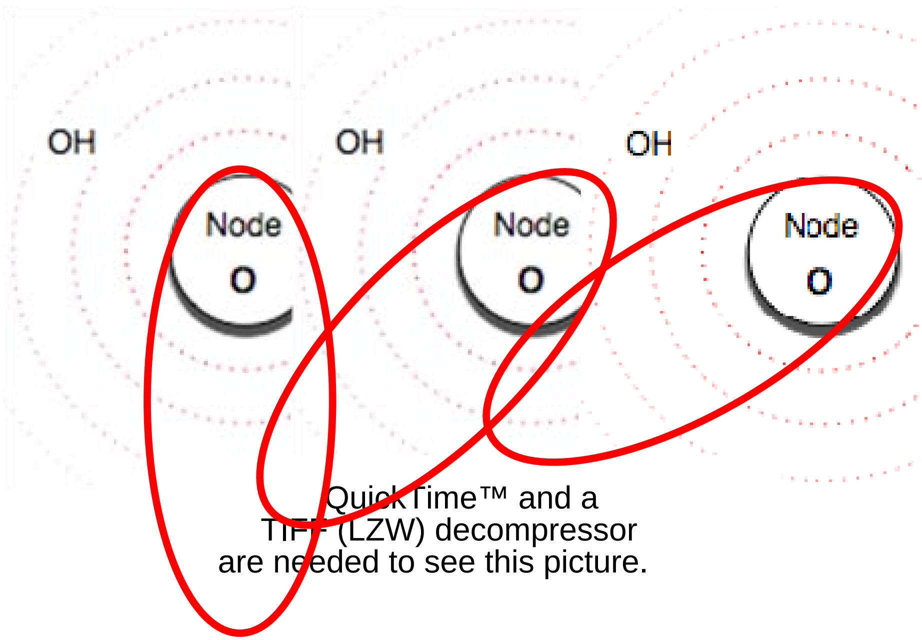
- Define WOM to quantify the effect of the bits of overhead
  - O is a set of OH-injecting nodes, where $o \in O$
  - λ_O is bits/sec of injected overhead from O
  - $t_{s \to r}^{\{s,r\}}$ is saturation throughput of tx (s) and rx (r)

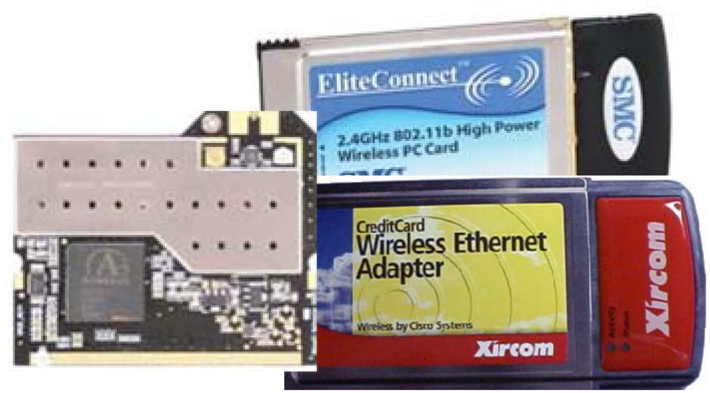
$$W_{s \to r} = \frac{t_{s \to r}^{\{s,r\}} - t_{s \to r}^{\{s,r\} \cup O}}{\lambda_O}$$



Link Behavioral Classes for Heterogeneity

- Typical WOM experiment set-up
  - TX (s) fully backlogged to RX (r)
  - UDP, TCP traffic, RTS disabled
- Node o (OH-injecting node) has various link quality to s and r
- Classes of transmitter behavior according to IEEE 802.11 (o to s)
  - Decode Transmission
  - Detect Channel Activity
  - Unable to Detect Channel Activity
- In-lab experiments on widely used chipsets (Prism and Atheros) and drivers (HostAP and MadWiFi)
  - No threshold where carrier sense occurs





WOM for Two TFA Link Classes

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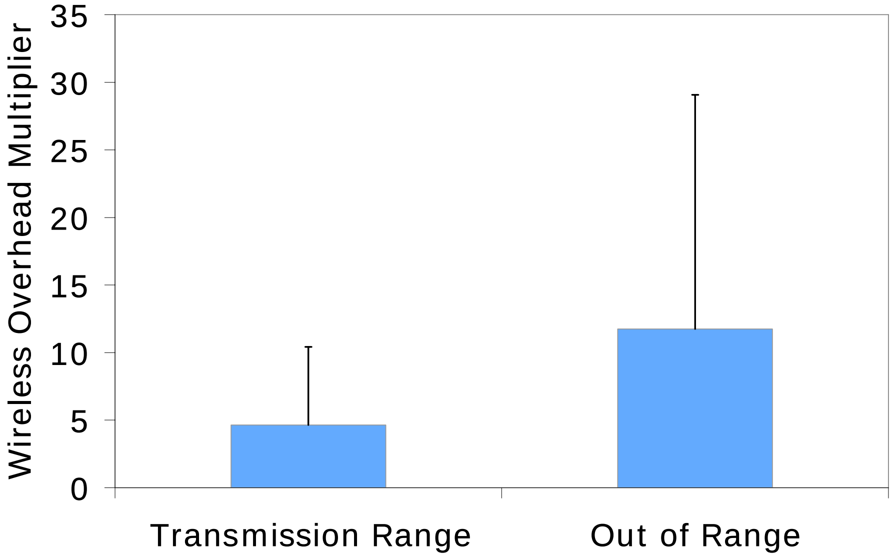
- Data Set of 3-node Topologies
  - All one-hop nodes around GW
  - TCP and UDP traffic
  - Autorate enabled, RTS off
  - Measured injected overhead: 10 kbps

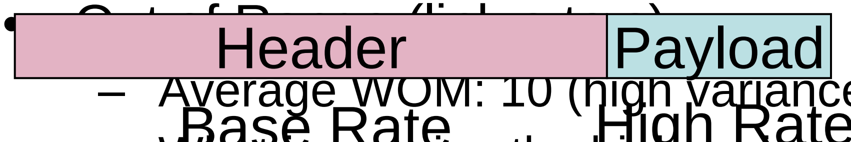
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- Transmission Range (link o to s)
  - Overhead effectively sent at base rate (2 Mbps)
  - On average, quality of TFA links enables 11 Mbps operation



TCP data traffic (1500 byte),
Autorate enabled, RTS off

- Out of Range (link o to s)
  - Average WOM: 10 (high variance)
  - What is causing the high variance in WOM?



Relative Link Quality of Competing Links

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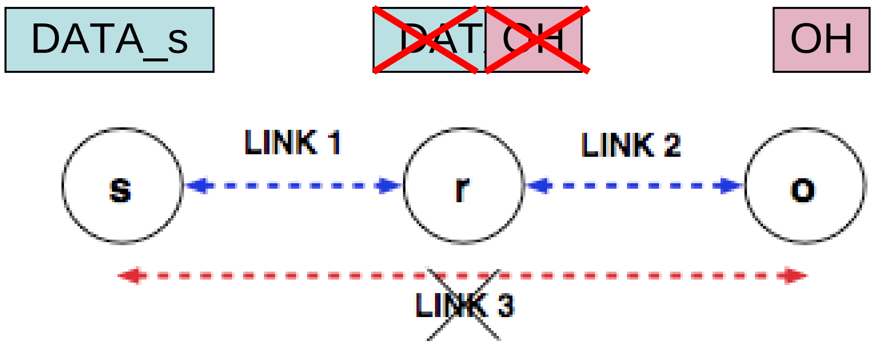
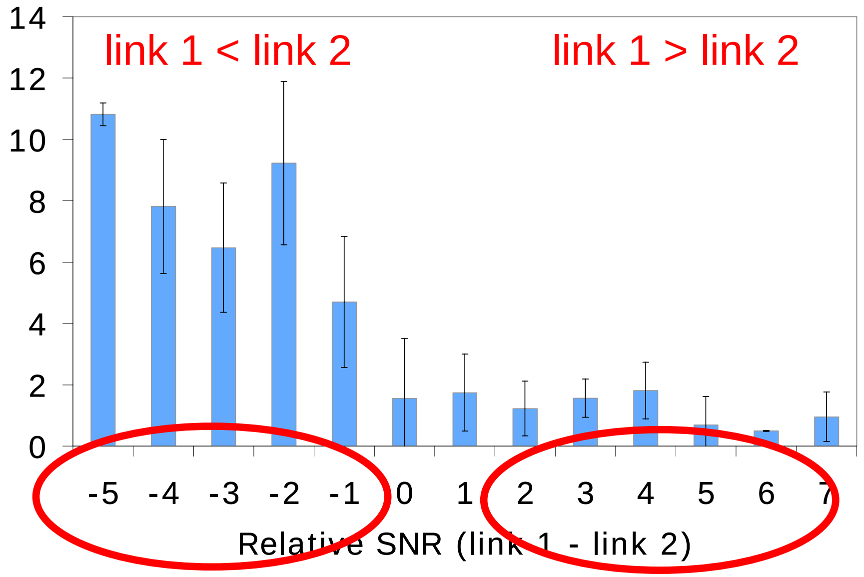
- Same link behavior as defined by 802.11 (unable to carrier sense) but high variance - why?
  - Same injected overhead and non-forwarding links
  - Expect high WOM values (low variance)
- Find impact of relative forwarding link quality
- Expected high WOM as data flow has lower quality
- Asymmetric WOM with forwarding link differences

physical layer capture

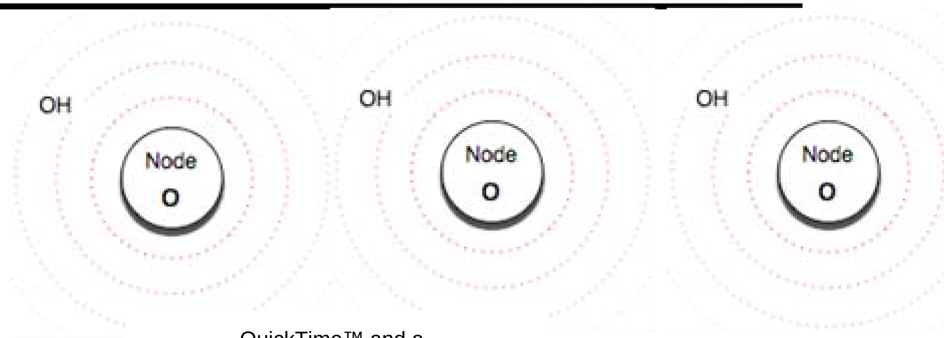




UDP data traffic (1500 byte), Autorate disabled, RTS off

Reconsidering Link Classes for WOM

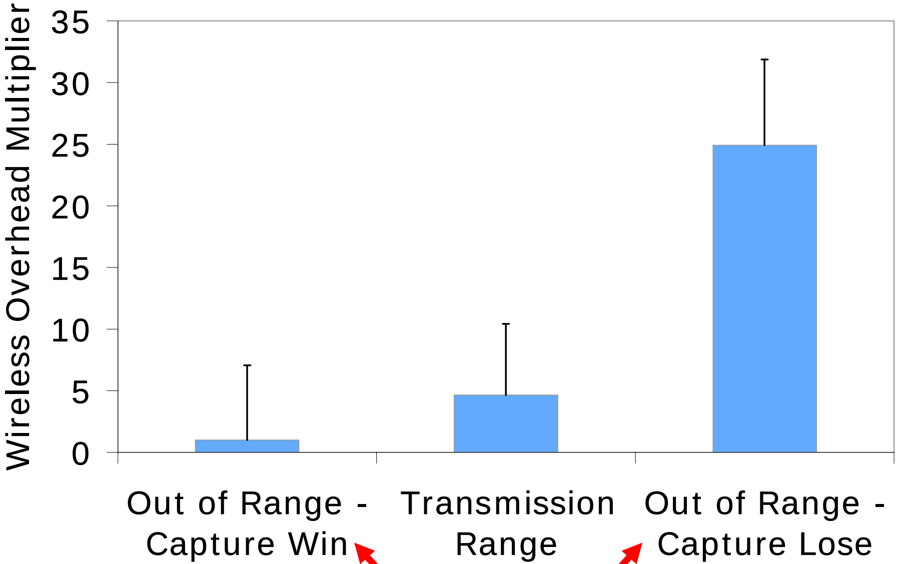
- Asymmetry of hidden terminal class, must reconsider WOM classes
  - Split hidden terminal link class



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- Node winning capture has minimal WOM
  - Slightly better than transmission range

- Node losing capture has WOM of up to 30



TCP data traffic (1500 byte),
Autorate enabled, RTS off

Cumulative Link Effects

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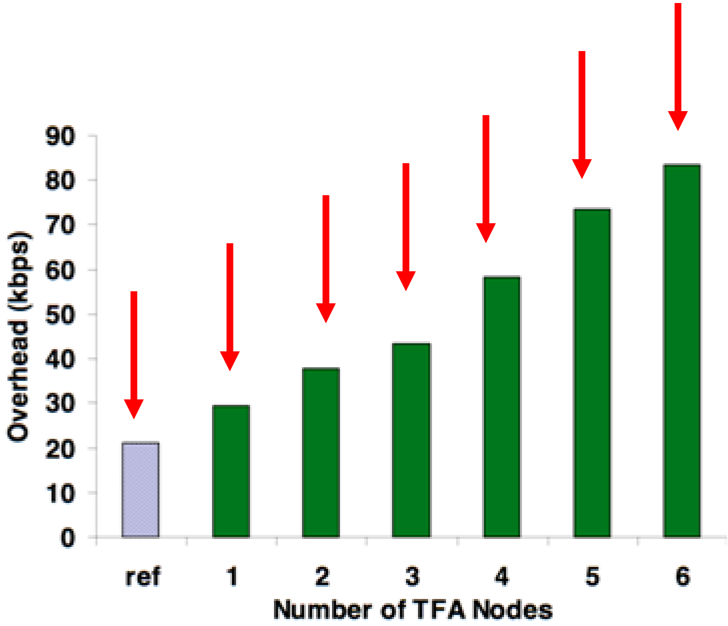
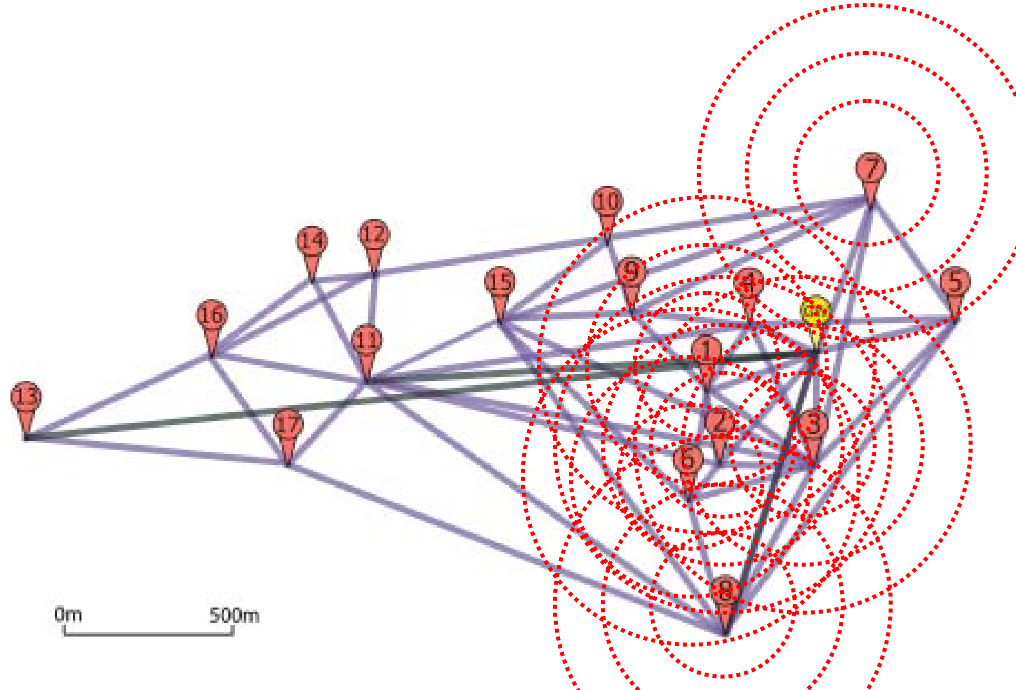
- Measure injected overhead as it scales with TFA backhaul nodes
- Measure achievable throughput with increasing number of OH-injectors

- Measured Overhead (AODV, Beacons)
- Reference point for overhead of other networks (no TFA nodes on the channel)
- **10 kbps** overhead per node





Cumulative Link Effects

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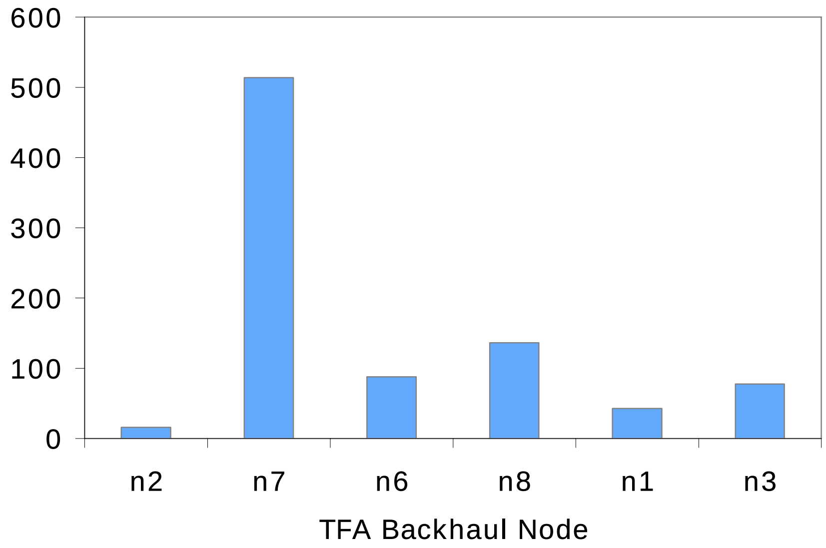
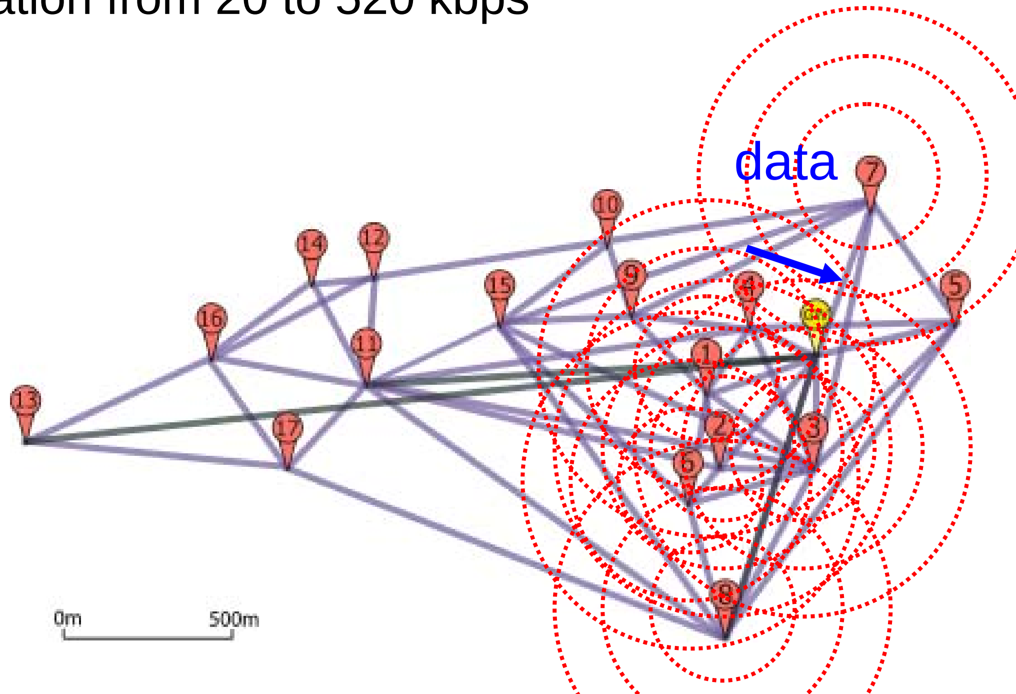
- Findings in 3-node topology hold for more complex topologies
- Node n4 sends data to GW
  - Wins capture with n2 (20 kbps)
  - Loses capture with n7 (520 kbps)
  - Hidden, unclear capture result with n6 and n8 (differ < 1dB at GW)
  - Transmission range with n1 and n3
  - Span of throughput degradation from 20 to 520 kbps





Worst Case WOM Scenario for Data Flows

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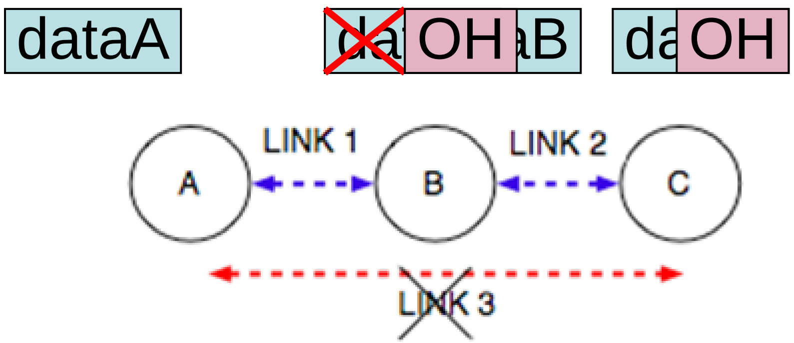
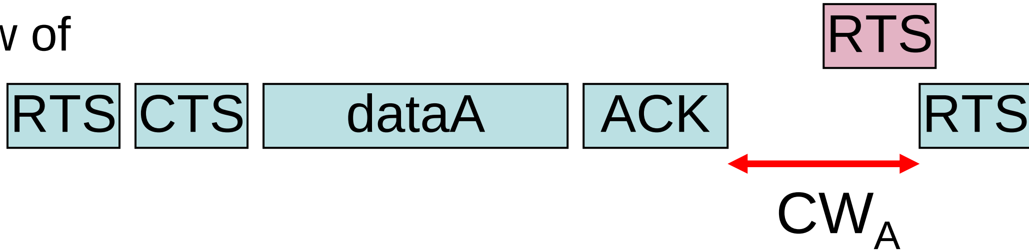
- Capture-losing data flow with competing OH
- Capture-losing data flow with competing data
  - Frequency of loses sufficient to trigger autorate policy (unlike OH)
  - Prolongs transmissions of capture losing node, less likely to transmit successful packet
- Even RTS ineffective for capture losing node
  - RTS packet also captured and must fit into backoff window of capture winning node

physical layer capture



Worst Case



In Summary

- Low-rate control frames can produce multiplicative throughput degradation effects on the forwarding links
  - Up to 50 times the actual overhead load!
  - Protocol designers forced to reconsider tradeoff of injected overhead bits with protocol gains
  - Potentially zero-overhead control algorithms
- Severe throughput imbalance and aggregate throughput degradation due to coupling of:
  - Physical layer capture effect yields RTS/CTS ineffective
  - Prolonged transmissions from falsely triggering rate lower decreasing ability of capture losing node to transmit packets

Questions?

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Backup Slides

Asymmetry between Hidden Nodes

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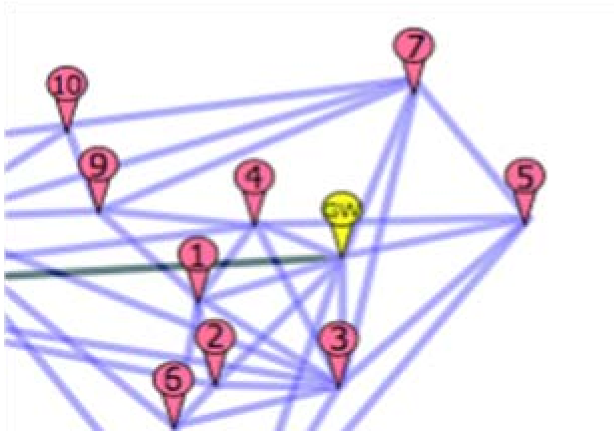
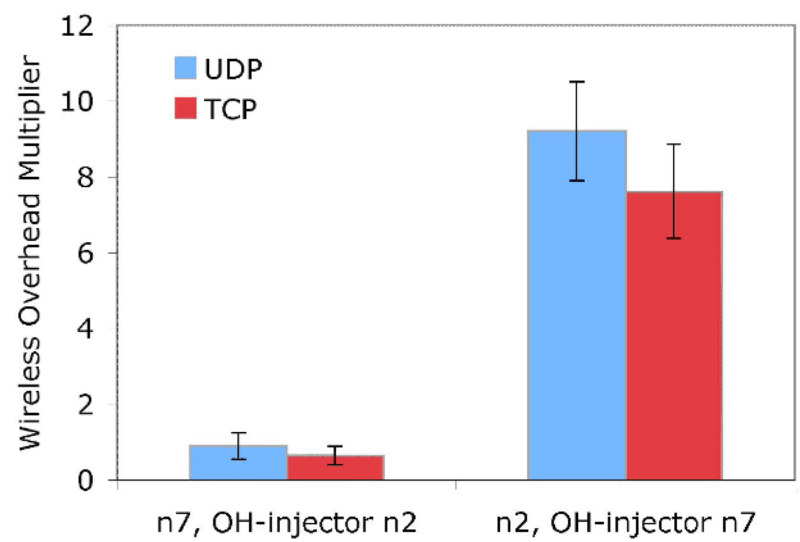
- Choose two nodes with large relative difference in link quality at GW
- Relative SNR difference of 5 dB at mutual receiver
- Physical layer capture occurs at node
  - n7 has WOM of 1
  - n2 has WOM of 10
- TCP/UDP perform similarly with respect to WOM

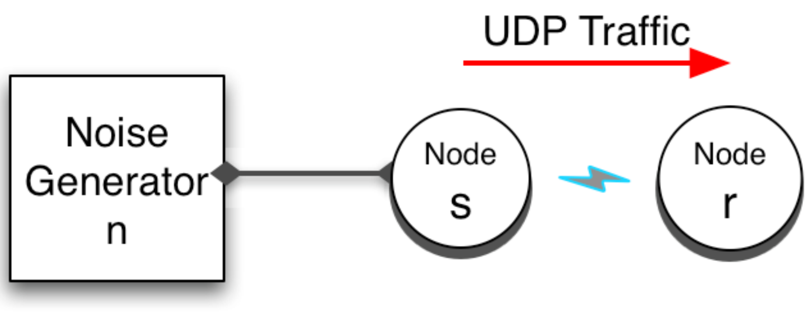


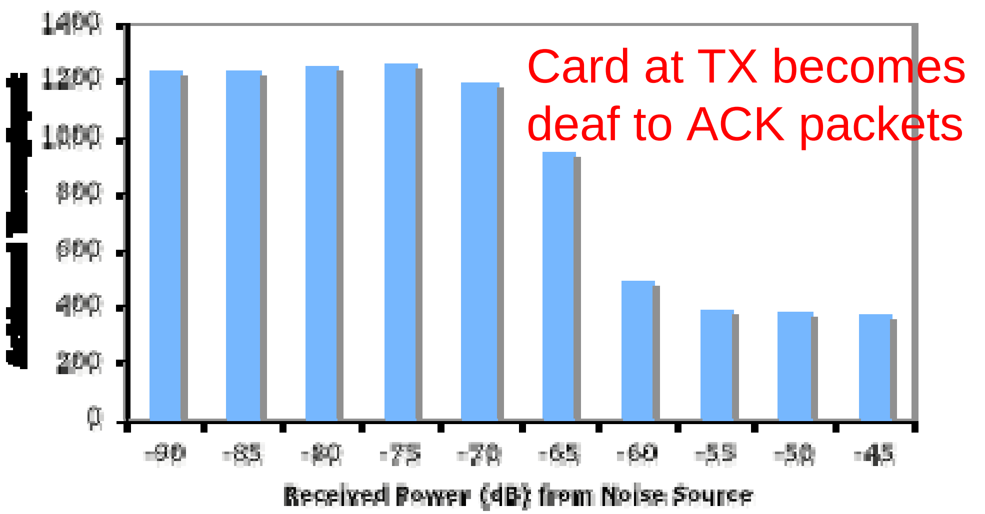


TCP/UDP data traffic (1500 byte), Autorate disabled, RTS off

Energy Detect and Carrier Sense in OTS Card

- In-lab measurements shows no carrier sense threshold
- Set-up: 3 different cards (2Mbps fixed modulation rate, UDP traffic)
  - Constant Noise
  - External 802.11 source heard only at transmitter (not shown)
- Throughput degradation due to transmitter becoming deaf to ACK
  - Producing excessive backoff
  - Continues to transmit
  - MAC traces taken with Kismet





RTS Effect on WOM

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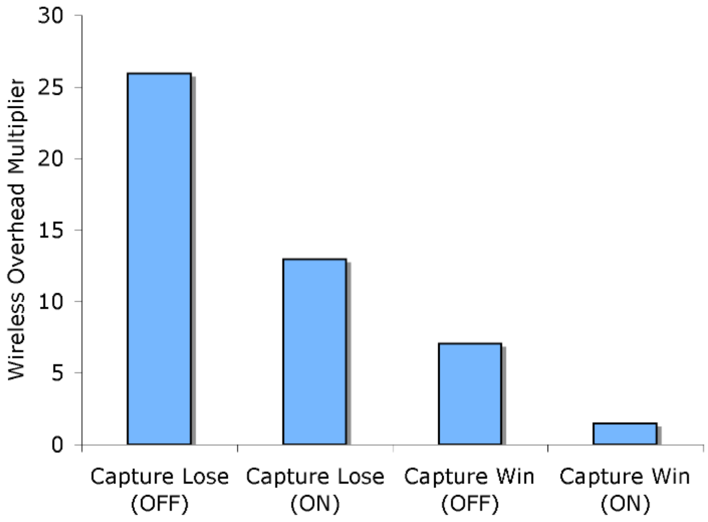
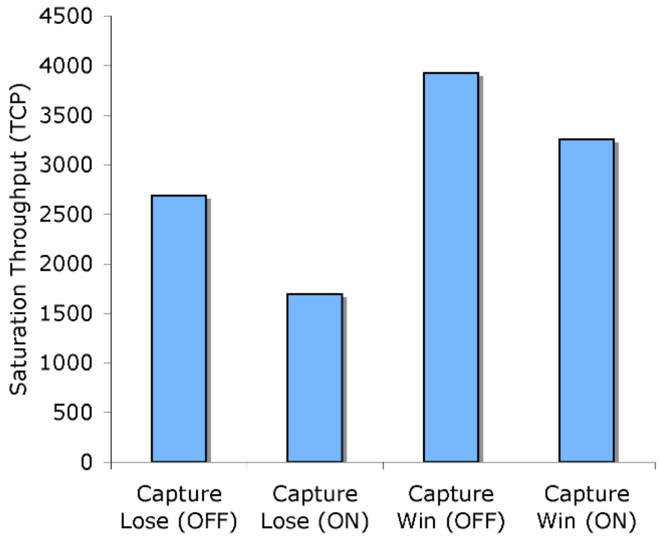
- RTS/CTS designed to overcome hidden terminal problem
- Tradeoff of using RTS/CTS mechanism when capture occurs
  - WOM reduced with the use of RTS in both cases (winning and losing)
  - However, aggregate throughput is lower when using RTS
- Overall, RTS mechanism ineffective





Related Work

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- **Mesh Network:** Increasing mesh node density increases throughput and connectivity [1], in contrast, we show backhaul link degradation
- **Scaling Overhead:** AODV shown to be linearly increasing [2], while we confirm w/ measurements, we show severe multiplicative effects
- **Collision-aware Multirate:** [3] shows adaptively enabling RTS able to make loss-based multirate collision-aware, we show RTS ineffective
- **Measurement Study:** [4] and related works measure performance of routing metrics in mesh networks, in contrast, we show the multiplicative losses due to routing and beaconing overhead

[1] J. Bicket, S. Biswas, D. Aguayo, and R. Morris, "Architecture and Evaluation of the MIT Roofnet Mesh Network," *MobiCom*'05.
[2] A. Iwata, C. Chiang, G. Pei, M. Gerla, and T. Chen, "Scalable routing strategies for ad hoc wireless networks," *Selected Areas of Communica- tion*, 1999.
[3] J. Kim, S. Kim, S. Choi, and D. Qiao, "CARA: Collision-aware rate adaptation for IEEE 802.11 WLANs," *Infocom*'06.
[4] D. De Couto, D. Aguayo, J. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing, *MobiCom*'03.