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

- Serving 4,000 users over 3 km²
- 802.11b access and backhaul tiers
- 802.11a directional tier for capacity injection
- Multiple radios at gateway nodes, single radios elsewhere

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

Node Down!
Contributions

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
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
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

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

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

- **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

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

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

![Graph showing WOM for Two TFA Link Classes](image-url)
Relative Link Quality of Competing Links

- 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

![Diagram showing physical layer capture and data flow between links S, r, and O with link 1 < link 2 and link 1 > link 2].

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

- 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

- 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

- 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

- 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

\[ \text{RTS} \quad \text{CTS} \quad \text{dataA} \quad \text{ACK} \quad \text{RTS} \]
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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Asymmetry between Hidden Nodes

- 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

![Graph showing wireless overhead multiplier for TCP and UDP]

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

- 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

- **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 with 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.