On the Scalability of Hierarchical Ad Hoc Wireless Networks

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Outline

- Motivation
  - Ad hoc wireless network architecture
- Three-tier hierarchical hybrid network architecture
- Capacity analysis
  - Analytical model
  - Capacity of three-tier hierarchical hybrid wireless networks
- Performance evaluation
  - Simulation model
  - System performance and scaling properties
- Conclusions and future work
Challenges of Ad Hoc Wireless Networks

- Broad usage
  - Both military projects and commercial scenarios

- Bottleneck on scalability
  - Capacity of ad hoc networks tends to zero as node density approaches to infinity [Gupta, Kumar 2000]

- Challenge for architecture and system design
  - Scaling via hierarchical hybrid architecture
  - Scaling via cross-layer routing
  - Scaling via multi-frequency multi-radio network
Ad Hoc Wireless Network Architecture

Flat
- Simple
- Poor scalability

Hierarchical e.g. clustering
- Transmission management
- Backbone formation

$n$ nodes:
$\sim 1/\sqrt{n}$ per node

$k$ clusters:
$\sim 1/\sqrt{k}$ per clusterhead

Hybrid wired/wireless
- Infrastructure serves as the “shortcut” for traffic.
- Density of infrastructure nodes required is high.

$m$ infrastructure nodes:
$\sim m/n$ per ad hoc node
Three-Tier Hierarchical Hybrid Network

Access Points (AP): route packets between radio links and the wired infrastructure.

Forwarding Nodes (FN): offer multi-hop routing capability.

Mobile Nodes (MN): low-power nodes, limited functionality of routing.

- Improve scaling properties.
- Reduce wired infrastructure cost.
- Consider traffic flows to and from the Internet, e.g. in mesh networks, sensor networks
Related Work on Capacity Analysis

- Capacity of “flat” multi-hop wireless networks [Gupta, Kumar 2000].
- Aggregate capacity of two-level hybrid wireless networks with regularly placed infrastructure nodes [Liu, Liu, Towsley 2003].
- Achievable throughput of a randomly deployed flat multi-hop network with any-to-one communication [Duarte-Melo, Liu 2003].
- Asymptotic per user throughput for different regimes for a two-level hybrid network with arbitrarily placed infrastructure nodes [Zemlianov, de Veciana 2005].
- Capacity of multi-channel wireless networks [Kyasanur, Vaidya 2005].
System Analytical Model (1)

- $n_1$ AP’s, $n_2$ FN’s, and $n_3$ MN’s in a disk of area $1 m^2$.
  - MN’s are randomly distributed.
  - AP’s and FN’s are placed on a regular grid.
  - MN’s and AP’s: data sources/sinks.
  - FN’s relay traffic between MN’s and AP’s.
- Traffic pattern:
  - Internet traffic (e.g. MN1 to AP1)
  - Local traffic (e.g. MN2 to MN3)
- TDMA scheme
- Interference model: the Protocol Model
System Analytical Model (2)

- Low-tier transmissions (frequencies $f_1$, bandwidth $W_1$)
  - Transmissions to and from MN’s

- High-tier transmissions (frequencies $f_2$, bandwidth $W_2$)
  - Inter-cluster traffic
    - Packets always go through infrastructure nodes
  - Intra-cluster traffic
    - Packets are relayed by FN’s (ad hoc mode)
Capacity of Three-tier Hierarchical Hybrid Wireless Networks (1)

Low-tier capacity

- Aggregate low-tier capacity is $\Theta(n_2 W_1)$
- Low-tier capacity increases linearly with $n_2$.

- Suppose each MN carries traffic of rate $\lambda$ bps on an average, then

$$n_3 \lambda = \Theta(n_2 W_1)$$

- The key parameter is the traffic carried by MN’s instead of their number.
- We may increase the number of FN’s to accommodate the network traffic.
Capacity of Three-tier Hierarchical Hybrid Wireless Networks (2)

High-tier capacity

- $W_3$ for Internet traffic; $W_4$ for local traffic.
- For $n_1 = o(\sqrt{n_2})$
  $$T_h = \Theta(n_1 W_3) + \Theta\left(W_4 \sqrt{\frac{n_2}{\log(n_2 / n_1^2)}}\right)$$
- For $n_1 = \Omega(\sqrt{n_2})$
  $$T_h = \Theta(n_1 W_2)$$

- High-tier capacity increases linearly with $n_1$, if $n_1$ grows asymptotically faster than $\sqrt{n_2}$.
- Linear relationship is achieved with any bandwidth allocation to different kinds of traffic.
Performance Evaluation

- System performance evaluation
  - Compare system performance of hierarchical with flat network
    - System throughput
    - Average end-to-end delay
    - Packet delivery ratio
    - Normalized routing overhead
  - Scaling properties

- Monarch extensions to the *ns-2* network simulator

- Model:
  - MAC: 802.11b ad-hoc mode
  - Discovery: a hierarchical network topology is computed
  - Routing: modified DSR and AODV
Simulation Model

- Nodes are randomly distributed in the network.
- AP’s are placed in a regular pattern.
- Nodes associate to the closest AP and form clusters.
- Dividing the simulated site into clusters
  - AP located at the center
  - An evenly distributed topology
  - Balanced traffic
# Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage area</td>
<td>1000m x 1000m</td>
</tr>
<tr>
<td>Number of clusters</td>
<td>4 (500m x 500m each)</td>
</tr>
<tr>
<td>Number of AP’s; FN’s; MN’s</td>
<td>4; 20; 100</td>
</tr>
<tr>
<td>Movement pattern</td>
<td>All FN’s keep moving; half of MN’s are static and the remaining are in movement.</td>
</tr>
<tr>
<td></td>
<td>Random waypoint model with maximum speed 1m/s</td>
</tr>
<tr>
<td>Traffic pattern</td>
<td>Exponential on/off model.</td>
</tr>
<tr>
<td></td>
<td>● Burst time: 500 ms; Idle time: 500 ms</td>
</tr>
<tr>
<td></td>
<td>● Packet size: 64 bytes</td>
</tr>
<tr>
<td></td>
<td>● Packet generation rate: 1/4/8/.../32 pkts/s</td>
</tr>
<tr>
<td></td>
<td>● Fraction of MN-Internet traffic: 100%</td>
</tr>
<tr>
<td>AP-AP link speed</td>
<td>100 Mbps</td>
</tr>
<tr>
<td>MAC (802.11b ad-hoc mode)</td>
<td>Data rate 1 Mbps; Radio transmission range 250 m</td>
</tr>
<tr>
<td>Number of comm. pairs</td>
<td>20/40/60</td>
</tr>
</tbody>
</table>
The throughput gain is obtained for a specific AP density.

Similar results are observed for different number of communication pairs.
Performance Results (AODV)

- Single frequency simulations.
Scaling Behavior

- The capacity scaling factor depends on the spatial distributions and the relative densities of AP’s and FN’s.
- The performance improvements and throughput increase come at the expense of increased hardware.
- How to design the hierarchical network to obtain scalable capacity while minimizing the investment in new devices?
Simulation Model

- Key parameters (consistent with analysis)
  - MN’s offered load density
  - Density of AP’s
  - Density of FN’s

- Regular planar network
  - AP’s and FN’s deploy regular placements.
  - FN’s cover the entire network.
  - The number of AP’s is changed.
  - MN’s move using the random waypoint model.

- Two simulated regions (identical FN density):
  - 1200 m x 1200 m (36 FN’s)
  - 800 m x 800 m (16 FN’s)

- Measure the normalized throughput capacity
  - as a function of the normalized offered load
Simulation Results

- ~4 AP’s is a good operating region for this scenario.
- System capacity scales quite well with a mix of several FN’s and just a few AP’s.
Conclusions

- Proposed a three-tier hierarchical hybrid architecture for scaling ad hoc wireless networks
- Developed an analytical model for asymptotic capacity
- Evaluated performance using simulations
- Both analytical and experimental results demonstrate the value of adding FN’s to improve scaling behavior and reduce infrastructure cost.
- Future work: the impact of bandwidth allocation to two tiers of transmissions in dual-radio dual-frequency networks.
Thank you!

Related publications:


http://www.winlab.rutgers.edu/~sulizhao/Papers.html