Making Multi-hop Wireless Networks Scale

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About BBN

• Diversified R&D company, advanced research mostly for DoD (mostly for DARPA)
  – Networking, both wired and wireless
  – Distributed computing and AI
  – Speech and natural language
  – Underwater acoustics

• Networking
  – Mobile and wireless networking algorithms and protocols
  – Optical networks
  – Disruption tolerant networks
  – Network infrastructure security
  – … many others…
<table>
<thead>
<tr>
<th>Year</th>
<th>1948</th>
<th>1950s</th>
<th>1960s</th>
<th>1970s</th>
<th>1980s</th>
<th>1990s</th>
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<td>• 1st Person-to-Person Network Email</td>
<td>• Secure Email for DoD</td>
<td>• Call Director</td>
<td>• DARPA Agent Markup Language</td>
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<td>• 1st Person-to-Person Network Email</td>
<td>• Acoustic Analysis of JFK Assassination Tapes</td>
<td>• Secure Email for DoD</td>
<td>• Microthunder Urban Environment Surveillance System</td>
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<tr>
<td>• Acoustic Design for UN General Assembly Hall</td>
<td>• Acoustic Analysis of JFK Assassination Tapes</td>
<td>• Multi-Gigabit Router</td>
<td>• Ultra*Log Agent-Based Network Survivability</td>
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<td>• AI Program for Pattern Recognition</td>
<td>• Analysis of Nixon Watergate Tapes</td>
<td>• Information Assurance</td>
<td>• Boomerang Acoustic Counter Sniper System</td>
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<td>• Demonstration of Time Sharing</td>
<td>• First Symmetric Multi-processor</td>
<td>• Genetic Algorithm Scheduling Tools</td>
<td>• Quantum Cryptographic Network</td>
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<td>• LOGO Programming Language</td>
<td>• First TCP for UNIX</td>
<td>• Collaborative Planning for Desert Storm</td>
<td>• GENI</td>
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<tr>
<td>• ARPANET-First Multi-node Packet Switched Network</td>
<td>• First Electronic Mail</td>
<td>• ATM Switch</td>
<td>• Ultra*Log Agent-Based Network Survivability</td>
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<td>• First Electronic Mail</td>
<td>• 40K Word Speech Recognition System</td>
<td>• Boomerang Acoustic Counter Sniper System</td>
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<td>• Defense Data Network</td>
<td>• National Science Foundation Network (NSFNET)</td>
<td>• Quantum Cryptographic Network</td>
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<td>• National Language Computer Interface</td>
<td>• Logistics Anchor Desk Deployed for Bosnia</td>
<td>• GENI</td>
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<td>• Intelligent Agents</td>
<td>• Safekeyper Certificate Management</td>
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<td>• Defense Simulation Internet DSI</td>
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<td>• Collaboration Planning Technology</td>
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Outline

• Introduction

• Scalability: Theory vs Practice
  • Increasing effective capacity
  • Decreasing effective load
  • Research directions

• Concluding remarks
Multi-hop Wireless Network (MWN)

- Wireless communications
- Multiple Wireless hops
- Possibly mobile
- No centralized control

Multi-hop Wired (e.g. Internet) + Single-hop Wireless (e.g. W-LAN, cellular) ≠ Multi-hop Wireless (e.g. sensor networks)

Interactions

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Applications

- **Mobile Ad Hoc Network (MANET):** Military networks, disaster recovery, personal area nets, taxicab networks

- **Wireless sensor networks:** Industrial/environmental monitoring

- **Mesh networks:** Metro WiFi, city-wide last-mile

- **Research problems in each area are particular variations of the fundamental problem of (mobile) multi-hop wireless**

  Many “filler-apps” waiting for a “killer app”?!
The Scalability Problem

- Has fascinated researchers for a long time
  - US Defense Research
    - SURAN (mid-1980's)
    - GLOMO (mid-1990's)
    - WNAN (mid-late-2000's)
  - Global community mesh networks
  - Large scale sensor networks
  - Information Theory
Interpreting “Scalability”

• Meaning 1: **Asymptotic scalability**
  – Order of growth of some “metric” (e.g. capacity) as a function of some “parameter” (e.g. number of nodes)
  – **Unqualified** verb: “Network X does not **scale** with increasing size”
  – *Does not say at what size it actually fails, only says some such size exists*

• Meaning 2: **In-practice scalability**
  – Given a network with certain parameters, the number of nodes beyond which desired performance cannot be achieved
  – **Qualified** verb: “Network with parameter values \{P\} **scales to 450 nodes**”
  – Is what network engineers talk about when building MWNs
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## The Gupta-Kumar (GK) Result

- Seminal paper “The Capacity of Wireless Networks”
- Looks at scalability of transport capacity with size

Asymptotic per-node transport capacity in bit-meters/sec for an MWN

<table>
<thead>
<tr>
<th></th>
<th>Protocol Model</th>
<th>Physical Model</th>
</tr>
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<tbody>
<tr>
<td>Arbitrary Networks</td>
<td>$\Theta\left(\frac{1}{\sqrt{n}}\right)$</td>
<td>$\Theta\left(\frac{1}{n^{1/\alpha}}\right)$</td>
</tr>
<tr>
<td>Random Networks</td>
<td>$\Theta\left(\frac{1}{\sqrt{n \ln(n)}}\right)$</td>
<td>$\Theta\left(\frac{1}{\sqrt{n}}\right)$</td>
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</tbody>
</table>

$n=$number of nodes in unit area; $\alpha =$ propagation constant

- **Throughput per user diminishes as $n$ increases**
  - Analysis agnostic to routing/MAC protocol
  - Analysis depends upon certain assumptions
### Some Post-GK Results

<table>
<thead>
<tr>
<th>Relaxation of GK Assumption</th>
<th>Asymptotic Scalability</th>
<th>Relevance/Comments</th>
</tr>
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<tbody>
<tr>
<td>Stationary =&gt; Mobile</td>
<td>$O(1)$ [Grossglauser01]</td>
<td>Good news, relevant in the context of DTNs</td>
</tr>
<tr>
<td>Omni =&gt; Directional</td>
<td>$O(1/\sqrt{n})$ [Yi03]</td>
<td>Bad news, but constant is increased by $2\pi/\text{beamwidth}$, increases capacity in practice</td>
</tr>
<tr>
<td>No cooperation =&gt; Cooperative MIMO</td>
<td>$O(1)$ [Ozgur07]</td>
<td>Good news, but cooperative MIMO is research area</td>
</tr>
<tr>
<td>No Multi Packet Reception =&gt; MPR</td>
<td>$O(1)$ [Garcia-Luna07, Nagaraj06]</td>
<td>Good news, but MPR requires sophisticated hardware</td>
</tr>
<tr>
<td>Random Traffic =&gt; Power-law distributed traffic</td>
<td>$O(1)$ to $O(1/\sqrt{n})$ depending on exponent [Li01]</td>
<td>Perhaps great news since typically traffic is <em>not random</em>?</td>
</tr>
</tbody>
</table>
For Arbitrary Networks, Physical Model (more realistic), actual upper bound on trans. capacity from GK is

\[
\frac{1}{\sqrt{\pi}} \left( \frac{2\beta + 2}{\beta} \right)^{1/\alpha} \frac{W \sqrt{A}}{n^{1/\alpha}} \text{ bit-meters/sec}
\]

Using W=50 Mbps, \(\beta = \text{Min. SIR} = 10 \text{ dB}, \alpha = \text{pathloss exponent} = 4, n = 1000 \text{ nodes in a grid 1m apart}

- Per node throughput upper bound = 37 Mbit-m/s = \sim 6 \text{ Mbps}
- This is even with random traffic, which is a pessimistic assumption

While this is an upper bound and reaching it is far from easy, the point is that GK bounds are not limiting practically
In-practice Scalability

• Given actual system and network parameters, what size (or density or mobility etc) can we scale to?

• What is the balance between “capacity” and “load”?

\[ R = C - L \]

Residual capacity (must be > 0)  |  Effective capacity (higher the better)  |  Effective load (lower the better)

• Components of C: Data rate, number of relays, number of radios, number of frequencies, spatial reuse etc.

• Components of L: Traffic distribution, Routing overhead, MAC/link overhead, etc.
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Example Techniques

• A faster radio!

• Spatial Multiplexing (Multiple-Input Multiple Output)

• Dynamic Spectrum Access

• Topology Control
  – Increase effective capacity by adaptively adjusting radio parameters (power, frequency …)

• Beamforming
  – Increase effective capacity by longer range, better SNR, more spatial reuse
Topology Control: Power

- Adaptively control power to limit interference and battery usage, yet maintain adequate connectivity

- Challenge: Connectivity assessment requires global information

- Throughput gains of 63% in example to the right
  - up to 400% gains observed

- Rich scope for algorithmic research
  - Approximation algorithms
  - Connectivity management using purely local information
• Increase spatial reuse by pushing interfering nodes to different frequencies
  – Enablers: Wideband tuning, opportunistic access, cheap transceivers
  – Tradeoff between interference and connectivity
  – Can eliminate hidden terminals
  – Can eliminate the C/3 problem

• 20 nodes static, about 6x improvement when going from 1 to 2 radios
  – Not much thereafter
Directional/Beamforming Antenna

- Spatial bias in *gain* – more energy in one direction than the other

- Why directional?
  - More spatial reuse (capacity)
  - More range (lesser hops)
  - Better multipath immunity
Exploiting Beamforming in an MWN

- **MAC: “Directional Exposed Terminal”**
  - Unnecessarily prevents a node from transmitting

- **MAC: “Loss in channel state”**
  - A node cannot keep track of all goings-on in the channel
  - Allows collision to go through

- **Neighbor Discovery:** Receiver has to be pointing toward the transmitter at the exact time the transmitter points and sends Hello
  - How do they synchronize the pointing

- Need new MAC and Network layer protocols for multi-hop wireless networks to use beamforming
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Components of “Total Load”

• Control overhead
  – Control packets for MAC, Routing, Transport
  – Headers
  – *Send less control packets while achieving same result*

• Data packets
  – Actual data plus retransmissions
  – *Send less data packets while achieving same result*

• Sub-optimal routing overhead
  – Cost of bad routing resulting from control
  – Case in point: flooding
Routing Protocols

- Proactive: Know the route a priori
- Reactive: Discover route only when you need to
- Geographic: Using GPS
- Hierarchical: Divide and conquer
- Control dissemination radius
Hierarchical Routing

- Autonomous Clustering mechanism groups nodes into clusters, super-clusters etc. to facilitate scalable routing
  - Objectives: limit cluster size, number of clusters
  - Decentralized algorithms: cluster splitting, migrating, merging
BBN’s Hazy Sighted Link State

- Scoping of routing information without hierarchies
- Send more frequent Link State Updates to nearby nodes and less to farther away nodes

- Used in military and community wireless networks
  - CuWIN using HSLS deployed in Katrina disaster

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Network Coding

• Increase network capacity by “mixing” packets and allowing receivers to deduce information intended for it

• Network coding reduces effective network load, especially for multicast

• DARPA CBMANET program showed significant improvement in throughput
TARP

- Baseline load equivalent to flooding
- Rules allow trimming
- Target is to reduce total load, especially if you consider retransmissions
Which methods yield most benefit?

Abstract analytical model with actual system parameters (e.g. Header sizes etc) of the BBN WNAN system. 200 nodes, 11 Mbps, random static network.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Change</th>
<th>Possible Method</th>
<th>Change in Residual Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routing control overhead</td>
<td>Reduce by 5x</td>
<td>Hierarchical/ hazy-sighted</td>
<td>97 kbps</td>
</tr>
<tr>
<td>Average degree</td>
<td>Reduce by 5x (from 50 to 10)</td>
<td>Topology control</td>
<td>382 kbps</td>
</tr>
<tr>
<td>Radio data rate</td>
<td>Increase by ~5x (from 11 Mbps to 54 Mbps)</td>
<td>Buy a new radio</td>
<td>518 kbps</td>
</tr>
</tbody>
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Where the buzz is (was recently?)

- Opportunistic/Dynamic Spectrum Access/Cognitive Radio
- Network coding
- Cooperative communications
- Disruption Tolerant Networks
- Network Science
Cooperative Diversity

- Near-simultaneous transmission of the same information by multiple nodes with an intent to coherently combine at receiver
  - Also called “Active Retransmission”, “Active Multipath”
  - Like MIMO but transmit side diversity is obtained by other “nodes” acting as “elements”
Goal is to facilitate reliable message delivery in networks where episodic or intermittent connectivity is the norm.

Traditional MANET routing
Fails if a stable end-to-end path does not exist between S and D
This requirement is too stringent for episodic networks (=> high msg loss!)

DTN-enhanced MANET routing
Successful delivery possible as long as the S--D path is eventually transportable
Use store-n-forward hand-in-hand with routing
Network Science

• The world is full of networks
  – Transportation, social, communication, information, biological….
  – They interact in complex ways

• There is as yet no fundamental understanding of the “network concept”
  – Imagine building a plane with no understanding of fluid dynamics

• The US Army Research Lab has started a collaborative program
  – Social network center (Rensellaer Polytechnic University)
  – Information network center (University of Illinois)
  – Communication network center (Pennsylvania State University)
  – Integration Research center (BBN)
Make your own: Exploit enablers

- Continued proliferation of wireless platforms
  - iPhone 3G, Android G1...

- Low cost of chip manufacturing

- Software radios
  - GNU Radio

- Economy, energy, health, biology

“MWN Inside”!!

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Making MWNs scale

• The two different meanings require different but mutually informed effort
  – Asymptotic (theoretical) scalability depends on assumptions
  – In practice scalability depends on network and load

• Practical scalability requires methods for reducing effective load as well as increasing effective capacity
  – OFDM, MIMO, topology control (power, frequency), beamforming
  – Hierarchical/hazy-sighted routing, network coding etc.

• It is very hard to show the “proof in the pudding” for scalability
  – When do we know when we are done?
Lessons from the scalability journey

- Rather than one magic bullet, there may be several small incremental steps to solve a hard problem.

- Hard problems change with time as technology evolves, need a re-think every so often.

- Not having a clear driving application is a disadvantage: makes folks look at “interesting” rather than “useful”.

- Not having a clear driving application is an advantage: makes folks look at “interesting” rather than “useful”!
Communities need to come together

Dr. CS

Computer Science/Engineering

Dr. EE

Electrical Engineering

Multi-hop Wireless Network

Transport

Network

MAC/Link

Physical

graphs
E2E flows
QoS
routing
links
NP-hard

signal
cdma
interference
mimo
ofdm
coherence
modulation

Dr. Math

algorithms
routing
The End