Fundamental Limits of Wireless Systems (FLoWS):

Vision, Challenges, Progress, Roadmap

Andrea Goldsmith
Program Objective

- Define the fundamental performance limits for MANETs in terms of desired metrics.
- Obtain upper and lower performance bounds for these metrics for a given set of MANET models.
- Define the negotiation between the application and network for picking the operating point.
- Bound the cost of using this set of metrics as the interface between the network and applications.
- Repeat as needed
**Capacity and Fundamental Limits**

- **Capacity**
- **Delay**
- **Energy/SNR**

**Upper Bound**

**Lower Bound**

**Utility**

**Source Coding and Separation**

**Cooperation and Coding**

TC, ME, AG, RK, MM, PM, SM, LZ

**Cutsets and Upper Bounds**

AG, RK, MM, LZ

**Models and Dynamics**

- **Degrees of Freedom**
- **Constraints**

**Network Coding/Forwarding**

ME, AG, RK, MM, AO

**Utility Optimization**

SB, RJ, SM, AO, DS

**Application Metrics**

**MANET Metrics**

**Constraints**

**New MANET Theory**
**Area Thrusts and Organization**

**Metrics and Problem Definition (Models, Degrees of Freedom, and Constraints)**

Leads: Goldsmith and Medard
All PIs Contribute

- **Cooperation and Coding**
  - Lead: Goldsmith
  - Coleman
  - Effros
  - Koetter
  - Medard
  - Meyn
  - Moulin
  - Zheng

- **Cutsets and Upper Bounds**
  - Lead: Koetter
  - Coleman
  - Goldsmith
  - Medard
  - Zheng

- **Optimization**
  - Lead: Boyd
  - Johari
  - Meyn
  - Ozdaglar
  - Shah

- **Source Coding and Separation**
  - Lead: Effros
  - Coleman
  - Goldsmith
  - Koetter
  - Medard
  - Shah

- **Network Coding and Forwarding**
  - Lead: Medard
  - Effros
  - Koetter
  - Ozdaglar

- **Resources and DoF**
  - Lead: Meyn
  - Goldsmith
  - Johari
  - Medard
  - Moulin
Challenges

λ Metrics

λ What are the right set of metrics for networks and applications in the “near” future?
λ Should there be different metrics for different systems?
λ How to capture dynamics in these metrics
  ● Is averaging (e.g. average delay) good enough? If not, then what?
  ● For adaptive techniques, how to quantify the impact of feedback and imperfect estimates.

λ Models

λ There are many different aspects to a network model (#nodes, propagation, flows, jamming, dynamics,…)
λ Hence, there are uncountable many different models.
λ How do we find models that are tractable, yet lead to general design and performance insight?
More Model Challenges

- Degrees of freedom
  - What are they?
  - How should they be used?
  - Does capacity scale with each DoF?
    - Are some more valuable than others?
    - Are there diminishing returns?

- Constraints
  - What defines the network constraints (e.g. security, robustness)?
  - How are constraints incorporated into our framework?
  - What is the relationship between DoF and constraints?
MANET Research Challenges

- Area talks
- Focus talks
- Posters
Distance to Nearest Neighbor (DNN) with respect to the data set.

- Min-flow max-cut upper bounds
- Fano’s inequality and extensions
- Genie-aided (CSI and cognition) bounds
- Network equivalence classes
- Fundamental limits under practical constraints and hostile environments
- Physical layer coding and network coding
- Network coding with multiple access and broadcasting
- Network coding and optimization
- Generalized network coding and forwarding
- Byzantine attack reliability
- Functional distributed compression
- Joint source/network/channel coding
- Source coding for broadcast and multicast
- Robust architectures and source reconstruction methods
- Feedback and adaptation
- Capacity scaling with DoF
- Optimal resource allocation over DoF
- Robustness through DoF
- Capacity with (imperfect) feedback
- Stochastic stability
- Cooperation and competition
- Energy/channel variability trade-off

Utility = U(C, D, E)
Capacity and Fundamental Limits

Application Metrics

- Capacity
- Delay
- Energy/SNR

Utility = U(C, D, E)

Source Coding and Separation

Cooperation and Coding
TC, ME, AG, RK, MM, PM, SM, LZ

Cutsets and Upper Bounds
AG, RK, MM, LZ

Resources, DoF, and Feedback
SB, TC, AG, RJ, PM, SM, DS

Source Coding and Separation
TC, ME, MM, DS

Constraints

Models and Dynamics

Network Coding/Forwarding
ME, AG, RK, MM, AO

Degrees of Freedom

MANET Metrics

Constraints

Utility Optimization
SB, RJ, SM, AO, DS

- Multicommodity optimization
- Finite horizon optimization
- Distributed implementations
- Utility optimization as a framework for separation
New theory since kickoff

- Utility optimization and separation
- Generalized capacity
- Capacity under mismatch detection
- Network coding with relays and/or noisy links
- Cooperation in BCs, virtual MIMO and cognitive radios
- Jamming and degrees of freedom
- Stability and optimization of dynamic resource allocation
- Spectrum allocation/topology formation via game theory
- Distributed compression and joint source/network codes
- Distributed and centralized utility optimization
Posters

Cutsets and Upper Bounds
- “On MANET jamming,” P. Moulin
- "Information Geometry and Capacity Limits" L. Zheng

Network Coding and Forwarding
- "Joint Relaying and Network Coding in Wireless Networks," I. Maric, M. Medard, A. Goldsmith
- “Network coding on noisy links,” Ralf Koetter

Cooperation and Coding
- "Capacity Gain from Transmitter and Receiver Cooperation," C. Ng. and A. Goldsmith
- "Fundamental Limits of Networks with Cognitive Users," I. Maric and A. Goldsmith
- "Capacity Definitions of General Channels with Receiver Side Information,” M. Effros, A. Goldsmith, and Y. Liang
- "Crosslayer Cooperative Broadcast Communication via Dualized Erasure Correction Codes", T. Coleman
Source Coding, Separation, and Feedback for MANETs

- "Distributed Functional Compression Through Coloring," D. Shah and M. Medard
- "Optimal Power Distribution and Minimum Expected Distortion in Gaussian Layered Broadcast Coding," C. Ng, D. Gunduz, A. Goldsmith, and E. Erkip

Resource Allocation and Degrees of Freedom

- "Dynamic Spectrum Management for Cognitive Radios." S. Adlakha, R. Johari, and A. Goldsmith
- Topology formation: when can local competition yield global cooperation, R. Johari
- “Generalized Maxweight for resource allocation” S. Meyn

Optimization in MANETs

- "Rolling Horizon Control for Networks with Random Link Capacities,” S. Boyd, A. Zymnis, D. O’Neill, and A. Goldsmith
- "Iterative Power Control in Wireless Networks with Interference" S. Boyd and N. Tricharis
- "Distributed optimization for nonseparable utilities," A. Ozdaglar
Team Collaborations

Collaborative mechanisms: Existing collaborations, student/postdoc exchanges, faculty visits, workshops
18 Month Roadmap

- Problem definition
- Thrust area progress
- Demonstrated gains
- New ideas/synergies

- More complex models
- Thrust area progress
- New ideas/synergies
- Demonstrated gains across thrust areas
- Utility maximization as separation principle

- New capacity regions
- Utility maximization/SC over these regions
- Synergies w/ CBMANET
# Project Roadmap

<table>
<thead>
<tr>
<th>MANET Capacity</th>
<th>Period 1 1/07-6/08</th>
<th>Period 2 7/08-6/09</th>
<th>Period 3 7/09-6/10</th>
<th>Period 4 7/10-6/11</th>
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</thead>
<tbody>
<tr>
<td>Small networks, known CSI, MIMO Robustness to uncertainty</td>
<td>Formulate Problems</td>
<td>Prelim Results</td>
<td>Final Results</td>
<td>Final Results</td>
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<tr>
<td>Large networks with fading, imperfect CSI, mobility</td>
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<tr>
<th>Energy/Delay Tradeoffs</th>
<th>Period 1 1/07-6/08</th>
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<tr>
<td>Throughput/stability results Scheduling</td>
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<td>Integrated coding and queuing</td>
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<th>Node Cooperation</th>
<th>Period 1 1/07-6/08</th>
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<td>Virtual MIMO, cooperation diversity, conferencing, relaying</td>
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<td>High/low/moderate SNR regimes</td>
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<th>Resource Allocation</th>
<th>Period 1 1/07-6/08</th>
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<tr>
<td>Rate, power, spectrum, antennas</td>
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<td>Routing, end-to-end metrics</td>
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<td>Jamming w/ w/out cooperation</td>
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<td>Capacity limits w/ inside attacks</td>
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<td>Joint S/C/N Coding &amp; Sep.</td>
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<td>Src-chan. and Src-netw. codes</td>
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<th>Network App., Utility, Opt.</th>
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<td>Optimal operating pt on cap. reg.</td>
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<td>More complex nets and app. reqts</td>
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<th>Experiments (Sec. II.H)</th>
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Goals for next meeting

- Baseline consensus on models, metrics, DoF, and constraints

- Progress in thrust areas (possibly merge resource allocation/DoF and optimization)

- New capacity theory with demonstrated performance gains

- Synergistic developments across thrust areas

- Mini-workshop co-located with ISIT
Summary

- We have made progress on defining the problem and refining the area thrusts.

- We have developed new theory in each of the area thrusts.

- We have made progress in determining the interface between networks and applications that incorporates all area thrusts.