ITMANET

FLoWS

Information Theory for Mobile Ad-Hoc Networks (ITMANET):
The FLoWS Project

FLoWS Overview and Update

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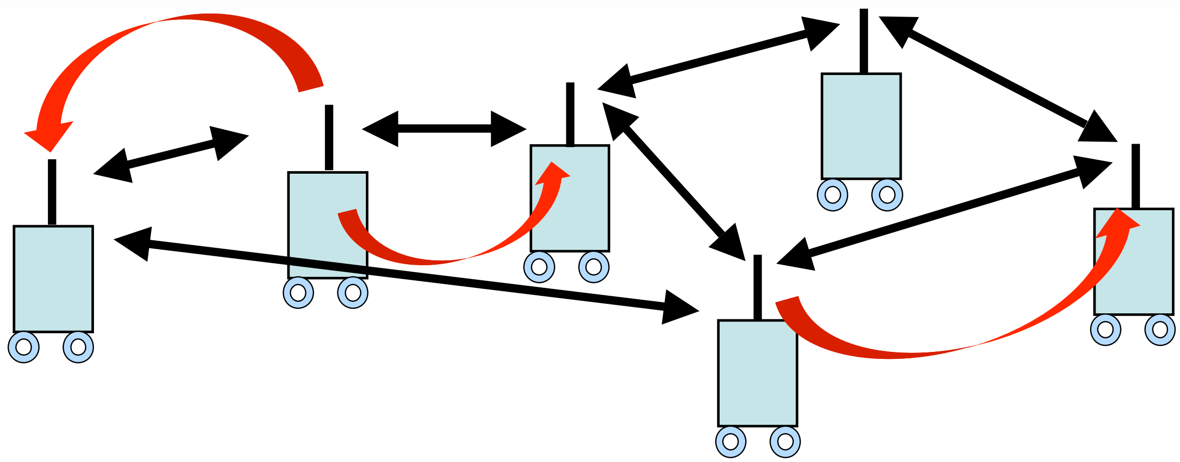
DARPA's Grand Challenge



- Develop and exploit a more powerful information theory for mobile wireless networks.
- Anticipated byproducts include new separation theorems to inform wireless network "layering" as well as new protocol ideas.

Hypothesis: A better understanding of MANET capacity limits will lead to better network design and deployment.

Limitations in Existing Theory

- Much progress in finding the Shannon capacity limits of wireless single and multiuser *channels*
- Little known about these limits for mobile wireless *networks*, even for simple (canonical) models
- Shannon's capacity definition based on infinite delay and asymptotically small error was brilliant!
  - Has also been limiting
  - Cause of unconsummated union between networks and information theory
  - What is the alternative?

Capacity beyond Shannon

FLoWS Program Objectives

- Develop tractable and insightful metrics and models for MANET information theory.
- Define fundamental performance limits for MANETs in terms of desired objective 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 resource allocation and performance optimization of our given metrics
- Bound the cost of using our set of metrics as the interface between the network and applications.

Thrust Objectives and Scope

- **Models and Metrics** (Leads:Effros and Goldsmith):
  - ***Objective:*** Develop a set of metrics for dynamic networks that capture requirements of current and future applications
  - ***Scope:*** Develop a set of models for MANETs that are tractable yet lead to general design and performance insights

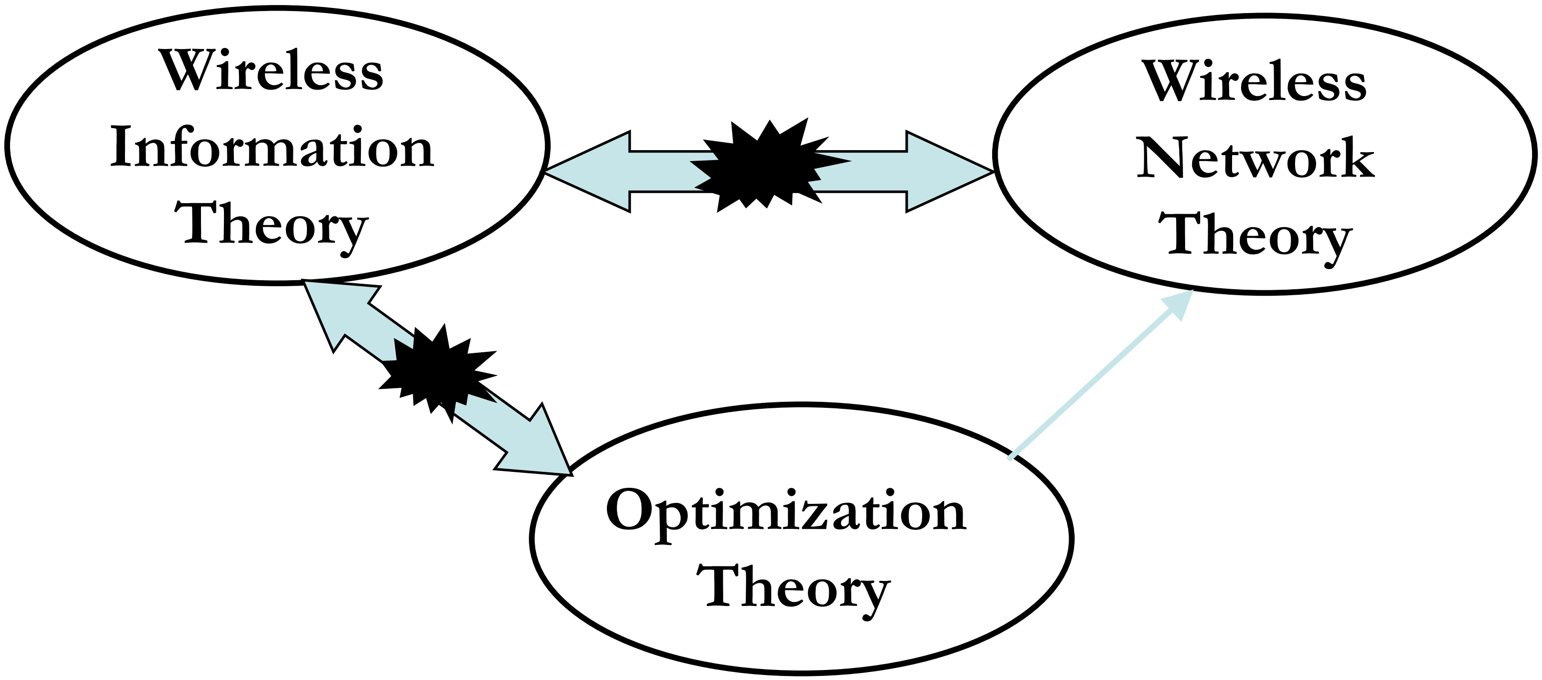
- **New Paradigms for Upper Bounds** (Leads:Koetter and Medard)
  - ***Objective:*** Obtain bounds on a diversity of objectively-defined metrics for complex interconnected systems.
  - ***Scope:*** A comprehensive theory for upper bounding the performance limits of MANETs

- **Layerless Dynamic Networks** (Lead:Zheng)
  - ***Objective:*** Design for networks as a single dynamic probabilistic mapping, without pre-assigned layered structure
  - ***Scope:*** Remove layering and statics from MANET information theory.

- **Application Metrics and Network Performance** (Lead:Ozdaglar)
  - ***Objective***: Provide an interface between application metrics and network performance
  - ***Scope:*** Develop a theory of generalized rate distortion, separation, and network optimization for MANETs

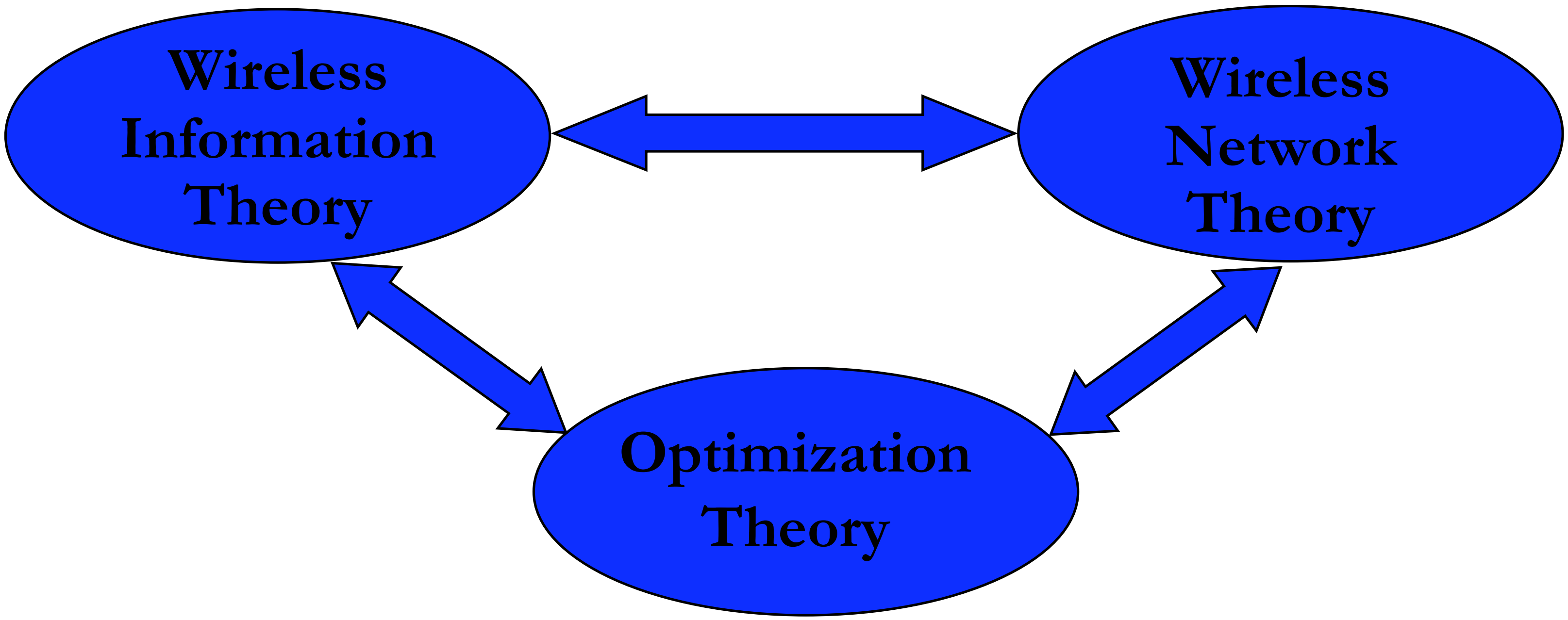
Today's Unconsummated Unions

B. Hajek and A. Ephremides, "Information theory and communications networks: An unconsummated union," *IEEE Trans. Inf. Theory*, Oct. 1998.



- Success on narrowly-defined information theory of wireless networks.
- Large body of wireless (and wired) network theory that is ad-hoc, lacks a basis in fundamentals, and lacks an objective success criteria.
- Little cross-disciplinary work spanning these fields, except applying optimization techniques to existing wireless network designs.

Challenge: Consummate Union



- When capacity is not the only metric, network theory is needed to deal with delay, random traffic, and application requirements
- Optimization provides the missing link for consummation
  - Becomes a menage-a-trois

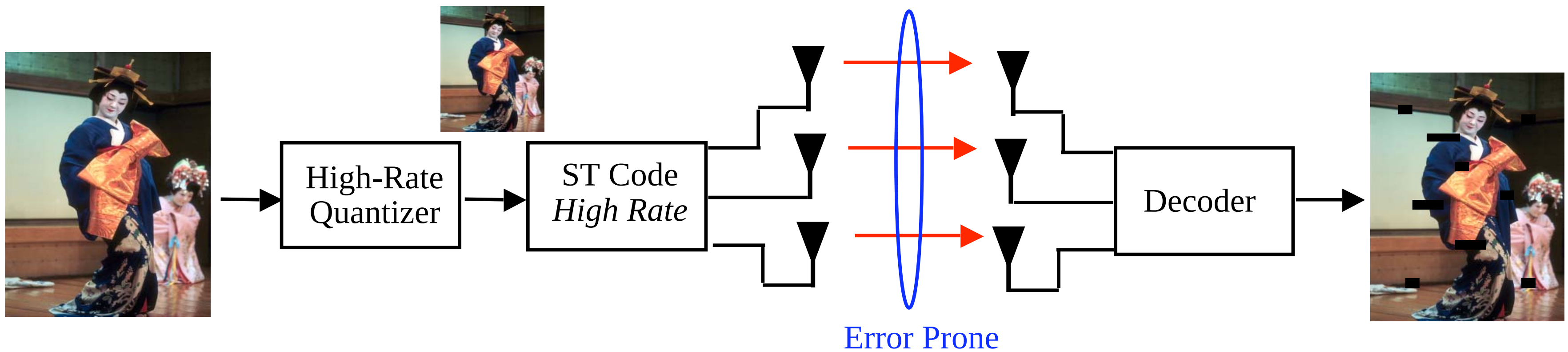
Optimization as the missing link

- Shannon capacity analysis generally becomes intractable for more than a few nodes, except in scaling laws.
- Capacity results are generally built around asymptotics
  - Asympototically large blocklength/delay
  - Asymptotically high SNR
  - Asymptotically small probability of error
  - Infinitely many users
  - Infinite data backed up
- These asymptotics usually make all the interesting wireless and networking problems go away
  - Shannon theory generally breaks down when delay, error, or user/traffic dynamics must be considered

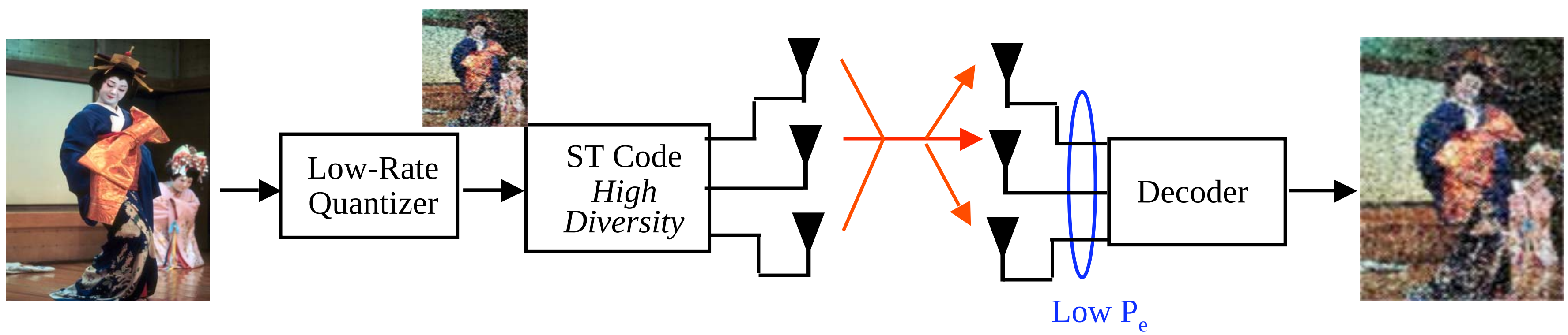
Optimization tools can be highly adept at obtaining fundamental limits when the Shannon tools break down

Example: MIMO Tradeoffs

- Use antennas for multiplexing:



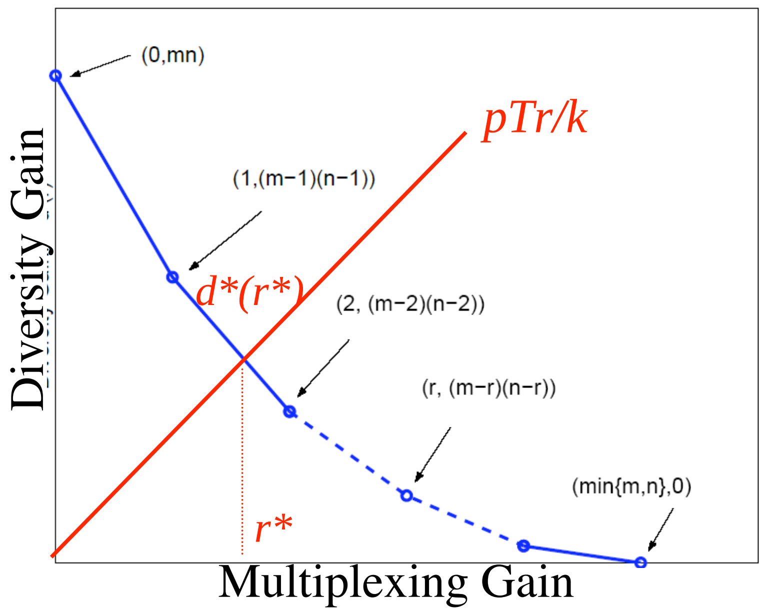
- Use antennas for diversity



How should antennas be used? Depends on higher layer metrics

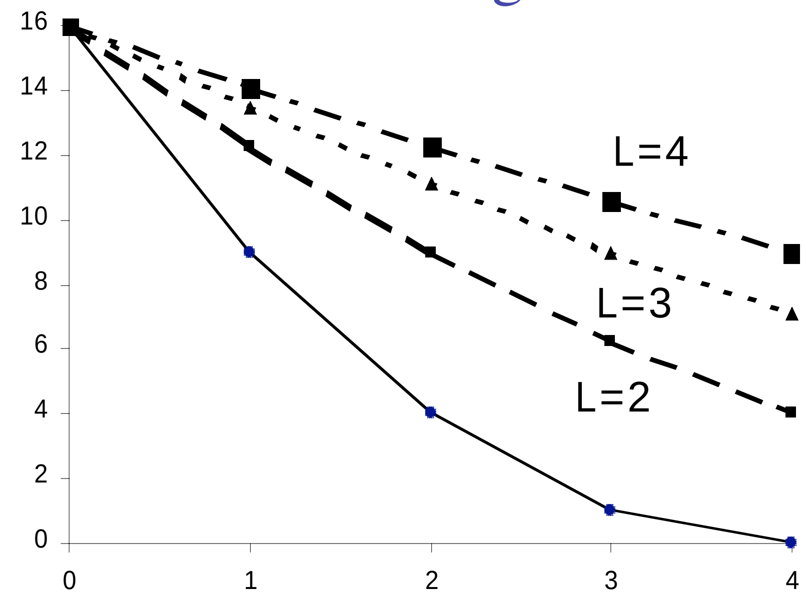
Minimizing End-to-End Distortion

Diversity-Multiplexing Tradeoff at high SNR



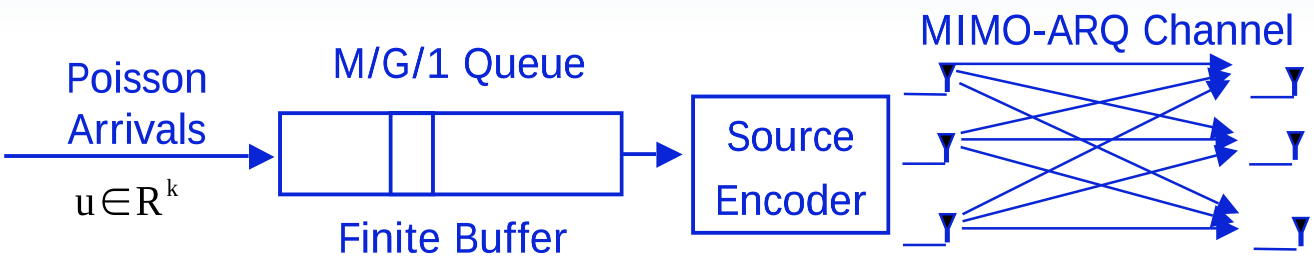
- Can obtain closed-form expression for optimal operating point on tradeoff curve to minimize end-to-end distortion
- Separate source/channel coding optimal
- Minimum distortion is *–d*(r*)*
- *At moderate SNR, solve via optimization*

Diversity-Multiplexing-ARQ Tradeoff at high SNR

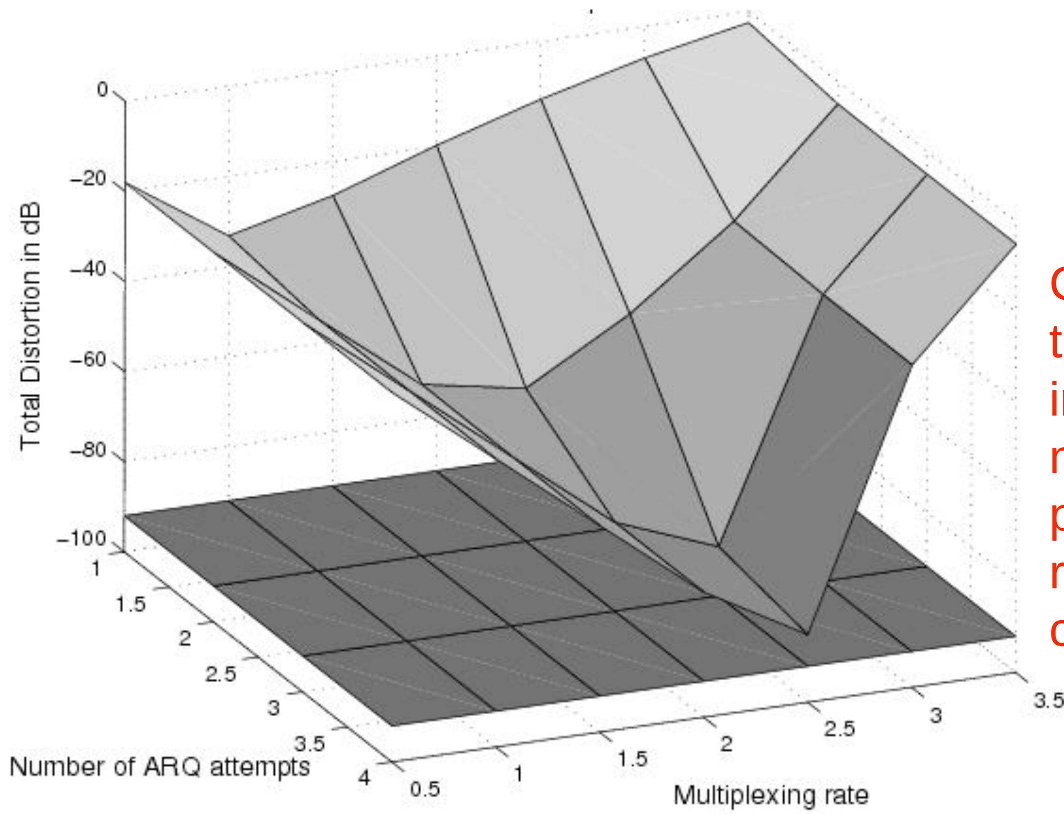


- Allows a diversity/multiplexing/delay tradeoff analysis
- High SNR leads to rare ARQ errors
- Effectively removes delay; " free" retransmissions (Bernashev, 1976)
- Cannot capture queuing impact with high SNR (Shannon) analysis!

Can solve with optimization tools



$$Min\ D_T(F, \mathrm{SNR}) \leq D_s(F) + P_e(\mathrm{SNR}) + P\{Delay > k\}.$$



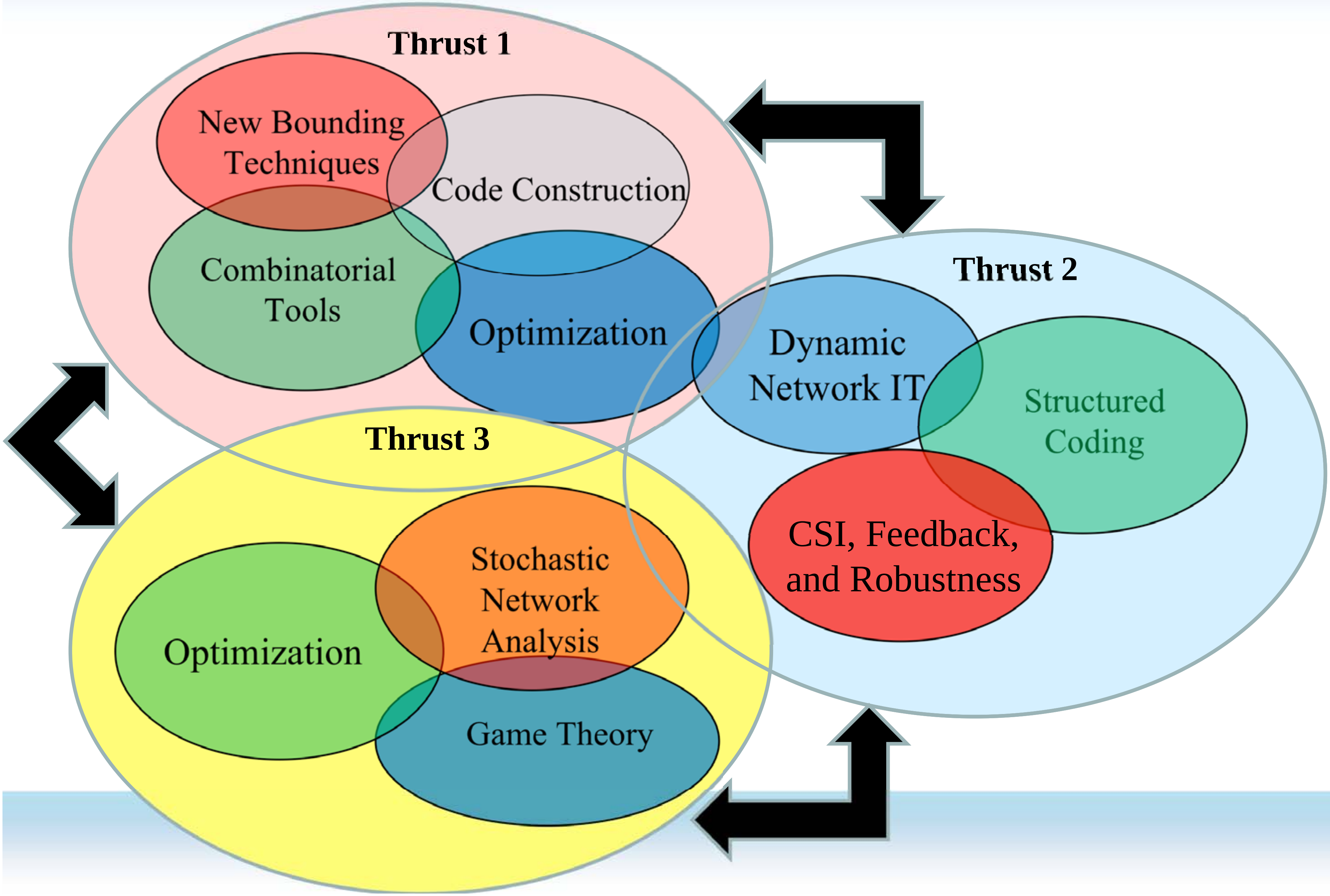
Connects to Shannon-theoretic results; indicate where ARQ is most useful, and provides insight into refining analysis for closed-form soln.

Progress since July

- A wealth of results extending prior our work, developing new ideas, and forging new synergies within and between our thrust areas
- New and ongoing collaborations among PIs, including student/postdoc exchanges
- Overview paper
  - Co-authors: Effros, Goldsmith, Medard
  - Targeted for Scientific American (or similar publication)
  - Outline complete and writing begun; plan to complete in Jan.
- JSAC Tutorial on MANET Capacity with Cognitive Radios
  - Co-authors: S. Jafar, I. Maric, and A. Goldsmith
  - Paper will be submitted at the end of December
- Website updated with July PI meeting slides, recent publications, recent results, and thrust area descriptions*

*After this meeting.

Thrust Synergies and New Intellectual Tools



Thrust 0: New Models and Metrics

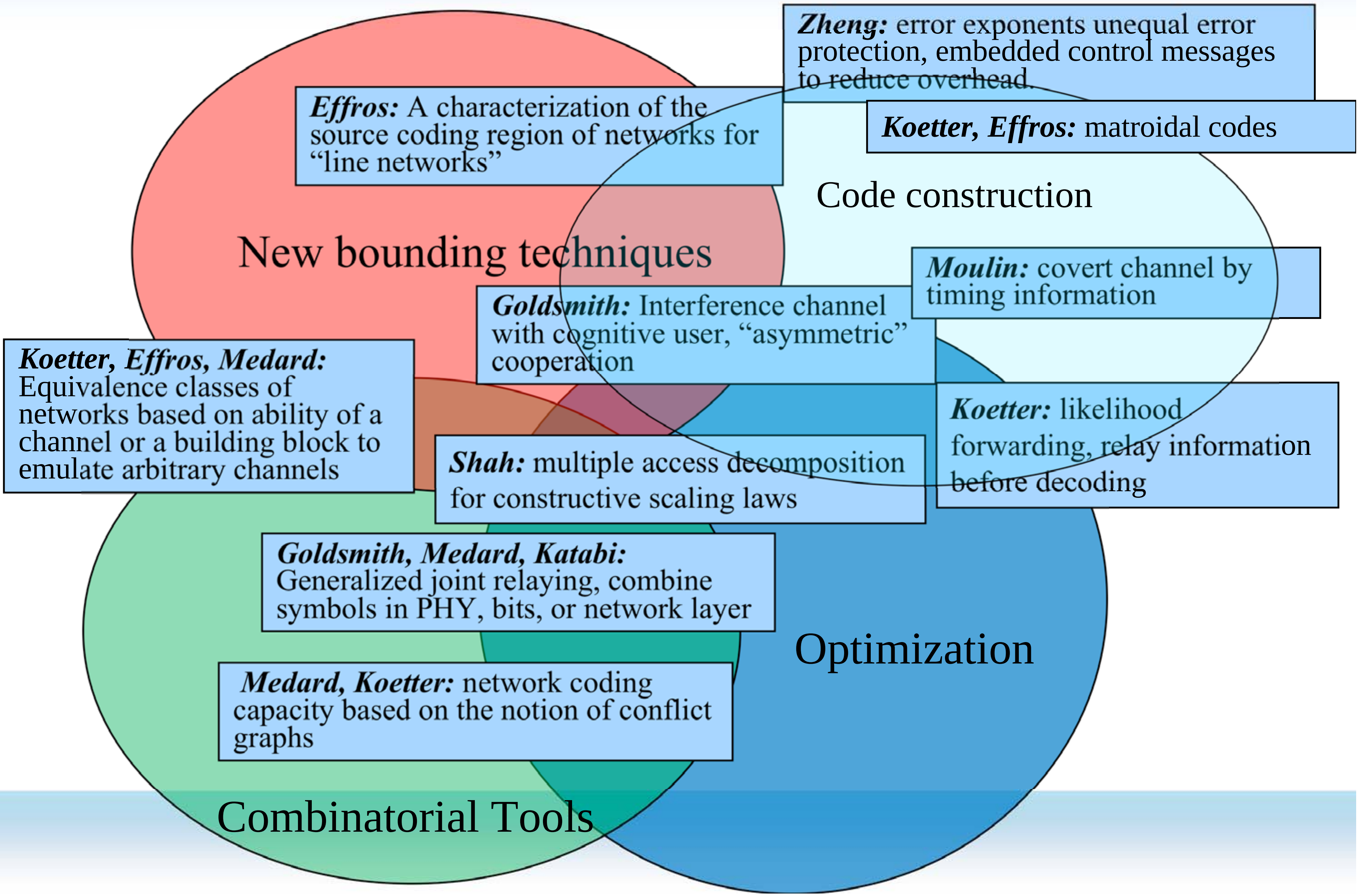
New Models

-Finite-state Markov dynamics in multiuser channels
- Fading channels with unknown statistics
-Cognitive transmitters
-Large networks with arbitrary node placement
- Arbitrary data flows
-Multicast traffic

New Metrics

- Generalized Capacity and UEP
- Capacity Region for Scaling Laws
-Throughput vs. Delay
-Generalized Distortion
-Queuing Distortion
- Multiperiod Network Utility
-Quantized Utility
- Game-theoretic equilibrium
-Oblivious equilibrium

Thrust 1 Synergies and Results



Thrust 2 Synergies and Results

Dynamic Network Information Theory

Goldsmith, Medard, Katabi: Joint relaying, combine symbols in PHY, bits, or network layer

Coleman: Rate Distortion of Poisson Processes

Zheng: Euclidean Information Theory

Goldsmith: Degraded FS Broadcast Channels

Goldsmith: Cognitive users and interference

Moulin: Information flow via timing

Coleman: Joint Source/Channel Coding in Networks

Goldsmith: Feedback and Directed Information

Effros, Goldsmith: Generalized capacity, distortion, and joint source/channel coding.

Moulin: Universal Decoding in MANETs

Meyn, Zheng, Medard: mismatched receiver, online robust algorithm to combat imperfect channel info.

Goldsmith: Broadcasting with layered source code, graceful degradation for weaker users

Zheng: Embedded Coding and UEP

Structured coding

CSI, feedback, and robustness

Thrust 3 Synergies and Results

Optimization Theory
Distributed efficient algorithms for resource allocation

Boyd: Dynamic and stochastic network utility maximization with delivery constraints

Ozdaglar: Distributed optimization algorithms for general metrics and with quantized information

Boyd, Goldsmith: Network utility maximization with adaptive modulation

Medard, Ozdaglar: Efficient resource allocation in non-fading and fading MAC channels using optimization methods and rate-splitting

Shah: Optimal capacity scaling for arbitrary node placement and arbitrary multi-commodity flows

Goldsmith, Johari: Game-theoretic model for cognitive radio design with incomplete channel information

Shah: Low complexity throughput and delay efficient scheduling

Meyn: Generalized Max-Weight policies with performance optimization

Johari: Dynamics and equilibria in stochastic games

Stochastic Network Analysis
Flow-based models and queuing dynamics

Game Theory
New resource allocation paradigm that focuses on hetereogeneity and competition

Progress Criteria: Phase 1

- Develop tractable and insightful metrics and models that expand the definition of information theory to encompass the degrees of freedom, constraints, and dynamics inherent to wireless networks √
- Develop new upper bounding techniques for MANET capacity and other performance metrics and evaluate these bounds for small to medium sized networks under relatively simple assumptions. √
- Develop new achievability results for key performance metrics by optimizing dynamic node cooperation and resource allocation over available degrees of freedom. √
- Use rate distortion theory and network utilization to optimize the interface between networks and applications. √
- Use new theory along all three thrusts to characterize trade-offs between delay, energy and capacity, and possibly other metrics. √
- Demonstrate significant performance gains in key performance metrics based on our developed theory in each thrust area. √
- Use the new MANET information theory and its associated insights to obtain breakthroughs in wireless network design. √

Posters

- Thrust 1
  - Network Capacity Equivalence: *Koetter, Effros and Medard*
  - General capacity using network coding: *Medard*
  - On Matroidal Solutions for Network Coding: *Cohen, Effros, ElRouayheb and Koetter* (Also Thrust 2)
  - The Intermediate Density Scaling Regime*: Johari*
  - On Optimal Capacity Scaling in Arbitrary Wireless Networks: *U. Niesen, P. Gupta and D. Shah* (Also Thrust 3)

- Thrust 2
  - Euclidean Information Theory: *Zheng*
  - The Degraded Finite-State Broadcast Channel: *Dabora and Goldsmith*
  - Feedback and Directed Information in Wireless Networks: *Permuter, Weissman, and Goldsmith* (Also Thrust 1)
  - Universal Decoding in MANETS: *Moulin*
  - Capacity of Interference Channels with Cognitive Transmitters: *Maric, Goldsmith, Shamai, Kramer* (Also Thrust 1)
  - General Relaying for Multicast in Wireless Networks: *Maric, Goldsmith, and Medard* (Also Thrust 1)
  - Capacity and Queue-based Codes for Timing Channels: *Moulin*

Posters (Cont'd)

- Thrust 2 (Cont's)
  - Rate Distortion of Poisson Processes under Queuing Distortion: *Coleman, Kiyavash, and Subramanian*
  - Embedded Coding and UEP: *Borade and Zheng* (Also Thrust 1)
  - Joint Source/Channel Coding in Networks: *Coleman*
  - Capacity, Source/Channel Coding, and Separation: *Liang, Goldsmith, and Effros* (Also Thrust 1)
- Thrust 3
  - Utility Maximization and Cross-Layer Optimization in Dynamic Networks: *Boyd* (Also Thrust 2 and 1)
  - Network Utility Maximization and Adaptive Modulation: *O'Neil, Goldsmith, and Boyd* (Also Thrust 2)
  - Wireless networks: Algorithmic trade-off between Throughput and Delay: *D. Shah, D. Tse, J. Tsitsiklis* (Also Thrust 1)
  - Optimizing MaxWeight: Routing Implementation*: Meyn and Chen* (Also Thrust 1)
  - Distributed Control and Optimization Methods for Wireless Networks: *Ozdaglar*
  - Incomplete information, dynamics, and wireless games: *Adlakha, Johari, and Goldsmith*
  - *Oblivious Equilibrium for General Stochastic Games: Johari*

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Project Summary

Project Summary

- We have made substantial progress on many topics within our thrust areas: satisfied progress criteria
- Synergies between thrusts are emerging, in particular the role of optimization in consummating the union
- Ongoing challenges to be addressed (food for thought)
  - How to define and address reliability explicitly: what is fundamental?
  - Models: What common canonical models are useful for information theory and networking
  - Design and “verification” for robustness to models
  - Along what axes should separation be defined?
    - Protocol/function layers, time, space, …

Also in Team Meeting

- Dynamics in equivalence classes
- Reliability in our project, particularly DNUM
- Red teaming (format and specific feedback)

Thanks to Chris

For your vision, inspiration, and leadership in creating and managing the ITMANET program

Information Theory for Mobile Ad-Hoc Networks (ITMANET):
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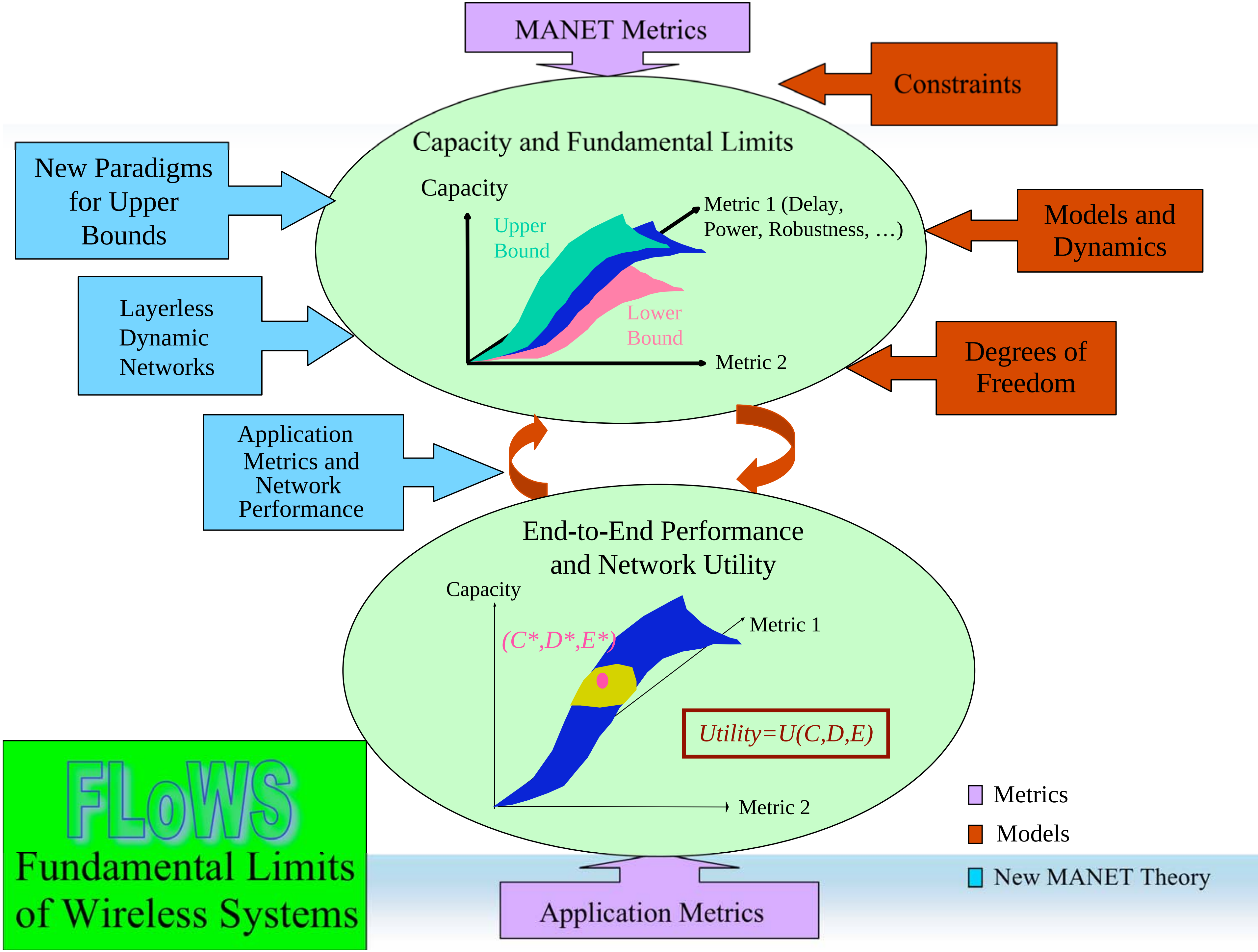
Team Meeting


MANET Metrics
Constraints
Capacity and Fundamental Limits
Capacity
Upper
Bound
Metric 1 (Delay,
Power, Robustness, …)
Lower
Bound
Metric 2
New Paradigms
for Upper
Bounds
Models and
Dynamics
Layerless
Dynamic
Networks
Degrees of
Freedom
Application
Metrics and
Network
Performance
End-to-End Performance
and Network Utility
Capacity
(C*,D*,E*)
Metric 1
Utility=U(C,D,E)
Metric 2
FLoWS
Fundamental Limits
of Wireless Systems
Metrics
Models
New MANET Theory
Application Metrics

R^3: Robustness/Reliability/Resilence

- Definition: Graceful performance degradation in the face of modeling errors and uncertainty
  - Performance refers to both capacity and policies.
  - Modeling errors/uncertainties include model variations, dynamics, lack/imperfections of knowledge, model-free notion
- How to fundamentally address robustness
  - Design to be robust to sensitivity in modeling
  - Explicitly include robustness mechanisms in design
    - Feedback
  - At PHY layer: universality, UEP, outage, worst-case, inherently-robust capacity definitions, ARQ…
  - At NET layer: incorporate link dynamics, pessimistic distributions, Expectation to induce risk aversion, (rateless) coding across the network, network management

What is R^3 (Subject to some debate)

- Robustness: Optimizing against a parametric class of models
- Reliability: Good performance for unanticipated events
- Resilence: Graceful degradation with respect to imperfections in model assumptions

Separation

- Definition
  - Breaking a large problem into smaller problems
  - What is the price?
  - Examples
    - Equivalence results (Channel vs. network coding)
    - All Optimization work (PHY vs. Network)
    - Hierarchical Scaling Laws (spatial)
    - Generalized capacity and separation (channel vs. source coding)
    - MAC under uncertainty (timescale separation)
    - DNUM (timescale separation)
    - Workload relaxation (spatial decomposition)
- What are the right axes?
  - PHY vs. Network vs. Application
  - Spatial separation
  - Timescales

Next Steps

- Start work related to Phase 2 goals
- Develop further the synergies between thrusts that have emerged, and develop new ones.
- Clearly articulate
  - Lessons learned from CBMANET, and how to incorporate them into our work
  - What metrics we are taking into account, and which ones we aren't.
  - More on robustness, separation, and canonical models.