ITMANET

FLoWS

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

Thrust 3

Application Metrics and Network Performance

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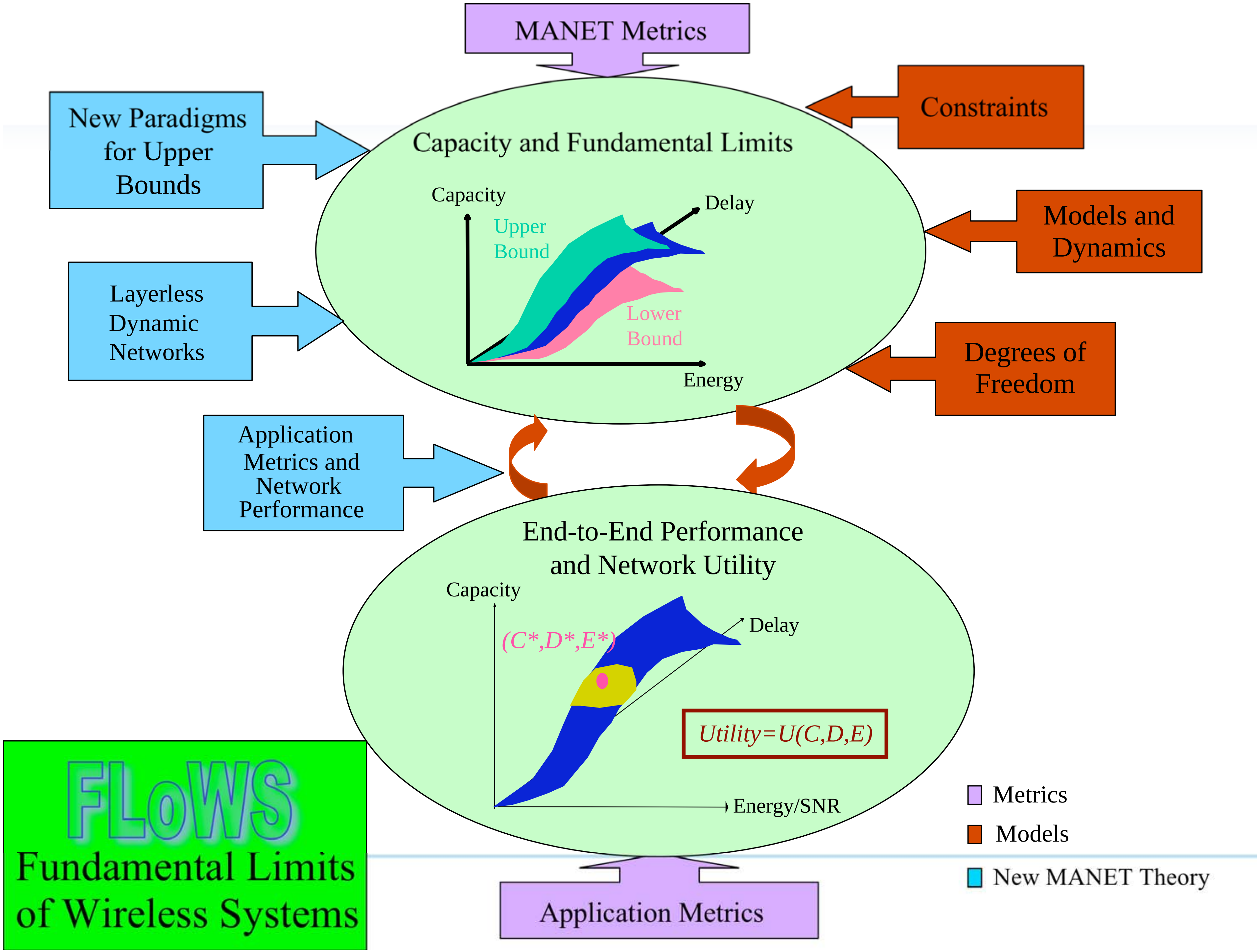

MANET Metrics
Constraints
New Paradigms for Upper Bounds
Capacity and Fundamental Limits
Capacity
Delay
Upper Bound
Lower Bound
Energy
Models and Dynamics
Layerless Dynamic Networks
Degrees of Freedom
Application Metrics and Network Performance
End-to-End Performance and Network Utility
Capacity
(C*,D*,E*)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

Optimizing Application and Network Performance

FLoWS

- Objective:
  - Developing a framework for optimizing heterogeneous and dynamically varying application metrics and ensuring efficient operation of large-scale decentralized networks with uncertain capabilities and capacities
  - Providing an interface between application metrics and network capabilities
    - Focus on a direct involvement of the application in the network, defining services in terms of the function required rather than rates or other proxies
- Application and Network Metrics: utility functions of users-applications, distortion, delay, network stability, energy…
- We envision a universal algorithmic architecture:
  - Capable of balancing (or trading off) application requirements and network resources
  - Adaptable to variations on the network and user side
  - Operable in a decentralized manner, scalable
  - Robust against non-cooperative behavior

Algorithmic Architecture for Optimizing Application and Network Performance

Thrust Areas

1. Optimization Methods for General Application Metrics

Our goal is to develop new optimization algorithms with the following properties:

- Optimize general application metrics (e.g., coupled performance measures, hard-delay constraints)
- Strong focus on physical layer constraints
- Completely distributed and scalable
- Robust against dynamic changes in channel characteristics and network topology
- Incorporate networked-system constraints (asynchronism, delays, quantized and noisy information)

Thrust Areas

2. Stochastic Network Algorithms and Performance Analysis

   Understand queuing dynamics and effect on flow-level network behavior:

   – Designing macro (flow) level and micro (queuing) level network algorithms to yield desired performance
   – Integration of macro and micro level models

3. Game-Theoretic Models and Multi-Agent Dynamics

   New resource allocation paradigm with focus on heterogeneous and non-cooperative nature of users:

   – Understanding when local competition yields globally desirable outcomes
   – Studying dynamics that achieve the equilibrium

Thrust Achievements
Optimization Methods for General Application Metrics

- **Utility Maximization in Dynamic Networks (Boyd)**
  - Multi-period model and distributed algorithm for dynamic network utility maximization with time-varying utilities, link capacities, and delivery constraints
  - Delivery contracts model hard-delay requirements on applications, which cannot be captured by static NUM.
  - Model extended to the stochastic case when the problem data (i.e., link capacities) not known ahead of time. A distributed control policy developed based on model predictive control.
- **Distributed Optimization Methods with Quantized Information and Local Constraints (Ozdaglar)**
  - Combined earlier work from July on distributed optimization methods for general performance metrics with specific quantization rules and local projections
  - Performance guarantees for new distributed optimization algorithms that can operate with:
    - communication bandwidth and storage constraints
    - local constraints on decisions
    - time-varying network connectivity

Thrust Achievements
Optimization Methods for General Application Metrics

- **Optimizing Adaptive Modulation via Utility Maximization (Goldsmith and Boyd)**
  - Cross-layer rate and power allocation policies for several practical modulation schemes
  - Developed optimization formulations, closed-form solutions, and algorithms in the presence of instantaneous BER constraints
  - Cross-layer policies very different from policies based on physical layer optimization only
- **Resource Allocation in Non-Fading and Fading Multiple Access Channel (Medard and Ozdaglar)**
  - Efficient resource allocation over the information theoretic capacity region of multiple access channel to maximize a general concave utility function of transmission rates
  - For the non-fading channel, developed a gradient projection method, with efficient approximate projection that relies on the rate-splitting idea
  - For the fading channel, extended the gradient projection method to develop greedy allocation policies with performance guarantees

Thrust Achievements
Stochastic Network Algorithms

- **Algorithmic Trade-off between Throughput-Delay (Shah)**
  - Simultaneous performance guarantees for stochastic network algorithms in terms of delay and throughput has been a major challenge
  - Impossibility result: For an arbitrary wireless network operating under SINR channel model, it is not possible to have a computationally efficient algorithm that has both: (a) high throughput, and (b) low delay

- **Performance Optimization for MaxWeight Policies (Meyn)**
  - Maxweight scheduling/routing policies have become popular in view of their throughput properties. However, these policies are inflexible with respect to performance (delay) improvement
  - Extended maxweight using general Lyapunov functions
  - Demonstrated excellent performance on practical topologies

Thrust Achievements
Game-Theoretic Models and Algorithms

- **Incomplete Information, Dynamics, and Wireless games (Johari and Goldsmith)**
  - Existing work on resource competition among multiple nodes using game theoretic techniques assume complete information and rely on static models
  - Developed a game-theoretic model for power allocation among competitive users in the presence of incomplete information about channel conditions of other nodes and dynamic interactions
  - Provided a full-characterization of the Bayes-Nash equilibrium, which shows very different predictions than the complete information/static models

- **Dynamics and Equilibria in Stochastic Games (Johari)**
  - Dynamics in stochastic games not well-understood beyond zero-sum stochastic games
  - Developed a new notion of equilibrium “oblivious equilibrium” for general stochastic games that admits convergent dynamics and is a good model for dynamic wireless interference games

Inter-Thrust Achievement

- **Optimal Capacity Scaling in Arbitrary Wireless Network (Shah)**
  – Scaling laws for networks with arbitrary node placement and arbitrary multicommodity flows
    - Made use of topological structure to design algorithms which can achieve the optimal capacity scaling
  – Philosophical distinction: Achievability through algorithmic thinking
    - For arbitrary node placement, designing cooperative schemes involves combinatorial elements, such as geographic clustering and multihop communications

Achievements Overview

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

Johari: Dynamics and equilibria in stochastic games

Meyn: Generalized Max-Weight policies with performance optimization

Stochastic Network Analysis

Flow-based models and queuing dynamics

Game Theory

New resource allocation paradigm that focuses on hetereogeneity and competition

Thrust Synergies

- General objective of the thrust requires:
  - Flow-level algorithms for optimizing heterogeneous application metrics
  - Packet-level algorithms for ensuring efficient and stable functioning of the network
  - Integration of application metrics and network capabilities

- Our thrust achieves these objectives through an algorithmic approach based on:
  - Development of efficient distributed optimization algorithms
  - Strong emphasis on physical layer constraints
  - Stochastic network analysis for stability and performance
  - Synergy in the integration of the macro and micro level models and of algorithmic optimization and stability analysis
  - Game-theoretic analysis of equilibrium models for
    - robustness against adversarial, competitive, and non-compliant behavior
    - modeling information structures and dynamics

Synergies with Other Thrusts

- Resource negotiation for performance tradeoffs
  - Thrust 1 provides upper bounds on "performance region"
  - Thrust 2 provides achievable region
  - Thrust 3 chooses operating point on these regions
- Algorithms for implementing "building blocks" within network context
  - Thrust 2 uses information-theoretic analysis to provide closed-form or asymptotic solutions for canonical networks
  - Thrust 3 designs algorithms to incorporate these insights/building blocks into a network
- Combinatorial algorithms for upper bounds

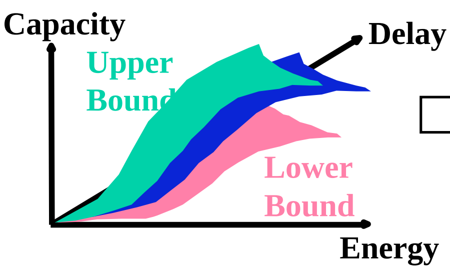
Thrust Synergies: An Example

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

Combinatorial algorithms for upper bounds

Thrust 1
Upper Bounds

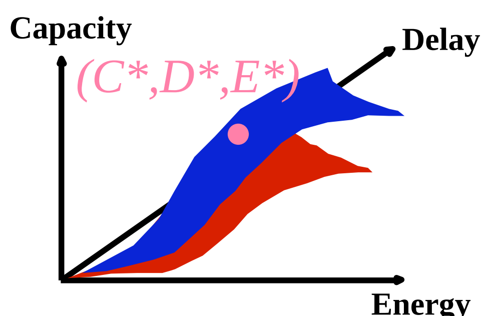
Γ_1



Γ_2

Thrust 2
Layerless Dynamic Networks

Thrust 3
Application Metrics and Network Performance



Boyd: Dynamic and stochastic network utility maximization with delivery constraints

T3 solves this problem:

Boyd, Goldsmith: Network utility maximization with adaptive modulation

level considerations

•Modeling information structures (may

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

Algorithmic constraints and sensitivity analysis may change the dimension of performance region

Roadmap

- Multi-period dynamic NUM for optimally trading-off metrics such as delay, rate, admission costs
- Incorporation of networked-system constraints (bandwidth limitations, delays, noise) on distributed algorithm design
- Layers of bipartite graphs as a model for the network and resource allocation using scheduling and distributed optimization across layers
- High throughput low delay distributed scheduling algorithms for particular topologies in the presence of interference effects
- Decentralized implementations for generalized maxweight policies
- Design of dynamic algorithms for achieving equilibrium in game-theoretic models

Recent Publications

- V. Abhishek, S. Adlakha, Johari, and Weintraub, “Oblivious Equilibrium for General Stochastic Games with Many Players,” Allerton 2007.
- S. Adlakha, Johari, and Goldsmith, “Competition Between Wireless Devices with Incomplete Channel Knowledge,” submitted to *IEEE Journal on Selected Areas in Communications*.
- E. Ahmed, A. Eryilmaz, A. Ozdaglar, and M. Medard, “Economic Gains from Network Coding in Wireless Networks,” submitted for publication 2007 (also appeared in Allerton 2006)
- E. Arcaute, E. Dallal, R. Johari, S. Mannor, "Dynamics and Stability in Network Formation Games with Bilateral Contracts", Submitted to *IEEE Conference on Decision and Control* (CDC) 2007.
- E. Arcaute, R. Johari, and S. Mannor, “Network Formation: Bilateral Contracting and Myopic Dynamics” submitted to IEEE TAC 2007.
- Bayati, Prabhakar, Shah and Sharma, “Iterative Scheduling Algorithms,” IEEE Infocom, 2007.
- Bayati, Shah and Sharma, “Maximum Weight Matching via Max-Product Belief Propagation,” To appear in IEEE Information Theory Transactions, 2007.
- T.P. Coleman, E. Martinian, and E. Ordentlich, "Joint Source-Channel Decoding for Transmitting Correlated Sources over Broadcast Networks", submitted January 2007, IEEE Transactions on Information Theory (also appeared in 2006 International Symposium on Information Theory, Seattle, WA, July 10-14, 2006).

Recent Publications

- V. Doshi, D. Shah and M. Medard, “Source Coding with Distortion through Graph Coloring,” IEEE ISIT, 2007.
- V. Doshi, D. Shah, M. Medard and S. Jaggi, "Distributed Functional Compression through Graph coloring,” DCC, 2007.
- V. Doshi, Shah, M. Medard and S. Jaggi, “Graph Coloring and Conditional Graph Entropy,” Asilomar conference, 2006, pp: 2137-2141.
- A. Eryilmaz, A. Ozdaglar, E. Modiano, “Polynomial Complexity Algorithms for Full Utilization of Multi-hop Wireless Networks,” IEEE Infocom, 2007.
- S. P. Meyn. "Stability and asymptotic optimality of generalized MaxWeight policies," Under revision for *SIAM J. Control & Opt.* (Preliminary version to appear at the 46th IEEE Conference on Decision and Control, December 2007).
- S. P. Meyn. Control techniques for complex networks, Cambridge University Press, 2007.
- Mosk-Aoyama and D. Shah, “Computing Separable Functions via Gossip,” Under preparation. Preliminary version appeared in ACM PODC, 2006.
- A. Nedic and A. Ozdaglar, “Distributed Asynchronous Subgradient Methods for Multi-Agent Optimization,” to appear in IEEE Transactions on Automatic Control, 2007.
- A. Nedic and A. Ozdaglar, "On the Rate of Convergence of Distributed Asynchronous Subgradient Methods for Multi-agent Optimization," *Proc. of Conference on Decision and Control, CDC*, 2007, New Orleans, Louisiana.

Recent Publications

- A. Nedic and A. Ozdaglar, "Convergence Rate for Consensus with Delays," *LIDS report 2774*, submitted for publication, 2007.
- D. O’Neill, A. J. Goldsmith and S. Boyd, “Optimizing Adaptive Modulation in Wireless Networks via Utility Maximization,” Submitted to *International Conference on Communications (ICC)* 2008.
- C. T. K. Ng, D. Gündüz, A. J. Goldsmith and E. Erkip, “Optimal Power Distribution and Minimum Expected Distortion in Gaussian Layered Broadcast Coding with Successive Refinement,” Submitted to *IEEE Transactions on Information Theory*, 2007.
- A. Ozdaglar, "Constrained Consensus and Alternating Projections," *Proc. of Allerton Conference on Communications, Control and Computing*, 2007.
- A. Parandehgheibi, A. Ozdaglar, M. Medard, A. Eryilmaz, "Utility Maximization in Multiple Access Channels," *Proc. of Asilomar Conference on Signals, Systems and Computers*, 2007, Monterey, CA.
- N. Trichakis, A. Zymnis and S. Boyd, "Dynamic Network Utility Maximization with Delivery Contracts," Submitted to *International Federation of Automatic Control (IFAC) World Congress*, 2008.
- F. Zhao, Lun, D., Médard, M. and Ahmed, E., “Decentralized Algorithms for Operating Coded Wireless Networks,” Invited Paper in *Information Theory Workshop (ITW)*, 2007, Lake Tahoe, CA.
- A. Zymnis, N. Trichakis, S. Boyd and D. O'Neill, "An Interior-Point Method for Large Scale Network Utility Maximization," Submitted to *Operations Research Letters*, 2007.