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

Thrust 3
Application Metrics and Network Performance

Asu Ozdaglar and Devavrat Shah
Capacity and Fundamental Limits

Application Metrics

End-to-End Performance and Network Utility

Constraints

Models and Dynamics

Degrees of Freedom

Layerless Dynamic Networks

New Paradigms for Upper Bounds

Application Metrics and Network Performance

FLoWS

Fundamental Limits of Wireless Systems

MANET Metrics

New MANET Theory

Capacity

Upper Bound

Lower Bound

Delay

Energy

Utility = U(C,D,E)

(C*,D*,E*)

Energy/SNR

Metrics

Models

New MANET Theory
Optimizing Application and Network Performance

- **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
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)
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
  - *Ozdaglar*: Distributed optimization algorithms for general metrics and with quantized information
- Efficient resource allocation in non-fading and fading MAC channels using optimization methods and rate-splitting
  - *Medard, Ozdaglar*
- Game-theoretic model for cognitive radio design with incomplete channel information
  - *Goldsmith, Johari*

**Stochastic Network Analysis**
- Flow-based models and queuing dynamics
  - *Shah*: Optimal capacity scaling for arbitrary node placement and arbitrary multi-commodity flows
- Low complexity throughput and delay efficient scheduling
  - *Shah*

**Game Theory**
- New resource allocation paradigm that focuses on heterogeneity and competition
  - *Johari*
- Dynamics and equilibria in stochastic games
  - *Johari*

**Network Utility Maximization**
- Dynamic and stochastic network utility maximization with delivery constraints
  - *Boyd*
- Network utility maximization with adaptive modulation
  - *Boyd, Goldsmith*

**Resource Allocation**
- Generalized Max-Weight policies with performance optimization
  - *Meyn*

**Game-Theoretic Model**
- Efficient resource allocation in non-fading and fading MAC channels using optimization methods and rate-splitting
  - *Medard, Ozdaglar*
- Game-theoretic model for cognitive radio design with incomplete channel information
  - *Goldsmith, Johari*

**Stochastic Network Analysis**
- Flow-based models and queuing dynamics
  - *Shah*: Optimal capacity scaling for arbitrary node placement and arbitrary multi-commodity flows
- Low complexity throughput and delay efficient scheduling
  - *Shah*

**Optimization Theory**
- Distributed efficient algorithms for resource allocation
  - *Ozdaglar*: Distributed optimization algorithms for general metrics and with quantized information
- Efficient resource allocation in non-fading and fading MAC channels using optimization methods and rate-splitting
  - *Medard, Ozdaglar*
- Game-theoretic model for cognitive radio design with incomplete channel information
  - *Goldsmith, Johari*

**Game Theory**
- New resource allocation paradigm that focuses on heterogeneity and competition
  - *Johari*
- Dynamics and equilibria in stochastic games
  - *Johari*
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

**Thrust 1**
Upper Bounds

- Using distributed algorithms
- Considering stochastic changes, physical layer constraints and micro-level considerations
- Modeling information structures (may lead to changes in the performance region)

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

**Thrust 2**
Layerless Dynamic Networks

**Thrust 3**
Application Metrics and Network Performance

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

Boyd: Dynamic and stochastic network utility maximization with delivery constraints

(\(C^*, D^*, E^*\)) optimal solution of Boyd:
Dynamic and stochastic network utility maximization with delivery constraints

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

**Upper Bounds**

**Lower Bounds**

- Capacity
- Delay
- Energy

\[ \Gamma_1 \]

\[ \Gamma_2 \]
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


Recent Publications


Recent Publications


