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

Thrust 1
Upper Bounds

Muriel Medard, Michelle Effros and Ralf Koetter
Non-Coherent Multipath Fading Relay Networks in the Wideband Regime – Fawaz, Medard

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

1) Achievable rate in non-coherent multipath fading relay channel
   - coincides with generalized block-Markov lower bound of AWGN-FD channel -> LB
   - coincides with cut-set upper-bound for -> Capacity
2) Non-coherent peaky frequency binning scheme
3) Min-cut on hypergraph model

HOW IT WORKS:

• Source: Low-duty cycle peaky FSK signaling
• Relay: Decode, Frequency Binning and Forward
• Destination: decodes relayed signal, then source signal using relayed information

ASSUMPTIONS AND LIMITATIONS:

• Wideband regime
• Relay decodes fully

Towards characterizing the capacity of the building block of MANETs

STATUS QUO

Capacity of general relay channel unknown
• Bounds on general relay channel
• Bounds on AWGN relay channel

NEW INSIGHTS

Wideband regime: not interference-limited, but energy-limited
point-to-point: $C_{\text{Fading}} = \frac{P}{N_0} = C_{\text{AWGN}}$

Hypergraph Model: min-cut on hypergraph

IMPACT

1) Achievable rate in non-coherent multipath fading relay channel
   - coincides with generalized block-Markov lower bound of AWGN-FD channel -> LB
   - coincides with cut-set upper-bound for $w^2 \geq 1 + \sqrt{\gamma}$ -> Capacity
2) Non-coherent peaky frequency binning scheme
3) Min-cut on hypergraph model

EXTENSION TO LARGER NETWORKS: multiple relays, layers...

Open question: closing the gap to Cut-set UB?

Virtual MIMO gain in the wideband regime?
Sufficient conditions under which linear operations at the internal nodes (combined with possible non-linear operations at the terminals) suffice to achieve optimality.

The same conditions are also sufficient to show that the rate region can be described without non-Shannon information inequalities.

Removing the linearity constraint at edge nodes increases the family of problems for which (mostly) linear codes are optimal.
Continuity for Network Coding Capacity Regions

Gu and Effros

ACHIEVEMENT DESCRIPTION

Question: Can a small change in source distribution mean a big change in capacity region?

- Previous ITMANET results:
  • Inner semi-continuity for many networks.
  • Outer semi-continuity only for a few simple networks.

How it works:
- Assume that the source alphabet is known.
  - In this case, \( p(x) > 0 \) for all \( x \) in the known alphabet.
  - Prove continuity under this assumption (called S-continuity).

Assumptions and limitations:
S-continuity results apply quite generally
- Zero-error coding (arbitrary demands – including functions)
- Lossless coding (arbitrary demands – including functions)
- Lossy coding (non-functional and separable)
- Lossy coding (functional when all demands have distortion constraints greater than 0)

- The difference between \( p(x) = 0 \) and \( p(x) = \epsilon \) can be very large.
- Capacity regions probably are NOT outer semi-continuous in the source distribution in general!

- For non-functional source coding, reliable source distribution estimations result in reliable approximations of capacity regions.
- For functional source coding, estimated source distributions should have the same support of the true distribution.

Upper bound approximation errors of capacity approximation when using estimated source distributions.
Investigate other abstract properties (for example, strong converses) that we can possibly exploit in practical code design.

S-Continuity holds for broad classes of network coding capacity regions.
Information Theory for Mobile Ad-Hoc Networks (ITMANET): The FLoWS Project

Thrust 2
Layerless Dynamic Networks

Lizhong Zheng, Todd Coleman
Achievable Rate Regions for BC With Cognitive Relays
Goldsmith, Jiang, Maric, Cui

Achievable Rate Regions for BC With Cognitive Relays

- Cognitive radio channel (CRC) & interference channel with a cognitive relay (ICCR) have been studied as variants of the IC
- Known interference assumption imposing a constraint on the encoding order cannot include Marton’s Region for the BC

NEW INSIGHTS
Relay 1
Base Station
Relay 2
Viewing both models as variants of the broadcast channel (BC):
Both models are regarded as the BC with cognitive one relay or two relays (BCCR)

ACHIEVEMENT DESCRIPTION

MAIN RESULT:
New coding scheme effectively integrates superposition coding, Gel’fand-Pinsker coding, and Marton’s binning scheme, and applies simultaneous joint decoding

• New achievable rate regions for both the CRC and the BCCR
• Special capacity results to be identified

HOW IT WORKS:
Rate splitting of both messages (common and private)
Private messages are encoded with two layers:
(1) Inner layer serves as cooperation base between relays and the sender
(2) Outer layer performs Generalized GP coding against each other’s inner layer, and perform Marton’s binning against each other

ASSUMPTIONS AND LIMITATIONS:
• Cognition is non-causal, but is practical in certain sensor network scenarios
• Region is derived in its implicit form

IMPACT
- New achievable rate regions for both the CRC and the BCCR
- New regions generalize Marton’s region for BC
- A simple achievable rate region obtained for a special case Gaussian CRC (potentially tight)

NEXT-PHASE GOALS
- Outer-bound of the capacity region to be developed from the BC perspective
- Special capacity results to be identified

Exploiting the broadcasting nature of CR channels leads to better achievable rates
Tilted Matching for Feedback Channels
B. Nakiboglu, L. Zheng

ACHIEVEMENT DESCRIPTION

MAIN RESULT:
Tilted a posteriori matching achieves the best error exponent

How it works:
- Smooth upper bound to error prob.
  \[ P_e \leq E \left[ \sum_k \varphi_n(k)^{1-\mu_n} \left( \sum_{\ell \neq k} \varphi_n(\ell)^n \right)^\mu \right] \]
- Make sure at each time t, conditioned on any history, the above metric decreases by a multiplicative factor;
- Match tilted a posteriori distribution to the desired input distribution.

AP tilting \( \varphi_n(\cdot)^n \) instead of \( \varphi_n(\cdot) \)

End-of-phase goal:
- Break away from uniform increment, allow coding to be considered as a dynamically changing optimization
- New performance metric and the resulting coding schemes for dynamic problems

Status quo:
- Feedback is an efficient way for error correcting, but often used for ACK/NACK and retransmissions
- Using feedback to guide FEC has only limited examples
- Performance metric for Dynamic coding is missing

Community challenge:
The dynamic aspect of FEC coding, which is crucial in understanding dynamic information exchange requires new formulation

New insights:
By finding the a posteriori matching scheme with the optimal error exponent, we expose the limitation of error exponent optimal FB coding

Uniform Belief Increment Limits Performance
Lyapunov Exponents and the Posterior Matching Scheme
Coleman

ACHIEVEMENT DESCRIPTION

**MAIN RESULT:**
- For the posterior matching scheme with encoder (*), the following dynamical system decoder - with arbitrary initial condition $u$ in $(0,1)$ - achieves capacity:
  \[
  \left[ \mathcal{P}^{\frac{1}{2}} \left[ j \frac{1}{2} \right] \right] = \mathcal{C}_L \left( \mathcal{P}^{\frac{1}{2}} \left[ j \frac{1}{2} \right] \right) = \mathcal{C}_L \left( \mathcal{P}^{\frac{1}{2}} \left[ W + 1 \frac{1}{2} \right] \right) \]

**HOW IT WORKS:**
- Since the $Y$'s are independent and identically distributed, the decoder dynamical system is a Markov chain and has a Lyapunov exponent of $-C$ for any initial condition $u$ on $(0,1)$

\[
\frac{1}{\log \left( \mathcal{C} \left( \mathcal{P}^{\frac{1}{2}} \left[ W + 1 \frac{1}{2} \right] \right) \right)} \Rightarrow \mathcal{P}^{\frac{1}{2}} \left[ j \frac{1}{2} \right] > 2^{\mathcal{N}_C} ! 0
\]

**IMPACT:**
- Provides explicit capacity-achieving recursive encoders and decoders
- Can be extended to networks with tight converses

**STATUS QUO:**
- Deep understanding of feedback is still work in progress. Are there simple provably good iterative feedback encoders/decoders?

**NEW INSIGHTS:**
- Converse to coding theorem: next input should be independent of everything decoder has seen so far
- With an optimal decoder, such “posterior matching” schemes achieve capacity
- Does this motivate a simple iterative decoder, that achieves capacity?
- How do we analyze this easily, exploiting the dynamics?

**ASSUMPTIONS AND LIMITATIONS:**
- Noiseless feedback
- Memoryless Channels

Use Stochastic Control methodology for a principled, canonical approach to address:
- Noisy feedback (POMDP)
- Unknown channel (Q-learning)
- Delayed feedback

---

A Canonical Controls Methodology to Design Iterative Feedback Coding Systems in MANETs
Efficient Codes using Channel Polarization
Bakshi, Jaggi, and Effros

ACHIEVEMENT DESCRIPTION

At each encoder:

- Divide input of blocklength \( N \) into \( N/f(N) \) sub-blocks of length \( f(N) \) each
- Apply high rate R-S code on the entire input followed by a polar code on each sub-block
- When the polar code fails on few of the sub-blocks, the R-S code can correct the error
- \( P(\text{error}) \) decays as \( \exp(-o(N)) \); Complexity is \( O(N\text{-poly log } N) \); excess rate goes to 0 asymptotically

How it works:

- Practical coding schemes for several different types of channels that have the following properties:
  - Low complexity
  - Low delay
  - Capacity achieving

Assumptions and limitations:

- Works for channels where capacity-achieving codes are known (e.g. point-to-point channels, degraded broadcast channels, multiple access channels)
- Dependence of error probability on excess rate unknown

Find Polar codes or a modification that work for a bigger class of channels

Use insight from the two-stage design to construct a better single stage code – currently works for special cases.

Concatenating Polar and R-S codes leads to more efficient codes for several different channels
Information Theory for Mobile Ad-Hoc Networks (ITMANET): The FLoWS Project

Thrusts 1& 2
Performance Bounds for the Interference Channel with a Relay
Ivana Marić, Ron Dabora and Andrea Goldsmith

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:
A new sum-rate outer bound to the performance of the Gaussian interference channel with a relay

HOW IT WORKS:
A genie gives to a receiver minimum information needed for decoding both messages

ASSUMPTIONS AND LIMITATIONS:
• The considered channel model: the interference channel with a relay
• The genie cannot be turned-off even when not needed i.e., in strong interference regime.

IMPACT
1) Tighter outer bound than cut-set bound and than existing cognitive ICR bounds
2) Close to achievable rates in strong interference

A sum-rate outer bound for the Gaussian interference channel with a relay developed
Joint Source/Channel Coding with Limited Feedback
Deniz Gündüz, Andrea Goldsmith and Vincent Poor

High SNR behavior of the average distortion in transmitting Gaussian sources over MIMO fading channels: “distortion exponent”

Multi-layer source coding followed by multi-rate channel coding
Each source layer is transmitted until successfully decoded by the receiver

- We study the high SNR regime
  - Consider 1 bit/channel use feedback
  - Use feedback as instantaneous ARQ

One-bit instantaneous feedback helps us achieve the optimal distortion exponent in MIMO systems. Feedback also helps us simplify the transmission scheme.

• Improves our understanding of how to utilize feedback optimally in communication systems

To find the optimal transmission scheme when the feedback resources are limited
Capacity and Achievable Rates for the Interference Channel: Deniz Gündüz, Nan Liu, Andrea Goldsmith and Vincent Poor

**Classical interference channel:**
- Each user has one message destined for its own receiver
- Receivers have no side information

**Networks are more complicated:**
- Some common messages might be destined for both receivers
- Each receiver might know a part of the interfering message

**NEW INSIGHTS**

**MODEL:**

**Interference Ch. with Message Side Information**

Each receiver knows a part of the interfering message

**X-Channel with Degraded Message Sets**

Achievable rates for general channel models

These are shown to be capacity achieving for two special classes:
- a class of deterministic interference channels
- a special class of Z-channels

**FLOWS & NEQUIT ACHIEVEMENT**

- More general models for interference channels are proposed
- These can model more complicated and realistic networks

**NEXT-PHASE GOALS**

- Extend the finite-bit capacity results for the classical Gaussian interference channel to these new models

**ACHIEVABLE RATES**

Achievable rates for more general interference channel models.
Multicasting with a Relay
D. Gündüz, O. Simeone, A. Goldsmith, V. Poor and S. Shamai

In multicasting multiple messages over a network, common strategies are:
- Routing
- Decoding both messages at the relay and using network coding

Relay need not decode the messages
Design codes that enable decoding of the modulo sum of the messages at the relay:
Structured coding

Main Result:
We develop structured codes that exploit the network topology such that the relay decodes and multicasts only the modulo sum of the messages.

Linear codes achieve the capacity region for finite-field modulo additive channels.
Nested-lattice codes for Gaussian channels: approach the upper bound and surpass standard random coding schemes.

Next-Phase Goals
- Extension to multiple relays
- Combine structured and random codes for uniformly higher rates

Structured codes improve multicasting rates over a relay network.
The Multi-Way Relay Channel
Deniz Gündüz, Aylin Yener, Andrea Goldsmith and Vincent Poor

Exact capacity regions are hard to obtain even with three nodes.
Random codes are capacity achieving for many models.
Decode-and-forward relaying used in most practical systems.

Joint source-channel coding techniques to achieve higher rates
Structured codes provide higher rates than random coding in some networks

FLOWS & NEQUIT ACHIEVEMENT

MAIN RESULT:

Clusters of users: Each user in a cluster wants messages of all other users in the same cluster.
Communication is enabled by the relay.

ASSUMPTIONS AND LIMITATIONS:
No signal received from other users
Symmetric capacity for a symmetric system is analyzed
* Achievable symmetric rate is characterized and compared to the upper bound

Model:

- Consider inter and/or intra cluster reception
- Combine structured and random codes
- Characterize non-symmetric achievable rate points

Impact:

• Joint source/channel coding helps achieve higher rates in networks
• Compress and forward relaying outperforms other strategies for this network topology

Next-Phase Goals:

Both compress-and-forward relaying and lattice coding achieve symmetric rates within a constant gap of capacity.
Network information theory is a theory of exchange of information among nodes.

**ACHIEVEMENT DESCRIPTION**

**MAIN ACHIEVEMENT:**

Mutual information $I(X;Y)$ characterizes the amount of information that must be sent in order to generate a desired joint distribution.

We characterize the tradeoff between the rate of available common randomness and the communication needed for achieving the desired coordination.

**IMPACT**

The result yields results in distributed game theory, task assignment and rate distortion theory. Specifically what is the set of all distributions $p(x_1, x_2, ..., x_m)$ inducible under communication rate constraints $R_{ij}$, $ij = 1, 2, ..., m$?

**NEW INSIGHTS**

We shift emphasis away from information exchange. One of the main purposes of distributed communication is the induced cooperation of the nodes of the network. How much dependence can be set up with a given set of communication constraints?

**HOW IT WORKS:**

The coordination scheme requires randomization at both encoder and decoder. A codebook of independently drawn sequences $U^n$ is overpopulated so that the encoder can choose one randomly from many that are jointly typical with $X^n$. The decoder then randomly generates $Y^n$ conditioned on $U^n$. 

**ASSUMPTIONS AND LIMITATIONS:**

We assume that the desired joint distribution is known.

We propose investigation of universal coordination schemes that work uniformly well over a family of problems.

We seek a theory of dependence and cooperation in mobile ad hoc networks.

There exists an optimal tradeoff between the amount of common randomness used and the required communication rate.
3-Receiver Broadcast Channels with Confidential Messages
Y.K. Chia, A. El Gamal

ACHIEVEMENT DESCRIPTION

MAIN RESULT:
- New rate-equivocation tradeoff regions for 3 receivers broadcast channels with 1 and 2 eavesdroppers
- Achieves capacity for several nontrivial special cases
- Generalizes inner bounds obtained in previous work

HOW IT WORKS:
- Via indirect decoding, legitimate receivers can decode a larger set of messages carried by auxiliary random variables. This improves the rate region
- Coding scheme uses randomization to confuse the eavesdropper but in a way which makes the message still decodable by the legitimate receiver

IMPACT
- Secrecy capacity regions for new classes of networks
- New coding techniques for secrecy capacity

NEXT-PHASE GOALS
- Secret message and key capacities for general network of legitimate receivers and eavesdroppers

NEW INSIGHTS
- Use a newly introduced technique of “indirect decoding” and the standard techniques of random binning, Marton binning and superposition coding to obtain new bounds on secrecy capacity that are tight in several cases of interest.

STATUS QUO
- Information-theoretic secrecy provides a strong notion of secrecy.
- But, capacity results are known only for a small number of setups (the wiretap channel and 2 receivers broadcast channels with degraded message set)

Indirect coding is the key to secrecy
**Sum Rate of Cyclically Symmetric Interference Channels**

Bernd Bandemer, Gonzalo Vazquez-Vilar, Abbas El Gamal

---

**Achievement Description**

**Main Achievement:**
Sum capacity is established for a K-user-pair, cyclically symmetric, deterministic interference channel with local interference (Wyner model).

**Achievement Description**

**Status Quo:**
- The Gaussian interference channel (IC) is practically relevant.
- Its capacity is a long-standing open problem.
- Asymptotic results and bounds with constant gap have been obtained.

**New Insights:**
A finite-field deterministic IC correctly reflects the asymptotic behavior of Gaussian IC. Coding in this model takes the form of simple single-letter bit pipe assignments. The sum capacity for a cyclically symmetric, locally connected interference channel has been found using this model.

**How It Works:**
- **Achievability:** Established using bit pipe assignments that depend on the interference parameters \(\alpha, \beta\).
- **Converse:** The optimality of the assignments is proved via standard weak converse techniques.

**Assumptions and Limitations:**
Channel gains are known globally. Symmetry is assumed in the channel and the data rates.

**Impact:**
- Progress has been made in understanding the capacity of the Gaussian interference channel.
- Worst- and best-case interference conditions can be identified.
- Immediate practical implications in full-reuse multi-user wireless systems.

**Next-Phase Goals:**
- Transform asymptotic result into upper and lower bound on capacity with finite gap.
- Extension to:
  - Non-symmetric rates
  - Non-symmetric channel
  - Fully connected channel
- Systematic ways to find optimal assignments.

---

We compute the sum capacity of a K-user deterministic interference channel.
Towards Harnessing Relay Mobility in MANETs
Naini, Moulin

ACHIEVEMENT DESCRIPTION

MAIN RESULT:
Network configuration dependent Optimal Relay Locations and Schemes under restricted mobility

HOW IT WORKS:
Correlated Noise at the Relay and the Destination due to the rest of the network
Optimal Location chosen based on available mobility region
Certain scenarios favor Decode-Forward while others entail Interference Mitigation through Compress-Forward

ASSUMPTIONS AND LIMITATIONS:
Gaussian Channel Models are assumed
An adjusted Quadratic Path Loss exponent is used
Network Configuration should be known to the relay

STATUS QUO
Relay Locations are taken as a given
Link-level Relaying Protocol is independent of network configuration
Mobility of nodes viewed in a passive setting

IMPACT
A step towards establishing optimal node locations to maximize throughput in a large network
Illustrates the potential of Compress-Forward scheme in a highly correlated noise regime
Establishes need for node cooperation in a large network with multiple end-end streams to maximize throughput

NEW INSIGHTS
Relay location and scheme are crucial especially in a network with other interfering nodes

NEXT-PHASE GOALS
Investigate parallel data-streams with dedicated mobile relays in a multi-objective game-theoretic setting.
Understand the role of mobility in other adhoc network blocks.
Devise mobility strategies for cooperative multi-hop relaying
Transmission over composite channels with combined source-channel outage: Goldsmith and Mirghaderi

**ACHIEVEMENT DESCRIPTION**

**MAIN RESULT:**
We define an end-to-end distortion metric, Distortion vs. Combined Outage and prove the optimality of source and channel code separation to minimize this metric.

**HOW IT WORKS:**

- Useful when partial loss of information is acceptable and only the low distortion of the retrieved data is concerned.
- Select the optimal source outage set (with prob. $q_s$) from the source alphabet and also the channel outage set (prob. $q_c$).
- Compress the non-outage subsequence of the source output and transmit along with the source outage indices using a separate channel code.
- In non-outage channel states, identify the source outage indices and then reconstruct the non-outage subsequence.

**ASSUMPTIONS AND LIMITATIONS:**

- **Perfect CSI at Rx.** Statistics (channel capacity vs. outage) known at Tx. Given a certain loss prob. trade-off b/w $q_s$ and $q_c$.
- Source is stationary and ergodic.

**IMPACT:**
Considerably lower distortion as compared with pure channel outage
Design flexibility provided by source channel code separation

**NEXT-PHASE GOALS:**
Consider a more general case with different end-to-end distortion requirements for different subsets of the source alphabet.
Extend the work to a network scenario where different reconstructions of a common information source are available at multiple nodes and are to be transmitted to a single receiver.
Investigate the effect of a feedback channel to this problem.

**COMBINATION:**
Combination of source and channel outage can improve the performance of lossy transmission systems.
Information Theory for Mobile Ad-Hoc Networks (ITMANET): The FLowS Project

Thrust 3
Application Metrics and Network Performance

Asu Ozdaglar and Devavrat Shah
Asymptotic Analysis for Large Scale Dynamic Stochastic Games
S. Adlakha, R. Johari, G. Weintraub, A. Goldsmith

**ACHIEVEMENT DESCRIPTION**

**MAIN RESULT:** Taxonomy of Stochastic Games

General Stochastic Games

- Competitive Model
  - Non-cooperative games.
  - Sub modular payoff.
  - Existence results for OE.
  - AME property.

- Coordination Model
  - Cooperative games.
  - Super modular payoff structure.
  - Results for special class of linear quadratic games.

**HOW IT WORKS:**

- Existence results for competitive model are based on continuity arguments.
- AME property for a competitive model is derived from the fact that opponents at higher states lead to lower payoff.

**ASSUMPTIONS AND LIMITATIONS:**

- Mean field requires all nodes to interact with each other – applies to Dense networks only.
- Coordination model requires different existence proof.

**STATUS QUO**

Many cognitive radio models do not account for reaction of other devices to a single device’s action.

In prior work, we developed a general stochastic game model to tractably capture interactions of many devices.

**IMPACT**

General Framework for interaction of multiple devices

Further, our results:

- provide common thread to analyze both competitive and coordination models.
- provide exogenous conditions for existence and AME for competitive models.
- provide results on a special class of coordination model – linear quadratic tracking games.

**NEXT-PHASE GOALS**

Provide existence and AME results for general class of coordination games.

Our main goal is to develop a related model that applies when a single node interacts with a small number of other nodes each period.

**NEW INSIGHTS**

In principle, tracking state of other devices is complex.

We approximate state of other devices via a mean field limit.

**New Paradigm for analyzing large scale competitive and coordination games**
Adaptive modulation with smoothed flow utility
Boyd, Akuiyibo, O’Neill

ACHIEVEMENT DESCRIPTION

MAIN RESULT:
Flow allocation to optimally trade off average smoothed flow utility and power.

HOW IT WORKS:
Optimal flow policy is a complicated function of smoothed flow and channel gain.

IMPACT
Different levels of smoothing lead to different optimal policies; different trade offs.

ASSUMPTIONS AND LIMITATIONS:
- Utilities are strictly concave, power is strictly convex; linear dynamics represent time averaging.
- At each time period, assumes the transmitter learns random channel state through feedback.

NEW INSIGHTS
- Derive network utility from smoothed flows.
- Smoothing allows us to model the demands of an application that can tolerate variations in flow it receives over a time interval.

STATUS QUO
Prevailing wireless network utility maximization and resource allocation methods focus on per period optimization.
These methods ignore the heterogeneous time scales over which network applications need resources.

NEXT-PHASE GOALS
Approximate dynamic programming (ADP) for MANETs
- Computationally tractable.

Optimally trade off average utility and power using smoothed flow utilities.
Network Aware Design: Dynamic/Stochastic NUM
Boyd, Goldsmith, O'Neill

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:
Wireless NUM – Learning Based
• Data Delivery Contracts and prioritization
• Distributed approaches
• Multi-time scale convergence applications

Multi-Period NUM
• Optimal control policies for infinite horizons
• Average cost infinite horizon Markov models
• Approximate relative value functions

HOW IT WORKS:
• Multi-period statistical approach to model properties of environment and traffic learn parameters

ASSUMPTIONS AND LIMITATIONS:
Unbiased CSI
Explicit QoS requirements

IMPACT
Improved performance and optimal resource allocation.
Quantify cost of traffic (QoS)
Explore rate-delay-energy trade-offs

NEXT-PHASE GOALS
Performance on Energy-Delay-Capacity Surface
• Approx MDP -Dimensionality reduction, Value function approximation and online learning
• Approx. optimal policies

Dynamically Optimize Network Resources to Match Traffic Needs
Supermodular Network Games
V. Manshadi and R. Johari

ACHIEVEMENT DESCRIPTION

MAIN RESULT:

Payoff of agent $i$:

$$\Pi_i(x_i, x_j, x_k) = u(x_i, x_j + x_k) - c(x_i)$$

We assume utility exhibits strategic complementarities.

HOW IT WORKS:

We exploit monotonicity of the best response to prove our results:

The best action for node $i$ is increasing in its neighbor’s actions.

ASSUMPTIONS AND LIMITATIONS:

We study equilibria of a static game between nodes. The eventual goal is to understand dynamic network games.

The power of a node in a networked coordination system depends on its centrality (global properties) not just on its degree (a local property).
ACHIEVEMENT DESCRIPTION

MAIN RESULT:
Q-Learning for network routing: by observing the network behavior, we can learn the optimal priority for each buffer or a small class of buffers, depending on the range of available local information.

Near optimal performance with simple solution:
Q-learning with steepest descent or Newton Raphson Method via stochastic approximation
- Theoretical analysis for the convergence and properties.
- Simulation experiments are on-going.

HOW IT WORKS:
Step 1: Generate a state trajectory.
Step 2: Learn the best value function approximation by stochastic approximation.
Step 3: Policy for routing: h-MW policy derived from value function approximation

KEY NEW INSIGHTS:
- Extend to wireless? YES
- Complexity is similar to MaxWeight. Policies are distributed and throughput optimal.
- Learn the approximately optimal solution by Q-learning is feasible, even for complex networks.
- New application: Q-learning and TD-learning for power control.

NEXT PHASE GOAL
- Implementation – Consensus algorithms & Information distribution
- Adaptation – kernel based TD-learning and Q-learning
- Integration with Network Coding projects: Code around network hot-spots

IMPACT
- Un-consummated union challenge: Integrate coding and resource allocation
- Generally, solutions to fluid model should offer insight for the stochastic model

Algorithms for dynamic routing: Visualization and Optimization
Distributed Scheduling via Reversible Dynamics
Devavrat Shah  Jinwoo Shin

ACHIEVEMENT

MAIN ACHIEVEMENT:
An efficient MAC protocol
- Random backoff style with access probability function of queue-size
- Totally distribute

HOW IT WORKS:
- Random backoff probability proportion to the logarithm of queue-size
- Performs literally unit amount of computation per time step

ASSUMPTIONS AND LIMITATIONS:
- Carrier sensing information

IMPACT

Finally, after a long history, we have a fully distributed MAC protocol that is indeed optimal
New theory for distributed algorithm design

STATUS QUO

Medium Access Control (MAC) is fundamental protocol of modern wireless communication
- Random backoff protocols popular
- But, they usually perform poorly

NEW INSIGHTS

Distributed Algorithms via Reversible Dynamics
- A new theory for efficient distributed, simple network algorithm design

NEXT-PHASE GOALS

Beyond oblivious MAC
- dealing with hidden terminal
- Improving delay through utilization of geometry

Resolution of a long standing challenge for network & info. Th.: efficient MAC protocol
A Distributed Newton Method for Network Utility Maximization
(Wei, Ozdaglar, Jadbabaie)

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:
- A Newton method that solves general network utility maximization problems in a distributed manner
- Simulations indicate the superiority of the distributed Newton method over dual subgradient methods

HOW IT WORKS:
- Turning inequality constraints into barrier functions
- Employing matrix splitting techniques on the dual graph to solve the dual Newton step
- Using a consensus-based local averaging scheme, which requires local information only

ASSUMPTIONS AND LIMITATIONS:
- Routing information and capacity constraints are fixed
- Dual and primal steps are computed separately

IMPACT

Significant improvements with the distributed Newton method compared to subgradient methods

Next-Phase Goals
- Second order methods for distributed network utility maximization
  - Prove convergence and rate of convergence of our methods
  - Understand the impact of network topology on algorithm performance
  - Design algorithms that compute primal and dual steps simultaneously

Novel Distributed Second Order Methods for Network Utility Maximization Problems
Dynamic Resource Allocation for Delay-Sensitive Applications (Menache, Ozdaglar, Shimkin)

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:
A tractable and general framework for the analysis of delay performance of a dynamic resource allocation mechanism.
- Existence and uniqueness of a Nash equilibrium
- Preliminary results on efficiency loss

HOW IT WORKS
- Each (price-taker) user solves a simple optimization problem, accounting for a delay-price tradeoff.
- We employ a fluid-scale approximation of the stochastic service system.
- Under the approximation, queue sizes "freeze", giving rise to a fixed steady-state price.

ASSUMPTIONS AND LIMITATIONS:
While the proposed fluid model is motivated by the stochastic system, we do not provide here a formal convergence result that relates the two.

IMPACT
- Our model allows for fairly general dependence of delay on the allocated resource, thus suitable for different applications.
- The fluid approximation is appropriate under overloaded systems, where the user arrival rate and system resources become large.

NEXT-PHASE GOALS
- Efficiency loss bounds for different delay functions.
- Dynamic stability properties
- Comparisons with other resource allocation mechanisms.
- General network architectures

NEW INSIGHTS
- Allocation mechanism should be simple; users should have a clear notion of price.
- Natural candidate: Proportional fair mechanism, where the allocated capacity remains constant and is proportional to the bid.

STATUS QUO
Most existing work on resource allocation in networks considers:
- “Static” scenarios
- Rate (throughput) related performance metrics
However, in many applications:
- Resource not required when “job is done” -> Dynamic resource allocation
- Relevant performance metric: Delay or Completion Time

A fluid-Scale approximation is used to gain insights on the equilibrium of a dynamic resource allocation mechanism.
Canonical Decompositions of Games and Near Potential Games
(Candogan, Menache, Ozdaglar, Parrilo)

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:
• Any game can be decomposed to 3 orthogonal components: Nonstrategic, Potential, Harmonic
• The dynamic properties of near potential games are analyzed by considering the properties of their potential component

HOW IT WORKS
• Decomposition of the vector flows of any game to gradient, harmonic and curl flows.

• The potential component corresponds to the gradient flow
• The dynamic and equilibrium properties of potential games are approximately carried over to near potential games

ASSUMPTIONS AND LIMITATIONS:
• It is not clear how to find the closest ordinal potential game to a given game

The canonical decompositions of games are useful for understanding their static and dynamic equilibrium properties
Near-Optimal Power Control in Wireless Networks: A Potential Game Approach (Candogan, Menache, Ozdaglar, Parrilo)

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:

The Potential-Game Approach (approximately) enforces any power-dependent system-objective among competing users under natural dynamics.

HOW IT WORKS:

- Approximate the underlying power control game with a “close” potential game
- Derive prices that induce an optimal power allocation in the potential game
- The proximity between the two games establishes near optimal performance in the original game in the limit of distributed dynamics.

ASSUMPTIONS AND LIMITATIONS:

- Single-band networks
- Approximation is better for high-SINRs
- Multichannel networks
- Enhanced pricing schemes for low-SINR regime
- Distributed implementation of price generation

IMPACT

- Simple pricing scheme that can be used for any system objective
- Performance guarantees in the dynamical sense.
- A new paradigm for regulation of wireless networks

STATUS QUO

Most work on wireless games focus on static equilibrium properties without establishing convergence of distributed dynamics.

- There is no systematic framework for providing simple incentive mechanisms that can achieve an arbitrary system objective.

NEW INSIGHTS

Potential-game approximations lead to simple pricing schemes for any system objective.
Information Theory for Mobile Ad-Hoc Networks (ITMANET): The FLoWS Project

Thrusts 1 & 3
On the stability region of networks with instantaneous decoding Traskov, Medard, Sadeghi, Koetter

ACHIEVEMENT DESCRIPTION

MAIN ACHIEVEMENT:
Derive stability region under instantaneous decoding and provide online scheduling and network coding algorithm.

HOW IT WORKS:
• Opportunistic XOR-coding shows significant gains.
• However, stability region of instantaneous decoding is not known.

IMPACT
Network coding (red) increases the stability region over routing (blue) and leads, on average, to smaller delays.

ASSUMPTIONS AND LIMITATIONS:
• Need ACKs or NACKs
• Constrained queuing system

NEXT-PHASE GOALS
• Include analog network coding. Here, nodes a and b coordinate their transmission.

Instantaneous decoding increases the stability region and reduces delay.
Information Theory for Mobile Ad-Hoc Networks (ITMANET): The FLoWS Project

Thrusts 1, 2 & 3
Distributed Lossy Averaging
Han-I Su and Abbas El Gamal

**ACHIEVEMENT DESCRIPTION**

**MAIN ACHIEVEMENT:**
- Found the rate distortion function for 2-node network with correlated Gaussian sources
- A cutset lower bound on the network rate distortion function for general networks with independent white Gaussian noise sources
- A centralized protocol over a star network which achieves the cutset bound within a factor of 2
- A lower bound on the network rate distortion function for distributed weighted-sum protocols, which is larger than the cutset bound by a factor of \((\log m)\) in order
- An upper bound on the expected weighted-sum network rate distortion function for gossip-based weighted-sum protocols, which is at most \((\log \log m)\) larger than the above lower bound

**HOW IT WORKS:**
The bounds are obtained using a mix of information theory, linear systems and results from gossip protocols.

**ASSUMPTIONS AND LIMITATIONS:**
- The upper bounds generalize to non-Gaussian sources, but the lower bounds do not.

**IMPACT:**
- New problem formulation
- Upper and lower bounds on the network rate distortion function for centralized and distributed protocols are given
- The results suggest that using distributed protocols results in a factor of \((\log m)\) increase in order relative to centralized protocols.

**NEXT-PHASE GOALS:**
- Characterize the improvement of using the correlation (side information) between the node estimates
- Establish bounds for computing general functions

**AN INFORMATION-THEORETIC FORMULATION OF THE DISTRIBUTED LOSSY AVERAGING IS PRESENTED.**