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

Thrust 2:

Layerless Dynamic Networks

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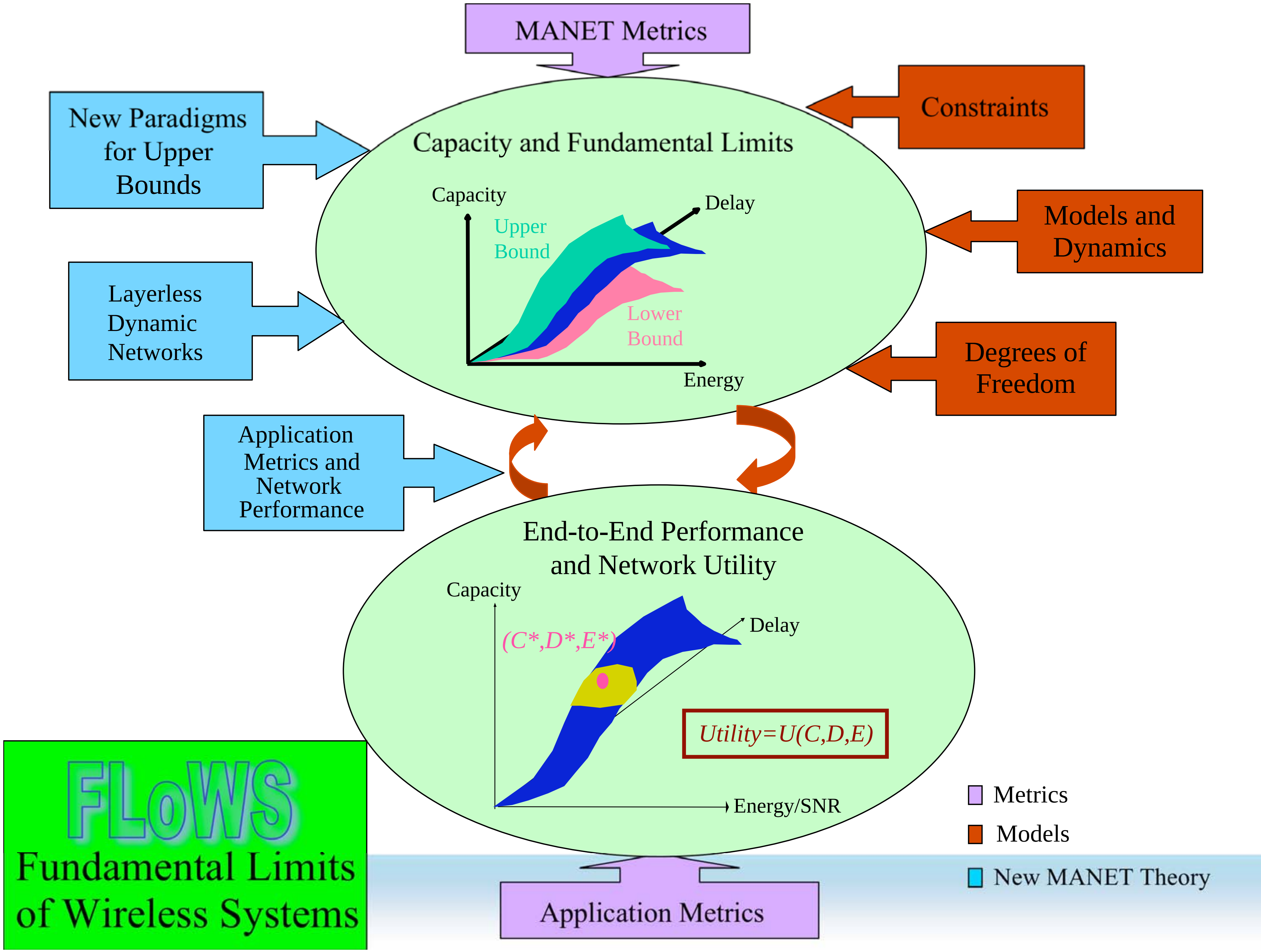

MANET Metrics
New Paradigms for Upper Bounds
Capacity and Fundamental Limits
Constraints
Capacity
Delay
Upper Bound
Lower Bound
Energy
Models and Dynamics
Layerless Dynamic Networks
Degrees of Freedom
Application Metrics and Network Performance
End-to-End Performance and Network Utility
Capacity
(C*,D*,E*)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

Layerless Dynamic Networks

- The challenge of *dynamic*
  - Side information not always precise or even reliable;
  - Overhead (for coordination/ adaptation) becomes significant;
  - Channel with memory, (noisy) feedback, interference, multi-hop, cooperation, … as necessary components;

Separation of functionalities with different time scale no longer valid

- *Layerless* as the solution
  - Network information theory: heterogeneous data and soft information processing;
  - Structured codes with good error exponent, flexibility for joint processing, combining and relaying, new interface to the physical layer;
  - Interference management, cooperative and cognitive networking;
  - Operating with imperfect side information or even model, robustness.

Not always obvious and directly address the dynamic issue

Intellectual Tools and Focus Areas

- Dynamic Network Information Theory: beyond point-to-point communications
  - Relay, soft information processing;
  - Channel dynamics and Feedback;
  - Generalized network coding;
  - Interference and cooperation;
- Structured coding: concrete designs for cross layer processing
  - Joint source/channel/network coding;
  - Flexible partial decoding for weak channels;
  - Unified joint encoding of control messages to reduce overhead;
- Assumptions and Robustness: networking without perfectly reliable/precise side information
  - Universal algorithms requires less coordination;
  - Tradeoff between cooperation and coordination.

Thrust Achievements
Dynamic Network Information Theory

- Relay, forwarding and combining soft information
  - Likelihood forwarding– *Koetter*
  - General relaying for multicast – *Goldsmith*
    - General schemes allow relays to jointly encode messages of many users and to use cooperation
    - Relays can combine symbols on the physical layer, bits on the network layer, etc.
    - outperform time sharing, routing, and store-and-forward
- Feedback, channel memory and dynamics
  - Degraded Finite State Broadcasting Channel – *Goldsmith*
    - Broadcasting with memory, generalize from the fading results
    - Choice of auxiliary random variables (and corresponding coding schemes) in the context of a BC with memory
    - Duality between multi-user channels with memory
  - Feedback and directed information in Networks – *Goldsmith*

Thrust Achievements
Dynamic Network Information Theory

- Generalized network coding
  - General capacity using network coding – *Medard*
  - Matroidal solutions – *Effros & Koetter*
- Interference, cooperation and coordination
  - Euclidean Information Theory – *Zheng*
    - K-L divergence approximated by squared Euclidean distance, allows analytical solutions for problems with high dimensionalities;
    - Variational analysis in the space of probability distributions, very noisy channel or thin layer of code;
    - Linear divergence translation between terminals, useful for cooperation, interference, and security problems.
  - Cognitive interference channel – *Goldsmith*

Thrust Achievements
Structured coding

- Joint source/channel/network coding with layered codes
  - Broadcasting with layered source codes – *Goldsmith*
  - Generalized capacity/distortion for joint source channel codes – *Effros & Goldsmith*
    - Source channel coding over non-ergodic channel, new performance metrics defined;
    - Relax the constraint that all transmitted info be decoded, MD codes
    - New extended interface to the physical layer
  - Joint S/C coding in networks – *Coleman*
- Layered code designs
  - Message embedding with UEP – *Zheng*
    - Encoding heterogeneous messages in a single code, improving efficiency to send critical data;
    - Partial decodability with unknown channel quality;
    - Optimal code designs from Euclidean approximations

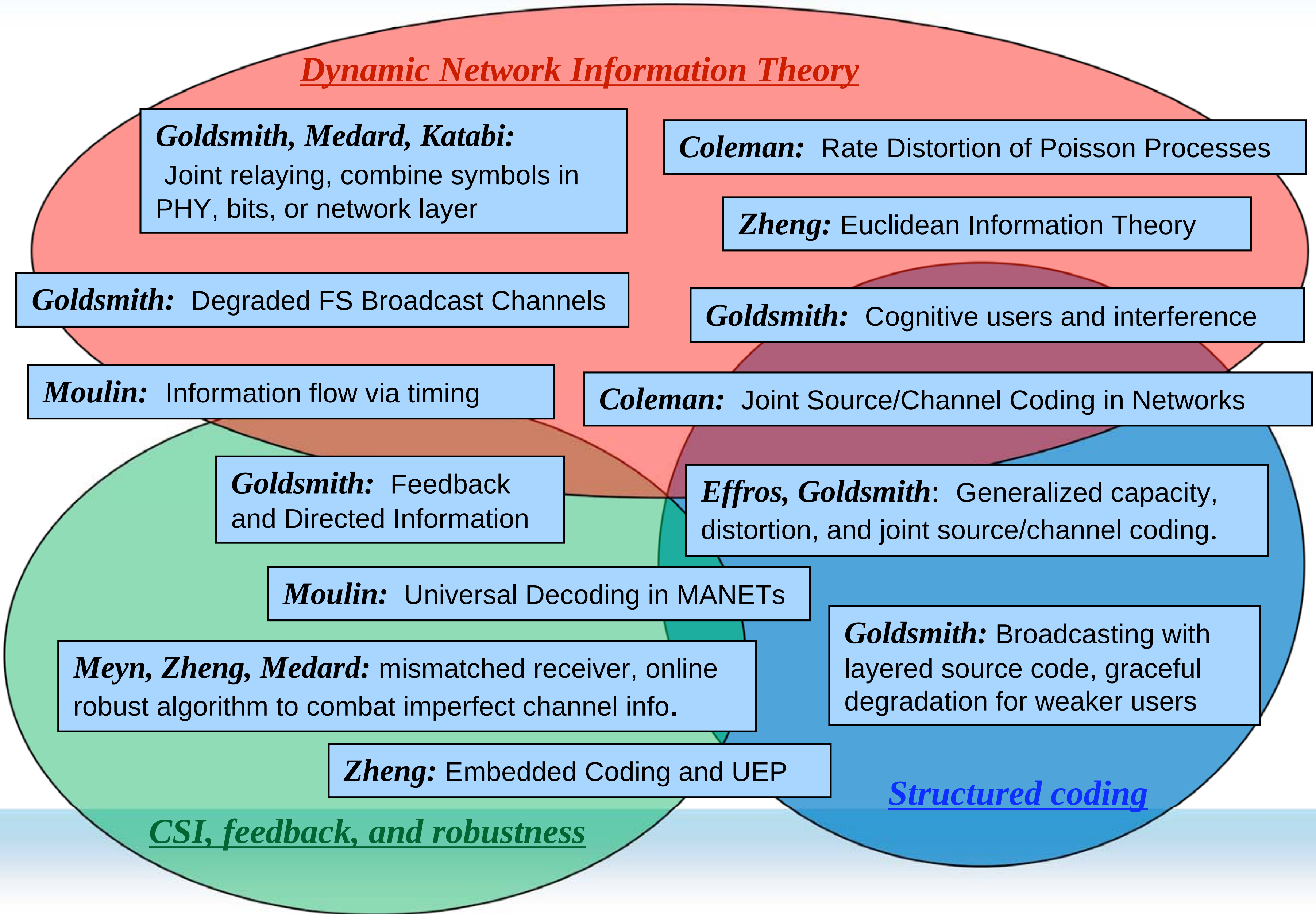
Thrust Achievements
Structured Coding

- Novel mode of communication
  - Information flow via timing – *Moulin*
  - Rate distortion for Poisson Processes – *Coleman*
    - Poisson process with queuing distortion analogous to Gaussian source with MSE and Bernoulli source with Hamming distortion
    - Timing of events in MANET can be encoded and transmitted, lossy or lossless;

Thrust Achievements
Robustness and Side Information

- Robust algorithms designs
  - Universal decoding with N-P setup – *Moulin*
  - Mismatched decoder – *Meyn, Zheng, Medard*
  - Gradient projection for power allocation in fading MAC – *Ozdaglar, Medard*
- Utilizing feedback channel
  - Feedback in wireless networks – *Goldsmith*
    - Directed information used to compute capacity of wireless channel with feedbacks
    - Benchmark for common practice of using feedback links to transmit CSI back to the transmitter
  - Joint source channel coding for CSI feedbacks

Thrust 2 Achievements Overview



Converging vision

- Heterogeneous networking
  - Network distinguishes classes of data and their processing by their precision, reliability, latency, in addition to application QoS requirements
  - Soft information combining and forwarding
  - Layered structured coding to allow flexible control of the physical media, joint processing across conventional interface.
- Dynamic view of networks
  - Efficient use of control links to reduce overhead costs
  - Robustness, adaptation, and mistake recovering in presence of imperfect knowledge
  - Error exponents and variational analysis for probability distributions
- Principle of Network coding
  - Accumulating information through the network
  - New interface based on "bit", allow flexible cross layer designs and backward compatibility

Thrust Context

Thrust 1

New Paradigm of outer bounds

Provide building blocks for large networks, translate design constraints into network modeling assumptions

Performance benchmark and design justification

Thrust 2

Example: Layered joint source channel codes, new model of physical layer, interface, and flexible for global resource allocation

Guide problem formulation by identifying application constraints and relevant performance metrics

Provide achievable performance region, based on which distributed algorithms and resource allocation over large networks are designed

Thrust 3

Application Metrics and Network Performance

Roadmap – larger and faster

- General relay, cognitive operation, interference management, under MANET constraints (dynamic, interface, side information, etc.), and large networks
- Duality of multi-user channels with memory, and dynamic network capacity
- Limited noisy feedback over wireless network
- Global resource allocation with interface to control layered coding structure in physical layer, fundamental tradeoff in reducing overhead
- Generalize network coding
- Geometric approach to multi-terminal information theory, cooperation, compound channel, and robust algorithms

Recent Publications

1. S. Adlakha, R. Johari, A. Goldsmith "Competition Between Wireless Devices with Incomplete Channel Knowledge", Submitted to *IEEE Journal on Selected Areas in Communications*.
2. Chris T. K. Ng and Andrea J. Goldsmith, "The Impact of CSI and Power Allocation on Relay Channel Capacity and Cooperation Strategies," Submitted to *IEEE Transactions on Wireless Communications*, 2007.
3. Chris T. K. Ng, Nihar Jindal, Andrea J. Goldsmith and Urbashi Mitra, "Capacity Gain from Two-Transmitter and Two-Receiver Cooperation," *IEEE Transactions on Information Theory*, vol. 53, no. 10, pp. 3822–3827, Oct. 2007.
4. 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.
5. T. P. Coleman, E. Martinian, E. Ordentlich, "Joint Source-Channel Decoding for Transmitting Correlated Sources over Broadcast Networks", Submitted to *IEEE Transactions on Information Theory*.
6. P. Moulin, "Universal Erasure and List Decoding for Single- and Multiple-Access Channels,", Submitted to *IEEE Transaction on Information Theory*.
7. I. Maric, A. Goldsmith, G. Kramer and S. Shamai (Shitz), "On the Capacity of Interference Channels with One Cooperating Transmitter", *European Transactions on Telecommunications*, Invited, 2007.
8. T. Holliday, A. Goldsmith and H. V. Poor, "Joint Source and Channel Coding for MIMO Systems: Is it Better to be Robust or Quick?," To appear in *IEEE Transactions on Information Theory,* 2007.
9. E. Abbe, M. Médard, S. Meyn, and L. Zheng. "Finding the best mismatched detector for channel coding and hypothesis testing," *Information Theory and Applications Workshop*, UCSD (invited), 2007.
10. M. Bakshi and M. Effros and W. Gu and R. Koetter, "On Network Coding of Independent and Dependent Sources in Line Networks", *International Symposium on Information Theory (ISIT)*, 2007, Nice France.
11. S. Borade and L. Zheng, M. Trott "Multilevel Broadcast Networks".
12. S. Borade and L. Zheng, "I-Projection and the Geometry of Error Exponents", *Allerton Conference on Communications Control and Computing*, 2006.

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13. T. P. Coleman, E. Martinian, M. Effros, M. Medard, "Interference Management via Capacity-Achieving Codes for the Deterministic Broadcast Channel", Proceedings of *IEEE Information Theory Workshop (ITW)* , 2005, Rotorua, New Zealand.
14. T. P. Coleman, E. Martinian, E. Ordentlich, "Joint Source-Channel Decoding for Transmitting Correlated Sources over Broadcast Networks", Submitted to *IEEE Transactions on Information Theory*. (also appeared in *International Symposium on Information Theory*, 2006 Seattle, WA..
15. M. Effros, A. Goldsmith and Y. Liang, "Capacity Definitions of General Channels with Receiver Side Information," *IEEE International Symposium on Information Theory*, 2007, Nice France, pp. 921-925.
16. V. Doshi, D. Shah, M. Médard, “Source Coding with Distortion through Graph Coloring”, *IEEE Symposium on Information Theory (ISIT)*, 2007, Nice, France.
17. V. Doshi, D. Shah, M. Médard, S. Jaggi, “Graph Coloring and Conditional Graph Entropy”, Asilomar Conference on Signals, Systems, and Computers,2006, Monterey, CA, pp. 2137-2141.
18. V. Doshi, D. Shah, M. Médard, S. Jaggi, “Distributed Functional Compression through Graph Coloring”, *Data Compression Conference (DCC)*, 2007, Snowbird, UT.
19. S. Katti, I. Maric, A. Goldsmith, D. Katabi and M. Médard, "Joint Relaying and Network Coding in Wireless Networks", *IEEE International Symposium on Information Theory (ISIT)* 2007, Nice, France.
20. Y. Liang, A Goldsmith, M. Effros, "Distortion Metrics of Composite Channels with Receiver Side Information". *IEEE Information Theory Workshop (ITW)*, 2007, Lake Tahoe, CA. pp 559-564.
21. I. Maric, A. Goldsmith, G. Kramer and S. Shamai (Shitz), "On the Capacity of Interference Channels with a Cognitive Transmitter", *Information Theory and Applications (ITA) Workshop*, 2007, UCSD, CA.
22. I. Maric, A. Goldsmith, G. Kramer and S. Shamai (Shitz), "On the Capacity of Interference Channels with a Partially-Cognitive Transmitter", *IEEE International Symposium on Information Theory (ISIT)* 2007, Nice, France.
23. Chris T. K. Ng and Andrea J. Goldsmith, “Capacity and Cooperation in Wireless Networks,” *Information Theory and Applications (ITA) Workshop*, 2006, UCSD, CA. (Invited)
24. Chris T. K. Ng, Deniz Gündüz, Andrea J. Goldsmith and Elza Erkip, “Minimum Expected Distortion in Gaussian Layered Broadcast Coding with Successive Refinement,” *IEEE International Symposium on Information Theory (ISIT)*, June 24–29, 2007, Nice, France.

Recent Publications

25. S. Yang and R. Koetter, "Network Coding over a Noisy Relay : a Belief Propagation Approach", *IEEE International Symposium on Information Theory (ISIT),* 2007, Nice, France.
26. 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.
27. Chris T. K. Ng, Nihar Jindal, Andrea J. Goldsmith and Urbashi Mitra, **"**Power and Bandwidth Allocation in Cooperative Dirty Paper Coding,**"** Submitted to *IEEE International Conference on Communications (ICC)*, 2008.
28. Chris T. K. Ng, Chao Tian, Andrea J. Goldsmith, Shlomo Shamai (Shitz), **"**Minimum Expected Distortion in Gaussian Source Coding with Uncertain Side Information,**"** *IEEE Information Theory Workshop (ITW)*, 2007, Lake Tahoe, CA, pp. 454–459.
29. J.-K. Sundararajan, Médard, M., Kim, M., Eryilmaz, A., Shah, D., and Koetter, R., "Network Coding in a Multicast Switch," Proceeding of *INFOCOM* 2007, pp. 1145-1153.
30. A. Fernandes, M. Raginsky, and T. P. Coleman, "A Low-Complexity Universal Scheme for Rate-Constrained Distributed Regression Using a Wireless Sensor Network", Submitted to *International Conference on Acoustics, Speech, and Signal Processing (ICASSP),* 2008.
31. T. P. Coleman, N. Kiyavash, and V. Subramanian. "Successive Refinability of Poisson Processes and an Alternative Proof of the Rate-Distortion Function with a Queuing Distortion Measure", Submitted to *IEEE Data Compression Conference (DCC)*, 2008.
32. M. Kim, Sundararajan, J.-K., and Médard, M., "Network Coding for Speedup in Switches," *International Symposium on Information Theory (ISIT)*,2007, Nice, France.
33. 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.
34. V. Doshi, Shah, D., and Médard, M., "Source Coding with Distortion through Graph Coloring," *International Symposium on Information Theory (ISIT)*,2007, Nice, France.
35. C. Fragouli, Lun, D., Médard, M., and Pakzad, P., "On Feedback for Network Coding," *Conference on Information Sciences and Systems (CISS),* 2007, Johns Hopkins, MD.
36. S. Ray, Moulin, P., and Médard, M., "On Optimal Signaling and Jamming Strategies in Wideband Fading Channels," *IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC)* 2006, Cannes, France, pp. 1-5.

Recent Publications

37. I. Maric, A. Goldsmith, G. Kramer and S. Shamai (Shitz), "An Achievable Rate Region for Interference Channels with a Cognitive Transmitter", *The 41st Asilomar Conference on Signals, Systems and Computers*, 2007, Monterey, CA.
38. I. Maric, A. Goldsmith and M. Medard, "Information-Theoretic Relaying for Multicast in Wireless Networks", *Military Communications Conference (MILCOM)*, 2007, Orlando, Florida.
39. 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.
40. P. Moulin, "Steganographic Communication over Network Timing Channels," Submitted to *IEEE Information Theory Workshop (ITW)*, 2008.