

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

Thrust 2 Intro: Layerless Dynamic Networks

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Layerless Dynamic Networks



- Layerless as a consequence dynamic
 - Separation over functions with different time scale no longer valid in dynamic networks
- Prior Works (what we don't like)
 - Network Information theory
 - Small networks, hard optimization problems, static environment/ long blocks
 - Cross-layer designs
 - usually driven by the properties of the wireless media
 - Idealized assumptions
 - Perfect channel knowledge, error-free coordination, static/ergodic systems, ...
 - Homogenous Networks
- Why are these hard? Shannon is not helping!
 - Long blocks not applicable, bits not the unique measure of information, no efficient separable processing, ...

Intellectual Tools and Focus Areas



- Beyond point-to-point communications, soft information processing:
 - Relay, cooperation, interference, two-way channel, cognitive radio;
 - Feedbacks, variable length codes, broadcasting, streaming;
 - Generalized network coding;
 - Combining and forwarding heterogeneous data;
- Network without guaranteed perfect reliability:
 - Error exponents, structured codes;
 - Imperfect side information/ control, robustness, error recovery;
 - Coordination overhead;
- Joint/cross-layer processing:
 - Joint source-channel-network coding;
 - Limited data exchange;
 - Source over non-ergodic channels, new distortion metrics.

Presentations



- Andrea Goldsmith Generalized relaying for multicast in wireless networks
- Lizhong Zheng Embedding prioritized data using unequal error protection
- Pierre Moulin Capacity and queue-based codes for MANET timing channels
- Todd Coleman Joint Source-Channel Coding in Networks

General Relaying for Multicast in Wireless Networks



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VEW INSIGHTS

Wireless networks today use multihop store-and-forward routing through

point-to-point links

Other signals treated as interference

Does not exploit broadcast nature of radio or information-theoretic relaying

Multiple data streams relayed using time sharing

source1 dest1 relay $Y_3[n] = X_3[n]$ source2 dest2 $X_3[n] = f_n(Y_3[n-1]..., Y_3[1])$

Time sharing is suboptimal

Cooperative relay strategies can outperform store-and-forward

General relaying allows for joint encoding of multiple data streams and cooperation. It results in improved rate performance in MANETS

FLOWS ACHIEVEMENT(S)

MAIN RESULT:

General relaying schemes outperform time-sharing outer bounds



HOW IT WORKS:

More general schemes allow relays to jointly encode messages of many users and to use cooperative strategies.

Relays can combine symbols on the physical layer, bits on the network layer, etc.

Why it works:

Bandwidth is used more efficiently

Time sharing and store-and-forward are special cases

ASSUMPTIONS AND LIMITATIONS:

Multicast traffic considered

Interference not considered in routing outer bound

Achievability results: there is a gap between rates achieved with different schemes and outer bounds on the capacity

Analysis too complex for larger networks



network of

relays

different encoding strategies for specific scenarios based on their performance and complexity

To get there:

sources

Analyze also existing strategies that use network coding approach shown to achieve unicast capacity for some scenarios

Evaluate above strategies for larger networks



Graduate level: Simple schemes employable in larger MANETs

Prize level: Capacity results for MANETs that employ general relaying

General relaying improves performance of MANETs

Key Results



• General relaying schemes outperform time-sharing



•Decoding at the relay (DF) outperforms routing outer bound and amplifying (AF) at the relay

•AF outperforms routing outer bound only for no delay at the relay

•We have also shown that in *unicast* AF outperforms routing outer bound

• What to take away from this?

Key Insights for Small Networks



- Several general relaying strategies can improve performance:
 - Decoding and joint encoding of messages from different sources
 - Combining and amplifying of received signals, i.e. analog network coding
 - Compressing of received signals
 - Combining of bits on the network layer
- Exploiting capabilities of cognitive users improves performance
 - Cognitive users can perform general relaying based on obtained information about other users' messages
 - Improves their own rates (using precoding against interference techniques) and rates of other users (using node cooperation)
 - See the poster on cognitive radio

Community Challenges



- What strategies to be employed in large networks?
 - Simple and bring gains
- To answer that question we need to:
 - Analyze various schemes for large MANETs (perhaps using insights from thrust 1)
 - Evaluate their rate gains
 - Understand which strategies give capacity for smaller networks in certain scenarios such as strong interference, weak interference (*perhaps feeding insights to thrust 1*)
- Prize level challenge:
 - Capacity for MANETs that employ general relaying

Embedding prioritized data using unequal error protection



STATUS QUO

VEW INSIGHTS

 Physical links are viewed as equally reliable bit pipes.

- High priority control messages are sent over separated channels.
- No performance limits on UEP

Embedding key messages over UEP: performance analysis by information geometry



Limited analytical solutions

GOA • Joint Source-Channel coding with **END-OF-PHASE** lavered codes Feedbacks and two-way channels Data driven network controls, Layering and QoS as interface ENGE CHALL New protocols required to indicate, process, fuse, and **OMMUNITY** prioritize heterogeneous data transmissions over

networks

Embedding control messages/significant data with UEP

Capacity and queue-based codes for MANET timing channels



STATUS QUO

NEW INSIGHTS

Covert channels have mostly been used in an ad hoc way, with the exception of

- bits through single queue (Anantharam and Verdu 1998)
 - jamming game (Giles and Hajek 2002)

- steganographic capacity theory (Moulin and Wang 2004, 2007)

1) How to exploit/detect timing channels in MANETs

2) How much is there to exploit

ACHIEVEMENT DESCRIPTION

MAIN RESULT:

- 1) Characterize individual link capacity for timing channels in MANETs.
- 2) Identify family of capacityachieving queue-based codes.

HOW IT WORKS:

In asynchronous channels, the timings of symbols/packets can be used to covertly convey information. In a network, relays can covertly transmit information by modulating incoming packet timings. We define a timing capacity for this process and analyze the mathematical structure of codes that approach this capacity limit.

ASSUMPTIONS AND LIMITATIONS:

A statistical model (e.g., Poisson) is assumed for the flow of symbols in the network. Covert transmission preserves those statistics. Extend results from link level to network level.

GOAI

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CHALLENG

COMMUNITY

- Combine queuebased codes at
- link level with
- network codes.

Informationtheoretic work on network security & network covert channels, including the capacity cost of security

MANET covert channels present both a vulnerability and an opportunity.

MANET Timing Channel





- Packet network
- Relays may covertly transmit information by modulating interdeparture packet times
- Such modulation should be statistically undetectable
- We derive covert capacity for this problem
- We identify the structure of capacity-achieving codes

Joint Source-Channel Coding in Networks





coherence gains do not apply, do we need to do joint-source channel coding at the decoder **and** the encoder?

NEW

FLOWS ACHIEVEMENT(S)

We prove that separate source-channel encoding and joint source-channel decoding is sufficient for broadcast networks with no multiple access interference.

Joint Source-Channel Encoding Unnecessary when Correlation Beamforming Gains are Not Possible



How it works:

- R_{SEPencJSCCdec} ⊆ R_{JSCCencdec} is easy and can be expressed in closed form.
- $R_{JSCCencdec} \subseteq R_{SEPencJSCCdec}$ is shown by using a list decoder followed by using side information; interestingly, each rate is larger than point-to-point channel capacity

Assumptions and limitations:

- Noisy channels are link-oriented, no multiple access interference
- Metrics other than achievability may be affected (e.g. rate-distortion, error exponents).



Notions of Joint Source-Channel Coding Should be Qualified: Sometimes Enc/Dec Asymmetries Optimal

JSCC in Networks (cont'd)

Assumptions

- Each Rx observes output of channel from each Tx independently \Rightarrow no MAI
- Coherent/incoherent interference, beam-forming, transmitter cooperation not possible
- "Broadcast Interference": each transmitter cannot choose to send indep. messages to each receiver
- "Distribution Interference": Tx *i* cannot choose a different input distribution for each channel

Discussion



• $C_{i,j}$: point-to-point capacity of channel Tx $i \rightarrow \text{Rx } j$:

$$C_{i,j} \triangleq \max_{P(x_i)} I(X_i; Y_{i,j})$$

• **Proposition:** Considering **only** *Rx j*, all sources can be successfully communicated to Rx *j* iff

 $(C_{1,j}, C_{2,j}, \ldots, C_{S,j}) \in \mathcal{R}_{SW}(U_1, U_2, \ldots, U_S)$

 Source-Channel Separation Insufficient for all Rx's at once (Cut-Sets): R₁ ≤ 0.6; R₂ ≤ 0.6; ⇒ R₁ + R₂ ≤ 1.2< H(U₁, U₂)

Theorem





Theorem

The sources U_1, \ldots, U_S can be reliably communicated to all Rxs simultaneously iff there exist random variables X_1, \ldots, X_S satisfying $H(U_A|U_{A^c}) < \sum_{i \in A} I(X_i; Y_{i,j}) \ \forall j \in T$

for all $\mathcal{A} \subseteq \{1, ..., S\}$, where $U_{\mathcal{A}} = \{U_i\}_{i \in \mathcal{A}}$. Moreover, all achievable rates can be attained using using separate source and channel encoding and joint source-channel decoding.

Conclusion

•Notions of Joint Source –Channel Coding should be qualified

Sometimes Enc/Dec Asymmetries Optimal

•What implications does this have on the design of network architectures, from both performance and complexity perspectives?



Random Thoughts: "A Gut Feeling"



Deterministic Broadcast

Channel

(Rel1,Rel2)	Rx1	Rx2	Rx3
(-1,-1)	-1	-1	1
(-1,1)	-1	*	1
(1,-1)	1	*	-1
(1,1)	1	1	-1

•Although DBC dual to SW, developing practical codes is non-trivial.

•Encoding is hard, decoding easy

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•On opposite side of entropy boundary; so using off-the-shelf LDPCs yields exponentially many codewords consistent with what observed

A low-complexity capacity-achieving strategy:

Rate-splitting applies; focus on coding at vertices

•First stage of pipeline, can use Cover's "enumerative source coding" technique

- •Later stages: use Luby's generator-form LT codes
- •Dualize the algorithm + dualize the linear code
- •In 1-to-1correspondence with Digital Fountain coding on the binary erasure channel

•Also can be shown to be equivalent to coding on the Blackwell channel

Challenge: Develop an equivalence class of multiterminal source/channel coding problems that have equivalent low-complexity iterative message-passing solutions

•These equivalences go beyond just the erasure setting (An Allerton 07 submission essentially shows this equivalence for the BSC setting)



FLoW

An Aside: A Recent Result that Might be of Interest to FLoWS



Verdu & Anantharam's Award-winning 1996 Paper: "Bits Through Queues"



•Naturally enables covert communication. But also *improves raw throughput as well as throughput-delay tradeoffs significantly*

•Question in my mind since reading this paper and taking Dave Forney's "Coding on Steroids" class in graduate school: *how would you realize this practically*?

•Not Trivial – Verdu & Anantharam's 1999 Reflections on the best paper award: "Coding Theory for Timing Channels is Virtually Nonexistent"

•Might have figured out a way to look at the problem that enables an efficient practical encoding/decoding solution. It uses:

- •Algebraic coset codes
- •A *shaping* technique dating back to Gallager's 1968 IT book and more recently rekindled for LDPCs
- •Viewing the proposed encoding technique in terms of a first-order stochastic dynamical system
- •Viewing the dynamics of a FIFO queue a stochastic first-order dynamical system

•This results in a state-space viewpoint of the likelihood that naturally leads to an efficient iterative message-passing decoding algorithm

•Simulation results look very promising (poster this evening has more details)



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Layerless Dynamic Networks Summary





Achievements Overview



Network Information Theory

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

Koetter: likelihood forwarding, relay information before decoding

Moulin: covert channel by timing information

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

Goldsmith: Interference channel with cognitive user, "asymmetric" cooperation

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

Coleman: correlated source over BC, reduce coordination by separate encoding/ joint decoding

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

Zheng: error exponents unequal error protection, embedded control messages to reduce overhead.

Structured coding

CSI, feedback, and robustness

Thrust Summary



- Converging vision
 - Heterogeneous networking
 - Network distinguishes classes of data and their processing by their precision, reliability, latency, in addition to application QoS requirements
 - Cooperative networking
 - tradeoff between throughput gains and costs of coordination
 - Soft information processing
 - Quantify soft information and develop structured codes to handle soft information
 - Network operation with imperfect controls/knowledge
 - Robustness, adaptation, and mistake recovering
- Synergies with other thrusts
 - Outer bounds by thrust 1 used as performance references
 - Application metrics and implementation constraints by thrust 3 guide our problem formulations
 - We provide building blocks for larger network, to understand scaling behavior and design distributed algorithms
 - Novel cooperative techniques post new dimensions/challenges for resource sharing and protocol designs

Thrust Synergies: an Example





Recent Publications



- M. Bakshi and M. Effros and W. Gu and R. Koetter, "On network coding of independent and dependent sources in line networks", ISIT 2007
- E. Abbe, M. Médard, S. Meyn, and L. Zheng. "Finding the best mismatched detector for channel coding and hypothesis testing. ITA 2007
- S. Borade and L. Zheng, M. Trott "Multilevel Broadcast Networks", ISIT 2007
- S. Katti, I.Maric, A. Goldsmith, D. Katabi and M. Médard, "Joint Relaying and Network Coding in Wireless Networks", ISIT 2007
- I. Maric, A. Goldsmith, G. Kramer and S. Shamai (Shitz), "On the Capacity of Interference Channels with a Cognitive Transmitter", ITA 2007
- I. Maric, A. Goldsmith, G. Kramer and S. Shamai (Shitz),_"On the Capacity of Interference Channels with a Partially-Cognitive Transmitter", ISIT 2007
- Chris T. K. Ng and A. Goldsmith, "The Impact of CSI and Power Allocation on Relay Channel Capacity and Cooperation Strategies," submitted to *IEEE Trans. on Info. Theory*, 2007
- Chris T. K. Ng and A. Goldsmith, "Capacity and Cooperation in Wireless Networks," ITA 2007
- C. T. K. Ng, D. Gündüz, A. Goldsmith and E. Erkip, "Optimal Power Distribution and Minimum Expected Distortion in Gaussian Layered Broadcast Coding with Successive Refinement," submitted to IEEE Trans. on Info. Theory, 2007
- S. Yang and R. Koetter, "Network Coding over a Noisy Relay : a Belief Propagation Approach", ISIT 2007
- Ying Wang and Pierre Moulin, "Perfectly Secure Steganography: Capacity, Error Exponents, and Code Constructions" submitted to IEEE Trans. on Info. Theory, 2007