

Network Coding and Reliable Communications

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Professor Médard's group works extensively on various areas at the intersection of information theory and networking, in collaboration with other faculty at RLE, as well as at CSAIL, MTL, LIDS, Caltech, the University of Illinois Urbana-Champaign (UIUC), Stanford, the University of Porto, the University of Aalborg, the University of Waterloo, Northeastern University and the Technical University of Munich (TUM). In addition, Professor Médard has ongoing research programs and collaborations with Orange/France Telecom, Alcatel/Lucent and Technicolor. Network coding provides cost benefits in a variety of settings, for instance, wireless networks, where the cost may be measured in expended energy, or wireline networks, where they reduce congestion.

In the area of information theory, Professor Médard has obtained, with Professors Ozdaglar, Shah and Zheng, a DARPA contract for the study of information theory for MANETs (ITMANET) with UIUC, TUM, Stanford (lead) and Caltech. This work has led to work on fundamental properties of separation in networks, optimality of analog network coding at high signal-to-noise ratio (SNR) and optimality of digital network coding at low SNR.

The intersection of information theory, networking and computation is the topic of a program with the AFOSR. In this project, Professor Médard and her group have established new results for capturing and processing data in networked settings. One aspect of the work, in collaboration with Professor Goyal, considers the use of novel adaptive sampling approaches to be able to reduce the rate of sampling when signal variability decreases, without the need to sacrifice much in terms of distortion and without the need for a stochastic model of the underlying network.

The robustness of network coding is of particular usefulness when there is considerable variability and possible security issues. Professor Médard and her group have been considering the reliability of network coding in mobile ad-hoc networks, through an ARO project with UCSC (lead), UCLA, University of Maryland, UIUC and Stanford, and in vehicular networks, through a

MIT-Portugal Program. Their recent results have shown that network coding in wireless environments can lead to significant throughput benefits even when used in combination with traditional protocols such as TCP/IP. With Professor Barros of the university of Porto, Professor Médard and her group's work has also demonstrated considerable security benefits in wireless settings. Network coding is also very useful in the context of wireless video delivery. A new project with Orange/France Telecom in this area investigates the use of coding with protocols and multi-resolution approaches.

A new application area for network coding is that of body-area networks, supported by the Interconnect Focus Center (Georgia Tech lead). In collaboration with Professors Chandrakasan (PI), Katabi and Weinstein, she has established, with her students, the usefulness of network coding for energy efficiency in BANs. Moreover, they have recently proposed energy-aware implementations of network coding.

Professor Médard also works in the area of optical network performance, reliability and robustness. With Professor Maier and his student at INRS, she has considered the use of network coding in passive optical networks.

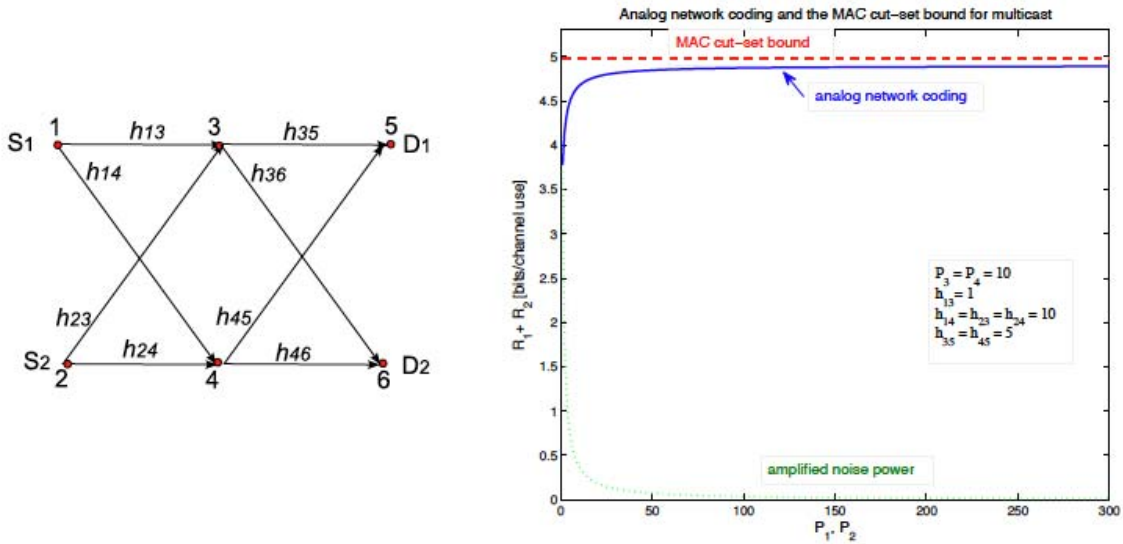
1. Information Theory for MANETs

Sponsor:

DARPA ITMANET under the FLOWS project

The purpose of this project is to investigate the information-theoretic limits of MANETs. The intrinsic limits consider topology, bandwidth, delay, capacity and energy.

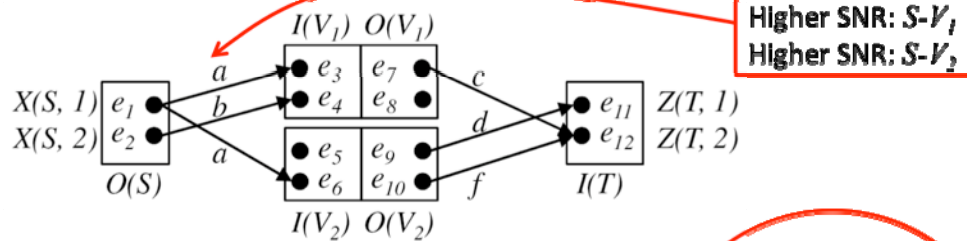
One of the main thrusts of this project is to determine the capacity of wireless ad-hoc networks. In this context, we have considered results for high-SNR networks. The first set of results, done in collaboration with Professor Goldsmith and Dr. Maric, both of Stanford, considers analog network coding. A node performing analog network coding simply forwards a signal it receives over a wireless channel. This allows for a (noisy) linear combination of signals simultaneously sent from multiple sources to be forwarded in the network. As such, analog network coding extends the idea of network coding to wireless networks. However, the analog network coding performance is limited by propagated noise, and we expect this strategy to perform well only in high SNR. We have formalized this intuition and determined high-SNR conditions under which analog network coding approaches capacity in a layered relay network. By relating the received SNR at the nodes with the propagated noise, we determine the rate achievable with analog network coding. In particular, when all the received powers are lower bounded by $1/\delta$, the propagated noise power in a network with L layers is of the order $L\delta$. The result demonstrates that the analog network coding approaches the cut-set bound as the received powers at relays increase. As all powers in the network increase at the same rate, the analog network coding rate is within a constant gap from the upper bound. The gap depends on number of nodes. We further demonstrate by an example that analog network coding can perform close to sum-capacity also in the multicast case. The figure below illustrates the quasi-optimality of analog network coding by comparing it to a minimum-cut bound.



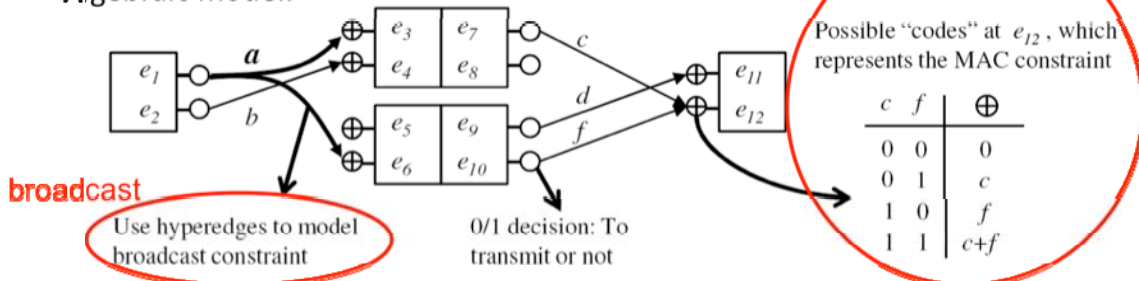
Another approach that has recently been considered for high SNR networks is that of a deterministic approximation. The deterministic wireless relay network model, introduced by Avestimehr et al., has been proposed for approximating Gaussian relay networks. This model, known as the ADT network model, takes into account the broadcast nature of wireless medium and interference. Avestimehr et al. showed that the Min-cut Max-flow theorem holds in the ADT network. We have shown that the ADT network model can be described within the algebraic network coding framework introduced by Koetter and Medard. We proved that the ADT network problem can be captured by a single matrix, called the system matrix. The gist of the equivalence is captured in the figure below.

- **Original ADT model (Binary field)**

- **Broadcast:** multiple edges (bit pipes) from the same node
- **Interference:** additive MAC over binary field



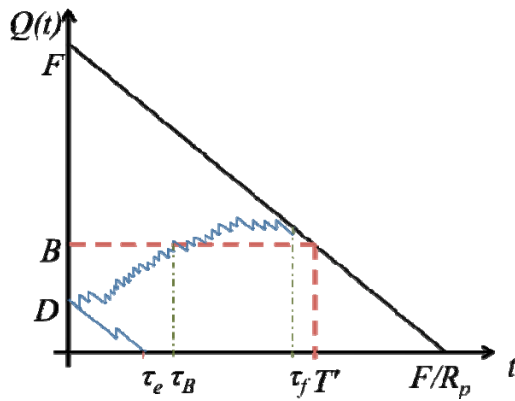
- **Algebraic model:**



We have shown that the min-cut of an ADT network is the rank of the system matrix; thus, eliminating the need to optimize over exponential number of cuts between two nodes to compute the min-cut of an ADT network. We have extended the capacity characterization for ADT networks to a more general set of connections. Our algebraic approach not only provides the Min-

cut Max-flow theorem for a single unicast/multicast connection, but also extends to non-multicast connections such as multiple multicast, disjoint multicast, and two-level multicast. We also have provided sufficiency conditions for achievability in ADT networks for any general connection set. In addition, we showed that the random linear network coding, a randomized distributed algorithm for network code construction, achieves capacity for the connections listed above. Finally, we extended the ADT networks to those with random erasures and cycles (thus, allowing bi-directional links).

With Professor Ozdaglar and our student, we have considered new metrics of particular interest to applications such as progressive download of video. The figure below shows the video queue behavior $Q(t)$ with an initial depth D under simple Poisson traffic assumption. For zero interruption the queue should be F but that would mean the maximum waiting time F/R_p with R_p the playback rate. Even if we are ready to live with a small probability of interruption want to avoid the queue to go to zero at τ_e before the video completion at τ_f . Our initial results indicate that that with linear NC the initial buffering times τ_B as well as the playback smoothness are greatly improved: for arrival rates slightly larger than the play rate, the minimum initial buffering time τ_b remains bounded as the file size grows. The results show a closing gap between Information Theory and NC that is relating traditional block encoding to the window based requirements of streaming protocols. We intend to prove that there are measurable trade offs between QoE, link quality and rate and buffer size.



We have also considered the intersection of scheduling, acknowledgements, coding and interference. Current medium access control mechanisms are based on collision avoidance and collided packets are discarded. The recent work on ZigZag decoding departs from this approach by recovering the original packets from multiple collisions. Our recent work has viewed each collision as a linear combination of the original packets at the senders. The transmitted, colliding packets may themselves be a coded version of the original packets. We have designed acknowledgment (ACK) mechanisms based on the idea that if a set of packets collide, the receiver can afford to ACK exactly one of them without being able to decode the packet. We have characterized the conditions for an ACK mechanism under which the receiver can eventually decode all of the packets. In the context of a wireless erasure network, we have shown that the senders' queues behave as if the transmissions are controlled by a centralized scheduler, which has access to channel state realizations in each time slot at the beginning of the slot. Taking advantage of this relation, we propose two ACK policies that stabilize the system.

One of these policies only requires the arrival rate information and the other one only needs queue-length information. We also have shown that our ACK policies combined with a completely decentralized transmission mechanism based on random linear network coding achieves the cut-set bound of the packet erasure network, which is strictly larger than the stability region of centralized scheduling schemes without collision recovery.

Finally, we have explored the intrinsic structure of network coding through matroidal networks introduced by Dougherty et al., who showed that if a network is scalar-linearly solvable over some

finite field, then the network is a matroidal network associated with a representable matroid over a finite field. We have proven the converse. It follows that a network is scalar-linearly solvable if and only if the network is a matroidal network associated with a representable matroid over a finite field and that determining scalar-linear solvability of a network is equivalent to finding a representable matroid over a finite field and a valid network-matroid mapping. As a consequence, we obtain a correspondence between scalar-linearly solvable networks and representable matroids over finite fields. We note that this result, combined with the construction method due to Dougherty et al., can generate potentially new scalar linearly solvable networks.

2. Practical approaches to wireless network coding in wireless settings

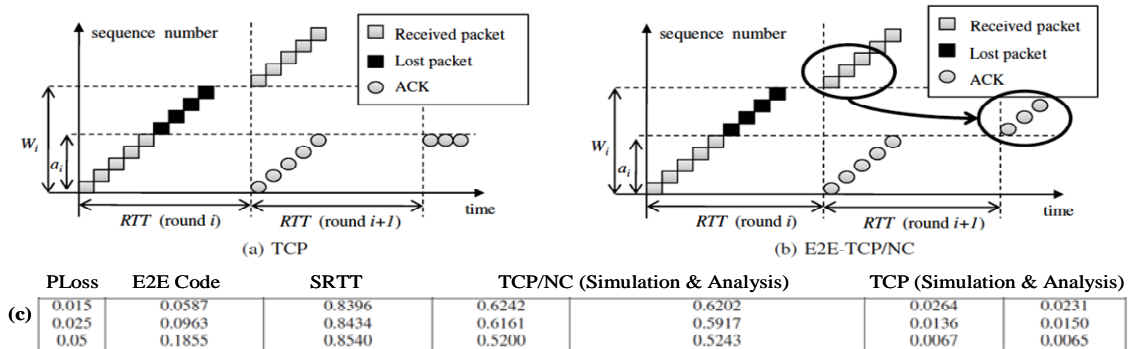
Sponsors:

ARO DAWN program

MIT-Portugal Program

Wireless networks suffer from interference and, in some cases, considerable delay. We have considered how to create practical schemes that allow us to design network coding mechanisms in the context of wireless settings. A particularly challenging issue is that of erasures, which can significantly affect protocols.

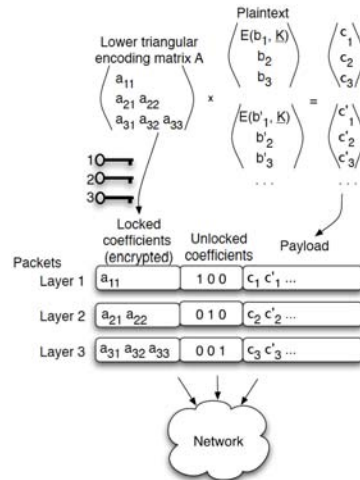
For example, consider network coding with TCP (TCP/NC), which we have developed. Network coding is particularly robust to random losses as shown in the figure below. Despite the loss of several packets, the window has been able to advance in the TCP/NC case, but was reduced in the uncoded case. We have obtained preliminary results, which use the analytical approach of Padhye et al, applied them to TCP/NC and compared it to NS simulations. The table below considers the probability of loss inflicted by the censor, the throughput that would be available with end-to-end coding only, the smoothed round-trip time (SRTT), which is the round trip time estimate that TCP maintains by sampling the behavior of packets sent over the connection, as well the throughputs obtained for TCP and NC under simulation and analysis.



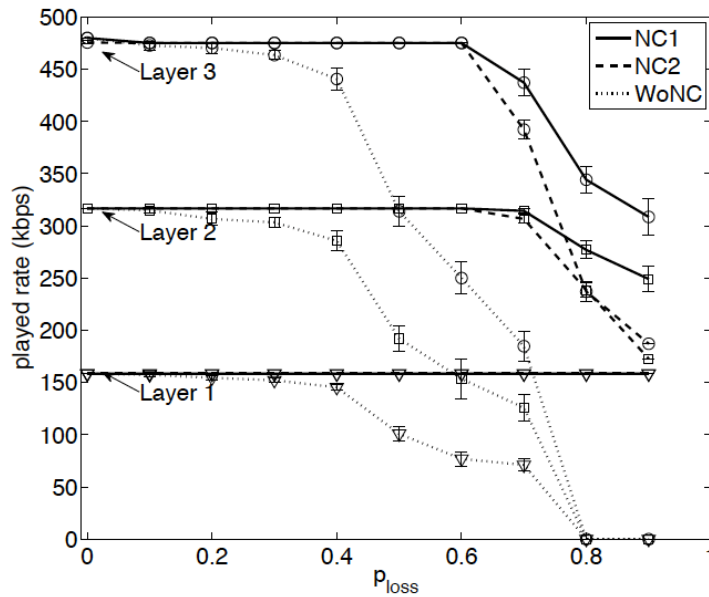
The effect of erasures: (a) TCP sees triple-duplicate ACKs, and results in $W_i+2 \rightarrow W_i+1/2$. However, (b) TCP/NC masks the erasures allowing TCP to advance its window. The effect of losses (c) shows better performance for TCP/NC.

Our work has also considered, in collaboration with Professor Barros and his group, the effect of security on system performance. Emerging practical schemes indicate that algebraic mixing of different packets by means of the random linear network coding algorithms developed by our group can increase the throughput and robustness of streaming services over wireless networks. However, concerns with the security of wireless video, in particular when only some of the users are entitled to the highest quality, have uncovered the need for a network coding scheme capable of ensuring different levels of confidentiality under stringent complexity requirements. We have shown that the triple goal of hierarchical fidelity levels, robustness against wireless packet loss and efficient security can be achieved by exploiting the algebraic structure of network coding. The

key idea is to limit the encryption operations to a critical set of network coding coefficients in combination with multi-resolution video coding. We have derived a new algorithm providing multi-level encryption for network coding, as shown below.



The header-only encryption provides excellent performance. The inclusion of all three layers in the same scheme outperforms a system (NC2), which considers layers separately (NC1). The performance advantages are captured in the figure below, which shows rate in function of loss probability for NC1, three streams with network coding NC2 and without network coding (WoNC) (results performed in collaboration with Telefonica).



3. Video delivery using network coding.

Sponsors:

Orange/ France Telecom
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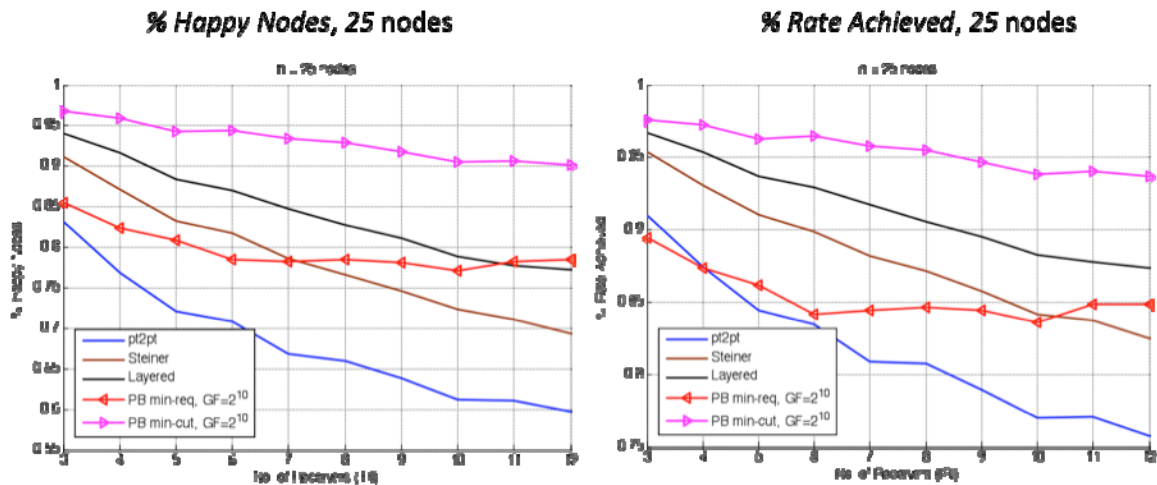
In our group's prior work, we have already developed hybrid-coding schemes for both statistical models of and for video. As shown in the figure below, we have used MPEG 4 with network coding. The approach uses both network coding over generations of size denoted by h , with packets allowed to be part of a number O of generations (O stands for overlap) for the purpose of

affording redundancy. Our results are shown in the opposite figure. We see that network coding outperforms systems that do not use network coding but that the benefits depend strongly on the correct choice of parameters. This is all part of the work we intend to pursue in this proposal as we move to new codecs like Scalable Video Coding (SVC) and others.



Perceptual evaluation at 768 kbit/s: (a) no network coding, encoding rate 1 (b) no network coding, encoding rate 0.5 (c) network coding at $h=4$, $O=2$ (d) network coding at $h=6$, $O=3$ (e) network coding at $h=10$, $O=5$ (f) network coding at $h=15$, $O=8$

We are also considering the use of network coding for networks with unequal throughput to different receiver nodes. Multi-resolution codes enable multicast at different rates to different receivers, a setup that is often desirable for graphics or video streaming. We have proposed a simple, distributed, two-stage message-passing algorithm to generate network codes for single-source multicast of multi-resolution codes. The goal of this pushback algorithm is to maximize the total rate achieved by all receivers, while guaranteeing decodability of the base layer at each receiver. By conducting pushback and code generation stages, this algorithm takes advantage of inter-layer as well as intra-layer coding. Numerical simulations show that in terms of total rate achieved, the pushback algorithm outperforms routing and intra-layer coding schemes, as shown below. In addition, the performance gap widens as the number of receivers and the number of nodes in the network increases. We also observe that naïve inter-layer coding schemes may perform worse than intra-layer schemes under certain network conditions.



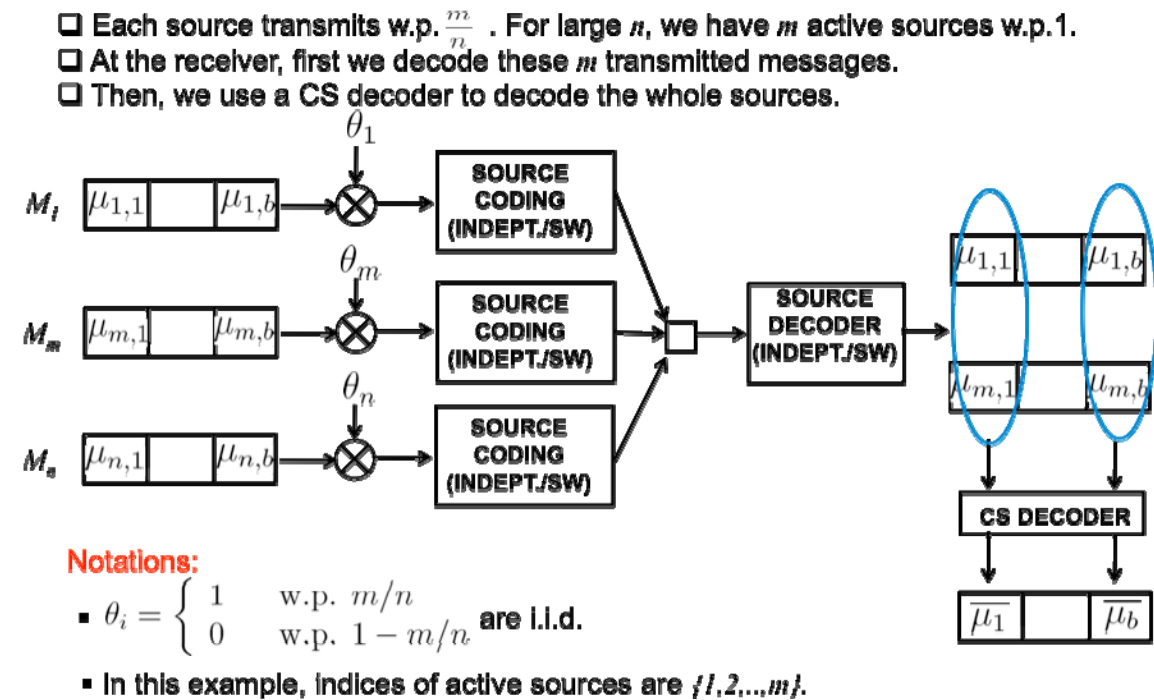
5. Managing on degrees of freedom.

Sponsor:

Interconnect Focus Center

We consider the issue of making optimal use of degrees of freedom when we have joint computation, source coding and network coding.

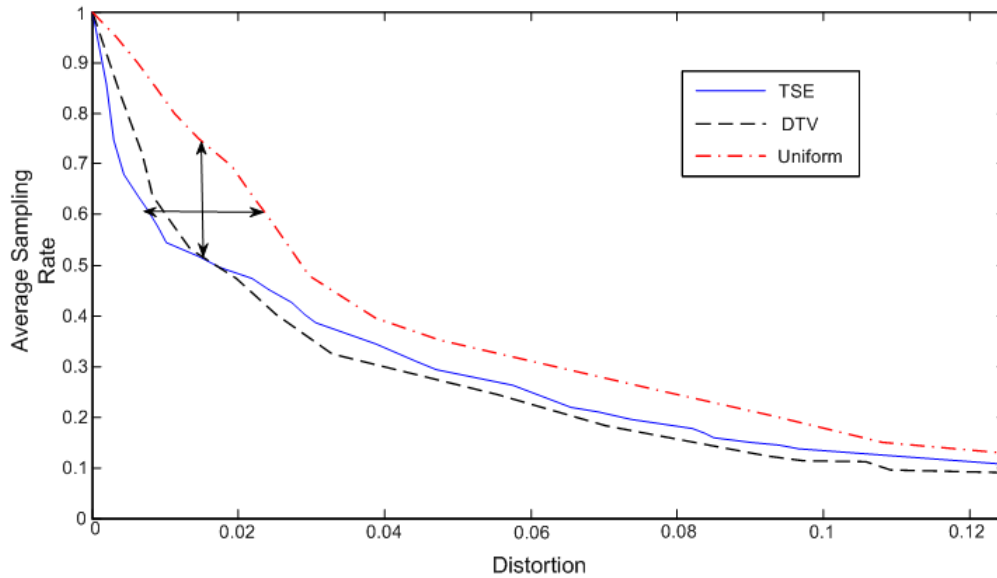
With Professor Effros of Caltech, we have made a connection between compressive sensing (CS) and traditional information theoretic techniques in source coding and channel coding. Our results provide an explicit trade-off between the rate and the decoding complexity. The key difference of compressive sensing and traditional information theoretic approaches is at their decoding side. Although optimal decoders to recover the original signal, compressed by source coding have high complexity, the compressive sensing decoder is a linear or convex optimization. First, we have investigated applications of compressive sensing on distributed compression of correlated sources. Here, by using compressive sensing, we propose a compression scheme for a family of correlated sources with a modularized decoder, providing a trade-off between the compression rate and the decoding complexity. We call this scheme Sparse Distributed Compression. The main blocks of this technique are shown below. The source coding is done using simple independent source coding or joint Slepian-Wolf (SW) coding.



We use this compression scheme for a general multicast network with correlated sources. Here, we first decode some of the sources by a network decoding technique and then, we use a compressive sensing decoder to obtain the whole sources. We have also investigated applications of compressive sensing on channel coding. We propose a coding scheme that combines compressive sensing and random channel coding for a high-SNR point-to-point Gaussian channel. We call this scheme Sparse Channel Coding. We propose a modularized decoder providing a trade-off between the capacity loss and the decoding complexity. At the receiver side, first, we use a compressive sensing decoder on a noisy signal to obtain a noisy estimate of the original signal and then, we apply a traditional channel coding decoder to find the original signal.

Compressive sensing is, at its core, based on a type of probabilistic sampling. We have considered, with Professor Goyal, another issue around sampling, by introducing a class of

Locally Adaptive Sampling schemes. In this sampling family, time intervals between samples can be computed by using a function of previously taken samples, called a sampling function. Hence, though it is a non-uniform sampling scheme, we do not need to keep sampling times. The aim of LAS is to have the average sampling rate and the reconstruction error satisfy some requirements. We have proposed four different schemes of LAS. The first two are designed for deterministic signals. The first of these two is a Taylor Series Expansion (TSE) sampling function, which only assumes the third derivative of the signal is bounded, but requires no other specific knowledge of the signal. We have also proposed a Discrete Time-Valued (DTV) sampling function, where the sampling time intervals are chosen from a lattice. A performance comparison among these techniques and uniform sampling, in terms of rate-distortion, is given in the figure below.



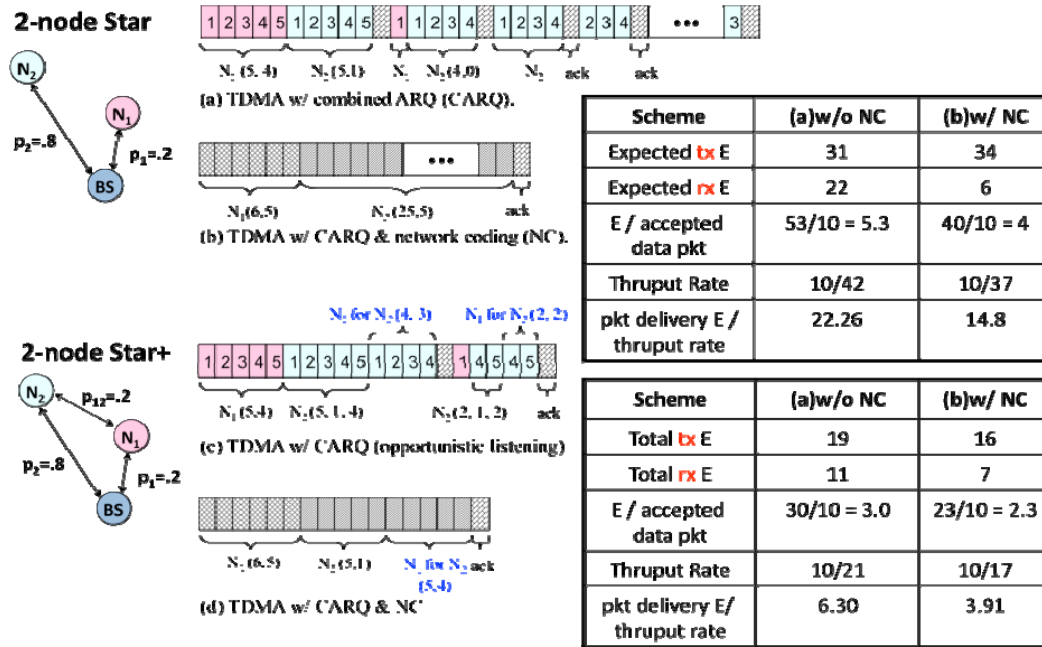
We have also considered stochastic signals. We have proposed two sampling methods based on linear prediction filters: a Generalized Linear Prediction (GLP) sampling function, and a Linear Prediction sampling function with Side Information (LPSI). In the GLP method, we only assume the signal is locally stationary. However, LPSI is specifically designed for a known signal model.

6. Network coding for BANs.

Sponsor:

Interconnect Focus Center

We have proposed, in collaboration with Professor Lucani of Porto, a network coding scheme for practical implementations of wireless body area networks is proposed, with the objective of providing reliability under low-energy constraints. We have proposed a simple network layer protocol, studied the mean energy to complete in-cast transmissions of given packets from the sensors to the base station, and shown through numerical examples that this scheme can reduce the overall energy use. More specifically, Time Division Multiple Access (TDMA) is used to allocate the wireless channel to individual nodes within the network. Each sensor node linearly combines its data packets before taking turns to send the ensuing mixtures to the base station. An automatic repeat request (ARQ) message is broadcasted by the base station to all nodes after each round of transmissions. The figure below illustrates the performance benefit that network coding provides over uncoded TDM techniques.



We parametrically have studied the optimal numbers of coded data packets to send, in terms of overall completion energy, given the packet erasure probabilities, and the energy use for transmitting data packets as well as listening to acknowledgement (ACK) packets. This analysis shows that minimization of energy is a difficult problem; thus we consider its performance numerically. Numerical results show that for a two-node star network, when transmitting and receiving energy are approximately the same, the amount of energy reduction achievable through the network coding approach can be on the order of 27%, while the reduction in the packet delivery energy per throughput rate can be as high as 37%. When receiving costs a lot more than transmitting, the network coding approach can offer more than 80% reduction in completion energy. The amount of achievable gains depends on the number of nodes in the network, the degree of asymmetry in channel conditions experienced by different nodes, and the relative difference between transmitting and receiving power at the sensor nodes.

In collaboration with Professor Chandrakasan, we are considering different options for implementation of network coding in chips for BANs. This work has concentrated on determining the trade-off between the energy needed to code and that saved by avoiding the repetition of transmissions.

Publications

Journal articles, accepted for publication

1. M. Kim, Lima, L., Zhao, F., Barros, J., Médard, M., Koetter, R., Kalker, T. and Han, K., "On Counteracting Byzantine Attacks in Network Coded Peer-to-Peer Networks", *IEEE Journal on Selected Areas in Communications: Special Issue on Mission-Critical Infrastructure*, vol28, Issue 5, May 2010**
2. L. Lima, Gheorghiu, S., Barros, J., Médard, M., and Toledo, A. T. "Secure Network Coding for Multi-Resolution Wireless Video Streaming," accepted in the *IEEE Journal of Selected Areas in Communications*, 2010
3. W. Chen, Traskov, D., Heindlmaier, M., Médard, M., Meyn, S., and Ozdaglar, A., "Coding and Control for Communication Networks", accepted to the *Queueing Systems Erlang Centennial Issue*
4. G. Durrett, Médard, M., and O'Reilly U.-M., "A Genetic Algorithm to Minimize Chromatic Entropy", to be published in: P. Cowling and P. Merz (Eds.): *EvoCOP 2010*, LNCS 6022, pp. 59--70. Springer, Heidelberg (2010)

5. A. ParandehGheibi, Eryilmaz, A., Ozdaglar, A., and Médard, M., "On Resource Allocation in Fading Multiple Access Channels -- An Efficient Approximate Projection Approach", accepted to *IEEE Transactions on Information Theory***
6. M. Kim, Sundararajan, J.K., Médard, M., Eryilmaz, A. and Koetter, R., "Network Coding in a Multicast Switch", accepted to *IEEE Transactions on Information Theory***

Meeting papers, published

1. S. Feizi and Médard, M., "When Only Sources Need to Compute, On Functional Compression in Tree Networks", *2009 Annual Allerton Conference on Communication, Control, and Computing*, October 2009**
2. D. Lucani, Médard, M. and Stojanovic, M., "Sharing Information in Time-Division Duplexing Channels: A Network Coding Approach", *2009 Annual Allerton Conference on Communication, Control, and Computing*, October 2009**
3. M. Langberg and Médard, M., "The Multiple Unicast Network Coding Conjecture", *2009 Annual Allerton Conference on Communication, Control, and Computing*, October 2009
4. D. Lucani, Médard, M. and Stojanovic, M., "Random Linear Network Coding for Time-Division Duplexing: Field Size Considerations", *IEEE Globecom 2009 Communication Theory Symposium*, November-December 2009**
5. D. Traskov, Médard, M., Sadeghi, P. and Koetter, R., "Joint Scheduling and Instantaneously Decodable Network Coding", *IEEE Globecom 2009 Communication Theory Symposium*, November-December 2009
6. S. Feizi, and Médard, M., "Multi-Functional Compression with Side Information", *IEEE Globecom 2009 Communication Theory Symposium*, November-December 2009**
7. I. Maric, Goldsmith, A., and Médard, M., "Analog Network Coding in the High SNR Regime", **invited paper**, *ITA Workshop*, January 2010
8. F. Zhao and Médard, M. "[On analyzing and improving COPE performance](#)", **invited paper**, *ITA Workshop*, January 2010**
9. S. Huang, Ramamoorthy, A., and Médard, M., "Minimum cost content distribution using network coding: Replication vs. coding at the source nodes", *ITW 2010*
10. M.-J. Montpetit and Médard, M., "Video-centric Network Coding Strategies for 4G Wireless Networks: An Overview", *2010 IEEE Consumer Communications and Networking Conference*.
11. R. S. Thinniyam, Kim, M., Médard, M., O'Reilly, U.-M., "Network Coding in Optical Networks with O/E/O Based Wavelength Conversion", *OFC 2010***
12. D. Traskov, Lenz, J., Ratnakar, N. and Médard, M., "Asynchronous Network Coded Multicast", *2010 ICC Communication Theory Symposium*
13. A. ParandehGheibi, Ozdaglar, A., Effros, M. and Médard, M., "Optimal Reverse Carpooling Over Wireless Networks - A Distributed Optimization Approach", *CISS 2010***
14. M. Kim, Lucani, D., Shi, X., Zhao, F. and Médard, M., "Network coding for multi-resolution multicast", *INFOCOM 2010***
15. I. Maric, Goldsmith, A. and Médard, M., "Analog Network Coding in the High-SNR Regime", *IEEE Wireless Network Coding Workshop 2010*
16. A. ParandehGheibi, Sundararajan J.-K. and Médard, M., "Collision Helps - Algebraic Collision Recovery for Wireless Erasure Networks", *IEEE Wireless Network Coding Workshop***
17. C. Chang, Effros, M., Ho, T., Médard, M. and Leong, B., "Issues in Peer-to-Peer Networking: a Coding Optimization Approach", *NETCOD 2010*
18. N. Fawaz and Médard, M., "On the Non-Coherent Wideband Multipath Fading Relay Channel", *ISIT 2010*
19. D. Lucani, Médard, M. and Stojanovic, M., "Systematic Network Coding for Time-Division Duplexing", *ISIT 2010***
20. A. ParandehGheibi, Médard, M., Shakkottai, S. and Ozdaglar, A., "Avoiding Interruptions - QoE Trade-offs in Block-coded Streaming Media Application", *ISIT 2010***
21. W.-Y. Shin, Lucani, D., Médard, M., Stojanovic, M. and Tarokh, V., "Multi-hop Routing is Order-optimal in Underwater Extended Networks", *ISIT 2010*
22. S. Feizi and Médard, M., "Some Cases Where Finding the Minimum Entropy Coloring of

- a Characteristic Graph is a Polynomial Time Problem”, *ISIT 2010***
23. P. Oliveira, L. Lima, Vinhoza, T. T., Barros, J. and Médard, M., “Trusted Storage over Untrusted Networks”, accepted to *IEEE Globecom 2010 - Communication Theory Symposium*
 24. M. Thakur and Médard, M., “On optimizing low SNR wireless networks using network coding””, accepted to *IEEE Globecom 2010 - Communication Theory Symposium*
 25. D. Lucani, Médard, M. and Stojanovic, M., “Online Network Coding for Time-Division Duplexing”, accepted to *IEEE Globecom 2010 - Symposium on Selected Areas in Communications***
 26. A. Rezaee, Zeger, L. and Médard, M., “Multi Packet Reception and Network Coding”, accepted to *MILCOM 2010***
 27. M. Kim and Médard, M., “Algebraic Network Coding Approach to Deterministic Wireless Relay Network”, accepted to *Allerton Conference 2010***
 28. S. Feizi, Goyal, V.K. Goyal and Médard, M., “Locally Adaptive Sampling”, accepted to *Allerton Conference 2010***
 29. A. ParandehGheibi, Sundararajan, J.-K. and Médard, M., “Acknowledgement Design for Collision-Recovery-Enabled Wireless Erasure Networks””, accepted to *Allerton Conference 2010***

Meeting paper, presented

September 2009, “Bringing network coding into the network”, **Keynote Address**, International Teletraffic Conference, Paris, France

January 2010, “Some New(ish) Results in Information Theory”, **invited lecture**, Programme on New Topics at the Interface Between Probability and Communications, Newton Institute for Mathematics, Cambridge, UK

January 2010, “Bringing Network Coding into the Network”, **invited lecture**, Computer Laboratory Systems Research Group Seminar, Cambridge, UK, **invited lecture**,

February 2010, “Some New Directions in Information Theory”, **invited lecture**, Workshop on Frontiers of Controls, Games, and Network Science with Civilian and Military Applications, Austin, TX

May 2010, “On the practice of network coding. Bringing network coding into the network.” **Keynote lecture**, 5th IEEE International Symposium on Wireless Pervasive Computing, Modena, Italy

July 2010, “When network coding met the network”, **Keynote lecture**, International Conference on Infocomm Technology, Hanan, China

July 2010, “Some Perspectives on Scaling”, **Plenary presentation**, JTEN, MIT Lincoln Laboratory

Theses

Sheng, Jing, “Towards Unifying Multi-Resolution and Multi-Description - A Distortion-Diversity Perspective”, September 2009, (co-supervised with Lizhong Zheng) (Doctoral Thesis)

Zhao, Fang, “Distributed Control of Coded Networks”, October 2009 (Doctoral Thesis)

Lucani, Daniel, “Network Coding for Delay Challenged Environments” (co-supervised with Milica Stojanovic (Northeastern University)), March 2010 (Doctoral Thesis)

Shi, Shirley, “Joint Base-Calling of Two DNA Sequences with Factor Graphs”, September 2009 (co-supervised with Desmond Lun from the Broad Institute) (M.S. Thesis)

Feizi-Khankandi, Soheil, “Network Functional Compression”, June 2010 (M. S Thesis)

Kim, Anthony, “ On Network Coding Capacity - Matroidal Networks and Network Capacity Regions”, August 2010 (M. Eng. Thesis)