

Robust Wireless Network Coding: Joint Network/Channel Decoding for Cooperative Wireless Networks (JNCD4CoopNets)

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Abstract – Since the pioneering research work of Ahlswede et al. in 2000, Network Coding (NC) has rapidly emerged as a major research area in electrical engineering and computer science due to its wide applicability to communication through real networks. The main aim of JNCD4CoopNets was conceiving, studying, and optimizing new solutions to improve the reliability of network-coded multi-hop/cooperative wireless networks over realistic fading channels by resorting to a cross-layer design methodology encompassing demodulation, channel, and network decoding.

1 Introduction and Motivation

1.1 Beyond Routing via NC

Wireless networked systems arise in various communication contexts, and are becoming a bigger and integral part of our everyday life. In today practical networked systems, information delivery is accomplished through routing: network nodes simply store and forward data, and processing is accomplished only at the end nodes. Network Coding (NC) is a recent field in electrical engineering and computer science that breaks with this assumption: instead of simply forwarding data, intermediate network nodes may recombine several input packets into one or several output packets. NC offers the promise of improved performance over conventional network routing techniques. In particular, NC principles can significantly impact the next-generation wireless *ad hoc*, sensor, and cellular networks, in terms of both energy efficiency and throughput.

1.2 NC over Wireless Networks: The Challenge

However, besides the many potential advantages and applications of NC over classical routing, the NC principle is not without limitations. A fundamental problem that we need to carefully consider over lossy (*e.g.*, wireless) networks is the so-called error propagation problem: corrupted packets injected by some intermediate nodes might propagate through the network until the destination, and might render impossible to decode the original informa-

tion. As a matter of fact, the application of NC to a wireless context needs to take into account that the wireless medium is highly unpredictable and inhospitable for adopting existing NC algorithms, which have been mostly designed by assuming wired (*i.e.*, error-free) networks as the blueprint. Furthermore, in contrast to routing, this problem is crucial in NC due to the algebraic operations performed by the nodes of the network: the mixing of packets within the network makes every packet flowing through it statistically dependent on other packets, so that even a single erroneous packet might affect the correct detection of all the other packets. On the contrary, the same error in networks using just routing would affect only a single source-to-destination path.

Thus, in this context the fundamental issue to be carefully considered to understand the actual performance improvement and advantage of network-coded multi-hop/cooperative communications is to take into account that all the nodes of the network are error-prone, and that erroneous decoding and forwarding might have a significant impact on the end-to-end performance, diversity, throughput, and quality-of-service. The importance of this problem is increasing exponentially as a result of latest research achievements on the analysis of the performance of noisy cooperative networks with NC. In fact, recent results have highlighted that the conventional method that is often advocated as a solution to counteract the error propagation problem, *i.e.*, the adoption of a Cyclic Redundancy Code (CRC) check mechanism which aims at not forwarding corrupted packets, might be very ineffective in block-fading channels as long as being highly

spectral inefficient as an entire packet is blocked if just one bit is in error.

1.3 Robust Wireless NC: The Solution

In the light of all the above, new approaches and algorithms are needed for the adoption and exploitation of NC for multi-hop/cooperative wireless networks. More specifically, because of its well-acknowledged importance for these networks, how to tackle the error propagation problem has recently attracted the interest of many researchers, and has led to the birth of an important research area that is currently emerging in the NC and cooperative networking communities: the so-called Robust Wireless Network Coding (RWNC). RWNC is concerned with the development of efficient methodologies to conceive network codes, relaying methods, and decoding algorithms that: i) are robust to all kinds of errors possibly occurring in multi-hop/cooperative wireless networks, and ii) can be implemented in a computationally efficient way.

1.4 Objectives of JNCD4CoopNets

JNCD4CoopNets was motivated by the considerations above and its main objective was to provide fundamental contributions on the analysis and design of RWNC for multi-hop/cooperative wireless networks. In particular, it aimed at developing innovative solutions to improve the reliability of network-coded cooperative wireless architectures by resorting to a cross-layer design methodology, and by leveraging technologies from the physical and network layers to combat the dominant impairments, *e.g.*, noise, channel fading, and interference, for an error-free delivery of information over wireless networks.

More specifically, the specific objectives and expected contribution of JNCD4CoopNets were as follows:

- Understanding the performance degradation caused by error propagation over wireless networks for various network codes (*e.g.*, relaying vs. XOR-NC vs. non-XOR-NC) and receiver schemes (*e.g.*, the role played by channel state information at the receiver).
- Investigation of realistic fading channel models (*e.g.*, with decoding errors over all the wireless links) and network topologies (*e.g.*, heterogenous wireless networks with multiple sources and multiple relays).
- Development of simple and insightful analytical frameworks that provide a simple understanding, comparison of the performance, and eventually the optimization of network-coded cooperative wireless networks (*e.g.*, the analysis of the diversity/coding gain trade-off and the asymptotic optimality in the presence of decoding errors).
- Development of optimal receiver schemes and decoding algorithms based on a cross-layer optimization criterion (*e.g.*, joint demodulation and network decoding, and joint channel and network decoding).

2 Obtained Results

In this section, the most important research achievements obtained during the project are summarized.

2.1 Review of State-of-the-Art and Problem Understanding

During the first part of the project, we have performed a careful review of the state-of-the-art of NC and cooperative wireless networks research [1], [2], [3]. In particular, we have carefully analyzed the latest research achievements concerning the design of robust techniques to counteract the error propagation problem, such as: i) network error protection coding (also known as coding in projective spaces); ii) joint network and channel decoding algorithms; iii) threshold-based relaying; and iv) channel-aware receiver design. Advantages and disadvantages have been highlighted along with open research problems, which have been investigated and solved.

2.2 Flexible Network Code and Channel-Aware Receiver Design for Heterogenous Wireless Networks

In [4] and [5], we have proposed Unequal Error Protection (UEP) coding theory as a viable and flexible method for the design of network codes for multi-source multi-relay cooperative networks. As opposed to state-of-the-art solutions available for improving the diversity gain of cooperative networks, we have shown that the proposed method allows us to assign each source node the desired diversity gain, according to, *e.g.*, the requested Quality-of-Service (QoS) or power constraints. This flexibility is especially beneficial for heterogenous wireless networks where either i) multiple source nodes might have different QoS requirements, or ii) the relay nodes might not be all capable of performing NC on the received packets. The diversity advantage of the UEP-based network code design over conventional relay-only and XOR-only solutions has been proved for the canonical two-source two-relay network through analysis and simulation. Furthermore, Maximum-Likelihood (ML-) optimum channel-aware receivers for multi-source multi-relay cooperative networks have been developed, and their Average Bit Error Probability (ABEP) and achievable diversity over fading channels have been analytically studied. We have highlighted that only a cross-layer (joint) implementation of demodulation and network-decoding allows the destination to fully exploit the diversity inherently provided by the distributed network code.

2.3 Accurate Performance Analysis of Network Codes over Realistic Fading Channels and Optimal Receivers

In [6], we have proposed a simple analytical methodology to study the performance of multi-source multi-relay co-

TAB. 1: ABEP for high SNR, *i.e.*, $ABEP_\infty = (G_c \bar{\gamma}_\infty)^{-G_d}$, where G_c and G_d are coding and diversity gains, respectively, and $\bar{\gamma}_\infty$ is the SNR at the receiver. Two-source two-relay network topology. Scenario 1: relaying with no NC. Scenario 2: XOR-based NC. Scenarios 3 and 4: UEP-based NC.

	Ideal source-to-relay channels		Realistic source-to-relay channels	
	$ABEP_\infty^{(S_1)}$	$ABEP_\infty^{(S_2)}$	$ABEP_\infty^{(S_1)}$	$ABEP_\infty^{(S_2)}$
Scenario 1	$\left[\left(\sqrt{8/3}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt{8/3}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt{4/3}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt{4/3}\right) \bar{\gamma}_\infty\right]^{-2}$
Scenario 2	$\left[\left(\sqrt{8/3}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt{8/3}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt{8/3}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt{8/3}\right) \bar{\gamma}_\infty\right]^{-2}$
Scenario 3	$\left[\left(\sqrt{8/3}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt[3]{32/31}\right) \bar{\gamma}_\infty\right]^{-3}$	$\left[\left(\sqrt{8/9}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt[3]{64/249}\right) \bar{\gamma}_\infty\right]^{-3}$
Scenario 4	$\left[\left(\sqrt[3]{32/31}\right) \bar{\gamma}_\infty\right]^{-3}$	$\left[\left(\sqrt{8/3}\right) \bar{\gamma}_\infty\right]^{-2}$	$\left[\left(\sqrt[3]{64/249}\right) \bar{\gamma}_\infty\right]^{-3}$	$\left[\left(\sqrt{8/9}\right) \bar{\gamma}_\infty\right]^{-2}$

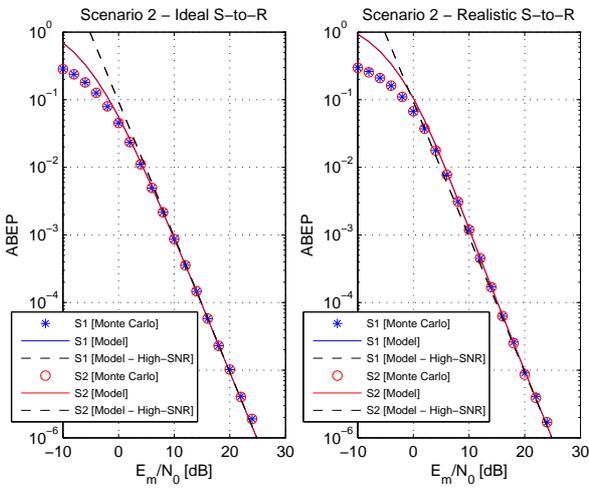


FIG. 1: ABEP against E_m/N_0 for XOR-based NC.

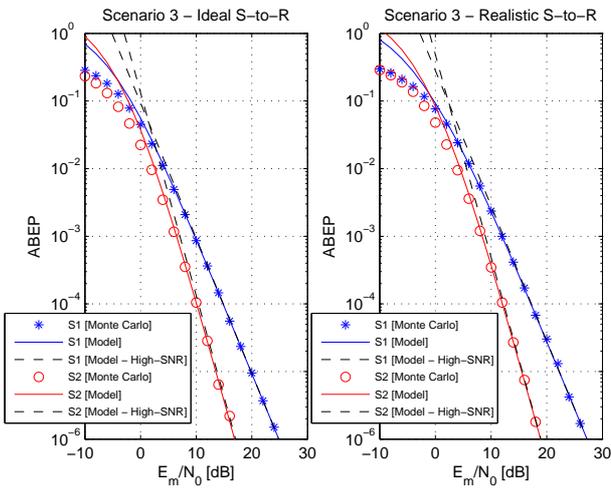


FIG. 2: ABEP against E_m/N_0 for UEP-based NC.

operative wireless networks with NC at the relay nodes and ML-optimum channel-aware detectors at the destination. Channel-aware detectors are a broad class of receivers that account for possible decoding errors at the relays, and, thus, are inherently designed to mitigate the

effect of erroneous forwarded and network-coded data. In spite of the analytical complexity of the problem at hand, the proposed framework turns out to be simple enough yet accurate and insightful to understand the behavior of the system, and, in particular, to capture advantages and disadvantages of various network codes and the impact of error propagation on their performance. It has been shown that, with the help of cooperation, some network codes are inherently more robust to decoding errors at the relays, while others better exploit the inherent spatial diversity and redundancy provided by cooperative networking. Finally, theory and simulation have highlighted that the relative advantage of a network code with respect to the others might be different with and without decoding errors at the relays.

As an example, in Fig. 1 and Fig. 2 we show the performance (*i.e.*, the ABEP against the Signal-to-Noise-Ratio (SNR) E_m/N_0) comparison of a NC design based on binary XOR, *i.e.*, XOR-based NC, and a NC design based on binary UEP coding theory, *i.e.*, UEP-based NC, proposed in [4]. We can notice that, for the same complexity, UEP-based NC provides better performance for at least one user. Also, it can be observed that the proposed analytical frameworks are quite accurate and can well capture the behavior of the system. Furthermore, the figures compare the performance for two important case studies, *i.e.*, ideal and error-prone source-to-relay channels. Finally, in Tab. 1 we summarize the frameworks for high SNRs. The table provides a clear indication that the conventional assumption of neglecting decoding errors at the relay, *i.e.*, the ideal source-to-relay channels case, provides the wrong conclusion that XOR-based NC is useless for wireless networks. On the contrary, the analysis of the case study with realistic source-to-relay channels, which takes into account decoding errors at the relays, clearly shows that NC is beneficial as it provides better performance than performing just relaying. This result shows that NC can be extremely useful for wireless networks with disruptive channel and connectivity conditions. Recent results are available in [7].

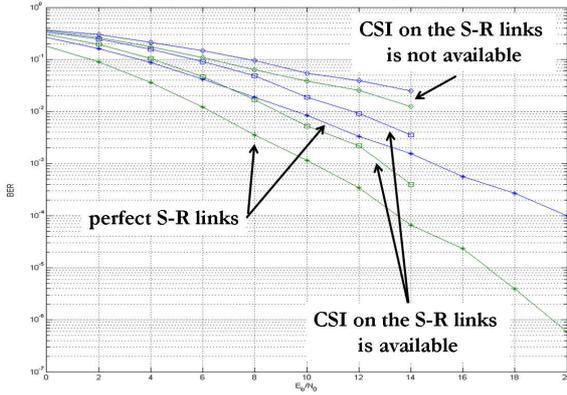


FIG. 3: ABEP against E_b/N_0 for UEP-based NC with convolutional codes.

2.4 Optimal and Sub-Optimal Joint Network and Channel Decoding for Error-Prone Wireless Networks

In [8], we have studied joint network/channel decoding for multi-source multi-relay heterogeneous wireless networks. We have shown that, when convolutional and network codes are used at the physical and network layers, respectively, the error correction and diversity properties of the whole network can be characterized by an equivalent and distributed convolutional network/channel code. In particular, we have proved that, by properly choosing the network code, the equivalent code can show UEP properties, similar to network-coded systems without channel codes. Using this representation, we have shown that ML joint network/channel decoding can be performed by using the trellis representation of the distributed convolutional network/channel code. Furthermore, to deal with decoding errors at the relays, an ML-optimum receiver which exploits side information on the source-to-relay links has been proposed. Finally, the impact of perfect and imperfect availability of Channel State Information (CSI) has been investigated, and, as shown in Fig. 3, the crucial role played by the CSI on the source-to-relay links to achieve the best diversity gain has been shown.

3 International Collaborations

The research activities of JNCD4CoopNets were also part of some national and international collaborations:

- Collaboration with Xuan-Thang Vu (L2S, France) and Pierre Duhamel (L2S, France) on joint network/channel decoding. Xuan-Thang Vu is a Ph.D. student of L2S co-supervised by Marco Di Renzo. Part of this research collaboration is conducted within the activities of the NEWCOM++ European Network of Excellence.
- Collaboration with Michela Iezzi (Univ. of L'Aquila, Italy) and Fabio Graziosi (Univ. of L'Aquila, Italy) on network code design for cooperative networks. Michela Iezzi is a Ph.D. student of the Univ. of

L'Aquila co-supervised by Marco Di Renzo. She visited L2S during the period April/July 2010 and March/June 2011. She received two Italian grants for these visits.

- Collaboration with Cristina Merola (Univ. of L'Aquila, Italy) and Fortunato Santucci (Univ. of L'Aquila, Italy) on performance analysis of network-coded cooperative networks with network interference. Cristina Merola was a Master student of the Univ. of L'Aquila co-supervised by Marco Di Renzo. She visited L2S during the period February/June 2011 under the ERASMUS Placement program.
- Collaboration with Christos Verikoukis (Telecommunications Technological Center of Catalonia, Spain) and Luis Alonso (Polytechnic Univ. of Catalonia, Spain) on cross-layer design of cooperative wireless networks including physical, medium-access control, and routing/network-coding layers. This collaboration is conducted within the research activities of the European ITN project GREENET.

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