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On bridging theory and practice of inter-session network coding for CSMA/CA based wireless multi-hop networks

Achuthan Paramanathan *, Simon Thorsteinsson, Daniel E. Lucani, Frank H.P. Fitzek

Department of Electronic Systems, Aalborg University, Denmark

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ABSTRACT

Inter-session network coding is well known for its ability to spectral efficiency and end-to-end throughput in wireless multi-hop networks by up to four fold on some scenarios compared to standard routing. However, a variety of inter-session network coding implementations have consistently shown a decrease in throughput when operating at high traffic loads and significantly below the values expected theoretically. While still being superior to forwarding, this discrepancy between past analytical studies and real measurement results requires further understanding to realize inter-session network coding's full potential in practice. This paper presents mathematical analysis for two of the key sources for this discrepancy, namely, long- and short-term channel asymmetries. We use this knowledge to develop, yet effective algorithm to cope with these asymmetries and bolster network coding's performance in real systems. Our algorithm and other alternative algorithms have been implemented in a hardware platform that uses a CSMA/CA based medium access control (MAC) protocol. Performance evaluation is carried out via an extensive measurement campaign with node deployments in different testing environments, channel conditions, and active devices in the network with the equivalent to more than a month of continuous testing. Based on the measurement results, we demonstrate that our algorithm is capable of closing the gap to theoretically expected results despite being influenced by real world channel conditions while maintaining fairness to other network devices at the MAC level.

1. Introduction

Devices with wireless communication capabilities are able to form large and complex wireless multi-hop, mesh networks. The key feature of these networks lies in the fact that nodes aid each other in passing data packets from the source to its intended destinations. This contrasts with infrastructure-based networks, where each node is directly connected to the infrastructure via a single wireless hop. Although mesh networks have been studied for several decades, the inherent throughput limitations and scalability issues [1–4] of it call for solutions that can increase the spectral efficiency and end-to-end throughput. In recent years, network coding (NC) has been shown to be a key enabler to deliver higher throughput and reliability to mesh networks. Although it cannot directly improve the scalability issues, it has been shown to increase throughput by several fold [5]. NC was first introduced by [6] as a way to achieve multicast capacity in wireline networks. The fundamental idea behind NC lies in the mixing (coding) of data packets belonging to either the same flow (intra-session), or different flows, (inter-session) in the network, i.e., the coding is not limited to end devices. Coding at intermediate

* Corresponding author. Tel.: +45 9940 8733.
E-mail addresses: ap@es.aau.dk (A. Paramanathan), sthors10@student.aau.dk (S. Thorsteinsson), del@es.aau.dk (D.E. Lucani), ff@es.aau.dk (F.H.P. Fitzek).

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nodes (recoding) is carried out using algebraic operations on a given finite field. In the case of intra-session NC, the destinations focus on gathering enough coded packets to decode the original data. For inter-session NC, the general problem of multiple unicast/multicast sessions is more complex. In fact [7] showed that linear operations are insufficient to solve the general problem.

For this reason, inter-session NC is typically realized using simpler approaches based on local optimizations. Current approaches follow a similar strategy. First, determine simple topologies within the network that can provide coding opportunities. Second, identify coding regions, where paths of two transmission sessions overlap in the mesh network. Third, combine (code) packets of the flows intersecting at a relay in the region and broadcast the combined (coded) packet to the nodes in the coding region. Thus, a single transmission will allow more than one node in the coding region to gain a useful packet after decoding locally. Finally, the outgoing flows from the region do not contain combinations of flows, i.e., each outgoing packet is a packet from its original flow.

Exploiting this idea [5] introduced a simple IEEE 802.11-based protocol, named COPE, that uses inter-session NC. Using real-life implementation and measurements. COPE demonstrated that a 3*x* to 4*x* gain in the throughput of UDP data flows over traditional routing is possible. More recently, CATWOMAN [8] was proposed as an alternative to COPE in order to run on commercial devices and exploiting an existing mesh network protocol, i.e., BATMAN. As of today, CATWOMAN is available in the Linux Kernel [9].

Although the problem has been studied using simulations and real-life implementation on different systems based on CSMA/CA, e.g., [8,10–13], there is a common trend in all these results. Namely, the system throughput decreases in high load scenarios, i.e., when network operates in channel congestion for the two-way relay topology, as shown in Fig. 1, and more marked for other scenarios, e.g., cross topology. The degradation for the two-way relay channel as well as the magnitude of the degradation for

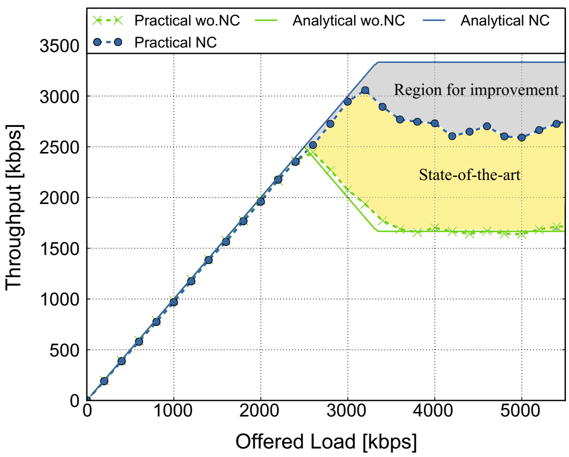

Fig. 1. Discrepancy between analytical results, based on [8], and practical results from [14]. Here, we clearly see the difference when using inter-session NC while there is a perfect match for the pure forwarding.

other topologies at high load was not predicted by the analysis of Zhao and Medard [14] and effectively reduces the impact of inter-session NC. As showed in our preliminary work in [11], part of the issue is that asymmetries in channel conditions can have an impact in the fairness of CSMA/CA. This can directly influence the gain from coding in the system. Our goal is then to characterize these issues and provide simple, implementable solutions for improving the gains in real systems.

In this paper, we propose new analytical and implementation strategies that are capable of providing a stable channel throughput for high load scenarios by controlling the channel access priority of the nodes within a coding region. Our aim is to increase the coding opportunities in the system with simple, efficient mechanisms as well as to increase and stabilize the throughput in high-load scenarios while maintaining a fair allocation to other sessions in the network. Our contributions are as follows.

1. **Mathematical analysis:** To characterize the effect of asymmetric channel conditions on a CSMA/CA based MAC protocol and its consequences in coding gain and system throughput for inter-session NC. We also show that the reduction in coding gain is influenced by short-term and long-term effects.
2. **Design of simple, effective algorithms:** Inspired by the mathematical analysis. These algorithms provide a stable throughput performance for high load scenarios under asymmetric channel conditions for CSMA/CA. The proposed solution combines buffer management, to cope with short-term asymmetries, and priority adaptation in the MAC, to cope with long-term asymmetries. Comparison algorithms are also proposed to understand where and how much gain is possible from pure buffer management and pure priority adaptation.
3. **Implementation and validation via extensive measurement campaigns:** The proposed solutions are implemented in a hardware platform. Our measurement campaign includes deployments in different channel conditions due to node placements and different testing environments as well as considering the effect of other active devices in the network. The latter allow us to show that the proposed solution can provide increased throughput without unfairly reducing performance of other active devices in the network. Our results contain data information equivalent to more than a month of continuous measurement.

2. System model

Our system analysis and designs focus on mesh networks that look for occurrences of the two-way relaying topology to define coding regions. The two-way relay topology considers three nodes *A*, *B*, and a relay node (*R*) (Fig. 2), which are part of the path of two unicast sessions but in opposite directions. Thus, *A* and *B* intend to exchange data packets with the help of *R*. Unless stated otherwise, we consider that both *A* and *B* are inducing/injecting symmetric data packets into the network. Node *R* does not generate data packets and is only responsible for relaying packets belonging to *A* and *B*. This relaying process can be done