Computer Networks 60 (2014) 101–114

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Practical throughput analysis for two-hop wireless network coding

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ARTICLE INFO

Article history:
Received 4 March 2013
Received in revised form 23 September 2013
Accepted 19 December 2013
Available online 27 December 2013

Keywords:
Network coding
Two-hop wireless networks
Cross-layer analysis
Throughput improvement

ABSTRACT

Network coding (NC) has been regarded as a promising technology for throughput improvement in wireless networks, so a thorough understanding on the possible throughput gain from using NC is essential for the application of such technology. Available studies of throughput gain from NC, which mainly focus on only coding sub-layer or both MAC layer and coding sub-layer but largely neglect the primary impact of physical-layer, may lead to an inaccurate (or even qualitatively incorrect) estimation of possible coding gain. To have a more thorough understanding on the practical throughput gain of NC, this paper explores the possible coding gain in the typical two-hop wireless relay network with a careful consideration of interactions among physical layer, MAC layer and coding sub-layer. We first develop an embedded Markov chain theoretical framework to capture the complicated interactions among physical layer, MAC layer and coding sub-layer, based on which the close-form expression of throughput is then derived. We further explore the optimal bandwidth allocation problem in relay nodes for throughput maximization, and also provide a coding condition to clarify the scenarios where network coding does improve the throughput. Our analysis indicates that network coding may actually degrade throughput under some scenarios that were misjudged as being beneficial by previous studies without a careful consideration of primary impact of physical-layer.

1. Introduction

Multihop wireless networks have been a class of attractive networks with many promising applications like wireless sensor networks, wireless mesh networks, wireless ad hoc networks, etc. In such networks, there is no network infrastructure or centralized administration, and each mobile node operates not only as a host but also as a router, forwarding packets for other nodes. One main challenge for the applications of multihop wireless networks is that they suffer from a severe throughput limitation and do not scale well as the number of network nodes increases [1–3].

Network coding (NC) technique [4], which allows network nodes to perform the coding operation in addition to the traditional routing function, has been proved promising for significantly improving the throughput of wireless networks. The NC was originally proposed to reduce bandwidth consumption and increase the throughput of the multicast session [4], and later was shown to be able to offer benefits for other connection cases as well [5–9]. Some recent studies indicate that network coding can significantly improve network throughput in multihop wireless networks, in particular for unicast traffic, which accounts for a large percentage of the total traffic in such networks.

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http://dx.doi.org/10.1016/j.bjp.2013.12.017

To understand the potential throughput benefits of using NC, two important questions that need to be answered are: under what scenarios NC can improve the throughput and how much throughput improvement we may have under these scenarios. The approaches for answering above questions can be roughly classified as two main categories: experimental studies [10,11] and theoretical analysis [12–22]. Regarding the experimental studies of NC, one typical and practically implemented system is COPE [10], a network coding-based packet forwarding architecture to improve the network throughput for multihop wireless networks. The COPE experimentally implemented an XOR-based network coding sub-layer between IP and MAC layers to evaluate the throughput enhancement from network coding, and the corresponding experimental results there indicate that network coding is able to significantly improve the networks throughput, especially when the network are congested with excessive traffic. For the theoretical analysis of NC-based throughput improvement, the available works mainly focus on the pure coding gain [12,13] or the coding + MAC gain in the typical two-hop wireless relay network [16,17,20–22], where only coding sub-layer or both MAC layer and coding sub-layer are considered in the analysis.

Although experimental studies can reveal the practical coding gain under some specified test scenarios, they cannot provide a full and systematic evaluation for all different scenarios. The available theoretical analysis, on the other hand, systematically evaluated the coding gain but largely neglected the primary impact of physical layer parameters (like packet length, bit-rate of channel, etc.). It is notable that the operation way of physical layer significantly affects the network throughput [23]. If the influence of physical layer on network coding is omitted, the analyzed throughput may be much inaccuracy due to the following reasons. First, the coding packets of different flows are simply treated to be with the same length and then the throughput gain of encoding K packets to deliver via a single transmission is inaccurately considered to be K folds. In fact, encoding a small packet with a large packet only provides a limited bandwidth saving as the encoded packet has the same size as the largest one of native packets [10]. Second, the links from relay node to destination nodes are simply treated to be with the same physical-layer transmission rate and then the throughput gain of delivering an encoded packet involving K native packets is inaccurately considered to be K folds. Actually, encoding a packet having a high transmission rate with a packet having a low transmission rate only provides a limited bandwidth saving as the encoded packet must be transmitted with the low transmission rate [25]. So neglecting the impact of physical layer parameters in throughput analysis may lead to a rather inaccurate estimate of throughput gain achieved by using NC. Actually, it may happen that under some scenarios using network coding will even degrade the throughput as compared to the non-coding case, while such scenarios will be misjudged as beneficial when the impact of physical layer is neglected in throughput analysis.

As a step toward to a more practical throughput analysis of general NC-based wireless networks, this paper explores the throughput gain from using NC in the typical two-hop wireless relay network with a careful consideration of interactions among physical layer, MAC layer and coding sub-layer. It is notable that the two-hop wireless relay network, although simple, serves as the basic unit (structure) of creating coding opportunities in general multihop wireless networks [10,13,16,17,22]. Thus, the study on two-hop wireless relay network provides important insights on the throughput gain from using network coding and also lays the foundation for further practical analysis of general NC-based multihop wireless networks.

In [26], we have made a preliminary attempt to investigate the throughput with the consideration of physical layer. In this old work, a simple scenario is considered where relay node has the same probability of obtaining transmission opportunities as the source nodes. Additionally, the used analysis model simply treats the dynamics of different queues' lengths as independent and approximately analyzes the throughput. The work in this article differs from (or improves) the above work in two dimensions. First, the considered scenario is more general. The relay node has "k-priority" to access the medium over source nodes. When $k = 1$, the considered scenario reduces to the scenario considered in [7]. Second, the Markov chain model proposed in this new work accurately reflects the dependence between the dynamics of different queues' lengths, and thus helps us accurately obtain the throughput.

The main contributions of this paper are summarized as follows:

(1) A general theoretical framework based on the embedded Markov chain is proposed to capture the interactions among physical layer, MAC layer and coding sub-layer in a two-hop wireless relay network.
(2) Based on the theoretical framework, the close-form expressions of throughput are then derived under both the non-network-coding scheme and the network-coding scheme.
(3) The optimal bandwidth allocation problem of the relay node is further explored for throughput maximization, and a coding condition is also provided to clarify the scenarios where network coding does improve the throughput.

The rest of this paper is organized as follows. Section 2 introduces two-hop relay networks and also the coding scheme considered in this paper. In Sections 3 and 4, we conduct the throughput analysis for both the non-network-coding scheme and network-coding scheme, respectively. Section 5 provides numerical results and discussions. Finally, Section 6 concludes this paper.

2. System model

In this section we first introduce the typical two-hop wireless relay network, and then define the non-network-coding and network-coding schemes adopted in