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Effect of network-coding overhead on end-to-end throughput for multihop wireless networks

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ABSTRACT

Network coding is expected to improve throughput performance of multihop wireless networks. However, the end-to-end throughput is significantly affected by the coding overhead. This paper considers the impact of the coding overhead on throughput performance for multihop wireless networks. Focusing on a three-node chain topology, we model an intermediate node as a single-server queueing system with two buffers. We construct a discrete-time Markov chain on the epochs where one of nodes starts a packet transmission, analyzing the per-flow throughput. The analysis is validated by simulation. Numerical examples show that a long processing time for coding significantly degrades the per-flow throughput.

1. Introduction

Network coding was originally proposed to increase the capacity of one-to-many communication like multicast communication [1]. Recently, it is also expected that network coding can improve the capacity of multihop wireless networks in which a wireless node encodes several input packets into one or multiple packets and broadcasts encoded packets to neighboring nodes.

In this paper, we consider the XOR (eXclusive OR) operation for network coding [2]. In this network coding, two different packets are encoded into one packet by the XOR operation. In the following, a packet which is not encoded is called an original packet, while a packet generated from two packets by XOR is referred to as an encoded packet. A typical scenario for improving the network capacity is as follows.

Consider the three-node chain-topology consisting of two terminal nodes A and B, and an intermediate relay node R. The relay node R encodes two original packets, say X and Y, into one packet by XOR. The relay node R broadcasts the encoded packet to its neighboring nodes A and B. Because Node A (resp. B) has packet X (resp. Y), Node A (resp. B) can retrieve packet Y (resp. X) by XOR of the encoded packet and packet X (resp. Y). This results in the reduction of the number of packet transmissions. It is also reported in [3,4] that the network capacity of wireless communication networks can be significantly improved by an opportunistic listening environment.

Recently, an advanced physical-layer network coding scheme called analog network coding has been proposed in [5,6]. Currently, however, it is expected that network coding is realized as a network-layer service. Therefore, the throughput performance over multihop wireless networks is significantly affected by the encoding time of intermediate wireless nodes.

In this paper, we analyze the end-to-end throughput in an IEEE 802.11-based multihop wireless network with network coding. Focusing on a three-node chain topology, we consider the case in which two end hosts transmit packets to each other via an intermediate relay node. The relay node has two buffers, managing two packet flows separately. If there exist

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packets in both buffers at transmission, the relay node encodes a pair of packets into one packet and then broadcast it. If one of the buffers has a packet to send but the other has no packet, the relay node send the packet without encoding.

We model the relay node as a single-server queueing system with two finite buffers, in which the packet-transmission time depends on the system state just before transmission. We assume that the packet transmission time with coding, that without coding, and the inactive period caused by the backoff algorithm are independent and generally distributed. Hence the analytical model is the extension of our previous work [7] in which those times are assumed to follow exponential distributions. We construct a discrete-time Markov chain on the epochs where one of nodes starts a packet transmission, analyzing the per-flow throughput. In numerical examples, we validate the analytical model by simulation. The throughput performance of the system with network coding is also compared to that of the system without network coding.

The rest of this paper is organized as follows: Section 2 gives an overview of related work, and Section 3 represents the analytical model. Section 4 shows the analysis of the queueing model, and numerical examples are presented in Section 5. Finally, we conclude the paper in Section 6.

2. Related work

In terms of the analysis of throughput performance for network coding, Ma et al. [8] considered the synchronization process of two Poisson input flows. They showed that the inter-departure time of the output packet-pair process is asymptotically distributed with an exponential distribution. With this result, the delay performance of the encoding process was analyzed with an M/M/1 queueing model.

In [9], the performance of network coding in multihop wireless networks with a chain topology was investigated from the point of rate stability, with which the queue length of each node never grows to infinity. The authors studied the throughput region for saturated queues and stability region for possibly emptying queues, evaluating the trade-offs among achievable throughput and processing energy costs.

In [4], the authors considered the encoding number, which is the number of packets that can be encoded by a relay node in a transmission. They derived the upper bound on the encoding number for general topology cases in which opportunistic listening is taken into consideration. The average coding number was also derived for random access link scheduling, and some case studies including saturation throughput and bandwidth allocation were considered by applying the mean coding number. The authors also proposed a distributed coding-aware routing (DCAR) scheme in [10], with which available paths and potential coding opportunities can be discovered.

The above three studies provide conceptual framework for analyzing the performance of network coding in multihop wireless networks, and the details of the medium access control (MAC) protocol in IEEE 802.11 is not taken into consideration.

Umehara et al. considered the throughput performance of network coding for a slotted ALOHA system in a three-node chain topology [11]. The system was modeled as a single-server queueing system with two distinct buffers. They analyzed the throughput, number of packet transmissions, and the transmission delay, showing that the network coding in the slotted ALOHA system can highly improve the throughput. Currently, IEEE 802.11 is the most prevalent wireless LAN standard [12]. Therefore, it is important to evaluate the throughput performance of network coding over IEEE 802.11-based wireless networks. As far as the authors know, the throughput performance in IEEE 802.11-based multihop wireless networks with network coding has not been fully investigated yet.

3. Analytical model

We consider a tandem network with three nodes, A, B and R (Fig. 1). We assume that Nodes A and B are out of the transmission range but within the sensing range of each other.[1] We also assume that each two neighboring nodes in the tandem network are within the transmission range. Therefore Node A (resp. B) transmits a packet to Node B (resp. A) via the relay node, i.e., Node R. The packet flow from Node A to Node B is called Flow 1, and the backward flow is called Flow 2 (Fig. 1).

In what follows, we consider two analytical models: network coding (NC) model and non-NC model. In NC model, the relay node performs network coding if it has packets of both Flows 1 and 2. On the other hand, non-NC model is based on the existing IEEE 802.11 MAC protocol. In non-NC model, the relay node sends packets on a packet-by-packet basis.

3.1. NC model

We make the following assumptions for the three-node tandem network (Fig. 2).

(a) At each time instant, at most a single node transmits a packet.
(b) The transmission times with (resp. without) network coding follow a distribution function $H_1(x)$ (resp. $H_2(x)$) ($x \geq 0$) with finite mean b_1 (resp. b_2).

[1] The sensing range is the range within which carrier sense detection is functioned by a sender node. This range is determined by the antenna sensitivity. On the other hand, the transmission range is the range within which a packet is successfully received by a receiver node if there is no interference from other radios. The transmission range is affected by transmission power and radio propagation properties such as attenuation. For details, the readers are referred to [13].