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Flow-oriented network coding architecture for multihop wireless networks

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ABSTRACT

Recently, a network coding-based packet forwarding architecture COPE was proposed for multihop wireless networks to improve the throughput. Both simulation and testbed results verified COPE's capability of enhancing throughput. However, COPE simply classifies all packets destined to the same nexthop into small-size or large-size virtual queues and then, to limit packet reordering, examines only the head packet of each queue to find coding solutions. Theoretically all the packets of distinct flows have the potential to be encoded together for throughput improvement, but the above packet size-oriented queue structure significantly limits this potential coding opportunity, since only one packet of a given size will be examined in the coding process. In this paper, we apply the standard flow-oriented queueing to network-coding-capable multihop wireless networks, which maintains a dedicated virtual queue for each flow and regards the head packets as coding candidates. Such flow-based architecture completely eliminates packet mis-order problem, and our theoretical analysis shows that in comparison with the simple size-based queuing, the new architecture is able to dramatically increase the potential coding opportunities. We further study the optimal network coding problem of the flow-oriented architecture. The COPE's simple coding algorithm is not effective enough since it does not consider several other key issues like the packet size gaps among the packets to be encoded, packet loss rates and decoding probabilities. Therefore, we develop a corresponding efficient algorithm for searching good coding solutions. Our extensive simulation results demonstrated that COPE can improve the node transmission efficiency, but the flow-oriented architecture with proposed coding algorithm can make this improvement much more significant.

1. Introduction

Multihop wireless networks have been an active area of research for many years. In such type of 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 mobile nodes. Promising applications of such type of networks include wireless sensor networks, wireless mesh networks, etc. One of the most significant problems of multihop wireless networks is that their current implementations suffer from a severe throughput limitation and do not scale well as the number of network nodes increases [2,3].

Network coding is a promising technique to improve the throughput of wireless networks. It was originally proposed to reduce bandwidth consumption and increase the throughput of the multicast session [4,5], and later was shown to be able to offer benefits also for other connection cases [8,9,7,6,10,11]. However, most prior work on network coding is theoretical and few practical

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implementations have been reported [11,12,1,14]. Recently, Katti et al. proposed the first practical network coding-based packet forwarding architecture (called COPE) to improve the network throughput for multihop wireless networks [1].

In the COPE architecture, each node simply classifies all packets destined to the same nexthop into small-size or large-size virtual queues and then, to limit packet reordering, examines only the head packet of each queue to find coding solutions. Such a virtual queue structure is quite simple and introduces limited packet reordering, which happens when the arrival order of packets of a flow is different from their departure (transmission) order. We define a flow as a stream of packets that have the same source/destination addresses and source/destination UDP/TCP port numbers. It is notable that theoretically all the packets of distinct flows have the potential to be encoded with the head packet of FIFO queue for throughput improvement. However, the above packet-size-oriented virtual queue structure significantly limits this potential coding opportunity,[1] since among packets destined to the same neighbor at most two packets (the head packets of small-size and large-size queues) will be examined in the coding process, regardless of the number of flows. To fully explore the potential coding opportunities and also do not introduce any packet reordering, in this paper we apply the standard flow-oriented queueing structure to network-coding-capable multihop wireless networks, where a dedicated virtual queue is maintained for each flow and all head packets of virtual queues are regarded as candidates for encoding with the head packet of FIFO queue. Since this new virtual queue structure ensures that one packet from each flow is considered in the coding process, the potential coding opportunities will be dramatically increased. Moreover, since among all packets of one flow only the oldest packet[2] is the candidate for coding, no any packet reordering will be introduced. It should be noticed that, same as COPE, we also aim at the immediate decodability guarantee (i.e., the intended receivers of one coded packet are able to immediately retrieve one native packet once they successfully receive the coded packet). For the flow-oriented virtual queue structure, we further study the optimal coding problem (i.e., finding the optimal coding solution for the case of using linear network coding with the immediate decodability guarantee). It is important to notice that the COPE's simple coding algorithm can still be applied to find coding solutions of this problem. However, this coding algorithm is not effective enough to find very good coding solutions due to several limitations. For example, it does not take into account the packet loss issue at the coding packet's intended receivers. Also, it does not explicitly consider packet size differences between the packets to be encoded. Therefore, we develop here a new and efficient coding algorithm for this coding problem.

A similar flow-oriented queueing architecture was recently proposed in [32]. In this architecture, any two flows that can perform two-packet coding will be first bound together as a two-flow group, and the future coding operations will be restricted only within each group. Per-flow queueing is provided for these grouped flows. Although the Biermann's scheme is similar to ours in the sense that both adopt the idea of per-flow queueing, they have two main differences. First, our coding scheme allocates a dedicated queue for each flow, whereas Biermann's scheme provides per-flow queueing only for these grouped flows (all the other ungrouped flows share one common queue); Second, in our coding scheme the coding operations are performed across all flows, whereas in Biermann's scheme the coding operations are restricted only within each two-flow group.

In summary, the main contributions of this work are as follows:

1. We apply the flow-oriented virtual queue structure to network-coding-capable multihop wireless networks, and also provide a theoretical analysis to show that this new structure offers much more coding opportunities.
2. We formulate the corresponding optimal coding problem as an optimization problem and prove its NP-completeness.
3. We present an efficient coding algorithm for finding good coding solutions.
4. We demonstrate that although the available COPE architecture can essentially improve the node throughput, this improvement can be much more significant if our proposed flow-oriented coding architecture is adopted.

The rest of this paper is organized as follows. First, Section 2 surveys related work. In Section 3, we briefly review the available COPE architecture and discuss its limitations. Section 4 introduces the flow-oriented virtual queue structure. In Section 5, we provide the formulation of the optimal coding problem, prove its NP-completeness, and then propose an efficient coding algorithm. Numerical results are presented in Section 6. Finally, Section 7 concludes this paper.

2. Related work

There is a huge body of literature on wireless network coding. Though many applications have been proposed, such as reliable data dissemination over wireless ad hoc networks [13], these results have been mostly confined to simulation.

A notable exception is COPE [1], which examines throughput gain from network coding in wireless mesh networks. The importance of opportunistic listening to realize capacity gain is further discussed in [14]. Based on the COPE-type XOR coding scheme, coding-aware routing was proposed in Sengupta et al. [15]. Some efforts have also been made to theoretically evaluate the throughput of COPE-type wireless networks. Sengupta et al. [15] presented a theoretical framework for computing the maximal

[1] By coding opportunity we mean that two or more packets can be encoded together and each nexthop of this encoded packet can decode its native packet with probability larger than a given value.

[2] Inside a node, the oldest packet of a flow is the firstly arrived packet among all the stored packets of this flow.