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Network coding-based reliable multicast in wireless networks

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ABSTRACT

Reliable multicast, the lossless dissemination of data from one sender to a group of receivers, has a wide range of important applications. Recently, network coding has been applied to the reliable multicast in wireless networks, where multiple lost packets with distinct intended receivers are XOR-ed together as one packet and forwarded via single retransmission, resulting in a significant reduction of bandwidth consumption. However, the simple XOR operation cannot fully exploit the potential coding opportunities and finding the optimal set of lost packets for XOR-ing is a complex NP-complete optimization problem. In this work, we intend to move beyond the simple XOR to more general coding operations. Specifically, we propose two new schemes (a static scheme which repeatedly retransmits one coding packet until all intended receivers receive it and a dynamic scheme which updates the coding packet once one or more receivers receive it) to encode packets with more general coding operations, which not only can encode lost packets with common intended receivers together to fully exploit the potential coding opportunities but also have polynomial-time complexity. We demonstrate, through both analytical and simulation results, that the proposed schemes can more greatly reduce the bandwidth requirement than the available coding-based schemes, especially in the case of high packet loss probabilities and a larger number of receivers. This reduction can vary from a few percents to over 15% depending on the packet loss probabilities and the number of receivers.

1. Introduction

Bandwidth has been one of the most precious resources in wireless networks. The *network coding* technique [1], which allows network nodes to perform coding operation in addition to the traditional routing function, has been proved promising for significantly reducing the bandwidth and energy consumptions in wireless networks.

By now, considerable efforts have been devoted to demonstrate the benefits of using network coding for different communication paradigms, such as unicast [6,2–5,7–12,14], multicast [15–17] and broadcast [18–20]. For the unicast scenario, Wu et al. [2] showed that the exchange of independent information between two nodes in a wireless network can be efficiently performed by exploiting both network coding and physical-layer broadcast. Li et al. [3,4] studied the cases of multiple unicast sessions, where network coding can only provide marginal benefits. Recently, Katti et al. [5] proposed a practical network coding-based packet forwarding architecture (called COPE) to essentially improve the network throughput of multihop wireless networks. Based on the COPE-type XOR coding scheme, coding-aware routing was proposed in Sengupta et al. [9] and [12]. Some efforts (e.g., [10,9,11]) have also been made to theoretically evaluate the throughput of COPE-type wireless networks, and Rouayheb et al. studied more general and complex coding operations rather than XOR under the name of "index coding" [13]. More recently, the physical-layer network coding was proposed to utilize wireless interference for network coding [14,7]. As for the

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multicast case, Wu et al. [15] showed that in a mobile ad hoc network, adopting network coding for minimum-cost multicast can be formulated as a linear optimization problem and solved in polynomial time. The corresponding decentralized algorithms were further proposed in Lun et al. [16] to establish the minimum-cost multicast tree. The theoretical throughput analysis of multicast with network coding has also been conducted in Park et al. [17] for unreliable ad hoc networks. Concerning the application of network coding for broadcast in wireless ad hoc networks, distributed probabilistic broadcast algorithms and deterministic broadcast algorithms have been proposed by Fragouli et al. [18,19] and Li et al. [20], respectively, resulting in a significant energy saving.

Reliable multicast [22,21], the lossless delivery of bulk data from one sender to a group of receivers, is widely used in many important applications such as the file distribution to a number of receivers and the dissemination of market data from a financial institution to its subscribers. Reliable multicast generally does not allow data loss, but can tolerate delay due to retransmissions. Traditionally, to ensure the reliable link-layer multicast the source simply retransmits one by one the *lost packets* (i.e., the packets that are not received yet by one or more receivers). Recently, Nguyen et al. [23] applied network coding to reliable link-layer multicast in wireless networks and proposed two network coding-based schemes (a static one and a dynamic one) for it. The main idea of these coding-based reliable multicast schemes is to first buffer the lost packets in the *lost-packet buffer* for some time, then, instead of transmitting these lost packets one by one, the source XORs an optimal set of lost packets with distinct intended receivers together into one packet and transmits this XOR-ed packet in one retransmission.[1] For example, suppose that a source node needs to send packets P_1, P_2 and P_3 to R_1 and R_2. The source node will first locally broadcast packets P_1, P_2 and P_3 one by one to receivers R_1 and R_2. We further suppose that R_1 successfully received P_1 and P_3, and R_2 successfully received P_1 and P_2. Since the lost packet P_2's intended receiver is R_1 and lost packet P_3's intended receiver is R_2, they have different intended receivers. Then source node will retransmit $P_2 \oplus P_3$ rather than retransmitting P_2 and P_3 separately. Upon receiving $P_2 \oplus P_3, R_1$ will XOR this coding packet with its possessed packet P_3 and consequently recover P_2. Similarly, R_2 can recover P_3 by XOR-ing the received coding packet with some of its possessed packets. The main difference between the static and dynamic schemes in Ref. [23] is that the static one will repeatedly retransmit the same XOR-ed packet until all its intended receivers successfully receive it, while the dynamic one can dynamically update the XOR-ed packet in each retransmission for a further improvement in transmission efficiency.

The adopted simple XOR operation has the advantage of encoding and decoding the packets fast, which is suitable for implementation in the networks whose node processing capability is very limited, like sensor networks. However, encoding packets with the XOR operation (over finite field $\mathbb{F}_2$) has two main limitations. First, only the lost packets with distinct intended receivers can be encoded together and thus the potential coding opportunities cannot be fully exploited. Actually, the lost packets with common intended receivers also have the potential to be encoded together by more general coding operations for transmission efficiency improvement. Second, the search for the optimal set of lost packets to XOR is very complex (actually, NP-complete), which significantly limits the scalability of these schemes.

In this paper, we intend to move beyond the simple XOR to more general coding operations, aiming to achieve a larger coding gain in ordinary wireless networks (like cellular networks). For reliable link-layer multicast in wireless networks, we propose two new coding-based schemes to conduct packet coding with more general coding operations rather than XOR, such that the above limitations of the available coding-based schemes can be significantly alleviated. In summary, the main contributions of this work are as follows:

(1) We first examine the limitations of simple XOR coding operation and then extend it to the more general coding operations. To support this extension, we propose two new schemes (also a static one and a dynamic one) to encode packets with the more general coding operations, such that the potential coding opportunities can be fully exploited while a significantly lower time complexity (polynomial time) is achieved.
(2) We provide analytical analysis to evaluate the performance in terms of both transmission efficiency and packet delay for two proposed reliable multicast schemes.
(3) We demonstrate that although the two available coding-based schemes result in a favorable reduction in the bandwidth requirement, the reduction can be more significant when the proposed schemes are applied, especially in the case of high packet loss probabilities and a large number of receivers.

The rest of this paper is organized as follows. Section 2 first introduces the limitations of the XOR coding operation and then presents two new coding-based multicast schemes. In Section 3, we analytically evaluate the transmission bandwidth and delay performance for the two proposed schemes. Numerical results obtained from the analytical model and simulation are presented in Section 4. Finally, Section 5 concludes this paper.

2. Network coding-based multicast schemes

In this section, we first introduce the limitations of the simple XOR coding operation and then present new schemes for reliable link-layer multicast in wireless networks. The new schemes encode packets with the more general coding operations rather than XOR, which not only can encode lost packets with common intended receivers together to fully exploit the potential coding opportunities but also have polynomial-time complexity.

[1] The intended receivers of a packet are the receivers that have not received this packet.