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Cooperative multicast with moving window network coding in wireless networks ☆

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ABSTRACT

Cooperative multicast is an effective solution to address the bottleneck problem of single-hop broadcast in wireless networks. By incorporating with the random linear network coding technique, the existing schemes can reduce the retransmission overhead significantly. However, the receivers may incur large decoding delay and complexity due to the batch decoding scheme. In addition, the dependency on the explicit feedback leads to scalability problem in larger networks. In this paper, a cooperative multicast protocol named MWNCast is proposed based on a novel moving window network coding technique. We develop analytical models and show three properties of the proposed scheme. Firstly, without explicit feedback, the packet recovery loss probability of the receivers drops almost exponentially with the increase of window size. Secondly, the average decoding delay of a receiver is upper bounded by $O\left(\frac{1}{(1-\rho)^2}\right)$ asymptomatically with respect to its traffic intensity ρ. Thirdly, given the target throughput, the decoding complexity of MWNCast scales as $O(W)$ as the window size W increases. Simulation results show that MWNCast outperforms the existing schemes by achieving better tradeoff between the throughput and decoding delay, meanwhile keeping the packet recovery loss probability and decoding complexity at a very low level without explicit feedback.

1. Introduction

Due to the broadcast nature of wireless channels, wireless networks have been deemed as an efficient solution for multicast file delivery, multimedia streaming services, etc. Under perfect channel conditions, multiple clients within the transmission range of a single transmitter node can receive the same piece of data simultaneously without incurring any extra overhead. However, this assumption is invalid in practice since wireless channels are subject to fading due to signal attenuation, shadowing and multipath effects, leading to random failure of packet reception at different clients.

Although packet error can be tolerated to some extents in most multimedia streaming applications, excessive packet losses are unacceptable because it can lead to the degradation of quality of experience (QoE) to the end users. In order to improve the reliability of multicast, many techniques and protocols have been developed. One class of solutions follow the error recovery path that try to tackle the packet loss problem using the automatic repeat

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request (ARQ) or combined with forward error correction (FEC) (e.g., [2,3]), which however lead to feedback storm problem since the source node relies on the feedback from clients to make retransmission decisions. To address this issue, another class of schemes adopt the rateless coding strategy (e.g., [4–6]), whereby the source node keeps transmitting coded symbols without explicit feedback, and any clients can decode the packet after accumulating enough symbols. Although such approaches are able to provide reliable transmissions, they may suffer from the bottleneck problem, that is, the throughput of the overall system is limited by the node with the worst channel capacity.

As a natural solution to the bottleneck problem in multicast, cooperative communications have drawn increasing attentions recently. In [7], integrated with layered video coding and packet level forward error correction, the randomized distributed space time codes are adopted to design cooperative multicast scheme that can provide efficient and robust video delivery. Relay selection has been studied in [8] to improve the performance of cooperative multicast in a mobile computing environment. The outage probability with cooperative multicast is analyzed in [9], which suggests that the performance can be improved with more relay nodes. These schemes demonstrate the effectiveness of physical-layer cooperation in alleviating the bottleneck problem in multicast, but they may incur some difficulties in practical implementation, such as tight time synchronization. Furthermore, the sequential retransmissions of the lost packets to multiple receivers (requested by feedback) can reduce the bandwidth efficiency.

One potential way to address this issue is to utilize network coding techniques whereby the lost packets can be encoded together to reduce the number of retransmissions. For example, [10] shows the benefit of cooperation at the network layer via a simple XOR network coding technique. In [11], the random linear network coding (RLNC) [6] is adopted for multicast applications, and the channel and power allocation in relaying nodes are optimized for maximizing the multicast rate. It is shown in [12] that compared to the physical-layer cooperation, the use of RLNC at the relays can enhance the system throughput. In [13], a RLNC-based opportunistic multicast protocol is proposed which can alleviate the bottleneck problem effectively. However, to avoid throughput degradation, the block size in RLNC has to scale with the number of receivers [14], which in turn leads to large decoding delay and complexity. In addition, the centralized scheduling policies in [10–12] rely on the feedback from the relays and receivers about the packet reception status, which make them difficult to scale to larger network size in practice.

In this paper, a cooperative multicast protocol named MWNCast is proposed based on the moving window network coding (MWNC) technique. By exploiting the residual capacity of relay nodes to serve the bandwidth starving receivers, the proposed scheme can effectively alleviate the bottleneck problem in wireless multicast. Based on the random walk and point process theory, we show three properties of MWNCast. Firstly, without explicit feedback, the packet recovery loss probability of the receivers drops almost exponentially with the increase of window size. Secondly, the average decoding delay experienced by a receiver is upper bounded by the order of $O\left(\frac{1}{(1-\rho)^2}\right)$, where ρ is the traffic intensity of the node. The decoding delay of receivers with diverse channel conditions are fairly balanced. Thirdly, the average decoding complexity scales as $O(W)$ (W is coding window size) for a given target throughput. Together with the first property, this suggests that the increase of the computational complexity for enhancing the reliability is moderate. We provide simulation results to validate the theoretical results, which show that the proposed scheme can not only guarantee the reliable transmission without explicit feedback, but also achieve high throughput with low decoding delay and complexity.

The rest of this paper is organized as follows. In Section 2, the system models assumed in this paper is introduced. We present MWNC in Section 3. In Section 4, an overview of MWNCast is firstly provided, followed by its functional modules in details. In Section 5, we establish the theoretical framework and then prove three key properties of MWNCast. Simulation results are provided in Section 6 and finally we conclude this paper in Section 7.

2. System model

We consider a wireless network consisting of a source node s (or base station interchangeably) and a set of $\mathcal{N}$ receivers. The source node has a stream of packets to be transmitted to all receivers. As discussed in previous section, due to the lossy wireless channel, the capacity of plain broadcast (even with a sophisticated network coding scheme) is limited by the worst receiver. To address this problem, we adopt a cooperative networking structure, whereby a subset $\mathcal{R} \subseteq \mathcal{N}$ of nodes are selected as *relays*, which perform not only the normal receiving function to receive data from the source, but also the *relaying* function that forwards the received data to the remaining subset $\mathcal{E}$ of *end receivers* ($\mathcal{E} = \mathcal{N} \setminus \mathcal{R}$). To simplify the design of protocol, we assume that relay nodes only receive data from the source, while the *end receivers* can receive data from both the source and the relay nodes.

Similar to [11], we assume that there are K orthogonal channels that can be operated by each node.[1] Therefore, in order to avoid co-channel transmission interference between the source and the relay nodes, at most $K-1$ relay nodes are allowed to transmit concurrently with the source. Time is divided into slots, and each node is equipped with one half-duplex radio, so a relay node cannot receive and relay at the same time.

The wireless channel between the nodes are modeled as memoryless erasure channel. For a packet sent by node $i \in \mathcal{R} \bigcup \{s\}$, node $j \in \mathcal{N}$ has probability $c_{i,j}$ to receive it successfully, where $c_{i,j}$ denotes the packet reception probability (PRP) of the link between nodes i and j. Similar to [15], successful packet receptions in different time slots and receivers are considered to be independent. In this paper, we assume the PRPs of all links in the network are stationary and collected by the source node through some online or offline measurements [16,17]. Note that the overhead of

[1] We assume frequency division multiple access (FDMA) in this paper, but it can be easily generalized to time division multiple access (TDMA) too.