Ad Hoc Networks 9 (2011) 164–179

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Performance analysis of slotted ALOHA and network coding for single-relay multi-user wireless networks

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ARTICLE INFO

Article history:
Available online 21 July 2010

Keywords:
Single-relay multi-user wireless networks
Bidirectional data flows
Slotted ALOHA
Network coding
Throughput
Delay
Traffic control

ABSTRACT

Deployment of wireless relay nodes can enhance system capacity, extend wireless service coverage, and reduce energy consumption in wireless networks. Network coding enables us to mix two or more packets into a single coded packet at relay nodes and improve performances in wireless relay networks. In this paper, we succeed in developing analytical models of the throughput and delay on slotted ALOHA (S-ALOHA) and S-ALOHA with network coding (S-ALOHA/NC) for single-relay multi-user wireless networks with bidirectional data flows. The analytical models involve effects of queue saturation and unsaturation at the relay node. The throughput and delay for each user node can be extracted from the total throughput and delay by using the analytical models. One can formulate various optimization problems on traffic control in order to maximize the throughput, minimize the delay, or achieve fairness of the throughput or the delay. In particular, we clarify that the total throughput is enhanced in the S-ALOHA/NC protocol on condition that the transmission probability at the relay node is set at the value on the boundary between queue saturation and unsaturation. Our analysis provides achievable regions in throughput on two directional data flows at the relay node for both the S-ALOHA and S-ALOHA/NC protocols. As a result, we show that the achievable region in throughput can be enhanced by using network coding and traffic control.

1. Introduction

Wireless relay nodes are highly effective use of connecting nodes located in rural areas [1] and expanding wireless service coverage [2]. The system capacity can be enhanced by substituting one long-distance low-quality link for multiple short-distance high-quality links. This paper considers *single-relay multi-user wireless networks* in which two multi-user single-hop networks are linked by a single relay node. *Network coding* allows intermediate nodes in networks to mix two or more received packets into a coded packet and forward it such that destination nodes can decode the original data, not only to replicate and forward received packets. Since the number of packets flowed in networks can be reduced by using network coding, network coding enables us to enhance the system throughput, reduce the energy consumption, and reduce the delay from the departure of a packet for source nodes to the arrival of the packet at destination nodes.

Network coding was originally proposed by Ahlswede et al. and they proved that the maximum achievable information flow of any single-source multicast networks can be achieved by using network coding in networks [3]. Ho et al. proposed random linear network coding for multi-source multicast networks and showed that it could approach to the multicast capacity as the length of code increases [4]. Wireless network coding allows us to send multiple packets to destination nodes in a single transmission because the wireless medium has a broadcasting nature.

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doi:10.1016/j.adhoc.2010.07.005

Katti et al. demonstrated that simple XOR-based network coding can achieve high throughput gains for multiple unicast communications in wireless multi-hop networks, where coding and decoding protocols were implemented in IEEE 802.11 stations as an intermediate layer, *COPE*, between routing layer and medium access control (MAC) layer [5]. COPE is composed of *opportunistic listening* and *opportunistic coding*, and does not require any modifications to routing and higher layers. Hasegawa et al. proposed a scheme jointly applying packet aggregation and XOR-based network coding, which is called bidirectional packet aggregation and coding (BiPAC), for bidirectional voice over IP (VoIP) flows in wireless linear multi-hop networks and demonstrated the increase of supportable VoIP sessions through the implementation to IEEE 802.11 networks [6]. Many nodes in wireless multi-hop networks will employ random access protocols on the MAC layer. Therefore, one should analyze the performance of network coding in wireless multi-hop networks with random access protocols and clarify system parameters that are crucial for maximizing the achievable throughput or minimizing the delay.

Before the pioneering work of network coding, several work has been presented for the analysis of random access protocols in wireless multi-hop networks. Gitman analyzed the capacity of two-hop wireless slotted ALOHA (S-ALOHA) networks for bidirectional data flows, where the frequency channel between the base station and relay stations did not share with that between relay stations and user stations [7]. Tobagi clarified the uplink throughput and delay for two-hop wireless access systems in the cases of S-ALOHA [8] and carrier sense multiple access (CSMA) [9], where the frequency channel from user stations to relay stations shared with that from relay stations to the base station. These results provided some important system parameters to maximize the throughput or minimize the delay. Sagduyu and Ephremides showed the achievable throughput region and throughput optimization in random access mode employing network coding over wireless linear multi-hop networks for several source packet transmission schemes in the case of saturated queues [10]. Le et al. proposed a fundamental coding structure and clarified the encoding number of packets in that structure taking into consideration physical wireless environments [11]. They also showed that the maximum number of coding flows was fewer than one expected because many of wireless transmissions interfered with each other. Argyriou proposed the use of opportunistic acknowledgements (OACKs) for overheard packets which are obtained from opportunistic listening [12]. OACKs help us to provide the available correct coding opportunities and enhance the throughput.

Many studies of random access protocols have an assumption that any wireless nodes always have packets to be transmitted, i.e. their queues are saturated because an efficient and accurate analytical model [13] to evaluate the saturated throughput was proposed for a complicated CSMA with collision avoidance (CSMA/CA) protocol with binary slotted exponential backoff algorithm, which is employed as an MAC protocol in the IEEE 802.11 standard [14]. It is however important to show analytical models on the unsaturated conditions in order to obtain fundamental understandings on behavior of random access protocols and provide reference performances of the throughput and delay according to the offered traffic, like the fundamental studies of S-ALOHA [15] and CSMA [16]. We developed analytical models of the throughput and delay for the S-ALOHA protocol with and without XOR-based network coding for simple single-relay two-user wireless networks with symmetric bidirectional flows [17]. This work was extended to two network models, one-to-one single-relay networks with asymmetric bidirectional flows and one-to-many single-relay networks with the same node traffic, in order to evaluate effects of network asymmetry on throughput and delay [18]. It further was extended to more general single-relay multi-user networks and we clarified the achievable region in throughput for the S-ALOHA protocol with and without network coding [19], which is an extension of the achievable throughput region for one-hop wireless networks with S-ALOHA [20,21]. More recently, we recognize that the analysis of S-ALOHA protocol with and without network coding substantially helps us to provide fundamental understandings on CSMA protocols with and without network coding [22].

The main contributions of this paper are summarized as follows:

- This paper proposes efficient and accurate analytical models of the throughput and delay in the S-ALOHA protocols with and without network coding for general single-relay multi-user networks. One can evaluate the throughput and delay through the proposed analytical models without any computer simulations regardless of whether the queue at the relay node is unsaturated or not. The proposed analytical models provide reference performances of the throughput and delay, which are compared with those obtained from other random access protocols.
- This paper succeeds in dividing the total throughput and delay into two directional throughput and delay, respectively, in S-ALOHA with and without network coding for single-relay multi-user wireless networks. One can formulate various optimization problems on traffic control so as to meet system requirements on two directional throughput and delay. In fact, this paper clarifies achievable regions in two directional throughput with and without network coding. The results show that network coding can enhance the achievable regions in two directional throughput, especially with symmetric network structure.
- This paper provides detailed descriptions of proofs in a number of theorems and lemmas with respect to the throughput and delay with and without network coding for single-relay multi-user wireless networks. These detailed descriptions help us to develop new analytical models for other random access protocols and evaluate effects of wireless link qualities or queue capacity on throughput and delay with and without network coding.

The rest of this paper is organized as follows: Section 2 describes the S-ALOHA protocol and the S-ALOHA with network coding (S-ALOHA/NC) protocol for single-relay