Ad Hoc Networks 16 (2014) 131–141

Contents lists available at ScienceDirect

Ad Hoc Networks

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

Performance evaluation of network coding in IEEE 802.11 wireless ad hoc networks

Kyu-Hwan Lee [a], Sunghyun Cho [b], Jae-Hyun Kim [a,*]

[a] School of Electrical and Computer Engineering, Ajou University, Suwon, Republic of Korea
[b] Department of Computer Science and Engineering, Hanyang University, Ansan, Republic of Korea

ARTICLE INFO

Article history:
Received 9 April 2013
Received in revised form 13 November 2013
Accepted 23 December 2013
Available online 2 January 2014

Keywords:
Network coding
Wireless ad hoc network
Wireless LAN
Performance evaluation

ABSTRACT

We evaluate the practical network coding (NC) gain in a wireless ad hoc networks. First, we introduce how network coding can be applied to IEEE 802.11 ad hoc networks. Next, we find obstructive factors by which the NC gain may decrease as compared with the theoretical NC gain. Finally, through the performance evaluation, we analyze why a performance difference occurs between practical and theoretical NC gains owing to the suggested obstructive factors. According to the simulated results, even though there is some overhead caused by the characteristics of the media access control (MAC) protocol and control signals to apply NC to wireless ad hoc networks, the practical NC gain is almost the same as the theoretical gain in an ideal environment for NC. However, in the NC system with the hidden node problem, the NC gain decreases because of packet collision. In the NC system using a promiscuous mode where packet overhearing is possible, nodes consume more power than the conventional system because of overhearing packets. For instance, when the number of overhearing nodes not related to NC is set to 15, the power reduction rate is -38.04%. Furthermore, under the network conditions inappropriate for NC, such as asymmetric flows and scarce coding structures, the NC gain can be considerably reduced. For example, in 5×5 and 7×7 grid topology networks, the load reduction rate by NC are only 4.12% and 7.01%, respectively. Therefore, research to solve the suggested obstructive factors is necessary to achieve sufficient NC gain in a practical wireless network such as an IEEE 802.11 ad hoc networks.

1. Introduction

Recently, network coding (NC) has attracted a great deal of research interest in wired and wireless network systems since its introduction in the area of information theory [1–6]. Generally, it is known that NC has the potential to yield better throughput and reliability for networks of both unicast and multicast applications. In particular, the number of packets sent by nodes can be reduced in a network where there exist chain and X structures. Furthermore, the NC can reduce the total power consumption in a wireless network, such as an IEEE 802.11 wireless ad hoc network, where the packet transmission power is more dominant than the packet reception power. Therefore, many studies have dealt with NC in wireless systems [7–22]. Fasolo et al. investigated how packets should be combined to obtain high gain in terms of the packet delivery ratio in an IEEE 802.11 system [7]. Li et al. showed that the NC gain is bounded by not only the maximum encoding number but also a sufficient buffer size in the link layer in an IEEE 802.11 system [8]. The COPE of Katti et al. used XOR NC with the broadcast nature of a wireless medium [9]. COPE suggested various coding structures such as chain and X. They showed that XOR NC can increase network throughput. They also mentioned implementation issues such as packet overhearing, packet header structure,

* Corresponding author. Tel.: +82 31 219 2477; fax: +82 31 212 9531.
E-mail addresses: lovejiyoon7@ajou.ac.kr (K.-H. Lee), chopro@hanyang.ac.kr (S. Cho), jkim@ajou.ac.kr (J.-H. Kim).

1570-8705/$ - see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.adhoc.2013.12.010

and the hidden node problem in IEEE 802.11 ad hoc networks. Argyriou proposed a practical approach for improving the efficiency of wireless network coding at the media access control (MAC) layer [10]. In the protocol of Argyriou, each node determines the optimality of coding decisions according to information on opportunistic acknowledgements (OACK). The OACK can also be implemented by simple extensions of the IEEE 802.11 MAC protocol and the distribution control function (DCF) channel access scheme. However, most previous studies have had more theoretical and biased results. Conventional studies did not consider the practical environments, which are as follows.

1. Characteristics of the MAC protocol not considered: By implementing NC, the hidden node problem reoccurs in a IEEE 802.11 ad hoc network.
2. Power consumption of the NC protocol not considered: The amount of consumed energy can be increased by the overhearing packets and control packets for the NC.
3. Network conditions inappropriate for NC not considered: In conditions such as asymmetric flows and scarce coding structures, the NC gain cannot be fully achieved.

Furthermore, they mostly work to create a system for NC without compatibility with legacy systems. Therefore, we compare the practical NC gain with the theoretical one through various aspects of the performance evaluation of NC in wireless ad hoc networks. We also evaluate why the NC gain is decreased in practical wireless networks. Finally, we suggest practical considerations for applying the NC to wireless networks. The rest of this paper is organized as follows. Section 2 reviews other related studies for NC. In Section 3, we show how NC can be applied in a wireless network and suggest technical problems influencing the NC gain. In Section 4, we show the performance analysis according to each technical problem influencing the NC gain. Finally, the conclusion and discussion are provided in Section 5.

2. Related works

NC was first introduced by Ahlswede's paper in 2000 [1]. It shows that the capacity of a multicast network with NC can be increased compared to that employing a traditional routing alone. NC is known to achieve the classical max-flow min-cut bound [1]. The studies in [2,3] theoretically show that linear coding is sufficient to achieve maximum capacity if the finite field size of the coding coefficient set is longer than the theoretical upper bound. Ho et al. have proposed a random linear network coding (RLNC) concept in a multicast network [4]. In a node using RLNC, a linear combination of incoming packets over a finite field with randomly chosen coding coefficients is transmitted to its outgoing links. The study of Ho et al. offers a successful decoding probability at the destination if the finite field size satisfies the given upper bound. Generally, NC used in the link layer is classified into two types: inter- and intra-session NC. Inter-session NC is allowed among packets belonging to possibly different sessions. Many studies have been conducted on inter-session NC [7–13]. In particular, COPE of Katti et al. uses XOR network coding and the broadcast nature of a wireless medium to perform opportunistic listening and coding [9]. Additionally, intra-session network coding is restricted to packets belonging to the same session. Several studies have examined intra-session network coding in a wireless network to increase throughput or offer reliability [14–18,23]. In particular, MORE of Chachulski et al. exploits an opportunistic routing scheme by using RLNC in packet transmission to provide each transmitted packet with unique information. Network coding can be utilized in the physical layer [24,25]. The PNC of Zhang et al. performs network coding in the wireless radio signal level by combining signals that consist of amplitude and phase terms. However, synchronized signal transmission is needed in two senders to perform PNC [24]. In the MIXIT of Katti et al., symbols rather than packets are coded [25]. Most of the previous works may not have been interested in practical considerations such as the characteristics of the MAC protocol, the power consumption by the NC protocol, and network conditions inappropriate for NC. Therefore, in this paper, we show that the NC gain can be decreased by these obstructive factors in a wireless network.

3. Network coding in wireless ad hoc networks

3.1. Operating procedure of NC

In this section, we introduce the operating procedure of the NC protocol. We consider a fixed multi-hop wireless network. An ad hoc on-demand distance vector (AODV) routing protocol in IEEE 802.11s is used [26,27]. For the coding structure, we consider the X topology where N flows are intersected in the crossover node. All of the NC functions are implemented in the NC layer, which lies between the network layer and the link layer. The definitions of some of the terms used in this paper are listed in Table 1. Fig. 1 shows the operating procedure of the NC, and its details are as follows:

1. NC preparation and information gathering: First, in the routing procedure, an NC node set that includes a crossover node, broadcasting nodes, and overhearing nodes is selected. Conditions for the NC node set are that each flow is intersected in the crossover node, and the overhearing node is able to overhear the packets from other broadcasting nodes of coding flows. For example, if N is two, flows 1 and 2 are intersected in the crossover node, node O_1 is able to overhear the packets from node B_2, and node O_2 is able to overhear the packets from node B_1, as shown in Fig. 2. If these conditions are satisfied, the crossover node sends a control packet to all the broadcasting and overhearing nodes. When receiving the control packet from the crossover node, the nodes then perform each role as shown in Table 1.
2. Network coding and data forwarding: Upon receiving packets from the broadcasting nodes, the crossover nodes move the received packets to their coding buffer until all packets of the coding flow arrive. To allow the overhearing node to decode the received packets, the