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Space–time efficient network coding for wireless multi-hop networks

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ABSTRACT

Network coding has been recently proposed as a new promising technique that can potentially improve the performance of a wireless multi-hop network significantly. However, most existing studies in this field perform network coding without considering the interplay between transmission power/rate and network coding gain. In many scenarios, the selection of the transmission power/rate brings big impact on network coding gain and consequently network throughput because they have big impact on both reception/overhearing probability and spatial reuse. Therefore, how to improve network throughput by appropriately exploiting the interplay between transmission power, data rate, and network coding gain via localized network operations has been a crucial issue in a multi-hop wireless network. That is, how to achieve a good trade-off between the space–time network resource usage (represented by level of spatial reuse and transmission time) and the network coding gain? To address this problem, in this paper, we propose a decentralized network coding aware power/rate control mechanism, which can enable each node to adjust its transmission power and data rate such that the space–time resource usage is optimized. Extensive simulation results show that the proposed mechanism yields higher performance in network throughput as compared with existing mechanisms.

1. Introduction

Network coding has been a promising technique for improving the throughput of a wireless multi-hop network, i.e., the average amount of information successfully delivered through the network in unit time. The benefit of localized network coding in wireless networks comes from the inherent broadcast nature of wireless medium. Wireless network coding allows packets received from multiple links to be mixed together at intermediate relay node, which can significantly improve the network throughput. Fig. 1 gives a typical example illustrating how wireless network coding can work to reduce the total number of transmissions over wireless links. In Fig. 1, nodes *A* and *B* want to exchange packets p_1 and p_2 to nodes *C* and *D*, respectively, via a common relay node *R*. After the relay node *R* receives both p_1 and p_2, it can create a new packet by performing "p_1 XOR p_2" and then broadcast it to the air. Upon receipt of the new coded packet, both *C* and *D* can then decode their interested packets by using the packets that they had directly overheard from nodes *A* and *B*, respectively. The number of total transmissions can then be reduced from four to three. However, in reality, the performance gain by wireless network coding largely depends on 1) overhearing of necessary native packets (for decoding purpose) and 2) reception of coded packets at expected recipients, both of which heavily depend on the transmission power/range subject to given carrier sensing threshold. Therefore, the achievable wireless network throughput depends on both network coding gain and link capacity, which are both affected by the transmission power/rate and the level of attainable spatial reuse, i.e., total number of concurrent transmissions allowed in the network.

1.1. Spatial reuse has big impact on network coding gain

In traditional wireless networks, increasing spatial reuse level by allowing more concurrent wireless transmissions at low transmission powers is considered to be helpful for increasing network throughput [1]. Following this philosophy, traditional transmission power control mechanisms typically try to minimize each sender's transmission power while still meeting each receiver's SINR (signal to interference and noise ratio) requirement. However, in a wireless network with network coding, such a greedy way of reducing transmission powers may affect the network coding gain and consequently network throughput. The reason is, in the context of wireless network coding, successful decoding of coded packets requires the recipients to have already overheard necessary native packets needed for the decoding.

In a wireless network, the wireless medium is essentially shared among neighboring nodes. For a network coding enabled wireless network, when the spatial reuse level is excessively high, although more concurrent transmissions could be accommodated, it may also lead to smaller effective transmission range and poor reception quality at some expected overhearing nodes. Thus, smaller transmission range might lead to lower number of packet recipients, and possibly lower potential network coding gain. Bad link quality could lead

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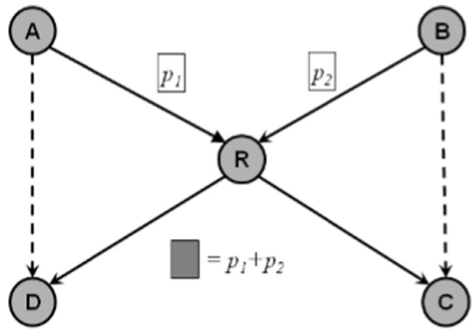

Fig. 1. A typical example illustrating how network coding improves the throughput of a wireless network.

to reception failures at both target receivers and expected overhearing nodes, which also leads to loss of network coding gain. Thus, the broadcast nature of wireless transmission leads to inherent tension between spatial reuse and network coding gain. Therefore, for a wireless network with network coding, the spatial reuse level should be carefully chosen to ensure a high network throughput. This implies that there exists a tradeoff between the level of spatial reuse and the amount of network coding gain.

1.2. Selection of transmission power/rate also has big impact on network coding gain

For a given carrier sensing threshold and transmit rate, there exists a requirement on the lowest SINR for a successful reception [2]. The higher the transmit rate is, the higher the required lowest SINR will be. Suppose a receiver's SINR requirement is given, the sending node can only use the maximal data rate that can still satisfy the receiver's SINR requirement to ensure the correct reception. As the transmission power decreases or the carrier sensing threshold increases, the SINR and consequently the maximal data rate will be decreased as a result. If the SINR at the receiver is below the threshold, then the transmission will fail. Thus, selection of data transmit rate has a big impact on the wireless link quality and also network coding gain. Given a transmission power level, the transmit rate of a node should meet the SINR requirements of all its expected recipients to ensure a high coding gain. For a given transmission power level, use of a higher transmit rate leads to smaller communication range and possibly lower network coding gain, while using a lower transmit rate causes larger communication range and possibly higher network coding gain. Lower transmission data rate also means longer transmission time, which obviously has negative effect on network throughput. Previous work in wireless network coding [3] takes advantage of the broadcast nature of wireless medium and makes use of low transmit rates for increased network coding gain. However, such an approach does not always lead to higher network throughput. Overall network performance improvement is possible as long as we could find the optimal interplay between transmission power/rate, transmission time, and network coding gain. That is, there exists a trade-off among transmission power/rate and network coding gain.

As discussed above, the performance of a wireless network is determined by the interplay of spatial reuse level, transmission power/rate, and network coding gain. These factors and their interplay lead to the following questions: What is the relationship between spatial reuse level and network coding gain? What is the trade-off between transmission power/rate and network throughput? In this paper, we shall answer these questions. Specifically, unlike existing work, we intend to enhance the network throughput of a wireless multi-hop network by jointly selecting the transmission power/rate and network coding pattern (when applicable) at different network nodes while maximizing the space–time resource usage efficiency of the network. The contributions of this paper are summarized as follows.

- First, we design an analytical framework for adaptive transmission power/rate control, which facilitates the optimal selection of the power/rate and coding pattern by considering the space–time efficiency of each transmission. This framework consists of two parts: 1) The power/rate selection for native packet transmission: Each forwarder of such packet selects the power/rate that optimize the space–time usage efficiency and simultaneously ensure the probability of successful overhearing at target recipient nodes to be larger than predefined threshold; 2) The power/rate selection for coded packet transmission: Each forwarder of such packet selects the power/rate to maximize the expected coding gain of each such transmission by taking into account the probability of successful reception of the coded packet at each target recipient.
- Second, based on the above analytical framework, we propose a localized coding aware transmission power/rate adjustment mechanism, referred as CAPA, to achieve high network throughput. In CAPA, the selection of transmission power/rate at each node is determined in a way such that the transmission can obtain the optimized local space–time resource usage, while causing the minimal interference to other concurrent transmissions in the vicinity.
- Third, extensive simulation results demonstrate that our proposed mechanism can improve the performance of wireless multi-hop networks greatly as compared with existing work.

The rest of this paper is structured as follows. In Section 2, we review related work. In Sections 3 and 4, we give the detailed design description of our proposed framework and the proposed localized mechanism CAPA. In Section 5, we present detailed simulation results to evaluate the performance of CAPA by comparing it with existing work. In Section 6, we conclude this paper.

2. Related work

In this section, we briefly review existing work in the following categories: wireless network coding, wireless power/rate control, and network coding related power/rate control.

2.1. Wireless network coding

The concept of network coding was first proposed by Ahlswede et al. [4] and it was originally used for solving the multicast problem in wireline networks [4–11]. Recently, it has been shown that network coding can also provide significant throughput gain in wireless networks for both multicast [9] and unicast communications [3]. In [9], Lun et al. showed that the problem of wireless network coding communications can be formulated using linear programming and solved in a distributed way. Sengupta et al. [10] proposed a linear programming based coding-aware routing scheme by taking the wireless interference and broadcast based transmission scheduling into consideration. Chaporkar and Proutiere [11] proposed an adaptive network coding and scheduling algorithm for symmetric sessions, each of which takes the same routing path but reversed source and destination. COPE [3] is the first practical mechanism that bridges the gap between the theory of network coding and practical wireless network protocol design. However, although COPE and its variants leads to performance improvement in many scenarios, neither COPE nor its variants consider the space–time trade-off in packet transmissions and also the difference of available network coding opportunities at nodes due to use of different power levels. This largely reduces their capabilities for further improving the network throughput performance. Our work in this paper differs from the above existing work in a way such that practical coding-aware power/rate control is used to maximize the network throughput via localized operations.