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Integration of scheduling and network coding in multi-rate wireless mesh networks: Optimization models and algorithms

Zhaolong Ning[a,b,c], Qingyang Song[a,*], Lei Guo[a], Zhikui Chen[b], Abbas Jamalipour[d]

[a] *School of Information Science and Engineering, Northeastern University, Shenyang 110819, China*
[b] *School of Software Technology, Dalian University of Technology, Dalian 116020, China*
[c] *State Key Laboratory for Novel Software Technology, Nanjing University, Nanjing 210093, China*
[d] *School of Electrical and Information Engineering, University of Sydney, NSW 2006, Australia*

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ABSTRACT

In order to fully utilize spectrum resource in wireless mesh networks (WMNs), we propose a combination of some popular communication techniques, including link scheduling, spatial reuse, power and rate adaptation and network coding (NC), to activate as many transmission links as possible during one scheduling period, so that the total scheduling length can be minimized and network throughput can be maximized. Different from previous studies, we consider the interplay among these techniques and present an optimal NC-aware link scheduling mechanism in multi-rate WMNs, which relies on the enumeration of all possible schedules. Due to the high computational complexity of our proposed model, we utilize a column generation (CG)-based method to resolve the optimization problem and decompose it into a master problem (MP) and a pricing problem (PP). Furthermore, we present a distributed power control algorithm for PP, by which the computational complexity of the CG-based scheme can be largely reduced. Simulation results demonstrate the superiority of our method under various network situations.

1. Introduction

Wireless mesh networks (WMNs) are increasingly deployed on the last mile to provide cheap and low-maintenance Internet access, which are infrastructure-based in the form of wireless mesh routers that are not energy constrained. The main design challenge of WMNs is to support a flexible and low-cost extension of the Internet, in particular, to provide high throughput and reliability [1,2]. In order to satisfy the ever-increasing demand of wireless spectrum resource, a number of works have been presented to improve the efficiency of network resource allocation by considering link scheduling, spatial reuse, power and rate adaptation, and network coding (NC).

The authors in [3] demonstrated that designing appropriate scheduling schemes is critical for achieving the throughput gains brought by NC schemes. A practical opportunistic scheduling method for conventional network coding (CNC) was proposed in [4], where a set of nodes are opportunistically selected according to the instantaneous link conditions and link load. In order to minimize the number of transmissions for fulfilling the requirement of each node, the authors in [5] presented backpressure-based NC and scheduling schemes, and compared the network throughput for both digital and analog NC schemes. In [6], the authors proposed an NC-aware proportional fair scheduling scheme in relay-based networks by considering the tradeoff between network performance and overhead.

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[*] Corresponding author. Tel.: +8613804008890.
E-mail address: songqingyang@ise.neu.edu.cn, lilysong76@gmail.com (Q. Song).

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The interaction between NC and transmission rate diversity in multi-hop wireless networks was investigated in [7], and the authors demonstrated that capacity for multicast flow can be maximized by combining rate diversity with NC properly. The authors in [8] and [9] illustrated that although nodes can transmit at high rates for throughput increasement, the high transmission rates reduce the opportunities of overhearing and the NC gain as a result. Therefore, it is necessary to study the interaction between overhearing opportunity and bandwidth utilization. In [10], the authors studied rate adaptation and inter-session NC transmission, and demonstrated that rate adaptation is effective for increasing the NC gain and decreasing congestion at relaying nodes. The authors in [11] proposed a utility function to maximize network capacity for the multi-rate multicasting problem with NC in general multi-hop networks. Due to the high computational complexity of the considered problem, two novel approaches were proposed based on layered multicasting and nested optimization.

Since the input of any component stated above is partially determined by the outputs of the other components, a joint scheduling, power control and NC scheme, by considering spatial reuse and rate adaptation, should be designed to fully utilize the spectrum frequency in WMNs. However, less attention has been paid to the interaction among these techniques. In our work, we take two kinds of interplays into account, namely the interplay between NC and spatial reuse, and the interaction between NC and multi-rate transmission. Our rationales are explained in the following.

Although NC schemes, including CNC and physical-layer network coding (PNC), can deliver traffic with less time than plain routing, they are not always good choices. One reason is that the relaying node in the NC schemes has to broadcast with higher transmission power to ensure the destination node with worse channel state to decode the received packet correctly, which suppresses the concurrent transmissions of neighboring nodes. The other reason is that the greedy NC methods may reduce spectrum spatial reuse, and decrease network throughput as a result. Therefore, the interplay between NC and spatial reuse should be studied. Furthermore, simply seeking more coding opportunities in a greedy method or encoding more packets into one frame without exploiting multi-rate feature may decrease network throughput. This is because if the channel state of one node is particularly poor, attempting to satisfy the transmission requirement of this node may degrade the network performance of other nodes in broadcast transmission. Therefore, the interaction between NC and multi-rate transmission should not be ignored.

We utilize Fig. 1 to state the above mentioned problems. The illustration topology and the corresponding scheduling lengths for different transmission methods are demonstrated in Fig. 1(a) and (b), respectively. In Fig. 1(a), the solid lines with arrows indicate the directional links on which packets are transmitted, the length of each solid line indicates the distance between two nodes, and the dotted lines indicate the potential interference caused by other activated links. For the sake of state convenience, protocol interference model is only assumed in this section, while physical interference model is considered in the other parts of our work. Before introducing system model, it is necessary to state the difference between protocol interference model and physical interference model.

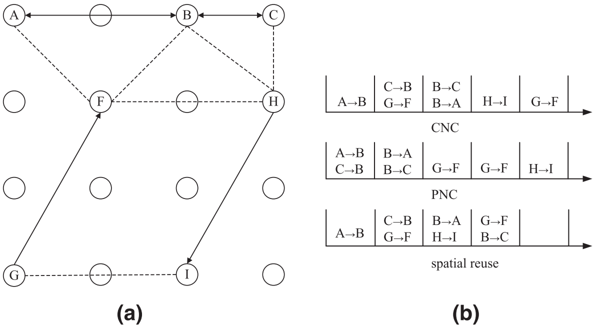

Fig. 1. (a) Illustration topology, and (b) optimal scheduling length for CNC, PNC and spatial reuse respectively.

The authors in [12] firstly defined these concepts to the best of our knowledge. As mentioned in that paper, suppose node X_i transmits packets to node X_j , it is assumed that the transmission can be successfully received by the destination node if $|X_k - X_j| \geq (1+\Delta)|X_i - X_j|$, where node X_k is the node that transmits simultaneously over the same wireless channel. The value of Δ is defined according to different protocols to prevent neighboring nodes transmitting on the same wireless channel at the same time. Although the protocol interference is simple, it prevents simultaneous transmissions on the same node, since it is assumed that they would cause collision. However, with physical interference model, the feasibility of simultaneous link activations is determined by the SINR at the receivers. It should be noted that the packet error rate at a receiver is a monotonically decreasing function of SINR. Therefore, network performance evaluated by the physical interference model is more accurate than the protocol interference model.

In Fig. 1, we firstly assume no traffic exists on links $G \rightarrow F$ and $H \rightarrow I$. Nodes A and C, where each node has one packet (x and y respectively) for exchange, intend to communicate via relaying node B. If plain routing is applied, four time slots are required to complete the packet exchange, namely $A \rightarrow B$, $B \rightarrow C$, $C \rightarrow B$ and $B \rightarrow A$. If node B performs CNC,[1] three time slots are sufficient for the transmission. Node A delivers packet x to node B in the first time slot, node C sends packet y to node B in the second time slot. In the third time slot, node B transmits the encoded packet $z = x \oplus y$ to nodes A and C during the BroadCast (BC) stage, where $\oplus$ is the XOR operation. Since node A has known packet x, packet y can be decoded from the encoded packet z. Similarly, node C can decode packet x with the known information of packet y. The network throughput can be further increased by PNC, where the source nodes A and C can transmit packets simultaneously to relaying node B in the first time slot, known as multiple access (MA) stage. According to ElectroMagnetic (EM) theory, simultaneously transmitted EM waves are superposed in space and received by the relaying node. In the second time slot, node B broadcasts the encoded packet to nodes A and C,

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[1] We mainly focus on the XOR-based CNC method in this paper, random NC and linear NC methods are beyond our scope due to their complexity for implementation.