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A novel adaptive spectrum allocation scheme for multi-channel multi-radio wireless mesh networks

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ABSTRACT

The rapidly developed wireless services and applications have an increasing demand of spectrum resource, which is actually limited. Therefore, how to allocate spectrum resource effectively for network throughput improvement is an urgent issue. Although the utilization of spectrum can be enhanced by link scheduling for spatial reuse, Network Coding (NC) for broadcast transmission, multicast transmission and multi-channel multi-radio techniques, their interactions cannot be ignored. This is because on one hand, the achieved network performance by NC is strongly dependent on the MAC layer, and greedy NC method may in fact reduce network throughput owing to the reduction of spectrum spatial reuse. On the other hand, channel assignment faces more challenges brought by NC and multicast transmission since the broadcast or multicast links are dominated by the link with the worst channel state. In order to utilize the spectrum resource adaptively while not bringing additional constraints, we present a two-phase solution approach. On the first step, we formulate the NC-aware scheduling scheme to an optimization problem, by which the interference-free links are allocated into the same link set and can be activated in the same time slot and channel. Then, we assign different channels to the link sets according to the radio constraints in a heuristic method, which can further increase the utilization of spectrum resource. Finally, simulation results demonstrate that our proposed method can largely increase the utilization of spectrum resource and improve network throughput.

1. Introduction

Wireless Mesh Networks (WMNs) are designed to meet the ever increasing demand for broadband wireless services, however, the bandwidth capacities of WMNs are fundamentally limited due to the scarcity of spectrum resource. One common solution is to combine multiple wireless transmission technologies together to make full use of wireless spectrum resource, so that network throughput can be maximized.

It has been demonstrated by Galvez and Ruiz (2015) that link scheduling, Network Coding (NC), multicast transmission and Channel Assignment (CA) are dependent on each other, and the output of any factor stated above is determined by the inputs of the other factors in part. Therefore, in order to fully utilize network spectrum resource, link scheduling for spatial reuse, NC for broadcast transmission, multicast transmission and channel assignment to make use of the multi-channel multi-radio techniques should be solved as a joint problem. This problem is rather challenging and some questions should be made certain. The first one is how to allocate spectrum resource so that frequency diversity brought by spatial reuse and broadcast transmission fulfilled by NC can be conducted effectively. The second one is given a certain number of available channel and radio, how to distribute the links into the same link set for concurrent transmission in the same frequency spectrum.

To handle the problems mentioned above, we consider two kinds of network interactions. The first one is the interaction between link scheduling and NC. This is because on one hand, the achieved network performance by NC is strongly dependent on the MAC layer, and greedy NC may in fact reduce network throughput owing to the reduction of spectrum spatial reuse. The second one is the interaction between CA and NC. This is because CA faces more challenges brought by NC and multicast transmission since the broadcast or multicast links are dominated by the link with the worst channel state. Before illustrating the main work of this paper, we would like to give some brief introduction about NC, CA, and multicast transmission.

Overlapped signals are always considered to be harmful in wireless communication systems. However, the emergence of NC has shifted the process of network communication.

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In Conventional Network Coding (CNC) scheme, the relay node encodes packets after receiving them in separate communication phases. Physical-layer Network Coding (PNC) is becoming a research hotspot in recent years, which encodes packets through simultaneous transmissions. It is a simple fact in physics that when multiple ElectroMagnetism (EM) waves come together within the same physical space, they can add. The mixed EM wave is a form of NC performed by the nature. Although the same amount of packets can be conveyed by CNC and PNC schemes with less transmission time, they may not achieve the optimal network performance all the time. This is because the relay node has to broadcast with high transmission power to guarantee all the receiving nodes can decode the packet successfully in the broadcast stage, which may lower the spectrum spatial reuse, decrease concurrent transmissions and degrade network throughput as a result. It has been demonstrated in Mohammed et al. (2013) that the NC performance has a close relationship with the joint decision of physical and MAC layers. This is because a large gap may exist among the channel states of different links due to the time-varying characteristic in wireless networks, therefore NC and scheduling should be jointly studied (Ning et al., 2013).

Furthermore, with the development of wireless equipment in recent years, the utilization of Multi-Channel and Multi-Radio (MC–MR) technology is regarded as a promising solution for throughput improvement in WMNs. In addition, IEEE 802.11b/g and IEEE 802.11a standards provide 3 and 12 non-overlapped frequency channels, respectively. MC technology can increase the utilization of wireless medium through non-interfering simultaneous communications on different frequency spectrum ranges. In MR networks, more than one network interface card, referred as radio, can be installed on the nodes. The utilization of multiple radio interfaces is a common solution for throughput improvement, on which the radios are able to switch over multiple orthogonal channels and send or receive packets on any particular channel at one time. Obviously, the interfaces on different nodes can communicate when they are tuned onto the same channel subject to the radio resource constraint, and CA is required.

In order to utilize network spectrum resource effectively, we study the interaction among link scheduling, NC and CA, and propose a two-phase solution approach to select the transmission scheme in an adaptive method. On the first step, a NC-aware scheduling method is proposed to improve the network throughput by considering the interaction between NC and spatial reuse. After that, the interference-free links are allocated into the same link set and can be activated in the same time slot and channel. On the second step, we assign different channels to the link sets according to the radio constraints on each node in a heuristic method to improve network throughput further. The rest of this paper is organized as follows. Section 2 illustrates the related works. The NC-aware link scheduling scheme is presented in Section 3, and the CA scheme is proposed in Section 4. Simulation results are given in Section 5, and some concluding remarks are provided in Section 6.

2. Related works

A joint scheduling and CNC method that aims to maximize network throughput while considering the packet deadline was studied by Rajawat and Giannakis (2011), which relied on a time-unwrapped graph in order to construct linear periodic time-varying network coding. As the requirement of delay looses, the lower bound of network throughput approaches to the upper bound. A cross-layer optimization problem combining rate control, NC and link scheduling with wireless broadcast was studied in Cui et al. (2010), where the authors demonstrated that in some cases the proposed method with broadcast feature has even lower complexity than the case without broadcast transmission. However, the authors in Wang et al. (2015) and Rajawat and Giannakis (2011) only considered the protocol interference, while ignoring the information in the physical layer. Initial works in the scheduling problem mainly employ simplistic channel models, such as the collision channel, where the transmission “range” is chosen arbitrarily and no interference is assumed outside the transmission range. In recent years, research literatures began to integrate physical layer information into scheduling schemes. One example is if the Signal to Interference plus Noise Ratio (SINR) value in the receiving terminal is above some threshold, it can receive information successfully. Although Mohammed et al. (2013) and Ning et al. (2014) considered the SINR-based interference model and attempted to maximize network performance by considering scheduling for spatial reuse in WMNs, they ignored the multicast or broadcast nature in wireless communication.

Some applications (such as video gaming, video conference), whose contents involve multicast packets to a set of receivers, increase sharply nowadays, and how to handle multicast traffic is undoubtedly attracting more and more interests. Random linear NC in multicast networks was introduced by Li et al. (2012). You et al. (2011) investigated an optimal cross-layer design including routing, NC and scheduling to utilize the broadcast advantage of wireless medium. Although network throughput can be largely increased, the considered topology is rather simple. In order to minimize transmission delay for wireless relay networks, the interplay between NC and multicast transmission was studied by Lu and Liao (2012). Due to the high complexity of the considered model by Lu and Liao (2012), heuristic algorithms were presented to study the tradeoff between the achieved network performance and the computational complexity. Although NC can save bandwidth and increase network throughput, it does not consider the Quality of Service (QoS) of multicast routing directly. In order to meet the QoS requirements of end-to-end delay and jitter from source to destination nodes, Raayatpanah et al. (2014) attempted to minimize network cost and the number of multicast sessions, by decomposing the NP-hard problem into master problem and sub-problems through feasible path generation. However, these works mainly focused on the single-channel and single-radio scenario.

The decreasing cost of hardware makes MC–MR technology reality, which has attracted increasing interest. Alicherry et al. (2005) proposed a joint CA and routing scheme for the purpose of maximizing network capacity subject to fairness constraints in WMNs. Both distributed and centralized load-aware CA algorithms were presented by Wang et al. (2015) to make transmission decisions dynamically based on network traffic. The study on CA in MC–MR network has become a hot topic after these pioneer works. Chieochan and Hossain (2013) formulated the joint problem of NC, CA and link scheduling, and developed a suboptimal, auction-based solution to obtain the overall network throughput. A practical NC scheme in MC–MR network was implemented by Chi and Agrawal (2012), where the authors demonstrated this scheme can improve network performance not only on network throughput, but also on end-to-end delay. A novel approach for link scheduling and CA to improve the overall capacity and throughput of WMNs was presented by Kumara et al. (2011), and this problem was formulated as an Integer Linear Programming (ILP) problem with associated constraints to ensure network connectivity. In order to maximize the total transmission rate achieved by the receivers while preserving their fairness, Farzinvash and Dehghan (2014) employed a multicast-based MC–MR algorithm to handle the bandwidth heterogeneity of different destination nodes by resolving the optimization model. Capone et al. (2010) studied the joint scheduling and routing