Proceedings of the Asia-Pacific Advanced Network 2013 v. 36, p. 49-56.
http://dx.doi.org/10.7125/APAN.36.7
ISSN 2227-3026

A Joint Network Coding and Scheduling Algorithm in Wireless Networks

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Abstract: Network coding (NC) is an emerging technique of packet forwarding that encodes packets at relay node in order to increase network throughput. It is understood that the performance of NC is strongly dependent on the physical layer as well as the MAC layer, and greedy coding method may in fact reduce the network throughput owing to the reduction in the spatial reuse. In this paper, we propose a NC-aware scheduling method combining link aggregation to improve the network throughput by considering the interplay between NC and spatial reuse. Simulation results demonstrate the effectiveness of our proposed link aggregation method compared with the unicast transmission model.

Keywords: network coding; scheduling; spatial reuse.

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1. Introduction

Overlapped signals are always considered to be harmful in wireless communication systems. However, the emergence of network coding (NC) has shifted the design method of network communication. In conventional network coding (CNC) scheme, the relay node encodes packets after receiving them in separate communication phases. Physical layer network coding (PNC) was first proposed in 2006 and then received widely research. It 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 mixing of EM waves is a form of NC performed by nature. Although CNC and PNC schemes can convey the same number of packets with less transmission time, they may not always be the optimal transmission methods. One reason is that the relay node has to broadcast with higher transmission power to guarantee all the receiving nodes can receive the packet successfully in the broadcasting stage, which may decrease concurrent transmissions. Another reason is performing NC in a greedy method may lower the spectrum spatial reuse, and decline network throughput. Therefore, NC and scheduling for spatial reuse should be jointly considered for network design.

It has been demonstrated in [1] that the NC performance has a closely relationship with the joint decision between physical layer and MAC layer. Because greedy NC may decrease spatial reuse and lower network throughput, a trade-off should be conducted between spatial reuse and NC gain. Due to the time varying characteristics in wireless network, there may be a huge gap among different links, nodes should adopt scheduling scheme in order to optimize network performance. Since the applications (such as video gaming, video conferencing), whose content involves multicasting data to a set of receivers, increase sharply nowadays, handling multicast traffic is undoubtedly becoming of significant interest. In this paper, we study the interplay between scheduling and NC, and present a NC-aware link scheduling scheme to improve network throughput by adding virtual links for link aggregation. The rest of this paper is organized as follows. Section 2 reviews some related works, and the optimal NC-aware link scheduling scheme is presented in Section 3. Simulation results are illustrated in Section 4, and some concluding remarks are provided in Section 5.

2. Related works

A joint scheduling and CNC algorithm that aims to maximize the average throughput while respecting the packet deadlines was studied in [2]. This paper relied on a time-unwrapped graph expansion in order to construct linear periodic time-varying network codes. With the requirement of delay becomes loose, the lower bound of throughput can approach to the upper bound promptly. A cross-layer optimization combining rate control, NC and scheduling with wireless broadcast advantage was studied in [3]. The authors proposed a locally greedy and randomized approximation algorithm to approach the worst case performance, which demonstrated that in some cases this algorithm with broadcast feature has even lower complexity than the case without broadcast. However, the authors in [2, 3] only considered the protocol interference, and did not consider the information in the physical layer. The authors in [4] proposed a distributed MAC protocol that supports PNC in multi-hop wireless networks, which is based on the carrier sense multiple access (CSMA) strategy and can be regarded as an extension to the IEEE 802.11 MAC protocol. The proposed MAC protocol increases throughput compared with non-PNC

MAC protocol. However, scheduling scheme is not considered, and only bidirectional data flow is considered in this paper.

Traditionally, the scheduling problem has been studied in the context of medium access control (MAC) protocols which ignores the physical layer. Initial works in the scheduling problem employ simplistic channel models, such as the collision channel. The transmission “range” is chosen arbitrarily and no interference is assumed to be possible outside the transmission range. In recent years, research literature began to integrate physical layer information into scheduling scheme. One example is if the signal to interference plus noise ratio (SINR) in receiving terminal is above some threshold, it can receive information successfully. The problem of joint scheduling and CNC in a multicast situation is becoming a hotspot in the wireless research area. However, the existing researches mainly focus on the joint optimization between scheduling and CNC, ignoring PNC method which can improve throughput further. In [5], the authors investigated an optimal cross-layer design of congestion control, routing, NC and scheduling utilizing the broadcast advantage of wireless medium. Although the throughput have been increased largely, the considered topology is quite simple compared with the random topology. In [6], the authors combined scheduling and PNC preliminary, however, multiple unicast flows are considered instead of multicast flows, besides, the efficiency of greedy algorithm proposed in that paper is low, and no spatial reuse is considered. Therefore, a lot of research area exists on the joint scheduling CNC and PNC scheme, and study the cross-layer optimization in a multicast pattern is very important for future wireless network.

3. NC-aware link scheduling Strategy

Define node pair *j-j'* as one session for packet transmission if this node pair can communicate with other node directly. If no direct link exists between the node pair due to high shadow fading or large separation, one relaying node *i* is needed for packet transmission. We define node group *j-i-j'* as one session in the relaying-aided situation, and also assume only one packet in each session is transmitted within one scheduling round by considering fairness issues as in [7].

We consider a wireless multi-hop network, represented by a directed graph $G=(V, E)$, where V is a set of nodes and E is a set of links between the nodes. Define V_i as a set of one-hop neighboring nodes of node *i*, V_i^+ and V_i^- are the outgoing and incoming node corresponding to node *i* respectively. We consider the sessions are scheduled based on time division multiple access (TDMA) as in [1]. Thus, transmissions in plain routing, spatial reuse and CNC are acceptable if the received SINR at node *j'* is more than a predefined threshold Γ, which is demonstrated in (1):

$$\Gamma_{j'} = \frac{P_{jj'}G_{jj'}}{\delta^2 + \sum_{h \in V-\{j\}} P_{hj'}G_{hj'}} \geq \Gamma \qquad (1)$$

$P_{jj'}$ and $G_{jj'}$ are the transmission power and channel gain between nodes *j* and *j'* respectively. The denominator contains the thermal noise δ^2 and the concurrent interference. We consider the denoise and forward (DNF) method with three-node NC link combination due to the synchronization problems as in [8], which can be regarded as a part of the wireless multi-hop network.

The SINR constraint for the DNF method in the MA phase is:

$$\Gamma_i = \frac{\min(P_{ji}G_{ji}, P_{j'i}G_{j'i})}{\delta^2 + \sum_{h \in V - \{j\}} P_{hi}G_{hi}} \geq \Gamma \tag{2}$$

where node *i* is the relaying node. From Eq. (2), we note that the received power of the two signals should be kept almost the same at the relaying node to simplify the demodulation process of the superposed signals.

Define *S* as the set of all possible configurations containing a set of sessions in the network, and ω_s is an integer variable which represents the number of time slots for a certain configuration $s \in S$ to be scheduled. x_{ij}^s is a binary variable, which equals to 1 if link $i \rightarrow j$ is activated in Configuration *s*, and 0 otherwise. We define u_i^s, c_i^s and d_i^s as the binary transmission variables to denote whether relay node *i* conducts unicast, CNC and DNF method or not. The joint scheduling and NC problem can be modeled as follows:

$$Min \sum_{s \in S} \omega_s \tag{3}$$

subject to:

$$x_{ij}^s + x_{ji}^s \leq 1 \tag{4}$$

$$u_i^s + c_i^s + d_i^s \leq 1 \tag{5}$$

Throughput can be improved if the totally required activating time $\sum_{s \in S} \omega_s$ is reduced to complete the entire transmission task. Therefore, our optimization objective is to minimize the activating time $\sum_{s \in S} \omega_s$ by choosing proper relaying method. Constraint (4) shows the half-duplex property, that is, any node cannot transmit and receive at the same time. Constraint (5) ensures that node *i* can choose at most one transmission mode during one scheduling period.

Constraints (6)-(10) determine the transmission mode chosen by relay node *i*. Constraint (6) guarantees that if more than one outgoing flow is from node *i*, it chooses either CNC or DNF method. Constraint (7) ensures that if more than one incoming flow exist, node *i* should choose DNF method. Constraint (8) forces d_i^s=0, if there is only one incoming flow (u_i^s=1 or c_i^s=1), and Constraint (9) guarantees a node to broadcast at most two of its outgoing flows to reduce the complexity of decoding. Constraint (10) restricts the maximum number of incoming links to two under the DNF method operation in order to guarantee the decodability.

$$c_i^s + d_i^s \ge \sum_{j\in V_i^+} x_{ij}^s - 1 \tag{6}$$

$$d_i^s \ge \sum_{j\in V_i^-} x_{ij}^s - 1 \tag{7}$$

$$d_i^s \le \sum_{j\in V_i^-} x_{ij}^s - u_i^s - c_i^s \tag{8}$$

$$\sum_{j\in V_i^+} x_{ij}^s \le 1 + d_i^s + c_i^s \tag{9}$$

$$\sum_{j\in V_i^-} x_{ij}^s \le 1 + d_i^s \tag{10}$$

The spectrum can be more efficiently utilized by multiple simultaneous transmissions by adjusting the transmit power of active links properly while satisfying the interference requirement constraints. Constraint (11) guarantees the SINR requirement of a broadcast transmission at node j and calculates the cumulative interference from current transmissions.

$$P_i G_{ij} + M_{ij}^s(1 - x_{ij}^s) + M_{ij}^s(1 - c_i^s - d_i^s) \ge \Gamma[\delta^2 + \sum_{h\in V-\{i\}} P_{hj}G_{hj} + \sum_{h\in V-\{i\}} P_h G_{hi}(c_h^s + d_h^s)] \tag{11}$$

where P_i is defined as the transmission power of node i when it is in the BC stage of CNC and DNF method, and $P_{jj'}$ is the transmission power when link $j \rightarrow j'$ is in the unicast situation.

When the transmission is in the unicast model, the interference constraint becomes:

$$P_{ij} G_{ij} + M_{ij}^s(1 - x_{ij}^s) + M_{ij}^s(1 - u_i^s) \ge \Gamma[\delta^2 + \sum_{h\in V-\{i\}} P_{hj}G_{hj} + \sum_{h\in V-\{i\}} P_h G_{hi}(c_h^s + d_h^s)] \tag{12}$$

Therefore, Configuration s is identified by x_{ij}^s, u_i^s, d_i^s, c_i^s and transmission power $P_{jj'}$. One schedule S is the set of such configurations, i.e. $s \in S$.

Since we have obtained the unicast links that can be activated simultaneously during one time slot, then we should determine the available relaying methods while satisfying the corresponding power constraints. It should be noted that if we have added one link in the scheduling period, the transmission power will increase due to the augment of interference. After that we determine the links without interfering with each other can transmit packet concurrently for spatial reuse. In this method, we can finish the scheduling for the unicast flows.

Then, we consider the link aggregation for multicast which is one of the most important characteristics of wireless nodes. When a wireless node transmits message, any node in the transmitter can receive this message if the SINR is above the threshold. It means if there is more than one node in the vicinity of a transmitting node which all belongs to the same scheduling time share, they can receive the same transmitted messages from the transmitting node. We propose a combination method to obtain the multicast model based on the information of unicast model. In order to use the optimization problem without introducing new constraints, we define virtual multicast edges to represent the multicast links as shown in the left side of Fig. 1. If there is more than one interference free links needs to be activated from node i, we define a multicast edges from node i to i' to abstract these links into one virtual link as shown in the right side of Fig. 1. However, the definition of transmission power is very complex since we consider the physical interference model instead of the protocol interference model, which only considers the distance between nodes. Because we have to choose the maximum transmission power between P_{il} and P_{im} to ensure the links with poor channel state can receive the message for multicast transmission, this method will destruct the interference free link collection obtained. In our work, we consider a greedy method that is conduct the virtual links for multicast transmission primarily, then select the transmission method according to the unicast model.

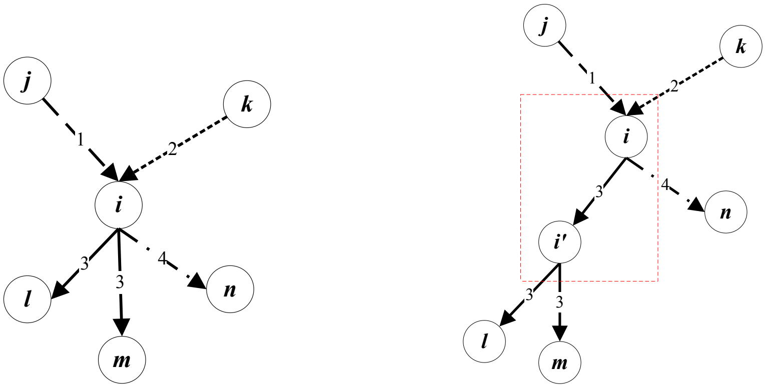

Figure 1. Link aggregation for multicast.

4. Simulation Results

We adopt MC_V, UC_V, MC_F and UC_F to denote the multicast and unicast under both variable and fixed power control method respectively. We consider a random network topology, 30 nodes are randomly distributed in a square region where each side is 333 meters, and adopt a simple path loss channel model where the channel gain $G_{ij} = d_{ij}^{-\alpha}$, and α=2. The SINR threshold value equals to 2.5.

Table 1. NC Traffic Percentage in the Random Topology under Different Network Session.

	10	20	30	40	50
MC_V	0.029	0.065	0.106	0.118	0.189
UC_V	0.049	0.121	0.149	0.171	0.229
MC_F	0.034	0.102	0.123	0.169	0.192
UC_F	0.074	0.125	0.168	0.198	0.215

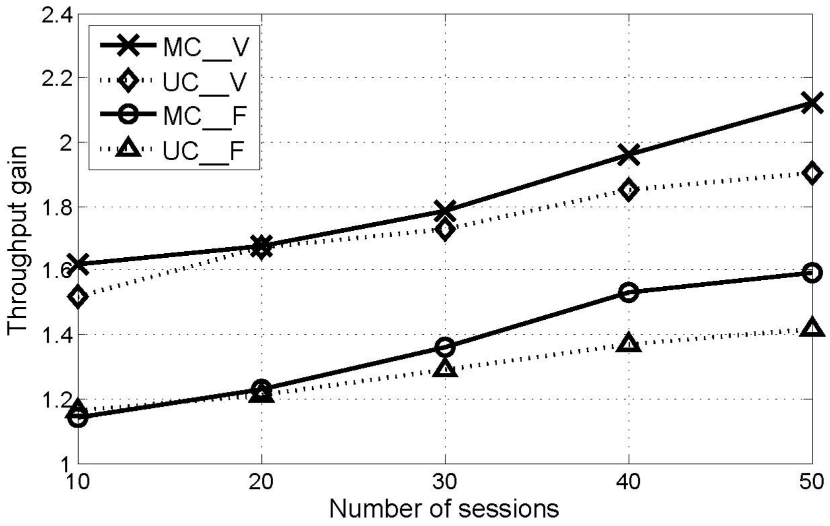

Figure 2. Network throughput gain in the random topology.

Table 1 demonstrates the percentage of the NC traffic, which is the ratio of the number of NC sessions (including DNF and CNC) to the number of all the sessions. We can observe that the NC traffic percentage under fixed power control is larger than that in the variable power situation. This is because more links prefer spatial reuse to decrease interference. We can also observe than the NC percent in multicast situation is less than that in the unicast situation due to links are considered for multicast primarily in our proposed method.

The throughput gain, which is defined as the ratio of the optimized scheduling length to the scheduling length by considering unicast only, is compared in Fig. 2. We can observe that the throughput gain in MC_F (UC_F) is lower than that in MC_V (UC_V) obviously. This is because the method with fixed transmission power increases link interference and therefore limits the possibilities of spatial reuse and NC. We can see that due to the multicast transmission, the values of MC_V and MC_F are larger than their counterparts, which demonstrates the advantage of multicast. Above all, the network throughput gains achieved by the MC_V and UC_V schemes increase 34% and 35% on average compared with the MC_F and UC_F schemes which demonstrate the effectiveness of our proposed method.

5. Conclusions

In this paper, we have proposed a joint NC-aware link scheduling method to optimize the throughput gain by considering the interplay between NC and spatial reuse with power control for unicast transmission at first. Then we extend this method to multicast situation by constructing virtual multicast links. Simulation results demonstrate that the network throughput obtained by multicast transmission after link aggregation is larger than the optimization method in unicast situation, which demonstrates the effectiveness of our proposed method.

Although our proposed method can maximize the throughput gain in different topologies, The problem of scheduling active links at fixed power and fixed data rate has been modeled and solved as an edge coloring problem, known as a NP-complete problem. Therefore, designing a sub-optimal scheme with low computing complexity is part of our future work.

Acknowledgements

This work was supported by KAKENHI (Grant-in-Aid for Scientific Research(C) 25330106) and the Fundamental Research Funds for the Central Universities (N120604001).

References

1. J. Najjar; H. AlAzemi, and C. Assi, “On the interplay between spatial reuse and network coding in wireless networks,” *IEEE Transactions on Wireless Communications*, 10(2): 560-569, 2011.
2. K. Rajawat and G. Giannakis, “Joint scheduling and network coding for multicast in delay-constrained wireless networks,” *IEEE Transactions on Signal Processing*, 59(12): 6186-6196, 2011.
3. T. Cui, L. Chen, and T. Ho, “On distributed scheduling in wireless networks exploiting broadcast and network coding,” *IEEE Transactions on Communications*, 58(4): 1223-1234, 2010.
4. S. Wang, Q. Song, X. Wang, and A. Jamalipour, “Distributed MAC protocol supporting physical-layer network coding,” *IEEE Transactions on Mobile Computing*, 12(5): 1023-1036, 2013.
5. L. You, L. Ding, P. Wu, Z. Pan, H. Hu, M. Song, and J. Song, “Cross-layer optimization of wireless multihop networks with one-hop two-way network coding,” *Computer Networks*, 55(8): 1747-1769, 2011.
6. H. Su and X. Zhang, “Modeling Throughput Gain of Network Coding in Multi-Channel Multi-Radio Wireless Ad Hoc Networks,” *IEEE Journal on Selected Areas in Communications*, 27(5): 593-605, 2009.
7. F. Wang, S. Wang, Q. Song, and L. Guo, “Adaptive relaying method selection for multi-rate wireless networks with network coding,” *IEEE Communications Letters*, 16(12): 2004 - 2007, 2012.
8. S. Wang, Q. Song, X. Wang, and A. Jamalipour, “Rate and power adaptation for analog network coding,” *IEEE Transactions on Vehicular Technology*, 60(5): 2302 –2313, 2011.