Journal of Network and Computer Applications 56 (2015) 19–27

Contents lists available at ScienceDirect

Journal of Network and Computer Applications

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

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

Zhaolong Ning [a,c], Qingyang Song [b,*], Lei Guo [b,*], Xiangjie Kong [a]

[a] School of Software, Dalian University of Technology, Dalian 116620, China
[b] School of Information Science and Engineering, Northeastern University, Shenyang 110819, China
[c] State Key Laboratory for Novel Software Technology, Nanjing University, Nanjing 210093, China

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form
9 May 2015
Accepted 22 June 2015
Available online 30 June 2015

Keywords:
Scheduling
Network coding
Multicast
Channel assignment

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.

* Corresponding authors. Tel./fax: +86 13804008890.
E-mail address: songqingyang@ise.neu.edu.cn (Q. Song).

http://dx.doi.org/10.1016/j.jnca.2015.06.004
1084-8045/

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 problem in MC–MR WMNs, and proposed a column-generation based algorithm to assign links to different interference-free configurations in order to minimize the number of used time slots. Su and Zhang (2009), the authors developed a joint link scheduling, CA and routing algorithm for CNC and PNC respectively in MC–MR wireless ad hoc networks, with the objective of maximizing network throughput.

Although the abovementioned works considered the network performance gain brought by link scheduling, NC and CA, none of them studied the interactions among these technologies to the best of our knowledge. In this paper, we propose a two-phase solution approach, by considering two kinds of interactions, to utilize network spectrum adaptively, with the objective of maximizing network throughput. Our main contributions are as followed: we consider more general network scenarios instead of the traditional star, wheel or two way relay channel topologies. Since NC may suppress the concurrent transmissions brought by link scheduling, we study the interplay between NC (including CNC and PNC) and spatial reuse. Furthermore, we formulate the CA problem into an ILP problem with the objective of increasing network throughput further in MC–MR scenario. Due to the high computational complexity of the ILP problem, we present a heuristic algorithm to allocate different channels to links while satisfying the radio constraints.

3. NC-aware link scheduling with multicasting

In this section, we first present a novel metric to evaluate the network throughput gain contributed by different transmission methods, then we identify link sets, which contain interference-free links for simultaneous transmission, and define them as transmission configurations. After that, we present a link aggregation method by combining the concurrent activated unicast links into multicast transmission.

Define node pair j–j' as one session for packet transmission if the source node can communicate with the destination node directly. If no direct link exists between the node pair due to high shadow fading or large separation, one relay node i is needed for packet relaying. We define node group j–i–j' as one session in the relay-aided situation. The major notations used in this paper are shown in Table 1.

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 nodes corresponding to node i respectively. We consider the sessions are scheduled based on Time Division Multiple Access (TDMA), where the channel time is slotted into identical synchronized time slots. Although TDMA avoids the interference among different wireless devices by dividing the time domain into contiguous time slots and assigns these slots to different wireless devices, it results in a poor spatial utilization efficiency since only one device can be activated during each time slot. Thus, Spatial Time Division Multiple Access (STDMA), which is an extension of TDMA, has been proposed to enhance the network performance by considering the capability of spatial reuse (Nelson and Kleinrock, 1985). Specifically, STDMA allocates a single time slot to activate multiple links according to their interference. That is, multiple communication pairs can be activated within the same time slot provided that these transmissions are interference free. Therefore, the spectrum can be utilized more effectively by adjusting the transmission power to activate more transmission links. Thus, transmissions in plain routing, spatial reuse and CNC are acceptable if the received SINR at node j' is above 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 interference generated by the other concurrent transmissions. DeNoise-and-Forward (DNF) and amplify-and-forward are two common PNC methods, and the former is adopted in our work since it avoids noise amplification (Sharma et al., 2010). We use DNF and PNC interchangeably in our discussions, and only consider the three-node-involved DNF method for simplicity due to the synchronization problem as stated by Wang et al. (2011). For the DNF method in the Multiple Access (MA) stage, we use the minimum received power, namely $\min(P_{ji}G_{ji},\ P_{j'i}G_{j'i})$, to calculate the SINR value. Without loss of generality, we assume $P_{ji}G_{ji} < P_{j'i}G_{j'i}$, and the SINR constraint for

Table 1
The variables and notations used in this paper.

V_i	Set of one-hop nodes of node i.
V_i^+	Set of one-hop outgoing nodes of node i.
V_i^-	Set of one-hop incoming nodes of node i.
μ_s	Integer variable which represents the number of time slots for completing transmissions in Configuration s.
δ^2	Thermal noise.
$P_{\max}$	Maximum transmission power of each node.
$P_{i,BC}$	Broadcast power of node i in Configuration s.
$P_{i,j}$	Transmission power from nodes i to j in Configuration s.
$G_{i,j}$	Channel gain between nodes i and j.
Γ_i	SINR threshold of node i.
	Number of packets intended to be sent on link li, j in Configuration s per time slot.
x_{ij}^s	Binary variable which is 1 if link li, j is activated in Configuration s.
u_i^s	Binary variable which is 1 if node i transmits uncoded packets in Configuration s.
c_i^s	Binary variable which is 1 if node i transmits CNC-coded packets in Configuration s.
d_i^s	Binary variable which is 1 if node i transmits DNF-coded packets in Configuration s.
ζ_s	Integer variable which represents the number of time slots for completing the transmission in MC–MR scenario.
$\|O\|$	Number of orthogonal channels.
	Number of per node interfaces.
y_c^s	Binary variable which is 1 if Configuration s is assigned to channel c.
$r_{i,c}^s$	Binary variable which is 1 if node i utilizes channel c in Configuration s for transmission.
a_i^s	Binary variable which is 1 if node i appears in Configuration s.

the DNF method in the MA phase is

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

where node i is the relay node.

Define S as the set of all possible configurations containing a set of sessions in the network, and $\mu_s$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. Define u_i^s, c_i^s, d_i^s and m_i^s as the binary transmission variables to denote whether relay node i adopts unicast, CNC, DNF and multicast or not. Given the information of transmission rate, NC opportunity, packet size and overhead, the scheduling task at the relay node is to decide the best link combination including different transmission methods, so that the utilization of spectrum resource can be fully utilized for throughput improvement. Unfortunately, this problem has been demonstrated to be NP-Complete, and the challenge escalates if we take multi-rate transmission into consideration. Therefore, we present the following heuristic method to solve this problem. By utilizing Ω_i^s to denote the unified transmission rate by considering the transmission rate and NC cost, the objective of the joint problem can be modeled as:

$$\max \sum_{i \in V} \sum_{s \in S} \Omega_i^s \tag{3}$$

Different from Yomo and Popovski (2009) which merely considered the number of packets to perform CNC, our model jointly considers spatial reuse, NC and multi-rate transmission, and adds different factors into the corresponding metric, Ω_i^s can be calculated by

$$\Omega_i^s = \begin{cases} c_i \times \omega_{i,BC} \times \frac{2n_i^C}{2n_i^C - 1} \times \frac{n_i^C \times L}{n_i^C \times L_C + L} & \text{if CNC is applied} \\ d_i \times \omega_{i,BC} \times \frac{n_i^D}{n_i^D - 1} \times \frac{n_i^D \times L}{n_i^C \times L_D + L} & \text{if DNF is applied} \\ m_i \times \omega_{i,MC} \times \alpha_i & \text{if multicast is applied} \\ u_i \times \omega_{ij} \times \beta_i & \text{others} \end{cases} \tag{4}$$

herein, $\omega_{i,BC}$, $\omega_{i,MC}$ and ω_{ij} are the transmission rate for broadcast, multicast and unicast on node i, respectively. The transmission rates are worked by *Shannon* formula which relies on the SINR value, and it should be noted that the transmission rates for broadcast and multicast are limited by the link with the worst channel state. $2n_i^C/2n_i^C - 1$ and $n_i^D/n_i^D - 1$ are the gain factors for network throughput improvement brought by CNC and DNF respectively as demonstrated by Nelson and Kleinrock (1985), where n_i^C and n_i^D are the number of nodes that perform CNC and DNF, respectively. α_i and β_i are the number of links that can be activated simultaneously for multicast and spatial reuse. If β_i equals to one, this link is activated by unicast. L_C together with L_D are the extra header cost that every node has to add into the packet for CNC and DNF, respectively. L is the size of each packet. The summation of these four parts in (4) expresses the ability for network throughput improvement conveyed by each combination (CNC, PNC, multicast and spatial reuse) in one configuration. In order to maximize network throughput, we should select the link combination that can maximize the total transmission rate in (4). The reason behind is that network throughput is directly proportional to link transmission rate.

The following constraints should also be satisfied for the NC-aware link scheduling problem

$$x_{ij}^s + x_{ji}^s \leq 1 \tag{5}$$

$$u_i^s + m_i^s + c_i^s + d_i^s \leq 1 \tag{6}$$

$$\sum_{j \in V-\{i\}} x_{ij}^s \leq 1 + (1 - u_i^s) \tag{7}$$

$$\sum_{s \in S} (u_i^s + c_i^s + d_i^s + m_i^s) x_{ij}^s \mu_s Q_{ij}^s \geq u_i^s Y_{ij}^s + \sum_{j \in V_i} m_i^s Y_{ij}^s + \sum_{j' \in V_i^- - \{j\}} d_i^s Y_{jij'}^s + \sum_{j' \in V_i^+ - \{j\}} (c_i^s + d_i^s) Y_{jij'}^s \tag{8}$$

The half-duplex property is guaranteed in Constraint (5), that is, any node cannot transmit and receive at the same time. Constraint (6) ensures that node i can choose at most one transmission mode during one scheduling period. Constraint (7) shows that if node i is in the unicast mode, at most one link is activated during one time slot. The constraint of network capacity is illustrated in (8), that is one link should be activated for enough time so that all the sessions on the links can be fulfilled. μ_s is the required number of time slot to fulfill the entire transmission task, which is the summation of u_i^s, c_i^s, d_i^s and m_i^s.

In order to reduce the complexity of the scheduling problem, we consider link aggregation for multicast, which is one of the most important characteristics of wireless devices. When a wireless node transmits packet, any node within the transmitter range can receive this packet if the corresponding SINR value is above the threshold. It means if there exists more than one node in the vicinity of the transmitting node which can be activated in the same scheduling time, they can receive the same transmitted packet from the source node simultaneously. We propose a link combination method to obtain the multicast transmission based on the information of unicast transmission. In order to utilize the results worked out by the optimization problem without introducing new constraints, we define virtual multicast edges to represent the multicast links as shown in Fig. 1(a). If there is more than one interference-free links needs to be activated from node i, we define a multicast edge from node i to i' to abstract these links into one virtual link. That is if multiple links are required to be activated from the same source node to different destination nodes (for example, links i-l and i-m as shown in Fig. 1(b)), we can combine these links together by introducing a virtual link as shown in Fig. 1(b).

After that, the multicast transmission is transformed into the combination of unicast transmission, and we should note that the transmission power of multicast is the maximum value among the transmission power of unicast. If no power control is considered, namely all the nodes transmit with the maximum power, the SINR constraint for the fixed transmission power is

$$P_{\max} G_{jj'} + M_{jj'}^{s,\max}(1 - x_{jj'}^s) \geq \Gamma[\delta^2 + \sum_{h \in V-\{j,j'\}} P_{\max} G_{hj'}(u_h^s + c_h^s + d_h^s)] \tag{9}$$

where $M_{jj'}^{s,\max}$ is a constant value satisfying $M_{jj'}^{s,\max} \geq \Gamma[\delta^2$

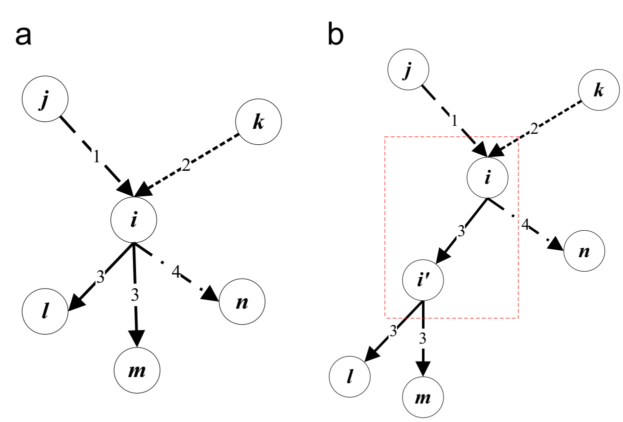

Fig. 1. Illustration of link aggregation. (a) Initial unicast transmission, (b) link aggregation for multicast transmission.

$+\sum_{h\in V-\{j,j'\}} P_{\max} G_{hj'}(u_h^s+c_h^s+d_h^s)]$. The right-side summation in (9) corresponds to the cumulative interference at the receiving node brought by other concurrent transmission links.

If power control method is adopted, derived by (1), when the transmission is in the unicast model, the interference constraint becomes

$$P_{jj'}G_{jj'}+M_{jj'}^s[(1-x_{jj'}^s)+(1-u_i^s)]\ge \Gamma[\delta^2+\sum_{h\in V-\{j,j'\}} P_{hj'}G_{hj'}u_h^s + \sum_{h\in V-\{j,j'\}} P_{h,BC}G_{hj'}(c_h^s+d_h^s)] \tag{10}$$

where $P_{h,BC}$ is defined as the transmission power of node h during the BC stage of CNC and DNF, $M_{jj'}^s \ge \Gamma[\delta^2+\sum_{h\in V-\{j,j'\}} P_{hj'}G_{hj'}u_h^s+\sum_{h\in V-\{j,j'\}} P_{h,BC}G_{hj'}(c_h^s+d_h^s)]$ and $P_{jj'}$ is the transmission power when link $j\to j'$ is in the unicast situation. The corresponding transmission power for unicast should satisfy

$$\frac{\delta^2 u_i^s}{G_{jj'}}\Gamma \le P_{jj'} \le u_i^s \times P_{\max} \tag{11}$$

where the low bound represents the situation where no parallel transmission exists in the network.

Derived by (2), the SINR constraint in the MA stage of the DNF method with variable transmission power is

$$P_{ji}G_{ji}+M_{ji}^s[(1-x_{ji}^s)+(1-d_i^s)]\ge \Gamma[\delta^2+\sum_{h\in V-\{i,j\}} P_{hi}G_{hi}u_h^s + \sum_{h\in V-\{i,j\}} P_{h,BC}G_{hi}(c_h^s+d_h^s)] \tag{12}$$

where $M_{ji}^s \ge \Gamma[\delta^2+\sum_{h\in V-\{i,j\}} P_{hi}G_{hi}u_h^s+\sum_{h\in V-\{i,j\}} P_{h,BC}G_{hi}(c_h^s+d_h^s)]$. Similar with (11), the corresponding transmission power for the DNF method should satisfy

$$\frac{\delta^2 d_j^s}{G_{ji}}\Gamma \le P_{ji} \le d_j^s \times P_{\max} \tag{13}$$

The SINR constraint in node j (similar for node j') during the BC stage of both CNC and DNF can be computed by

$$P_{i,BC}G_{ij}+M_{ij}^s[(1-x_{ij}^s)+(1-c_i^s-d_i^s)]\ge \Gamma[\delta^2+\sum_{h\in V-\{i,j,j'\}} P_{hj}G_{hj}u_h s+\sum_{h\in V-\{i\}} P_{h,BC}G_{hj}(c_h^s+d_h^s)] \tag{14}$$

where $M_{ij}^s \ge \Gamma[\delta^2+\sum_{h\in V-\{i,j,j'\}} P_{hj}G_{hj}u_h^s+\sum_{h\in V-\{i\}} P_{h,BC}G_{hj}(c_h^s+d_h^s)]$, and the constraint for broadcast power is

$$\varepsilon(c_i^s+d_i^s) \le P_{i,BC} \le (c_i^s+d_i^s)\times P_{\max} \tag{15}$$

where $\varepsilon << 1$ so that the transmission power for broadcast is between 0 and $P_{\max}$.

Therefore, Configuration s is identified by the scheduling factor, transmission method and transmission power. One schedule S is the set of such configurations, i.e. $s\in S$, where the transmission links inside the link combination are interference free and can be activated simultaneously during one time slot.

4. Heuristic method based channel assignment scheme

It has been demonstrated that network throughput can be considerably increased in MC–MR WMNs, where different transmission configurations can be allocated onto different orthogonal channels. By the worked out scheduling factor, transmission method and transmission power in Section 3, we can determine the corresponding transmission methods in Configuration s, where the activated links inside the link combination are interference free in single-channel single-radio transmission. In this section, we consider the case that each node is equipped with a number of wireless interfaces, which can be tuned onto one of the orthogonal channels, and switch quickly from one channel to another with a negligible switching delay (Chieochan and Hossain, 2013).

Since each configuration contains a set of transmission links that can be activated concurrently on the same spectrum frequency obtained by resolving the optimization problem, properly assigning channels to different configurations can reduce the required number of time slots and increase network throughput further. It should be noted that two interfaces can communicate only when they are tuned onto the same channel, which requires additional constraints. Denote ζ_s as the number of time slots to complete the transmission task in the MC–MR scenario by CA, Φ as the set of channels, η as the set of radio devices, $|I|$ as the number of interfaces on each node, and $|O|$ as the number of available orthogonal channels. In order to illustrate the CA problem in MC–MR WMNs, we introduce some binary variables. If channel c is assigned to Configuration s, $y_c^s=1$. If node i appears in Configuration s, $a_i^s=1$, and if channel c is utilized by node i in Configuration s, $r_{i,c}^s=1$. The CA problem can be formulated as:

$$\text{Min}\sum_{s\in S}\zeta_s \tag{16}$$

subject to:

$$\sum_{c\in\phi} y_c^s=1, \tag{17}$$

$$\sum_{c\in\phi}\sum_{s\in S} y_c^s \le |O|, \tag{18}$$

$$r_{i,c}^s \ge y_c^s a_i^s, \tag{19}$$

$$\sum_{c\in\phi}\sum_{s\in S} r_{i,c}^s \le |I|, \tag{20}$$

$$\left(\sum_{j\in V_i^+} x_{ij}^s+\sum_{j\in V_i^-} x_{ij}^s\right) y_c^s \le 1+c_i^s+d_i^s \tag{21}$$

Constraint (17) guarantees that each configuration is assigned to one time slot. The maximum number of available channels is restricted in (18), which means the number of configurations to be activated simultaneously should be less than the number of available orthogonal channels. Constraint (19) indicates the relationship between channel and interface assignment, that is not only the channel should be utilized by node i but also this node appears in Configuration s, the interface can be assigned to this node. Constraint (20) illusrtates the available number of interfaces per node, where the number of the utilized channels by node i is no more than the total available number of its radio interfaces. Constraint (21) indicates that both the incoming and outgoing links of one node cannot be activated together in the same time slot, this is because the transmitting process to relay node and broadcasting stage to source nodes must be processed in different time slots, and cannot be activated simultaneously in the same stage, therefore, Constraint (21) is necessary in MC–MR network due to the NC characters.

In order to minimize the required time slot in (16) to maximize network throughput, we should resolve the optimization problem of CA while satisfying Constraints (17)–(21). Unfortunately, the computational complexity of the proposed CA problem is high, and we implement a heuristic algorithm to approach the optimal solution. The objective of our method is to select a feasible solution that can utilize the given number of channels and radios while satisfying all the corresponding constraints. The input of our method is the obtained configurations where the links inside are interference free, and its output is the number of time slots that can complete all the transmission task in the MC–MR situation. Similar with Capone et al. (2010), we define the maximum number of the activated time slots (Upper Bound) as $\mathrm{UB} = \varphi / \min(|O|, |I|)$, and the minimum number of the activated time slots (Lower Bound) as $\mathrm{LB} = \varphi / \max(|O|, |I|)$, where φ is the number of configurations required to be activated. The required number of time slots equals to UB initially, if a feasible solution is found (e.g. the channel and radio constraints can be satisfied according to Constraints (17)–(21)), the number of the required time slots is iteratively decreased by one. Otherwise, this process stops, and the output are the number of the required time slots and the corresponding results obtained by CA to complete the transmission task in MC–MR networks.

5. Simulation results

We employ C++ for simulation study to obtain numerical results to verify the effectiveness of our proposed algorithm. Three kinds of network topologies are considered, including the linear topology with 20 nodes, the grid topology with 25 nodes and the random topology with 30 nodes. Some source nodes are randomly selected to generate network sessions to random destination nodes in each topology, and we assume only one packet in each session is transmitted within one scheduling round by considering fairness issues. The distance between two adjacent nodes is 100 m for linear and grid topologies. In the random topology, 30 nodes are arbitrarily distributed in a square region, where each side is 333 m. A simple path loss channel model with the cross gain $G_{ij} = \chi^S_{ij}\chi^F_{ij} d_{i,j}^{-\alpha}$ is considered (Zhang et al., 2009), where d_{ij} is the Euclidean distance between nodes i and j, and α is the path loss factor equals to 2. χ^S_{ij} and χ^F_{ij} are the gains that refer to channel fluctuations caused by large-time-scale shadowing and small-time-scale channel fading, respectively. We assume the shadowing gains are constant values. Without loss of generality, the small-scale fading gain χ^F_{ij} is normalized to a random value with unit mean. The maximum transmission power is 0.6 W, the thermal noise $\delta^2 = 10^{-6}$ mW, and the SINR threshold is set to 2.5.

Since the interaction of link scheduling, NC, multi-rate transmission and channel assignment has not been studied to the best of our knowledge, we borrow the idea by Niati et al. (2011) to demonstrate the network performance gained by multicast transmission, and denote it by optimal method under multicast transmission. OM_F and OM_V are the transmission methods by considering link aggregation for multicast with Fixed and Variable transmission powers, respectively. Furthermore, two greedy methods are proposed to approach the optimal network performance, which can largely reduce the searching space. In the first case, we utilize NC opportunity to conduct concurrent transmission before performing spatial reuse, while in the second case, we activate simultaneous transmission links before using NC opportunity. We adopt OU_F and OU_V as the Optimal methods with Fixed and Variable transmission powers, respectively. SN_F and SN_V stand for the greedy methods that perform Spatial reuse prior to NC, while NS_F and NS_V represent the greedy methods that perform NC prior to Spatial reuse, both with Fixed and Variable transmission powers, respectively. Network throughput gain is defined as the ratio between μ_u and μ_s, where the former is the scheduling length by considering unicast only, and the latter is the scheduling length by considering the link combination with different transmission methods.

The achieved network throughput gains under different topologies are shown in Figs. 2–4. It can be observed that the obtained network throughput gains with fixed transmission power are lower than those achieved with variable transmission power significantly. This is because the method with fixed transmission power, which is actually the maximum transmission power,

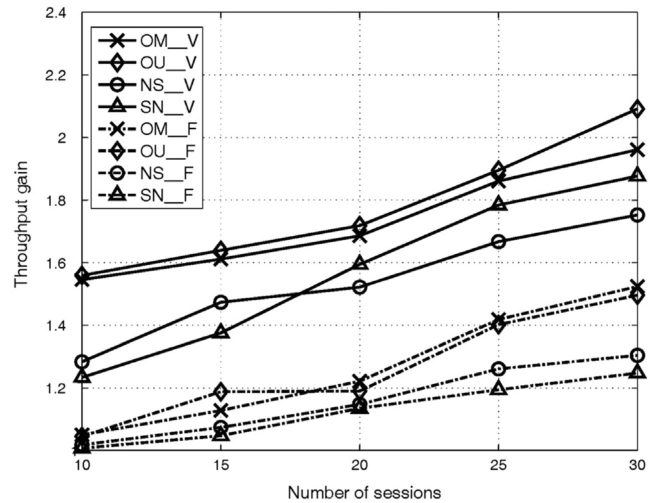

Fig. 2. Network throughput gain in the linear topology.

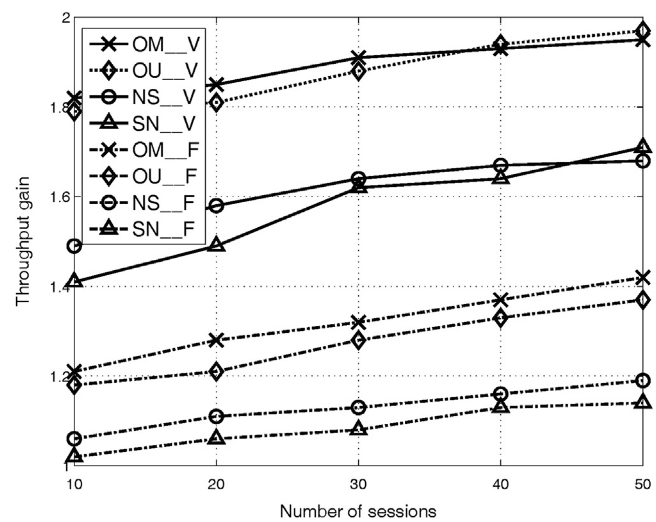

Fig. 3. Network throughput gain in the grid topology.

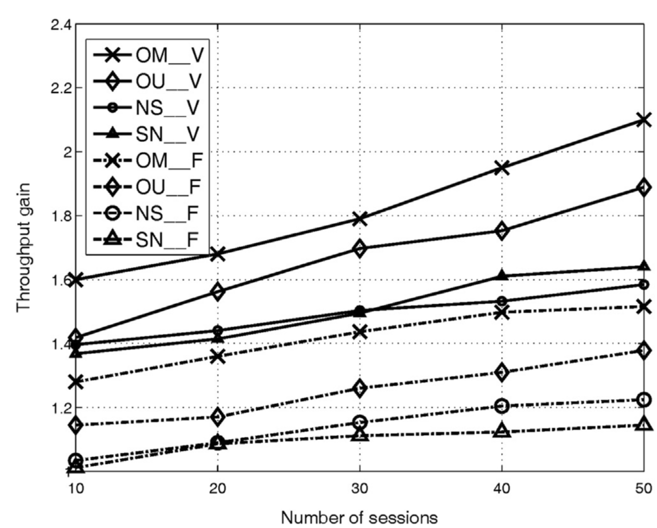

Fig. 4. Network throughput gain in the random topology.

Table 2
NC traffic percentage in the linear network topology.

	10	15	20	25	30
OU_V	0.093	0.172	0.211	0.251	0.285
OM_V	0.087	0.159	0.187	0.226	0.252
NS_V	0.139	0.196	0.313	0.357	0.369
SN_V	0.084	0.116	0.163	0.179	0.199
OPT_F	0.125	0.163	0.202	0.242	0.264
OM_F	0.111	0.161	0.196	0.239	0.248
NS_F	0.146	0.215	0.332	0.397	0.426
SN_F	0.079	0.146	0.152	0.202	0.229

Table 3
NC traffic percentage in the grid network topology.

	10	20	30	40	50
OU_V	0.122	0.133	0.145	0.171	0.173
OM_V	0.037	0.069	0.129	0.135	0.152
NS_V	0.131	0.136	0.158	0.188	0.198
SN_V	0.042	0.081	0.134	0.149	0.161
OPT_F	0.144	0.157	0.171	0.177	0.184
OM_F	0.058	0.097	0.138	0.169	0.177
NS_F	0.153	0.168	0.179	0.199	0.216
SN_F	0.039	0.059	0.092	0.125	0.145

Table 4
NC traffic percentage in the random network topology.

	10	20	30	40	50
OU_V	0.049	0.121	0.149	0.171	0.229
OM_V	0.029	0.065	0.106	0.118	0.189
NS_V	0.061	0.159	0.206	0.231	0.282
SN_V	0.031	0.092	0.116	0.134	0.164
OPT_F	0.074	0.115	0.168	0.198	0.215
OM_F	0.034	0.102	0.123	0.169	0.192
NS_F	0.083	0.162	0.231	0.267	0.296
SN_F	0.029	0.065	0.108	0.129	0.159

Table 5
Time slot requirement in the linear topology with 30 sessions under different number of channels and radios.

		$Ch=1$	$Ch=2$	$Ch=3$	$Ch=4$	$Ch=5$
OU_V	$r=1$	14.56	9.59	8.46	8.24	8.16
	$r=2$	13.07	7.43	6.27	5.28	4.78
	$r=3$	11.91	6.99	5.29	4.64	4.18
OM_V	$r=1$	14.19	9.31	8.28	8.19	8.11
	$r=2$	12.93	7.33	6.15	5.21	4.72
	$r=3$	11.86	6.82	5.27	4.56	4.04
NS_V	$r=1$	17.04	10.29	10.07	9.93	9.82
	$r=2$	13.38	9.47	6.72	6.58	6.24
	$r=3$	12.96	7.69	6.41	6.16	5.67
SN_V	$r=1$	15.78	8.95	8.73	8.59	8.14
	$r=2$	14.62	8.28	5.95	5.68	5.43
	$r=3$	14.18	8.17	5.74	5.25	4.68

increases interference and limits the possibility of spatial reuse and NC as a result. We can see that due to multicast transmission, the values of throughput gain achieved by MC_V and MC_F are larger than their counterparts in most cases. However, the gap between MC_V and OPT_V is limited, especially in the linear and grid topology. This is because for one node in the linear topology, there are only two neighboring nodes, and the situation for multicast transmission can be realized by NC. For grid network topology, the multicast transmission would increase network interference especially when the density of network flow is high. Therefore, multicast transmission is not always a good solution comparing with NC and spatial reuse in grid topology. Furthermore, although multicast transmission can increase network throughput by activating multiple links simultaneously, the transmission rate is limited by the link with the worst channel state. Therefore, the network performance gained by multicast is not so obviously. It is interesting to observe that when the network load is relatively light (i.e. the density of network session is not large), the achieved network throughput gain of NS_V is slightly better than that gained by SN_V. This is due to the opportunity for spatial reuse is few by conducting SN_V, therefore NC is mainly adopted for transmission. However, as the number of network sessions increases to some extent (i.e. the link load in the network is relatively heavy), the obtained throughput gain by SN_V is larger than that of NS_V. The reason is that parallel transmissions, achieved by utilizing variable power, can increase network throughput through spatial reuse.

Table 6
Time slot requirement in the grid topology with 50 sessions under different number of channels and radios.

		$Ch=1$	$Ch=2$	$Ch=3$	$Ch=4$	$Ch=5$
OU_ V	$r=1$	25.26	16.53	16.02	15.78	15.52
	$r=2$	23.55	14.86	10.61	9.43	9.22
	$r=3$	22.62	13.74	9.51	7.53	6.34
OM_V	$r=1$	24.11	15.77	14.92	14.71	14.67
	$r=2$	22.09	13.61	9.78	9.12	9.09
	$r=3$	21.38	12.92	8.94	6.77	6.15
NS_V	$r=1$	29.76	18.95	17.19	16.94	16.12
	$r=2$	24.71	15.52	11.54	9.95	9.66
	$r=3$	24.36	13.39	10.43	9.41	7.31
SN_V	$r=1$	29.07	19.34	18.86	18.51	18.51
	$r=2$	25.94	15.93	11.23	9.69	8.61
	$r=3$	24.85	15.29	11.67	9.13	7.32

Table 7
Time slot requirement in the random topology with 50 sessions under different number of channels and radios.

		$Ch=1$	$Ch=2$	$Ch=3$	$Ch=4$	$Ch=5$
OU_V	$r=1$	26.31	16.75	16.31	15.87	15.63
	$r=2$	24.75	14.81	9.95	8.78	8.19
	$r=3$	24.14	14.32	9.53	7.76	6.17
OM_V	$r=1$	23.36	14.98	13.61	13.32	12.97
	$r=2$	21.95	12.82	9.19	8.18	8.01
	$r=3$	20.13	11.23	8.71	8.07	7.92
NS_V	$r=1$	31.64	22.39	21.81	20.93	20.93
	$r=2$	28.58	15.96	11.88	10.43	10.38
	$r=3$	26.94	15.13	11.07	8.78	8.16
SN_V	$r=1$	30.86	21.85	19.77	19.62	19.62
	$r=2$	29.24	16.29	11.59	9.98	9.87
	$r=3$	27.35	14.84	10.42	8.73	7.81

Although the trends in Figs. 2–4 are the same, the location of the inflection points are different. We can see the inflection point appears in the linear topology when the number of sessions is less than 20, while this point comes out in the grid topology when the number of sessions is more than 40. This illustrates that different transmission schemes are more suitable for different topologies according to the link load. Compared with the schemes with fixed transmission power, the network throughput gains achieved by variable transmission power increase around 38%, 30% and 34% on average in the linear, grid and random network topologies, respectively.

Tables 2–4 show the percentage of the NC traffic, which is the ratio of the number of NC sessions (including CNC and DNF) to the number of all the sessions. We can observe that the NC traffic percentage under fixed transmission power is larger than that in the variable power situation. This is because more links can be activated simultaneously due to the decrease of network interference by power control, and more opportunities exist for utilizing different transmission methods (i.e. spatial reuse and multicast). We can also see that the NC percent in multicast situation is less than that in the optimal situations. This is because the broadcast stage of NC methods is similar with the multicast transmission. As the number of network session increases, the NC percentage in NS_F becomes larger than that in NS_V. This is due to the parallel transmissions are limited by the maximum power under the fixed power transmission situation, and some nodes can achieve better network performance by spatial reuse instead of NC with the adaptive power control method. The values of the NC traffic percentages under the optimal scheme OPT_V (OPT_F) are between the values of SN_V (SN_F) and the NS_V(NS_F), since the optimal scheme considers the interaction between NC and spatial reuse. As the number of network sessions increases, the speed enhancement of the NC percentage in the grid topology is lower than the other two topologies. This is due to the topology characteristic of grid network, and more parallel links and NC opportunities exist, which results in the interplay between NC and spatial reuse in grid topology is more tight than the other two topologies. Therefore, the nodes in grid topology have more opportunity to select transmission methods according to the channel state.

At last, we study the total required number of time slots to complete all the transmission tasks in the MC–MR WMNs under different network topologies, as shown in Tables 5–7. The results illustrate that with more radios equipped, those links connecting to the same node with transmission task can be scheduled at the same time. Given the same number of radios and channels, the optimal methods (OU_V and OM_V) can complete all the network tasks with the minimum transmission slot. The required time slots decrease as the number of channels or radios increases. For example, the required time slot for two-channel and four-radio transmission ($r=2$, $ch=4$) is almost the half of that for single-channel and two-radio transmission ($r=1$, $ch=2$). With more radios applied to each node, multiple channels become more powerful for network performance improvement. We can also observe that given the same number of radios, although the number of channels keeps increasing, the required time slots to complete all the transmission tasks decrease to some extent and then keep almost stable. From the simulation results, we note that if there are C channels in the network, where $2 \le C \le 5$, at least $(C-1)$ radios per-node are needed in order to make full use of these C channels.

6. Conclusions

In order to exploit the wireless spectrum resource effectively, concurrent transmission links should be scheduled adaptively so that network performance can be optimized. Although the validities for throughput improvement by link scheduling, NC and channel assignment techniques have been studied, less attention has been paid to their interactions. In this paper, we present a two-phase solution. The first step is to allocate the interference-free links to the same configuration that can be activated in the same time slot and channel, by considering the interaction between NC and spatial reuse, and a novel metric to evaluate the contribution of transmission rates brought by different schemes is presented. On the second step, we assign the configurations, obtained by the first step, to different channels according to device characteristics and constraints, with the objective of minimizing the number of time slots. Due to the high computational complexity of the CA problem, a heuristic method is presented. Simulation results have demonstrated that, multicast transmission is not always the best choice, especially when more opportunities exist to conduct NC and spatial reuse. Besides, NC is preferred in the light-loaded network while spatial reuse is welcomed in the heavy-loaded network. It has also been shown that our scheme outperforms other methods since it makes a comprehensive consideration between spatial reuse and NC in MC–MR network.

Acknowledgements

This work was supported in part by the National Natural Science Foundation of China (91438110, 61302072, 61203165, 61174174), the Fundamental Research Funds for the Central Universities (DUT15RC(3)009, DUT15QY06, N140405007), the Program for New Century Excellent Talents in University (NCET-12-0102), and State Key Lab. for Novel Software Technology, Nanjing University (KFKT2015B12).

References

Alicherry M, Bhatia B, and Li L. Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks. In Proceedings of the ACM MobiCom; 2005. p. 58–72.
Capone A, Carello C, Filippini I, Gualandi S, Malucelli F. Routing, scheduling and channel assignment in wireless mesh networks: optimization models and algorithms. Ad Hoc Netw 2010;8(6):545–63.
Chi Y. and Agrawal D.Murco: an opportunistic network coding framework in multi-radio networks. In: Proceedings of the IEEE ICC; 2012. p. 5371–75.
Chieochan S, Hossain E. Channel assignment for throughput optimization in multi-channel multi-radio wireless mesh networks using network coding. IEEE Trans Mobile Comput 2013;12(1):118–35.
Cui T, Chen L, Ho T. "On distributed scheduling in wireless networks exploiting broadcast and network coding,". IEEE Trans Commun 2010;58(4):1223–34.
Farzinvash L, Dehghan M. Multi-rate multicast routing in multi-gateway multi-channel multi-radio wireless mesh networks. J Netw ComputAppl 2014;40:46–60.
Galvez J, Ruiz P. Joint link rate allocation, routing and channel assignment in multi-rate multi-channel wireless networks. Ad Hoc Netw 2015;29:78–98.
Kumara N, Kumara M, Patelb R. Capacity and interference aware link scheduling with channel assignment in wireless mesh networks. J Netw Comput Appl 2011;34(1):30–8.
Li H, Wu C, Li Z, Huang W, and Lau F. Stochastic optimal multirate multicast in socially selfish wireless networks. In: Proceedings of the INFOCOM; 2012. p. 172–80.
Lu H. and Liao W. Cooperative multicasting in network-coding enabled multi-rate wireless relay networks. In Proceedings of the INFOCOM; 2012. p. 334–42.
Mohammed A, Dai B, Huang B, Azhar M, Xu G, Qin P, et al. A survey and tutorial of wireless relay network protocols based on network coding. J Netw Comput Appl 2013;36(2):593–610.
Nelson R, Kleinrock L. Spatial TDMA: a collision-free multihop channel access protocol. IEEE Trans Commun 1985;33(9):934–44.
Niati R, Banihashemi A. and Kunz T. Scheduling and network coding in wireless multicast networks: a case for unequal time shares. In: Proceedings of the IEEE WCNC; 2011. p. 891–6.
Ning Z, Song Q, Guo L, and Jamalipour A. Throughput improvement by network coding and spatial reuse in wireless mesh networks. In: Proceedings of the IEEE GLOBECOM; 2013. p. 5072–7.
Ning Z, Song Q, Guo L, and Okamura K. Social-oriented adaptive transmission in wireless Ad Hoc networks. In: Proceedings of the IEEE ICC; 2014. p. 490–5.
Raayatpanah M, Fathabadi H, Khalay B, Khodayifar S. Bounds on end-to-end statistical delay and jitter in multiple multicast coded packet networks. J Netw Comput Appl 2014;41:217–27.
Rajawat K, Giannakis G. Joint scheduling and network coding for multicast in delay-constrained wireless networks. IEEE Trans Signal Process 2011;59(12):6186–96.
Sharma S, Shi Y, Liu Y, Hou Y, and Kompella S.Is network coding always good for cooperative communications? In: Proceedings of the IEEE INFOCOM; 2010. p. 1–9.
Su H, Zhang X. Modeling throughput gain of network coding in multi-channel multi-radio wireless Ad hoc networks. IEEE J Sel Areas Commun 2009;27 (5):593–605.

Wang J, Shi W, Cui K, Jin F, Li Y. Partially overlapped channel assignment for multi-channel multi-radio wireless mesh networks. EURASIP J Wirel Commun Netw 2015, 25. http://dx.doi.org/10.1186/s13638-015-0259-8.

Wang S, Song Q, Wang X, Jamalipour A. Rate and power adaptation for analog network coding. IEEE Trans Veh Technol 2011;60(5):2302–13.

Yomo H, Popovski P. Opportunistic Scheduling for Wireless Network Coding. IEEE Trans Wirel Commun 2009;8(6):2766–70.

You L, Ding L, Wu P, Pan Z, Hu H, Song M, et al. Cross-layer optimization of wireless multihop networks with one-hop two-way network coding. Comput Netw 2011;55(8):1747–69.

Zhang J, Liew S, and Fu L.On fast optimal STDMA scheduling over fading wireless channels. In: Proceedings of the IEEE INFOCOM; 2009. p. 1710–8.