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

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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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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.

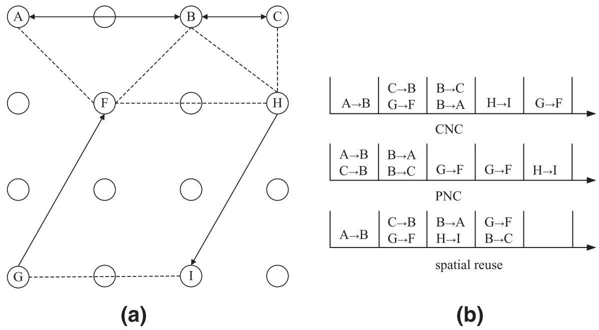

Fig. 1. (a) Illustration topology, and (b) optimal scheduling length for CNC, PNC and spatial reuse respectively.

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 $G \to F$ and $H \to I$. 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 $A \to B$, $B \to C$, $C \to B$ and $B \to A$. 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,

[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.

and the source nodes can decode the superposed packet due to the awareness of the packets sent by themselves.

Denote $P_{X,Y}$ as the transmission power from nodes X to Y, where X and Y represent the arbitrary nodes in Fig. 1(a). In order to guarantee nodes A and C can obtain the coded packet during the BC stage for both CNC and PNC, the transmission power of relaying node B is P_B=max ($P_{B,A}$, $P_{B,C}$), so that the intended receiver with worse channel state can decode the broadcasted packet successfully. However, it is known that high transmission power suppresses other neighboring transmissions. To illustrate this problem, we now activate links $G \to F$ and $H \to I$, where link $G \to F$ has two packets, and all the other links have one packet for transmission. It can be observed in Fig. 1(b) that five time slots are necessary to complete the transmission task if CNC is performed. For PNC, the scheduling length is also five time slots although links $A \to B$ and $C \to B$ can be activated simultaneously for packet transmission in the MA stage. Then, we attempt to fulfill link transmissions in a parallel method by spatial reuse where the coding opportunity at node B is not exploited. Under this situation, transmissions can be activated on links $B \to C$ and $G \to F$ simultaneously within one time slot, and four time slots are enough for packet transmission. This is because node B transmits with power $P_{B,C}$ ($P_{B,C} < P_{B,A}$) instead of broadcasting with power P_B in the BC stage. Therefore, NC may not always achieve high network throughput, and its interaction with other transmission methods should not be ignored.

It has been demonstrated in [13,14] that the interplay between NC and spatial reuse with single rate transmission is an NP-complete problem. The challenge escalates if we take multi-rate transmission into consideration. Suppose in Fig. 1(a), where the distance between nodes C and B is significantly shorter than that between nodes A and B, since the maximum transmission power is required during the BC phase, the achievable transmission rate of packet y on link $B \to C$ is much larger than that of packet x on link $B \to A$. However, the broadcast transmission is dominated by the link with worse channel state, which leads to a rate reduction of the link with better channel state. Therefore, the interplay between NC gain and rate adaptation should be analyzed.

The promising link scheduling, spatial reuse, power and rate adaptation, and NC techniques motivate us to investigate the network performance gain achieved by integrating these techniques in multi-rate WMNs in order to maximize network throughput. The main contributions of this paper are as follows:

- We formulate the NC-aware link scheduling method as an integer linear programming (ILP) problem with multi-rate transmission in general WMNs, which supports different transmission methods, including store and forward-based unicast, NC-based multicast, and spectrum spatial reuse-based parallel transmissions to decide a set of links that can be activated simultaneously.
- Due to the high computational complexity of the proposed ILP problem, we develop a column generation (CG)-based method to decompose this problem into a master problem (MP) and pricing problem (PP) without losing optimality. In order to reduce the computational complexity of the PP further, we propose a distributed power control (DPC) scheme to solve the problem iteratively with a heuristic method, and work out its computational complexity.
- By evaluating network performance of the presented scheme through extensive simulations, we show that NC is preferred in the light-loaded network while spatial reuse is welcomed in the heavy-loaded network under the condition that link load is balanced. However, spatial reuse always outperforms NC when the link load is unbalanced.

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.
η	Thermal noise.
$P_{\max}$	Maximum transmission power of each node.
$P^s_{i,\mathrm{BC}}$	Broadcast power of node i in configuration s.
$P^s_{i,j}$	Transmission power from nodes i to j in configuration s.
$G_{i,j}$	Channel gain between nodes i and j.
$w_{i,j}$	Transmission rate on link $l_{i,j}$.
$\Gamma_{w_{i,j}}$	SINR threshold of link $l_{i,j}$ at rate $w_{i,j}$.
$Q^s_{i,j}$	Number of packets intended to be sent on link $l_{i,j}$ in configuration s per time slot.
$x^s_{i,j}$	Binary variable which is 1 if link $l_{i,j}$ is activated in configuration s.
u^s_{i,w_U}	Binary variable which is 1 if node i transmits uncoded packets in configuration s at rate w_U.
c^s_{i,w_C}	Binary variable which is 1 if node i transmits CNC-coded packets in configuration s at rate w_C.
d^s_{i,w_D}	Binary variable which is 1 if node i transmits DNF-coded packets in configuration s at rate w_D.
λ_s	Integer variable which represents the number of time slots for completing transmissions in configuration s by CG.
$\sigma^s_{i,j}$	Dual variable related to Constraint (22).

The remainder of this paper is organized as follows: The NC-aware link scheduling scheme is presented in Section 2. In Section 3, we introduce the CG-based method and present a distributed power control method to solve the PP with low computational complexity. The simulation results are shown in Section 4. Finally, some concluding remarks are provided in Section 5.

2. NC-aware link scheduling scheme

The objective of our NC-aware link scheduling scheme is to identify the link sets, which contain interference-free links that can be activated concurrently. The link set is defined as transmission configuration, where the transmission method and the power of each link are decided. The major notations used in this paper are shown in Table 1.

In our work, each packet is scheduled in a time division multiple access (TDMA)-based fashion [13–15], where the packet size is assumed to be fixed for simplicity.[2] In the TDMA-based model, the channel is further divided into a control sub-channel and a data sub-channel. The former is utilized to allocate time slots for packet transmission across

2 The problems on scheduling packets with variable sizes for CNC and PNC have been addressed in [16] and [17], respectively.

the data sub-channel, and it is also used by nodes to report their activities. Thus, the information interaction among different nodes for scheduling can be performed by making some changes in the control sub-channel. This assumption is reasonable in most cases since several wireless networks, including IEEE 802.11 Wireless Local Area Networks (WLANs), IEEE 802.16 Wireless Metropolitan Area Networks (WMANs) and the next generation cellular systems, perform in a centralized fashion, so that TDMA is commonly employed to guarantee the quality of service among individuals. Furthermore, nodes in WMNs can be mesh routers and mesh clients (PC, PDA et al), and most of them have strong computational capabilities since they usually do not have strict constraints on power consumption. Therefore, it is possible for the mesh nodes to collect and exchange information from the neighboring nodes.

Node pair $j-j'$ is defined as one session for transmission if the nodes can communicate with each other directly. If node j deliveries packets to node j' with the help of an intermediate node i, we refer the node group $j-i-j'$ as one session in the relay-based situation. We model the network as a directed graph G=(V, E), where V is a set of nodes and E is a set of links between the nodes. Each node is able to adjust its transmission power within a given range [0, $P_{\max}$], where $P_{\max}$ is the maximum transmission power. The nodes can convey packets with one of the transmission rates in the set $W=\{w_1, w_2, \ldots, w_{\max}\}$, where $w_1 < w_2, \ldots < w_{\max}$. Similar with [15], we define the minimum transmission rate w_1 as only one packet can be transmitted during one time slot. Channel time is slotted into identically synchronized time slot, and its duration equals to the time that is able to complete one-packet transmission under the lowest rate w_1. The transmission on link $l_{j,j'}$ is acceptable (in transmission rate and correctness) if the received SINR at node j' (denoted by $\Gamma_{j'}$) is no less than a certain threshold $\Gamma_{w_{j,j'}}$ with rate $w_{j,j'}$. The SINR constraint for unicast transmission is:

$$\Gamma_{j'} = \frac{P^s_{j,j'} G_{j,j'}}{\eta + \sum_{h \in V-\{j\}} P^s_{h,j'} G_{h,j'}} \geq \Gamma_{w_{j,j'}}, \tag{1}$$

where $P^s_{j,j'}$ is the transmission power from nodes j to j' in configuration s. $G_{j,j'}$ is the cross gain between nodes j and j', which is determined by the aggregate effects of path loss, channel fading and lognormal shadowing. A reciprocal channel state ($G_{j,j'} = G_{j',j}$) is assumed as most of the previous works. The denominator in (1) is the summation of the background noise η and the interference generated by other concurrent transmissions.

DeNoise-and-Forward (DNF) and amplify-and-forward are two common PNC methods. The DNF method is considered in our work since it avoids noise amplification [18]. 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 discussed in [19]. For the DNF method in the MA stage, the minimum received power, namely min $(P^s_{j,i}G_{j,i}, P^s_{j',i}G_{j',i})$, is utilized for SINR calculation. Without loss of generality, we assume $P^s_{j,i}G_{j,i} < P^s_{j',i}G_{j',i}$, and the SINR constraint for DNF is:

$$\Gamma_i = \frac{P^s_{j,i} G_{j,i}}{\eta + \sum_{h \in V-\{j,j'\}} P^s_{h,i} G_{h,i}} \geq \Gamma_{w_{j,i}} \tag{2}$$

Let S be the set of all possible configurations utilized to carry a set of sessions in the network, and μ_s be an integer variable representing the number of time slots for a certain configuration $s \in S$ to be scheduled. Let $x^s_{i,j}$ be a binary variable, which is 1 if link $l_{i,j}$ is activated in configuration s, and 0 otherwise. We set u^s_{i,w_U}, c^s_{i,w_C} and d^s_{i,w_D} as the binary transmission variables to denote whether node i transmits an uncoded, CNC-coded and DNF-coded packet with a specific rate in configuration s or not. Define V_i as a set of one-hop neighboring nodes of node i. For any node $j \in V_i^+$ or $j \in V_i^-$, node j is an outgoing or incoming node with respect to node i. Denote $Y^s_{i,j}$ as the number of packets on session $i-j$ intended to be transmitted by node i in configuration s, $\sum_{j' \in V_i^- -\{j\}} Y^s_{j,i,j'}$ express the number of packets carried by sessions $j-i$ and $j'-i$ in the MA stage of DNF, and $\sum_{j' \in V_i^+ -\{j\}} Y^s_{j,i,j'}$ represent the number of packets broadcasted by relaying node i on sessions $i-j$ and $i-j'$ in the BC stage for both CNC and DNF in configuration s. $Q^s_{i,j}$ is the number of packets on session $i-j$ to be transmitted in configuration s per time slot. The NC-aware scheduling problem can be formulated as follows:

$$\min \sum_{s \in S} \mu_s \tag{3}$$

Variables: $x^s_{i,j}$, u^s_{i,w_U}, c^s_{i,w_C}, d^s_{i,w_D} and $P^s_{i,j}$.

Subject to:

$$x^s_{i,j} + x^s_{j,i} \leq 1, \tag{4}$$

$$u^s_{i,w_U} + c^s_{i,w_C} + d^s_{i,w_D} \leq 1, \tag{5}$$

$$\sum_{j \in V-\{i\}} x^s_{i,j} \leq 1 + \left(1 - u^s_{i,w_U}\right), \tag{6}$$

$$\sum_{s \in S} \left(u^s_{i,w_U} + c^s_{i,w_C} + d^s_{i,w_D}\right) x^s_{i,j} \mu_s Q^s_{i,j} \geq u^s_{i,w_U} Y^s_{i,j} + \sum_{j' \in V_i^- -\{j\}} d^s_{i,w_D} Y^s_{j,i,j'} + \sum_{j' \in V_i^+ -\{j\}} \left(c^s_{i,w_C} + d^s_{i,w_D}\right) Y^s_{j,i,j'} \tag{7}$$

The objective of the optimization problem is to minimize the total activating time by proper link scheduling and relaying method selection. This is because the network throughput can be maximized if the totally required activating time $\Sigma_{s \in S} \mu_s$ for completing the entire transmission task is minimized. Half-duplex property is illustrated in Constraint (4), that is any node cannot transmit and receive simultaneously in the same configuration. Constraint (5) ensures that node i can choose at most one transmission mode during one scheduling period. If node i is in the unicast mode ($u^s_{i,w_U} = 1$), at most one link is activated during one time slot, which is guaranteed in Constraint (6). The constraint of network capacity is demonstrated in (7), which ensures that one link should be activated for enough time to complete all the sessions on the links.

We consider the fixed transmission power scheme first, where each node transmits with $P_{\max}$. Then we extend this scheme to a general case, where the transmission power of each node varies. The SINR constraint for the fixed transmission power is:

$$P_{\max} G_{j,j'} + M^s_{j,j'}\left(1 - x^s_{j,j'}\right) \geq \Gamma_{w_{j,j'}} \times \left[\eta + \sum_h P_{\max} G_{h,j'}\left(u^s_{h,w_U} + c^s_{h,w_C} + d^s_{h,w_D}\right)\right], \quad (8)$$

where $h \in V - \{j, j'\}$, and $M^s_{j,j'}$ is a constant value satisfying $M^s_{j,j'} \geq \Gamma_{w_{j,j'}}[\eta + \sum_h P_{\max} G_{h,j'}(u^s_{h,w_U} + c^s_{h,w_C} + d^s_{h,w_D})]$. The right-side summation in (8) corresponds to the cumulative interference at receiving node j' caused by other transmissions.

The transmission modes supported by relaying node i can be decided according to Constraints (9)–(14).

$$d^s_{i,w_D} + c^s_{i,w_C} \geq \sum_{j \in V_i^+} x^s_{i,j} - 1, \quad (9)$$

$$d^s_{i,w_D} \geq \sum_{j \in V_i^-} x^s_{i,j} - 1, \quad (10)$$

$$d^s_{i,w_D} \leq \sum_{j \in V_i^-} x^s_{i,j} - u^s_{i,w_U} - c^s_{i,w_C}, \quad (11)$$

$$u^s_{i,w_U} \geq x^s_{i,j} - c^s_{i,w_C} - d^s_{i,w_D}, \quad (12)$$

$$u^s_{i,w_U} \leq \sum_{j \in V_i^+} x^s_{i,j}, \quad (13)$$

$$1 + \sum_{j' \in V_i^+ - \{j\}} x^s_{i,j'} \geq x^s_{i,j} + c^s_{i,w_C} + d^s_{i,w_D} \quad (14)$$

Constraint (9) ensures that if more than one outgoing flow is from node i, it is able to perform either DNF or CNC. If more than one incoming flow is activated (at most two flows unless sophisticated self-interference cancellation techniques are adopted [19]), node i can conduct DNF as demonstrated in (10). If there is only one incoming flow to relaying node i ($u^s_{i,w_U} = 1$ or $c^s_{i,w_C} = 1$), it cannot perform DNF so that d^s_{i,w_D} is forced to 0 in (11). Constraint (12) forces u^s_{i,w_U} to 1 when only one link is activated, and the NC methods cannot be utilized under this situation. u^s_{i,w_U} is restricted to 0 in (13) if no link is activated. If more than one of the outgoing links are activated simultaneously, the relay node is in the BC stage ($c^s_{i,w_C} = 1$ or $d^s_{i,w_D} = 1$) as demonstrated in (14).

The fixed transmission power scheme is simple; however, not only inter-node interference increases significantly, but also the opportunities of spectrum spatial reuse are reduced with this scheme. Therefore, the transmission power of each node should be adaptively adjusted to allow more parallel transmissions while satisfying the SINR constraint.

Derived by (1), when the transmission is in the unicast mode, the SINR constraint becomes:

$$P^s_{j,j'} G_{j,j'} + M^s_{j,j'}[(1 - x^s_{j,j'}) + (1 - u^s_{j,w_U})] \geq \Gamma_{w_{j,j'}} \times \left[\eta + \sum_h P^s_{h,j'} G_{h,j'} u^s_{h,w_U} + \sum_h P^s_{h,BC} G_{h,j'}\left(c^s_{h,w_C} + d^s_{h,w_D}\right)\right], \quad (15)$$

Table 2
The utilized ILP to minimize the total activating time.

Objective:
min $\Sigma_{s \in S} \mu_s$
Subject to:
—Transmission method conditions:
Constraints (4)–(7) and (9)–(14).
—Transmission power conditions:
For fixed power: Constraints (8).
For variable power: Constraints (15)–(20).
—Variables:
$x^s_{i,j}, u^s_{i,w_U}, c^s_{i,w_C}, d^s_{i,w_D} \in [0, 1], P^s_{i,j} \in (0, P_{\max}]$

where $h \in V - \{j, j'\}$, and $P^s_{h,BC}$ is the broadcast power when node h is in the BC stage of CNC or DNF. $M^s_{j,j'}$ is a constant value satisfying $M^s_{j,j'} \geq \Gamma_{w_{j,j'}}[\eta + \sum_h P^s_{h,j'} G_{h,j'} u^s_{h,w_U} + \sum_h P^s_{h,BC} G_{h,j'}(c^s_{h,w_C} + d^s_{h,w_D})]$. The corresponding transmission power for unicast should satisfy:

$$\frac{\eta u^s_{j,w_U}}{G_{j,j'}} \Gamma_{w_{j,j'}} \leq P^s_{j,j'} \leq u^s_{j,w_U} \times P_{\max}, \quad (16)$$

where the low bound shows the case that no parallel transmission happens in the network.

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

$$P^s_{j,i} G_{j,i} + M^s_{j,i}\left[\left(1 - x^s_{j,i}\right) + \left(1 - d^s_{j,w_D}\right)\right] \geq \Gamma_{w_{j,i}} \times \left[\eta + \sum_h P^s_{h,i} G_{h,i} u^s_{h,w_U} + \sum_h P^s_{h,BC} G_{h,i}\left(c^s_{h,w_C} + d^s_{h,w_D}\right)\right], \quad (17)$$

where $h \in V - \{i, j\}$, and $M^s_{j,i} \geq \Gamma_{w_{j,i}}[\eta + \sum_h P^s_{h,i} G_{h,i} u^s_{h,w_U} + \sum_h P^s_{h,BC} G_{h,i}(c^s_{h,w_C} + d^s_{h,w_D})]$. Similarly with (16), the corresponding transmission power for the DNF method should satisfy:

$$\frac{\eta d^s_{j,w_D}}{G_{j,i}} \Gamma_{w_{j,i}} \leq P^s_{j,i} \leq d^s_{j,w_D} \times P_{\max}, \quad (18)$$

In the BC stage of both CNC and DNF, the SINR constraint in node j (similar for node j') can be computed as:

$$P^s_{i,BC} G_{i,j} + M^s_{i,j}\left[\left(1 - x^s_{i,j}\right) + \left(1 - c^s_{i,w_C} - d^s_{i,w_D}\right)\right] \geq \Gamma_{w_{i,j}} \times \left[\eta + \sum_h P^s_{h,j} G_{h,j} u^s_{h,w_U} + \sum_h P^s_{h,BC} G_{h,j}\left(c^s_{h,w_C} + d^s_{h,w_D}\right)\right], \quad (19)$$

where $h \in V - \{i, j, j'\}$, and $M^s_{i,j} \geq \Gamma_{w_{i,j}}[\eta + \sum_h P^s_{h,j} G_{h,j} u^s_{h,w_U} + \sum_h P^s_{h,BC} G_{h,j}(c^s_{h,w_C} + d^s_{h,w_D})]$. The constraint of the broadcast power is:

$$\varepsilon(c^s_{i,w_C} + d^s_{i,w_D}) \leq P^s_{i,BC} \leq (c^s_{i,w_C} + d^s_{i,w_D}) \times P_{\max} \quad (20)$$

where $\varepsilon \ll 1$ to satisfy that the broadcast power is between $[0, P_{\max}]$.

After obtaining the constraints stated above, we utilize Table 2 to illustrate the complete formulated ILP problem. Therefore, one configuration is the set of interference-free links identified by $x^s_{i,j}, u^s_{i,w_U}, c^s_{i,w_C}, d^s_{i,w_D}$ and transmission power. Due to the high computational complexity of the formulated optimization problem, we will propose a CG-based method with low computational complexity to resolve this problem in the next section.

3. Column generation-based method

The solution of the formulated optimization problem ($\min \Sigma_{s \in S} \mu_s$) relies on the set of all possible feasible configurations in S. Since the computational complexity of enumerating all the configurations is high especially when the size of network is large, a method which can approach to the optimal solution with low computational complexity should be adopted to resolve this problem. The CG-based method, which was originally presented in [20], is selected to resolve the NC-aware scheduling scheme in our work due to its computational efficiency [13,21], and the capability of CG to get the global or a near global optimal of an ILP solution has been demonstrated in [22].

Our CG-based method decomposes the NC-aware link scheduling problem into two subproblems, namely MP and PP. The MP starts with a small subset of columns S_0 ($S_0 \in S$) to resolve the problem preliminary, where the columns correspond to the transmission configurations. The PP is to identify whether the MP should be enlarged with additional columns or not. Therefore, as opposed to the linear programming (LP), where all the columns are utilized at the same time to obtain the optimal solution, CG alternates between the MP and the PP, until the MP contains the necessary columns required to obtain the optimal solution of the original problem. Furthermore, in order to reduce the computational complexity of the CG further, we present a DPC scheme, which enables us to remove the continuous variables from the PP.

3.1. Master problem

The objective of the MP is to find:

$$\min \sum_{s \in S_0} \lambda_s \tag{21}$$

Subject to:

$$\sum_{s \in S_0} \left(u^s_{i,w_U} + c^s_{i,w_C} + d^s_{i,w_D}\right) x^s_{i,j} \lambda_s Q^s_{i,j} \geq u^s_{i,w_U} Y^s_{i,j} + \sum_{j' \in V_i^- - \{j\}} d^s_{i,w_D} Y^s_{j,i,j'} + \sum_{j' \in V_i^+ - \{j\}} \left(c^s_{i,w_C} + d^s_{i,w_D}\right) Y^s_{j,i,j'}, \tag{22}$$

where λ_s is the number of time slots, for which configuration s is activated in the CG.

We can resolve the MP by LP relaxation [22], where λ_s is relaxed to a real value instead of an integer value, and obtain a preliminary optimal solution. Then the selected column (configuration) is resolved by setting λ_s as an integer variable in the LP problem. Once the MP has obtained the optimal solution, the column obtained by the CG and the LP is the same and the CG procedure terminates. Otherwise, the obtained solution is a lower bound of the optimal value.

3.2. Pricing problem

The PP keeps producing and adding columns to the MP as long as other configurations, which have better solutions to the MP, exist. Define $\delta^s_{i,j}$ as the dual variable associated to Constraint (22), and the reduced cost in PP is expressed as: $(1 - \sum_{l_{i,j} \in E} x^s_{i,j} \delta^s_{i,j})$. Based on the LP theory [22], any column with a negative reduced cost is a new and better solution to the MP. In other words, if we attempt to minimize λ_s in the MP, its dual variable $\delta^s_{i,j}$ associated to (22) should be maximized, that is $\sum_{l_{i,j} \in E} x^s_{i,j} \delta^s_{i,j}$ should be maximized and the reduced cost should be minimized. Therefore, the objective of the PP can be written as:

$$\min \left(1 - \sum_{l_{i,j} \in E} x^s_{i,j} \delta^s_{i,j}\right) \tag{23}$$

Subject to: Constraints (4)–(14) if transmitting with fixed power.

Subject to: Constraints (4)–(7) and (9)–(20) if transmitting with variable power.

We select the column which can lead to the most negative reduced cost among all the remaining columns, and add it into the MP during each iteration of CG. If the generated reduced cost is no less than 0, it means the network performance cannot be improved further, and CG terminates.

The MP is actually a small-scale LP problem and can be easily resolved by simplex method or branch-and-bound method. However, the PP is difficult to resolve since it contains both binary and continuous variables (e.g., transmission powers). In order to reduce the computational complexity brought by the continuous variables in (15)–(20), we propose a distributed algorithm to control the transmission power of each node.

3.3. Heuristic solution for PP

Due to the high complexity of the PP, we present a heuristic solution, named DPC scheme, which can solve PP efficiently with low computation complexity. The main idea of the DPC scheme is to add the links into the configuration through an iterative approach. Firstly, we rewrite the SINR constraint as:

$$P^s_{i,j} \geq \frac{I^s_j \Gamma_{w_{i,j}}}{G_{i,j}}, \tag{24}$$

where $I^s_j = \sum_{h \in V - \{i\}} P^s_{h,j} G_{h,j} + \eta$. If the computed SINR of one link cannot reach the corresponding threshold, it cannot be joined into the link configuration.

Since no transmission is activated at first, the initial link set in configuration s is empty. In order to reduce interference, the link with better channel state should be given higher priority for transmission. Similarly with [23], the link scheduling metric is defined as:

$$l_{(i \to j)} = \arg\left\{\max_{i,j \in V} \left(\frac{\Gamma_{w_{i,j}} G_{i,j}}{\sum_{h \in V - \{i\}} G_{h,j}}\right)\right\}, \tag{25}$$

where $w_{i,j}$ is the maximum possible transmission rate when link $l_{i,j}$ is activated. It is noted that the maximum number of packets to be delivered within one time slot should be no more than the total number of packets intended to be transmitted on the selected link; otherwise, the allocated network resource will be wasted. After selecting the optimal link for packet transmission at the first round, the minimum transmission power is:

$$P^s_{i,j} \geq \frac{\Gamma_{w_{i,j}}\eta}{G_{i,j}} \tag{26}$$

Note that if we intend to add another link $l_{m,n}$ with transmission power $P^s_{m,n}$ into configuration s according to (25), the interference of all the existing links in the configuration will at least increase by:

$$\Delta I^s_j \geq P^s_{m,n} G_{m,j} \tag{27}$$

In order to keep the transmissions in configuration s feasible after new links are added, the minimum increased power of one link in configuration s is:

$$\Delta P^s_{i,j} = \frac{\Delta I^s_j \Gamma_{w_{i,j}}}{G_{i,j}} \geq \frac{P^s_{m,n} G_{m,j}\Gamma_{w_{i,j}}}{G_{i,j}} \tag{28}$$

This puts a limit on transmission power $P^s_{m,n}$ of link $l_{m,n}$:

$$P^s_{m,n} \leq \frac{\Delta P^s_{i,j} G_{i,j}}{G_{m,j}\Gamma_{w_{i,j}}} = \frac{\left(P_{max} - P^s_{i,j}\right)G_{i,j}}{G_{m,j}\Gamma_{w_{i,j}}} \tag{29}$$

We then choose the link that has the maximum SINR value at the receiver:

$$l_{(m\to n)} = \arg\left\{\max_{m,n\in V-\{i,j\}}\left\{\min_{i,j\in V}\frac{\left(P_{\max} - P^s_{i,j}\right)G_{i,j}G_{m,n}}{G_{m,j}\Gamma_{w_{i,j}}I^s_n}\right\}\right\} \tag{30}$$

The maximum possible rate is assigned to this link based on the SINR value. If the transmission power of the newly selected link exceeds $P_{\max}$, this link cannot be added into the current configuration and the iteration of link selection is terminated. Otherwise, we repeat the iteration process and add the unicast links into the configuration until no more links can be added. After that, the number of the residual packets is calculated, and the process of the DPC algorithm goes on until all the transmission tasks are finished.

After conducting the DPC scheme, the only variables are binary to denote the corresponding relaying method, and the continuous power variables have been removed, which means the high computational complexity brought by the continuous variables in (15)–(20) can be reduced, and the PP after DPC algorithm becomes much easier to solve than the original PP.

Complexity of the CG-based method: Since the restricted MP in the CG-based method is an LP problem, it can be solved by the polynomial interior algorithm introduced in [24], whose computation complexity is O(n^3), and n is the number of the variables in the problem. Next, we study the computational complexity of the DPC method for the solution of PP problem.

Define the number of available data rates equal to m, the size of the maximum independent set of the concurrent transmission link set is denoted as C, and $|L|$ is the number of links to be scheduled. The selection of a maximal independent set from the link set collection in an iterative method requires an order of $m^2|L|^2$ computations. To check the feasibility of an independent set, our algorithm has to solve a number of linear inequalities with a size of at most $C \times C$, thus an order of C^2 computation is required. Hence, the computation complexity for the worst case of DPC algorithm is O($m^2|L|^2C^2$), and the computation complexity of the CG-based method is O($m^6|L|^6C^6$). Since m is a small number compared with L and C, the computational complexity is mainly decided by the numbers of links to be activated and the concurrent transmission links.

4. Simulation results

In order to evaluate the feasibility and efficiency of our schemes, we consider three kinds of network topologies including the linear topology with 20 nodes, the grid topology with 25 nodes and the random topology with 30 and 50 nodes, respectively. Some source nodes are randomly selected to generate sessions to random destination nodes in each topology. 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. Computational tests have been run on an Intel CORE i7 at 3 GHz and with 8 GB RAM. We consider a simple path loss channel model with the cross gain, which can be expressed as $G_{i,j} = \beta^S_{i,j}\beta^F_{i,j}d^{-\alpha}_{i,j}$ [25], where $d_{i,j}$ is the Euclidean distance between nodes i and j, and α is the path loss factor set to 2. $\beta^S_{i,j}$ and $\beta^F_{i,j}$ 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 $\beta^F_{i,j}$ is normalized to a random value with unit mean. The maximum transmission power $P_{\max}$ and the thermal noise η are set to 0.6 W and 10^{-6} mW, respectively.

We first consider only one packet is transmitted in each session by taking the fairness issue into account. Then we extend this situation by considering a more general scenario, where the number of packets intended to be transmitted is randomly generated from 1 to 10 in each session. For multirate transmission, we also set the SINR thresholds to 2.5, 3.8, 7.1 and 15.9, respectively for 1, 2, 4 and 8 packets transmitted per time slot as in [15]. Considering the interaction between NC and spatial reuse, we present two greedy methods to approach to the optimal network performance while reducing searching space. In the first case, we assign priority to NC (i.e., utilizing NC opportunities to activate concurrent transmissions before conducting spatial reuse); and in the second case, we assign priority to spatial reuse (i.e., searching the links that can be simultaneously activated for parallel transmissions before utilizing NC opportunities).

Denote OPT_F and OPT_V as the OPTimal methods (i.e., by enumerating all the feasible configurations) with fixed and variable transmission powers, respectively. CG_V represents the CG-based method with variable transmission power. We use SN_ F and SN_V to stand for the greedy methods that perform spatial reuse prior to NC, and denote NS_F and NS_V to stand for the greedy methods that conduct NC prior to spatial reuse, with fixed and variable transmission powers, respectively. We first compare the NC traffic percentage and throughput gain. The former is defined as the ratio of the number of NC sessions (including DNF and CNC) to the number of all the sessions, and the latter is defined as the ratio between μ_u and μ_s, where the former is the scheduling length

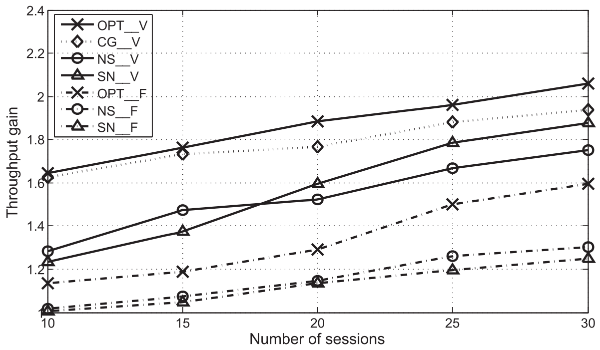

Fig. 2. Network throughput gain in the linear topology.

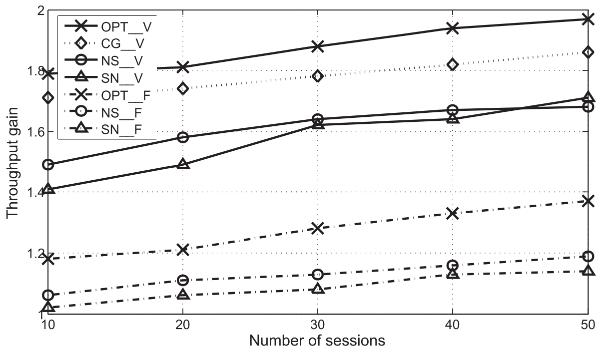

Fig. 3. Network throughput gain in the grid topology.

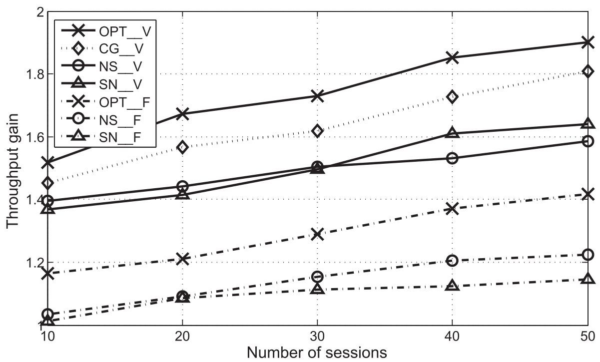

Fig. 4. Network throughput gain in the random topology.

by considering unicast only, and the latter is the scheduling length by jointly considering NC and spatial reuse.

Figs. 2–4 demonstrate the network throughput gain under different topologies, when each session has one packet for transmission. We can observe that the throughput gains with fixed transmission power schemes (OPT_F, SN_F and NS_F) are lower than their counterparts with variable transmission power schemes (OPT_V, SN_V and NS_V) obviously. This is because the method with fixed transmission power, which is actually the maximum transmission power, increases interference and limits the possibility of spatial reuse and NC as a result. The throughput gain of NS_F is larger than that of SN_F, which demonstrates that the maximum transmission power has less impact on NC than spatial reuse due to the broadcast characteristic of NC. We also note that when

Table 3
NC traffic percentage in the linear topology.

	10	15	20	25	30
OPT_V	0.093	0.172	0.211	0.251	0.285
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
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 4
NC traffic percentage in the grid topology.

	10	20	30	40	50
OPT_V	0.122	0.133	0.145	0.171	0.173
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
NS_F	0.153	0.168	0.179	0.199	0.216
SN_F	0.039	0.059	0.092	0.125	0.145

the density of network session is not large (i.e., the link load in the network is relatively light), the network performance of NS_V is slightly better than that of SN_V. This is because the opportunity for spatial reuse is few for SN_V and NC is mainly considered as the transmission method under this situation. However, when the number of network sessions increases to some extent (i.e., the link load in the network is relatively heavy), the throughput gain of SN_V is larger than that of NS_V. This is because more opportunities of spatial reuse appear and the link transmissions supported by spatial reuse are independent with each other, while the transmissions conveyed by NC are limited by the link with the worst channel state. Compared with the schemes with fixed transmission power, the network throughput gains achieved with variable transmission power increase around 38%, 30% and 34% on average in the linear, grid and random network topologies, respectively.

The utilization of the CG-based method can reduce the complexity of the NC-aware scheduling problem by searching only a small set of all the configurations, and the throughput gain achieved by this method can reach more than 90% of the gain obtained by the enumeration-based optimization method on average. This gap mainly comes from the following three aspects: (1) we simplify the process of PP by our heuristic solution, and utilize link scheduling metric to add links iteratively into the link set; (2) the decision of transmission power is also decided by the heuristic method instead of Eqs. (16), (18) and (20) to reduce computational complexity; (3) the LP is relaxed in MP.

Tables 3–5 demonstrate the percentage of the NC traffic under different topologies. We can observe that as the number of sessions increases, the NC percentages in NS_F are larger than those in NS_V, because some nodes attempt to conduct spatial reuse instead of NC with the adaptive power control method while parallel transmissions are limited by the maximum power under the fixed power transmission situation. Since the optimal scheme OPT_V (OPT_F) considers the interaction between NC and spatial reuse, the values of the NC traffic percentage are between the values of SN_V (SN_F) and the NS_V (NS_F). As the number of sessions

Table 5
NC traffic percentage in the random topology.

	10	20	30	40	50
OPT_V	0.049	0.121	0.149	0.171	0.229
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
NS_F	0.083	0.162	0.231	0.267	0.296
SN_F	0.029	0.065	0.108	0.129	0.159

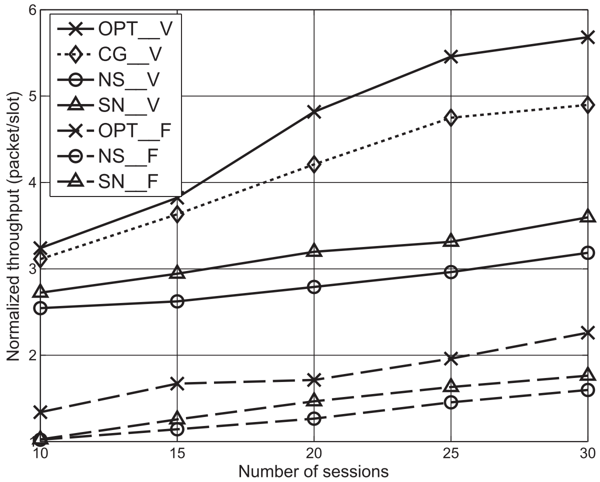

Fig. 5. Normalized network throughput in the linear topology.

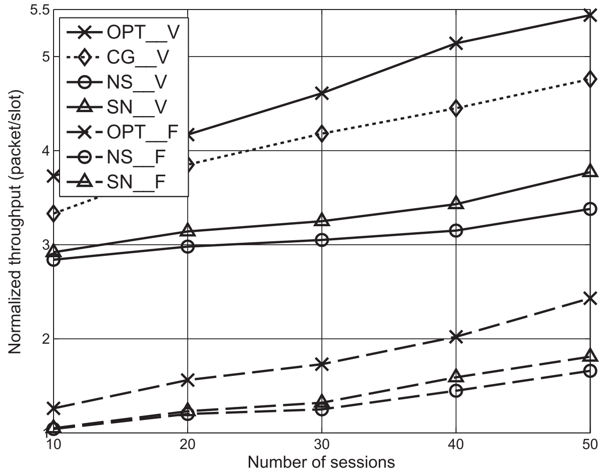

Fig. 6. Normalized network throughput in the grid topology.

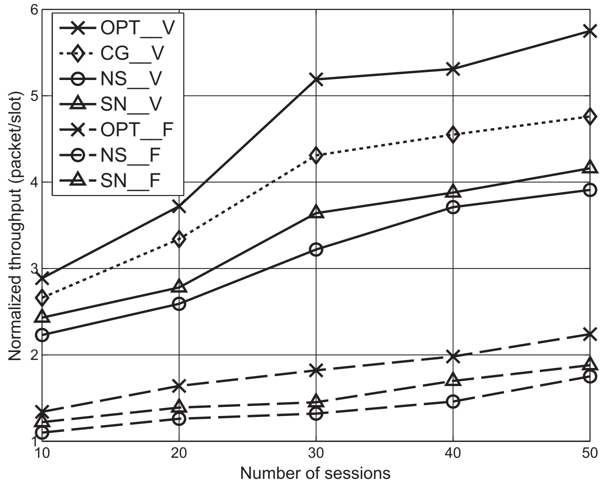

Fig. 7. Normalized network throughput in the random topology.

increases, the enhancement speed of NC percentage in the grid topology is lower than that in the other two topologies. This is due to the topology characteristic of the grid network, where more spatial parallel links and coding opportunities exist, and results in the interaction between NC and spatial reuse in the grid topology is more tight than the other two topologies. Therefore, the nodes in the grid topology have more opportunities to select transmission methods according to channel states. We can also observe that, the increase of NC percentage does not always accompany with the improvement of throughput gain. This conclusion is different from that obtained in [14], where greedy NC methods are considered and NC is the main contribution to throughput improvement. Our work demonstrates that NC is just one of the solutions for throughput improvement, while other techniques (e.g., spatial reuse and multi-rate transmission) should also be taken into account and performed jointly and adaptively.

In order to get more insight into the network performance gained by multi-rate transmissions, we define the network throughput as the ratio between Q_s and μ_s due to the network load on each link is unequal, where Q_s is the number of packets transmitted in configuration s. For different network topologies, the normalized network throughput in multi-rate transmission are demonstrated in Figs. 5–7. We can observe that, the network performance gaps between fixed and variable power schemes become large as the number of session increases. The reason is that the power and rate adaptation has a larger interaction with NC and spatial reuse in multi-rate transmission than that in single-rate packet delivery situation. Although the network performance obtained by the CG-based method is better than NS_V and SN_V, the gap between the OPT_V method and the CG-based method is rather distinct, and it is more difficult for the CG-based method to approach to the performance gained by the OPT_V method especially when the number of sessions is high. Compared with the network performance obtained by the OPT_V method, the network throughput achieved by CG_V is about 85% on average in multi-rate transmission situations. Besides, it can be observed that the OPT_V method outperforms NS_V and SN_V largely in the multi-rate transmission situation, which illustrates the importance of considering the interaction between different transmission methods. It should be noted that the throughput achieved by SN_V is always larger than that in NS_V under different topologies, which is different from the results obtained in Figs. 2–4. This illustrates that spatial reuse is more suitable for the situation where the link load is unbalanced in the network.

The achieved network performance is influenced by not only the number of network nodes, but also the number of network sessions to be activated. It should be noted that if

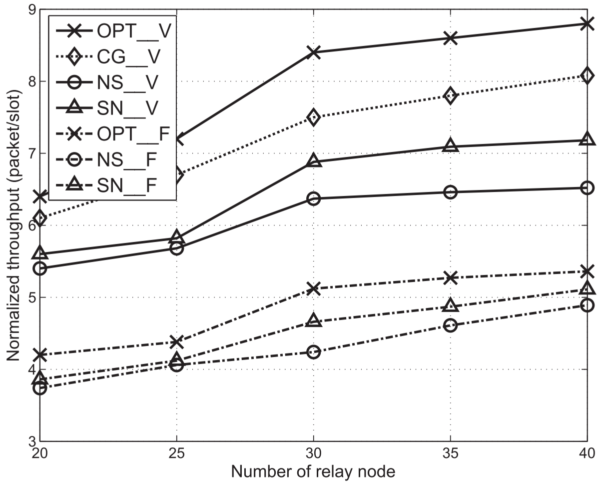

Fig. 8. Normalized network throughput achieved as the percent of relay node varies.

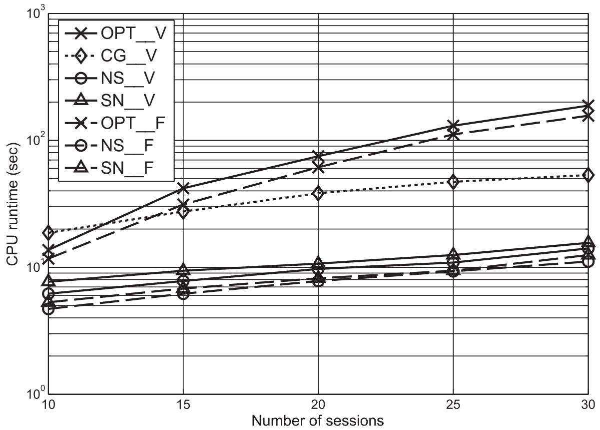

Fig. 9. The average runtime in the linear topology.

we keep the number of network sessions stable while enlarging network size, the obtained network performance cannot be observed directly, since the density of network sessions becomes lower and the opportunity to utilize NC and spatial reuse decreases, thus, the scalability of our presented method is not able to be demonstrated directly. Therefore, we further consider a random topology, set the number of network node to 50, and the number of network session is set to 100. We vary the number of relay nodes, and the achieved network performances can be seen in Fig. 8. It can be observed that as the number of relay nodes increases, more opportunities are brought for utilizing promising relaying method (i.e., NC and spatial reuse). Another observation is that as the number of relay nodes increases to some extent, network performance tends to be stable since the number of source nodes is not adequate for NC and spatial reuse.

Figs. 9–11 compare the average runtimes of different algorithms in different network topologies. We can observe that the runtimes of the CG and the greedy algorithms increase linearly with the number of network sessions, compared to the exponential increase of those of the optimal methods.

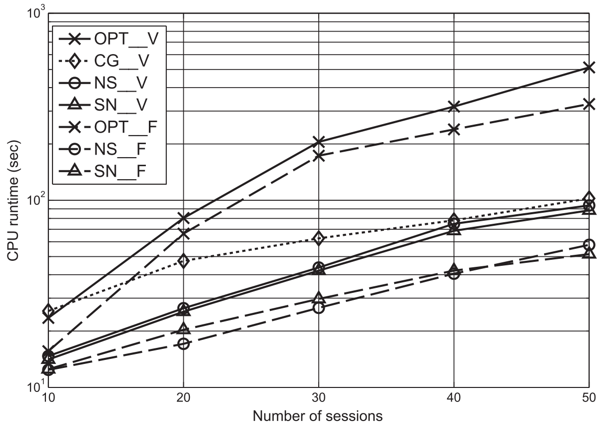

Fig. 10. The average runtime in the grid topology.

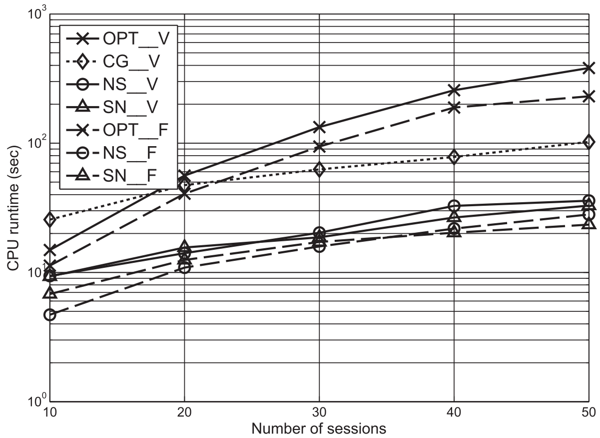

Fig. 11. The average runtime in the random topology.

It can also be seen that under the same network situation, the runtime of the algorithm with fixed power is less than that with variable power. This is because the opportunities to conduct NC and spatial reuse are suppressed by the maximum transmission power, which reduces the searching space of the algorithm and thus decreases the corresponding CPU runtime.

5. Conclusions

Link scheduling, power and rate adaptation, and NC techniques have been demonstrated as promising and effective methods for throughput improvement in WMNs. In order to maximize network throughput, we have first presented an optimization model and allocate the interference-free links to the same configuration that can be activated in the same time slot, by considering the interaction among NC, spatial reuse and multi-rate transmission. In order to resolve the formulated problem, we have utilized a CG-based method, which decomposes the proposed problem into two sub-problems that can be resolved efficiently. Furthermore, we have presented the DPC scheme which enables us to remove the continuous variables to reduce the computational complexity of the CG. Simulation results demonstrate that, when the link load is balanced, NC is preferred in the light-loaded network while spatial reuse is welcomed in the heavy-loaded network. However, spatial reuse always outperforms NC when the link load is unbalanced. It has also been demonstrated that the network performance obtained by the proposed CG-based method with low computational complexity can approach to that gained by the optimal method. Meanwhile, the CG-based method largely outperforms the greedy methods since it makes a comprehensive consideration of spatial reuse and NC in multi-rate network.

Acknowledgments

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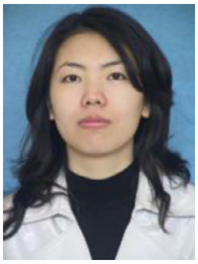

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