Network Coding-based Directional Scheduling for Fairness Provisioning in Wireless Mesh Networks

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Abstract—**This paper addresses the problem of fairness portioning in multi-channel, multi-radio wireless mesh networks by applying the integration of network coding and directional antennas techniques. It is the fact that Network coding can increase transmission efficiency in wireless networks. Moreover, directional antennas, concentrating the beam energy at a specified direction, can also improve the network performance. However, the interacting of the two techniques is scarcely studied. In this paper, we propose an analytical model to figure out the incorporation of directional antennas and network coding schemes to improve fairness provisioning. To address the problem, we first present integer linear programming formulation optimizations, which maximize the throughput while satisfying the fairness requirements. Based on solving the linear programming, we propose a link scheduling and channel assignment with a heuristic method. The evaluations show that the algorithm we propose can effectively take advantages of the number of channels and radios. In addition, it shows that our algorithm outperforms other algorithms which either coding-oblivious or directional antenna-oblivious.**

Index Terms—**Directional antennas, Network coding, Linear programming, Link scheduling, Channel assignment**

I. Introduction

Wireless multi-hop networks can provide good geographic coverage while cost low. However, the natural disadvantages of wireless links lie in limited capacity and interference among neighbor links. Moreover, lacking of feasible resource allocation scheme, some nodes may share the available network bandwidth unfairly, which relates to fairness [1]. To address this problem, we propose a directional scheduling algorithm by interactively using network coding and directional antenna techniques to provide fairness while keeping a high network throughput.

Fairness provisioning in wireless networks has been considered [2][3][4][5][6][7][8]. Ref. [2] studied how the imperfect scheduling influenced the network performance. Ref. [3] provided proportional fairness in single hop wireless networks using the mechanisms namely token counter. Ref. [4] also studied fairness provisioning using random access integrated with back-pressure. Ref. [5] discussed fairness problem in the cellular networks, where the nodes were equipped with single transmitter within one-hop communication. Ref. [6] provided fairness provisioning among individual flows using the utility functions.

With the increase in wireless use, current wireless systems are throughput limited. In order to increase network performance, multitudes of network technologies are advanced. Network coding is a efficient mechanism to improve the capacity of wireless networks [9]. The key idea of network coding is to combine more information within a single transmission at intermediate nodes, which leads to higher network throughput [9]. Network coding was traditionally used in wired networks until recent. Due to that wireless transmissions are inherently broadcast at the physical layer, it has been found that Wireless Mesh Networks (WMNs) offer natural background for the technique. Moreover, coding also promote better throughput even for unicast applications [10].

Compared to omni-directional antenna, the directional antenna model [11] was developed and attracted attentions rapidly. There are two critical new networking characters with directional antenna [12]. High main lobe gain covers more receivers and minimal side lobe allows spatial multiplexing, both of which can improve network capacity.

Obviously, it will obtain more benefit using directional antennas instead of omni-directional antennas in WMNs. The network coding techniques can also improve throughput performance on wireless networks. But to the best of our knowledge, there is no prior work that considers the problem of fairness provisioning in WMNs employing network coding and directional antennas.

The contributions of this paper are as follows:

- This paper takes the advantages of network coding and directional antennas techniques so as to address the problem of fairness provisioning with the constraint of throughput

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in wireless mesh networks.

- We formulate a framework to describe the transmission schemes with network coding as well as directional antenna using the linear programming technique. Furthermore, we propose a directional link scheduling and channel assignment algorithm under the developed framework, which can deal with optimal network throughput with fairness provisioning.
- We characterize quantitatively the network performance of network coding with directional antenna both in grid and random topologies with the number of channels, radios varied.

The rest of this paper is organized as follows. Related works are discussed in Section II. Section III describes the system model. Section IV investigates develops the general linear programming framework. Section V designs the directional link scheduling and channel assignment algorithm for wireless mesh networks. Extensive simulations are showed in Section VI. The paper concludes with Section VII.

II. Related Works

A. Network Coding

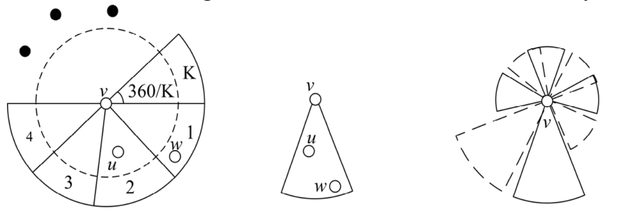
The concept of network coding was first introduced in [9] as a novel technique used in wired communications. Since then, numerous research works had focused on designing coding strategies and analyzing coding efficiency in wired networks[13][14]. However, wireless links offer natural background for applying of network coding [15][16], which mainly studied on applying network coding in multicast communications. Recently, some works have focused on providing efficient unicast communications using network coding [10][17][18][19]. Particularly, the COPE mechanism [10] first considered multiple unicast flows in WMNs, and applied network coding to increase the throughput. The authors in Ref. [17][18] proposed centralized network coding-aware routing schemes for maximizing the overall coding opportunities in the whole network, which may have scalability problem and be hardly applied in large and dynamic networks. MORE [19] randomly mixed packets before forwarding ensured the router not forward the same packets. This coding-aware strategy could directly run on top of 802.11, and need no special scheduler. Moreover, the throughput optimizing in WMNs with QoS provisioning by using network coding could be found in our previous research [20].

B. Directional Antennas

There are several popular directional antenna models. The most popular one described in [21] equally divided each node into K non-overlapping sectors. Each sector could be switched on either for transmission or for reception. Adjustable cone model is another directional antenna model [22] using the steerable beam system. This model can increase the channel capacity through forcing energy towards the particular direction. Moreover, the nodes can communicate simultaneously without interference using this model. Fig.1 shows several popular directional antennas sectoring, in this paper, we mainly discuss the model in Fig.1 (a).

Ref. [23] discussed the usage of directional antennas in wireless networks, and proposed a broadcast scheme using directional antennas to reduce redundancy. Ref. [24] offered numerous simulations of different routing protocols using directional antennas for wireless networks. In [24], the author compared two on-demand routing protocols (AODV and DSR) using directional antennas over arbitrary networks as well as random networks. The simulations results showed that DDSR outperformed DAODV significantly for that DSR's capability of learning multiple routes to the destination in a single request cycle.

Spatial reuse is an important application of directional antennas. Ref. [25] showed that directional antenna could provide longer transmission and reception ranges for the same amount of power. Ref. [26] studied the advantages of applying directional antenna in simple topologies, and indicated that integrating directional antenna and spatial reuse could obtain higher transmission rate, smaller delay.



(a) *Ideally sectorized* **(b)** *Adjustable cone* **(c)** *Irregular beam pattern*

Figure 1. Directional antenna models

C. Link Scheduling and Channel Assignment

Plenty of works on link scheduling and channel assignments in wireless networks can be found in [27][28][29][33]. Moreover, Ref. [30][31][32] proposed various routing metrics aiming at balancing load and throughput in wireless networks. The authors in [29][33] discussed general framework and proposed efficient algorithms in the link layer level for multi-channel wireless networks, which specified a foundation for our research.

III. System Models

A. Network Models

We model the WMNs as a directed graph $G=(V,E,I)$, where V represents the set of nodes, E is the set of data links can carry data, and I is the set of interference links can sense signals but not decode the dat. Let $E^-(v)$ and $E^+(v)$ be the sets of incoming and outgoing links of node v with $v \in V$, respectively. Denote by $e=(u,v)$ the directed link in the network from node u to node v with $u,v \in V$. Let $t(e)$ and $r(e)$ be the transmitting and receiving nodes, respectively, of link e. While let

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$\bar{e}=(u,v)$ be the reverse link of e. The transmission rate of link e is defined as $x(e)$.

The network is utilized by a number of sessions to transmit data packets. We denote the set of sessions by A. A session a, with $a \in A$, is characterized by a triplet $\{s(a), d(a), \theta(a)\}$, where $s(a)$, $d(a)$, and $\theta(a)$ represent the source node, destination node, and throughput of session a, respectively. Packets of session a with $a \in A$ are routed from $s(a)$ to $d(a)$ in multiple hops if there are no directed links between the source and destination nodes. Each node in the wireless network can be a source or destination, *i.e.*, $s(a), d(a) \in V$, $\forall a \in A$. There may be multiple routes for session a from $s(a)$ to $d(a)$. Let P_a be the set of available routes for session a. For a path $P \in P_a$ of session a, it can be considered as an ordered subset of links, $P=\{e_0, e_1, \cdots, e_{N_a}\}$, such that $t(e_0)=s(a)$ and $r(e_{N_a})=d(a)$. For any given path P, link e, and node v, we use $e \in P$ to represent that link e is on path P and $v \in P$ to represent that node v is on path P. Furthermore, we use $e_1 e_2 \in P$ to denote that path P includes links e_1 and e_2, and the link e_2 is immediately behind e_1, i.e., $r(e_1)=t(e_2)$.

B. Wireless Interference Model based on Directional Antennas

In this paper, we consider a directional antenna model that is used in previous works [34][35]. Sidelobes and backlobes are ignored in this model.

It is assumed that θ as the specific angle of the antenna, and at one time, the antenna can only point one special direction, thus the transmission circle is divided into $\theta/2\pi$ sectors.

Based on the protocol model in [36], we propose a directional antennas-based interference model. If node v_i transmits to node v_j over a channel, the transmission is successfully completed by node v_j if no nodes within the region covered by v_j's antenna beam will interfere with v_j's reception. Therefore, for every other node v_k simultaneously transmitting over the same channel, and the guard zone $r>0$, the following condition holds.

$$\begin{cases} |v_k - v_j| \geq (1+r)|v_i - v_j| \\ \text{or } v_k\text{'s beam cannot cover node } v_j \end{cases}. \quad (1)$$

Fig.2 shows an example of directional antennas-based interference model.

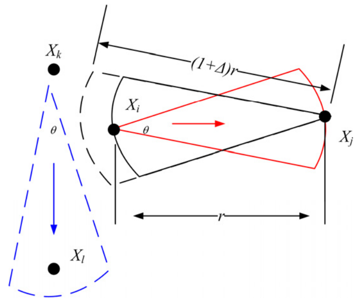

Figure 2. The directional antennas-based interference model

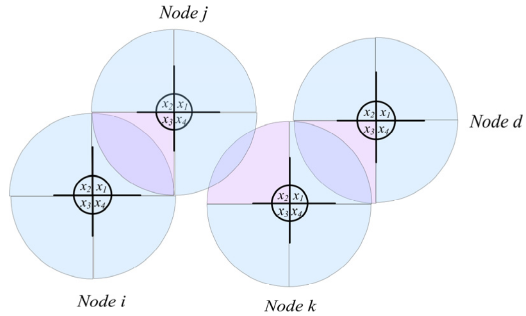

Figure 3. An example of directional transmission (K=4)

For simplicity, we will only consider the protocol model in this paper [32].

As shown in Fig.3, we use $\beta(i^{x_a})$ as an indicator to represent whether the sector x_a is free, which satisfies:

$$\delta(i^{x_a}) = \begin{cases} 1, & \text{the } x_a \text{ of node } i \text{ is free} \\ 0, & \text{the } x_a \text{ of node } i \text{ is busy} \end{cases}. \quad (2)$$

Furthermore, we use β_e as an indicator to represent that whether the beamwidth of node i can cover the node j where $t(e)=v_i$, $r(e)=v_j$. And β_e satisfies:

$$\beta_e = \begin{cases} 1, & \delta(i^{x_a})=1 \text{ and } \delta(j^{x_b})=1 \text{ and node } j \text{ is with } i \text{ the range of communicaiton} \\ 0, & \text{otherwise} \end{cases}. \quad (3)$$

C. Coding Model

Network coding within a multiple unicast sessions allows traffic from different transmission pairs to share network capacity. In this paper, we simply use XOR network coding strategy [10] for wireless mesh networks.

We assume k packets coming into a node, and can be coded as $p = p_1 \oplus p_2 \oplus \cdots \oplus p_k$ and can be broadcasted to all available next-hop nodes. This strategy is valid if the next-hop v_j for each packet p_i already has all other packets p_j for $v_j \neq v_i$ (subsequently it has enough degrees of freedom to decode p_i).

IV. Problem Formulation

Let $k(a)$ be the predetermined flow weight for session a, with $a \in A$. The larger the $k(a)$ for session a is , the more flow rate the session a requests. Let λ be the scaling factor by which the flows of each session can be

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scaled up. In this paper, we are aiming to maximize λ where at least $\lambda k(a)$ amount of throughput is guaranteed for any session a. Now, we propose the linear program for maximize throughput with fairness provisioning for wireless mesh networks as follows:

Max Fairness LP: max λ

$$\theta(a) = \Sigma F_a(P) = \lambda k(a)\ . \tag{4}$$

$$\prod_{e \in P} \beta_e = 1\ . \tag{5}$$

$$f(e) = \sum_{m \in M} f_m{}^{U}(e) + \sum_{m \in M} f_m{}^{NC}(e)\ . \tag{6}$$

$$f(e) = \sum_{a \in A} \sum_{P \in P_a : e \in P} F_a(P)\ . \tag{7}$$

$$\sum_{e \in E^+(v)} f(e) - \sum_{e \in E^-(v)} f(e) = \begin{cases} 0, & \forall v \neq s(a), d(a), \forall a \in A \\ \sum_{a \in A, s(a)=v} \sum_{P \in P_a} F_a(P) - \sum_{a \in A, d(a)=v} \sum_{P \in P_a} F_a(P), \forall v = s(a), d(a), & \forall a \in A \end{cases}\ . \tag{8}$$

$$\alpha_m{}^{NC}(e) = \begin{cases} \dfrac{f_m{}^{NC}(e)}{\min_{e \in E}\{c_m(e)\}}, & \min_{e \in E}\{c_m(e)\} > 0 \\ 0, & otherwise \end{cases} . \tag{9}$$

$$\alpha_m{}^{U}(e) = \begin{cases} \dfrac{f_m{}^{NC}(e)}{c_m(e)}, & c_m(e) > 0 \\ 0, & otherwise \end{cases} . \tag{10}$$

$$\sum_{e' \in E^C(e)} \alpha_m{}^{U}(e') + \sum_{e \in E_m{}^C(e)} \alpha_m{}^{NC}(e) \leq 1 \qquad \forall m \in M \ and\ \forall e \in E \cup I\ . \tag{11}$$

$$0 \leq f_m{}^{U}(e) \leq c_m(e), \quad \forall m \in M \ and\ \forall e \in E\ . \tag{12}$$

$$\sum_{m \in M} \Big(\sum_{e \in E(v)} \alpha_m{}^{U}(e) + \sum_{e \in E(v)} \alpha_m{}^{NC}(e) \Big) \leq W(v)\ . \tag{13}$$

Eq. (4) states that the throughput $\theta(a)$ of session a is equal to $\sum F_a(P)$ where $F_a(P)$ is the amount of flow on path P for session a. And it ensures the fairness of resource allocation among different sessions.

Eq. (5) states directional antennas constraint for transmissions of session a.

Eq. (6) gives that the total amount of flow, denoted by $f(e)$, of link e, is the sum of all unicast traffic and NC traffic, where $f_m{}^{U}(e)$ and $f_m{}^{NC}(e)$ represent unicast flow and NC flows over channel m, respectively.

Eq. (7) states that the amount of flow on link e is equal to the total flow of all sessions' route through link e.

Eq. (8) gives the flow balance at every wireless node for each session.

Eq. (9) - Eq. (11) give that transmission interference constraint. Let $\alpha_m{}^{NC}(e)$ and $\alpha_m{}^{U}(e)$ denote the fraction of time NC links and unicast links will be actively using channel m, respectively. Obviously from Eq. (11), the constraint not only applied to the data links (E), but also to the interference links (I). The reason is that given an interference link e, with $e \in I$, between two node v_i, and v_j, if one of the data links incident on either node v_i or v_j is active, thus the other node has to be silent for that time slot.

Eq. (12) gives the upper bound of the link capacity.

Eq. (13) gives the node radio constraint, where $W(v)$ denotes the number of radios that a node v has. Because a node v with $W(v)$ radios can work at most $W(v)$ channels simultaneously. The objective of the constraint is to guarantee the radios and channels assignments are feasible for any number of radios for each node and any number of channels.

The Max Fairness LP represents the general form for the throughput optimization problem combined with network coding scheme and directional antennas.

V. Joint Link Scheduling and Channel Assignment

Solving the Max Fairness LP [37] to obtain the optimal flows for each unicast links and NC links combination, we develop the link scheduling and channel assignment algorithm to acquire the approximate optimal λ^* of Max Fairness LP. We assume that the radio transceiver has to work over an assigned channel for a period of time before it can switch to another different channel. Let $T_s (T_s > 1)$ be this period in the unit of time slot, and further we assume that the channel assignment be updated every T_s time slots.

We assume $\pi(e)$ be the schedule for link e, and define $\pi(e)$ is a set of triplet (t, m, b) where t, $t = 1, 2, \cdots$ time slots, $\pi(e)$ contains the information during time slot t on channel m, moreover, $\pi(e)$ describes the type of traffic b is active. $b \in \{0,1\}$ indicates the traffic types. b=1 represents NC flows, while b=0 represents ordinary unicast flows

It is worth to note that the problem of optimal channel assignments is NP-hard. Therefore, we propose a heuristic greedy algorithm in order to obtain the schedule $\pi(e)$, $\forall e \in E$, which is the approximately optimal solution of Max Fairness LP. Table I shows the pseudo code of the link scheduling and channel assignment algorithm.

Similarly to Ref. [33], in every T_s time slots, the NC flows will be scheduled first, and then the unicast flows. Particularly, we sort the NC links combinations in a decreasing order of the unassigned flows (f^{NC}). We assign the first NC links combination to the channel that can provide maximum flow rate. We assign the channel to e if channel m exists and every node associated with NC combination links e is available. If there is no channel that can be assigned to NC links combination, we move on the second highest NC flow. The above procedure is repeated until all the NC flows are assigned. Then, we start the process of channel assignment and links

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schedule for the unicast flows. We repeat the process every T_s time slots until all unassigned flows become zero.

The proposed algorithm can ensure convergence and stability, but limited for the space, the certification is omitted in this paper.

VI. Pormance Evaluation

A. Evaluation Setups

We evaluate the performance of D-LSCA in the multi-channels multi-radio wireless mesh networks, where there are multiple unicast sessions. To have a basis for comparison, we mainly consider two typical topologies: 7*7 grid network and random graph topology with 32 nodes. Fig.4(a) shows the network topology of the 7*7 grid network, and the distance between two adjacent grid points is 1 unit. Fig.4(b) shows the network topology of the random graph network where 32 nodes are arbitrarily deployed in the square region where each side is 3.3 units long. For each node, the transmission range is 4 units, while the interference range is 8 units. For simplicity, we let the bandwidth of each antenna be 90°, so the number of sectors in the plane network is 4.

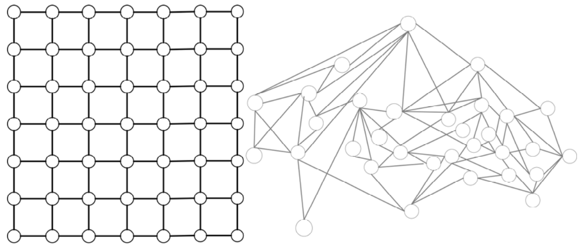
During the simulation runs, we take the following measurements:

(1) **Network throughput** This index counts the total number of data bits received by all the receivers per second.

(2) **Fairness index** This index measures under different mechanisms both:

1) The bandwidth sharing of all the network connections, and

2) The bandwidth sharing of node's connections averaged over all nodes in the network. We use Jain's fairness index [38].

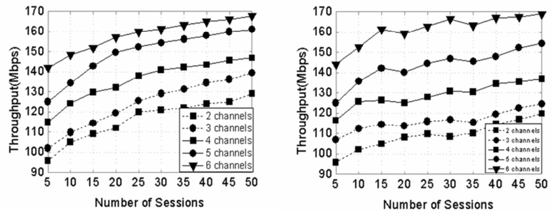


(a) *7*7 grid topology* **(b)** *32-node random topology*

Figure 4. Two typical topologies for evaluations

B. Performance of Multi-channel

In this evaluation, we study the affect of using multiple channels per node on the maximal throughput with fairness provisioning. We let the number of channels be 2 to 6, respectively. We fix the number of radios at 4. Fig.5(a) and (b) show the results of 5 settings with the varying number of radios available over two topologies. Each data point is averaged over 5 simulations. It is obviously that increasing the number of channels per radio increases the throughput in network.

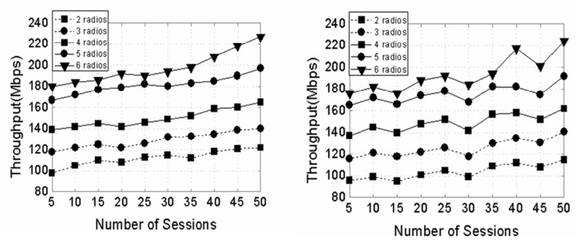


(a) 7*7 grid topology (b) 32-node random topology

Figure 5. Throughput performance impact of multi-channel

C. Performance of Multi-radio

In this evaluation, we study the affect of using multiple channels per node on the maximal throughput with fairness provisioning. We let the number of radios be 2 to 6, respectively. We fix the number of channels at 6. Fig.6(a) and (b) show the results of 5 settings with the varying number of radios available over two topologies. Each data point is averaged over 5 simulations. Each curve in the figure shows that increasing number of traffic in network increases the throughput.



(a) 7*7 grid topology (b) 32-node random topology

Figure 6. Throughput performance of multi-radio

D. Comparison with Routings

In this evaluation, the goal is to compare our proposed algorithm D-LSCA with the classical routing schemes including traditional shortest path routing with omni-directional antennas(SP-omni), COPE [10] as well as DDSR [23] for throughput and fairness. In this evaluation, we address the fairness issue based on Jain's fairness index. We fix the number of radios per node at 4 and the number of sessions at 10, 20, 50, respectively. We plot results in Fig.7 and Fig.8 for 3 settings with the varying of connections over two topologies. Each data point is averaged over 5 simulations. First, we observe that as the number of connections increases the throughput obtained by all the algorithms drop. On average, D-LSCA outperforms the single-path routing solution with omni-directional antennas (SP-omni) by 30% in terms of throughput. This is due to the fact that, in contrast to SP-omni, D-LSCA can fully exploit the broadcast nature of wireless channels by allowing packets to be coded together. In addition, directional antennas further help to reduce interference links, and it is likely to partition network into several disconnected sub-networks. Compared with COPE, D-LSCA does not significantly improve throughput. But when the number of channels

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increase, the gain of D-LSCA becomes obvious. The reason is that COPE introduce opportunistic listening which allows more than two packets coded together, while D-LSCA does not allow it so as to save buffer size, while when the number of channels increases, the benefit of channels assignment of D-LSCA is in effect. Moreover, it is obviously that D-LSCA outperforms DDSR by 21% in terms of throughput, which is due to coding opportunities.

Fig.9 and Fig.10 depict fairness of D-LSCA with the classical routing strategies over two topologies. In this evaluation, D-LSCA significantly outperforms other three algorithms. This is due to SP-omni does not consider fairness leading to un-balance problem. COPE, although facilitated with opportunistic listen, still lacking of consideration of interference links results in degradation in performance. DDSR performs better than SP-omni and COPE, but is sub-optimal than D-LSCA. This is due to directional antenna does help eliminating interference links. But facilitated with both network coding and directional antennas, our D-LSCA performs the best in fairness provisioning.

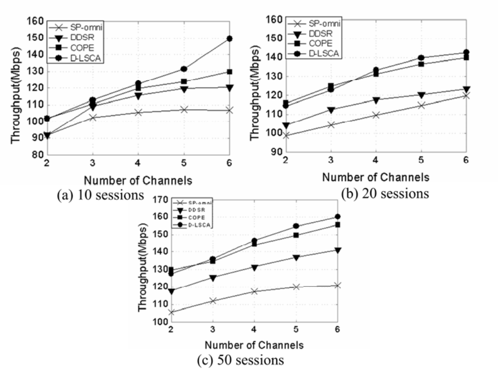

Figure 7. D-LSCA vs. SP-omni, DDSR and COPE: throughput over 7*7 grid topology

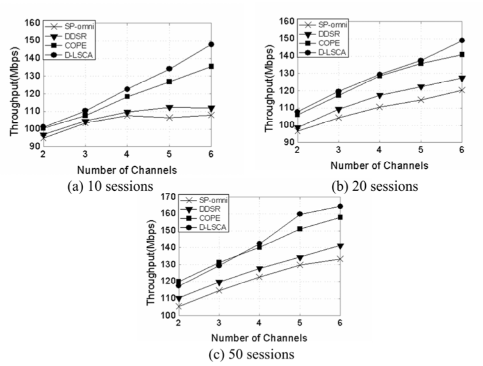

Figure 8. D-LSCA vs. SP-omni, DDSR and COPE: throughput over 32-node random topology

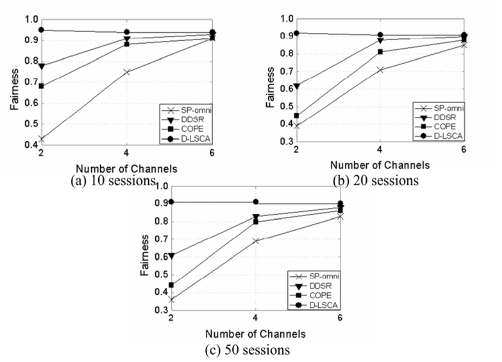

Figure 9. D-LSCA vs. SP-omni, DDSR and COPE: fairness over 7*7 grid topology

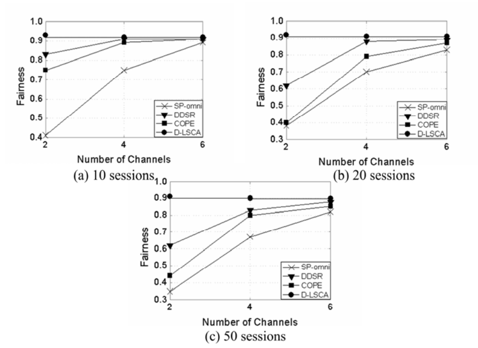

Figure 10. D-LSCA vs. SP-omni, DDSR and COPE: fairness over 32-node random topology

VII. CONCLUSION

In this paper, we study the joint problem of link scheduling and channel assignment for multi-channel multi-radios wireless mesh networks. The main objective is to optimize the throughput for multiple unicast sessions in a fair manner. To address the problem, we use network coding and directional antenna schemes to formulate the problem as a linear program that finds the flow (unicast and NC) combinations. Based on the solution to this linear program, we have proposed a heuristic algorithm that computes a feasible link scheduling and channel assignment for all nodes. Evaluation results have shown that our proposed algorithm D-LSCA can effectively exploit the increasing number of channels and radios, and it also outperforms several other classical routing schemes. The proposed framework can be further extended to the scenarios where delay is a major concern in the network. Development of distributed solutions for channels assignment is also an interesting avenue for future research.

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TABLE I.
ALGORITHM 1: D-LSCA

Algorithm 1 D-LSCA: Link Scheduling and Channel Assignment Algorithm
Input: $f_m^{U}(e),\ f_m^{NC}(e)\ \ \forall e\in E,\ m\in M$
Output: $\pi(e)\ \forall e\in E,\ T_p$
$f^{U}(e):=\Sigma_{m\in M} f_m^{U}(e),\quad \forall e\in E$
$f^{NC}(e):=\Sigma_{m\in M} f_m^{NC}(e),\quad \forall e\in E$
$T_p:=0;\ time\_idx=1;\ \ \mathrm{Z_U}=E_U;\ \mathrm{Z_{NC}}=E_{NC}$
while $(Z_U\neq\Phi \parallel Z_{NC}\neq\Phi)$
$B_U:=Z_U;\ B_{NC}:=Z_{NC}$
while $B_{NC}\neq\Phi$
$E_{NC}=\arg\max_{L'\in B_{NC}} f^{NC}(e)$
$m:=\arg\max_{m'\in M}[\min_{e\in E_{NC}} c_{m'}(e)]$
if
$\beta_e>0\ \&\&\ \min_{e\in E_{NC}} c_{m'}(e)>0\ \&\&\ \min_{e\in E_{NC}} V(t(e))>0\ \&\&\ \min_{e\in E_{NC}}$
then $\pi(e):=\pi(e)\cup\{t,m,1\},\ \forall e\in E_{NC},\ t\in[time\_idx,time\_idx+T_s-1]$
$f^{NC}(E_{NC}):=f^{NC}(E_{NC})-T_s\min_{e\in E_{NC}} c_m(e)$
$c_m(e):=0,\quad \forall e\in E: E_{NC}\in E^{C}(e)$
$V(t(e)):=V(t(e))-1,\ V(r(e)):=V(r(e))-1,\ \forall v\in\bigcup_{e\in E_{NC}}\{t(e)\cup r(e)\}$
if $f^{NC}(L)<0$ then $Z_{NC}:=Z_{NC}/E_{NC}$ end if
end if
$B_{NC}:=B_{NC}/E_{NC}$
end while
while $B_U\neq\Phi$
$E_U=\arg\max_{L'\in E_{NC}} f^{U}(L')$
$m:=\arg\max_{m'\in M} c_{m'}(e)$
if $\beta_e>0\ \&\&c_m(e)>0\ \&\&\ V(t(e))>0\ \&\&\ V(r(e))>0$
then $\pi(e):=\pi(e)\cup\{t,m,0\},\ \forall e\in E_{NC},\ t\in[time\_idx,time\_idx+T_s-1]$
$f^{U}(E_U):=f^{U}(E_U)-T_s c_m(e)$
$c_m(e'):=0,\quad \forall e'\in E^{C}(e)$
$V(t(e)):=V(t(e))-1,\ V(r(e)):=V(r(e))-1$
if $f^{U}(e)<0$ then $Z_U:=Z_U/E_U$ end if
end if
$B_U:=B_U/E_U$
end while
$T_p:=T_p+T_s$
end while

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