Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics
San Antonio, TX, USA - October 2009

Joint Algorithm of Scheduling and Network Flow in Cognitive Radio Wireless Mesh Networks

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***Abstract*—We suggested a joint algorithm for opportunistic spectrum and time sharing in cognitive radio (CR) wireless mesh networks (WMNs) in this paper. The problem was formulated using linear programming and solved by the simplex-II method. The flow optimization problem was first developed for grid topology of CR WMNs. Results showed optimized flow of the CR WMNs with ideal interference free link scheduling. Second, a practical interference free link scheduling algorithm was suggested. Simulation results showed that the normalized cost of the optimized algorithm was close to 1 and offered a cross-layer optimized solution between scheduling and network flow. The throughput of the CR WMNs using the suggested algorithm was optimally enhanced.**

***Keywords*—Cognitive radio, cognitive radio wireless mesh networks, opportunistic spectrum and time sharing, cross-layer optimization.**

I. INTRODUCTION

Spectrum measurement studies show that a lot of allocated spectrum bands are extremely underutilized in most crowded areas and are idle most of the time in the US [1]. According to recent measurement reports spectrum occupancies are only 1.7% ~ 13.6% of the spectrum from 30 MHz to 3 GHz [2]. In contrast, the numbers of wireless devices in the ISM bands have significantly increased. WiMax and city wide mesh networks are expected to add to this congestion resulting in interference with each other and degradation of overall performance [3]. The FCC (Federal Communications Commission) has studied new innovative policies to encourage dynamic access to the idle spectrum. Dynamic spectrum access is an approach that allows wireless devices to use idle spectrum holes [4]. Cognitive radio (CR) technologies are a physical layer technology which can be programmed to tune and operate on specific frequency bands over a wide spectrum range [5]. CR devices dynamically identify portions of the spectrum that are not in use by primary users and configure the radio to operate in the appropriate spectrum holes [6].

There are extensive studies related to effective sharing of spectrum and spectrum sensing. A number of approaches have been proposed for a multi-user single-hop communication in a network environment [7]. Game theory, pricing mechanism, utility maximization problem, etc. have been suggested for spectrum sharing, but routing is not considered [8].

In this paper, we focused on a cross-layer optimized algorithm between scheduling and network flow for opportunistic spectrum and time sharing in CR-based WMNs. In CR-based WMNs, the secondary user node, i.e. the CR mesh router, needs to avoid using frequency bands occupied by primary users. Also, an effective interference free link scheduling is required for secondary user mesh nodes. The frequency bands available for a particular node at a particular time can be reused within an interference range using the suggested interference free link scheduling algorithm in CR-based WMNs. In addition to interference free link scheduling, flow optimization for secondary user node networks is simultaneously required in CR-based WMNs. The optimization problem was formulated to minimize the system resource, which is occupied time to communicate in a particular link. To formulate the problem, we considered behaviors and constraints for time scheduling, interference avoidance and multi-hop routing in CR-based WMNs. This problem can be formulated using linear programming. The problem was solved by the simplex-II method in this paper. First, the flow optimization problem was developed for the grid topology of CR-based WMNS and the problem was solved using the simplex-II method. Results showed optimized flow of the CR-based WMNs with ideal interference free link scheduling. Then, the practical interference free link scheduling algorithm was suggested for avoiding interference links of secondary user nodes. Results of normalized costs showed that the suggested scheduling algorithm was reasonable. The throughput results revealed enhanced performance of CR-based WMNs using cross-layer optimization between interference free scheduling algorithm and network flow.

II. NETWORK MODEL WITH COGNITIVE RADIO

Generally, WMNs consist of static wireless mesh routers and end clients. Static wireless routers are equipped with traffic aggregation capabilities, e.g. access points, and provide network connectivity to mobile clients within their coverage area. Some of the wireless mesh routers are equipped with gateway functionality to enable integration of WMNs with various existing wireless networks. Reliability improves because the mesh structure ensures the availability of multiple paths for each node in the WMNs. Network coverage increases with the number of gateways and users. However, the throughput capacity per node decreases significantly when node density increases [3]. WMNs with cognitive radio are suggested as a way to solve these problems [9].

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Formally, we consider the CR-based wireless mesh backbone networks. In CR-based WMNs, wireless mesh routers work as a secondary user, sense spectrum holes of primary users and dynamically allocate the idle spectrum holes for their wireless interface. Wireless mesh routers typically have several wireless interfaces. We assume the CR routers have one wireless interface with each other to show cognitive radio functionality. CR routers schedule and dynamically allocate the spectrum holes in the interfering range.

Table I lists all of the relevant notation used in this paper. A mesh router *i* operates on a single channel selected from a set $M_i \in M$. *M* is a set of orthogonal channels available in the network. Since the router has CR capability, M_i can be changed at a specific time. Each router *i* in *N*, which is the set of routers in the network, aggregates the user traffic from all the mesh clients that are associated with *i*. The load l_i may be due to outgoing or incoming traffic, but we assumed that a router does not receive incoming traffic from wired Internet. So, l_i consists of only incoming traffic. c_e is the maximum traffic rate at which mesh router *i* can communicate with mesh router *j* in one hop on a single channel. $X_{i,j}^{m}$ is an indicator variable which is assigned 1 only if link *e=(i, j)* is active on channel *m*.

TABLE I. NOTATIONS

Symbol	Definition
E	*The set of links*
N	*The set of routers in the network*
M	*The set of available channels in the network*
M_i	*The set of available channels at router* $i \in N$
$f_{e,m}$	*The flow on link* $e = (i, j)$ *using channel* $m \in M$
l_i	*Aggregate user traffic load on i*
c_e	*The maximum rate for link* $e = (i, j)$
T	*The period of the schedule*
τ	*Specific time slot* $\tau \in T$
$X_{i,j}^{m,\tau}$	*Indicator variable which is assigned 1 only if link e=(i, j) is active in time slot* τ *on channel m.*
$X_{i,j}^{m}$	*Indicator variable which is assigned 1 only if link e=(i, j) is active on channel m.*
P	*The transmission power spectral density (PSD) of router*
P_T	*The minimum threshold of PSD at a receiver*
P_I	*The maximum threshold of PSD for interference at a receiver*

The advantage of CR networks is that secondary users, i.e. CR mesh routers, can use the spectrum holes which are not used by primary users. Fig. 1 shows the CR-based wireless mesh network model.

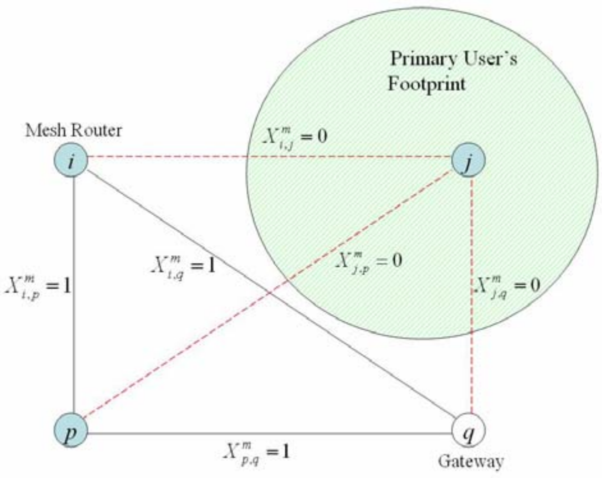

Figure 1. Wireless mesh network model with cognitive radio.

When channel *m* is occupied by primary users, secondary user routers cannot use channel *m* within the primary users' footprint, i.e., coverage. When a primary user is communicating using a specific channel, it consumes some space which is termed its footprint. Therefore, $X_{i,j}^{m}=0$, $X_{j,p}^{m}=0$, and $X_{j,q}^{m}=0$ show that the mesh router *j* cannot use channel *m* as shown in Fig. 1. In contrast, if secondary user nodes exist outside the footprint of the primary user, channel *m* can be used by the secondary users, i.e., mesh routers, *i, p* and *q*. $X_{i,p}^{m}=1$, $X_{i,q}^{m}=1$, and $X_{p,q}^{m}=1$ show that the mesh routers can use the spectrum channel *m* because the mesh routers are outside of the primary users' footprint. However, mesh routers *i, p,* and *q* cannot communicate using channel *m* at the same time because they interfere with each other. Effective time scheduling is required to share the frequency channel *m*. We assume that time is slotted by *τ*. The packet length is normalized in order to be transmittable in a unit time slot. $X_{i,j}^{m,\tau}$ is an indicator variable which is assigned 1 if and only if link *e* is active in slot *τ* on channel *m*.

We considered that $X_{i,j}^{m,\tau}$ is the main factor related to scheduling of time slots. Since communication at rate c_e happens in every slot, link *e* is active on channel *m*, and $f_{e,m}$ is the average rate attained on link *e* for channel *m*, then we have

$$\frac{1}{T}\sum_{1\le\tau\le T} X_{i,j}^{m,\tau}\cdot c_e = f_{e,m}\,. \tag{1}$$

Equation (1) can be simply changed to

$$\frac{1}{T}\sum_{1\le\tau\le T} X_{i,j}^{m,\tau} = \frac{f_{e,m}}{c_e}\,. \tag{2}$$

This represents the relation between the indicator variable and network flow.

A. Transmission Range and Interference Range

We denote the transmission power spectral density (PSD) of the mesh router as P. In this paper, we assumed that all mesh routers used the same PSD for transmission to simplify the formulation. We used the power propagation gain model that is widely used:

$$G_{i,j} = \beta d_{i,j}^{-n}, \tag{3}$$

where β is a constant related to antenna, n is the path loss constant, and d_{ij} is the distance between mesh router i and j. We assume that data is successfully transmitted only if the received PSD at the receiver does exceed a threshold P_T. Moreover, we assume that interference exists only if the received PSD exceeds a threshold P_I at the receiver. Based on the threshold P_T, the transmission range for a mesh router is $R_T = (\beta P/P_T)^{1/n}$, which is from $\beta\ (R_T)^{-n}\ P = P_T$. Similarly, the interference range for a mesh router is $R_I = (\beta P/P_I)^{1/n}$ based on the interference threshold P_I ($< P_T$). Since $P_I < P_T$, we have $R_I > R_T$.

B. General Scheduling and Interference Constraints

Scheduling must ensure that there is no interference among the mesh routers, i.e. mesh nodes. In this paper, we consider scheduling in the time domain as well as in the frequency domain. Optimized scheduling on time and frequency bands must ensure that there is no interference at the same router and among the mesh routers. We assume that both mesh router i and j can use channel $m \in M_i \cap M_j$. $X_{i,j}^m$ is an indicator variable which is assigned 1 only if link $e=(i, j)$ is active on channel m. For a mesh router $i \in N$ and a frequency band $m \in M_i$, we denote T_i^m as the set of routers that can use a frequency band m and are within the transmission range to the mesh router i, i.e.,

$$T_i^m = \left\{ j: d_{i,j} \le R_T, j \ne i, m \in M_j \right\}. \tag{4}$$

Due to the fact that mesh router i cannot transmit to multiple mesh routers on the same frequency band, we obtain

$$\sum_{j \in T_i^m} X_{i,j}^m \le 1. \tag{5}$$

Also, the mesh router j cannot use the same frequency band for transmission and reception. That is, if $X_{i,j}^m = 1$, then for any $p \in T_j^m$, $X_{j,p}^m$ must be 0. Then, we have

$$X_{i,j}^m + \sum_{p \in T_j^m} X_{j,p}^m \le 1. \tag{6}$$

In (6), if the frequency channel m is being used on the link $e = (i, j)$, the band cannot be used at $e = (j, p)$. In addition to the above constraints, scheduling constraints should be considered at a mesh router because of hidden interference among the mesh routers in WMNs. To set these constraints, we assume P_j^m is the set of mesh routers that can produce interference at mesh router j on frequency band m, i.e.,

$$P_j^m = \left\{ p: d_{i,j} \le R_I, p \ne j, T_p^m \ne 0 \right\}. \tag{7}$$

In the above definition, $T_p^m \ne 0$ means that mesh router p can use frequency band m for transmission to the other mesh router in T_p^m. Then, we have

$$X_{i,j}^m + \sum_{q \in T_p^m} X_{p,q}^m \le 1 \quad \left\{ p \in P_j^m, p \ne i \right\}. \tag{8}$$

In (8), if the frequency channel m is being used on the link $e = (i, j)$, the band cannot be used at $e(p, q)$ due to interference.

C. Modeling of Time Sharing

Now, we consider time sharing when the mesh routers want to use frequency channels at the same time. The mesh routers could share frequency bands using an optimized scheduling algorithm like time division duplex in WiMax.

Fig. 2 illustrates an example of the suggested time sharing scheme. Fig. 2 shows general scheduling and interference constraints. Now suppose the mesh router i is transmitting to the mesh router j on channel m. Any mesh router that can produce interference at the mesh router j (i.e., router p) cannot use the same channel for transmission. On the other hand, when the mesh router i is not using channel m to transmit data to the mesh router j, the mesh router p can use this channel m to transmit data to the mesh router q.

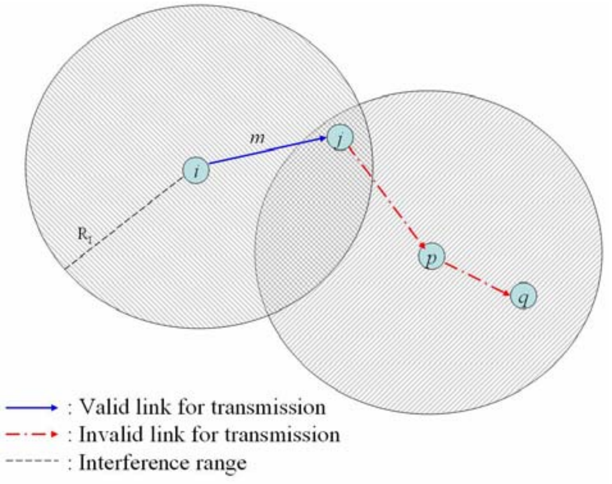

Figure 2. Wireless mesh network model with cognitive radio.

In contrast, now suppose mesh router i is transmitting to mesh router j on channel m and mesh router j also wants to transmit data to mesh router p on channel m. Also, mesh router p wants to transmit data to mesh router q. If we have enough time slots T, we can accommodate all requirements to transmit each using the suggested time sharing scheme. If this is done perfectly, data transmission does not fail in the interference range. If the mesh routers have CR functionalities in the CR-based WMNs, the mesh routers can manage their frequency bands and time schedule, which is effective scheduling for cross-layer optimization to enhance the overall performance. If we consider time sharing, scheduling constraints can be changed. If the optimized time sharing scheme is applied in CR-based WMNs, the number of mesh routers that can use the specific frequency channel can be increased because the specific channel can be simultaneously occupied by many mesh routers within the interference range.

As previously denoted, $X_{i,j}^{m,\tau}$ is an indicator variable which is assigned 1 if and only if link *e* is active in time slot *τ* on channel *m*. Therefore, (5), (6), and (8) can be derived as follows:

$$\sum_{j\in T_i^m} X_{i,j}^{m,\tau} \le T\ . \tag{9}$$

In contrast to (5), (9) shows that any mesh routers that want to communicate with the mesh router *i* can use the channel *m*. If there are enough time slots *T*, then mesh routers which want to communicate with the mesh router *i* can transmit data through the same channel *m*. (6) can be derived to

$$X_{i,j}^{m,\tau} + \sum_{p\in T_j^m} X_{j,p}^{m,\tau} \le T\ . \tag{10}$$

Also, the mesh router *j* can use the same channel *m* to transmit data to the mesh router *p* on different time slots. Though $X_{i,j}^{m,\tau}=1$, for any $p\in T_j^m$, $X_{j,p}^{m,\tau}$ can also be 1. In contrast, if $X_{i,j}^{m,\tau}=1$, for any , $p\in T_j^m$, $X_{j,p}^{m,\tau}$ must be 0 in (6). In addition, (8) also should be changed as follows:

$$X_{i,j}^{m,\tau} + \sum_{q\in T_p^m} X_{p,q}^{m,\tau} \le T \qquad \left\{p\in P_j^m,\, p\ne i\right\}. \tag{11}$$

In (8), if $X_{i,j}^{m,\tau}=1$, i.e., mesh router *i* uses channel *m* to transmit data to mesh router *j*, but mesh router *p*, which interferes with mesh router *j*, cannot use channel *m*, i.e., $\sum_{q\in T_p^m} X_{p,q}^{m,\tau}=0$. However, in (11), although $X_{i,j}^{m,\tau}=1$, $\sum_{q\in T_p^m} X_{p,q}^{m,\tau}$ can be more than 1. Even though mesh router *p* interferes with mesh router *j*, mesh router *i* uses channel *m* to transmit data to mesh router *j* and mesh router *p* can also transmit data to mesh router *q* on channel *m* using an optimized time sharing scheme.

III. PROBLEM FORMULATION AND ALGORITHM

A. Problem Formulation

Performance objectives need to be optimized for CR-based WMNs. We need to minimize system resources to increase overall utility. System resources are time slots for transmission and reception, frequency bands, throughput or network flow. We formulated the optimization problem to minimize the system resources, which are time slots in a particular link.

In (2), if we directly consider the time component, $X_{i,j}^{m,\tau}$, the problem will be very complex. Therefore, we transfer the indicator variable to the flow. Now we can formulate a linear programming to find a flow that minimizes system resource. From relation (2), we have the objective function as

$$\min \sum_{e\in E}\sum_{m\in M} \frac{f_{e,m}}{c_e}, \tag{12}$$

subject to

$$f_{e,m} \le c_e, \forall e\in E \tag{13}$$

$$f_{e,m} = 0, \forall e(i,j), m \notin M_{i,j} \tag{14}$$

$$\sum_{m\in M}\left(\sum_{e=(i,j)\in E}\frac{f_{e,m}}{c_e} + \sum_{e=(j,i)\in E}\frac{f_{e,m}}{c_e}\right) \le T \tag{15}$$

$$l_j + \sum_{e=(i,j)\in E}\sum_{m\in M}\frac{f_{e,m}}{c_e} = \sum_{e=(j,i)\in E}\sum_{m\in M}\frac{f_{e,m}}{c_e}\ . \tag{16}$$

(13) represents the flow on each link that can not exceed the link rate. (14) describes that a common channel must be available when mesh routers *i* and *j* want to communicate with each other. (15) represents mesh router radio constraints. The right side of (15) means the number of interfaces. Generally, a routing algorithm in WMNs has *T=1*. However, *T* can increase due to the suggested scheduling algorithm. (16) represents flow conservation constraints. The sum of flows between incoming flow and generated traffic must be the same as the outgoing flow to ensure fairness of the algorithm.

Fig. 3 shows an example of flow optimization in the CR-based WMN with 3 by 3 CR mesh routers and a gateway. Every flow is going to the gateway because we assume that there is only outgoing traffic. Every mesh router generates traffic, which is presented as load, l_i. Mesh routers 3 and 6 cannot transmit data to other mesh routers because the mesh routers are within the primary user's footprint in the network. Other mesh routers can transmit data to each other. The network flow is optimized using the suggested formulation as linear programming.

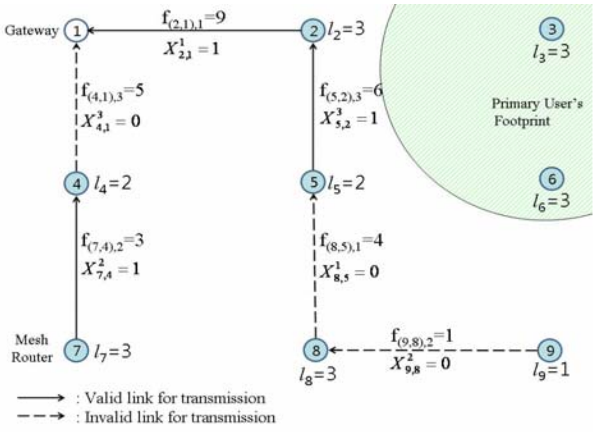

Figure 3. A result of flow optimization in the CR-based WMN has 3 by 3 CR mesh routers including a gateway.

Fig. 3 shows the results of flow optimization solved by the simplex II method. We assumed that all mesh routers were within the interference range in the network. We assumed that 3 channels are possible for use in the CR-based wireless mesh network. In contrast to only 3 channels possible, there are six flows after flow optimization. If all of the flows are transmitted using 3 channels, mesh routers interfere with each other. For example, there exists $f_{(2,1),1} = 9$ and $f_{(8,5),1} = 4$. These flows are within the interference range and use the same channel 1. These channels will interfere with each other. If there is no time scheduling between these two flows, one of two flows will fail and overall performance of the CR-based WMNs will decrease. Therefore, effective time scheduling is required to accommodate these flows, which interfere with each other.

B. *Interference Free Link Scheduling with Time Sharing*

We obtained the optimized flow values after solving the optimization problem by the simplex-II method. Previously, we did not consider time scheduling in this linear programming. We only assumed that time scheduling is ideally done while the optimized flow values are obtained. Scheduling information will be finally obtained through the proposed algorithm using the optimized flow values. The complete proposed algorithm is given in Fig. 4.

Proposed Algorithm

```
1. Set up and solve initial LP problem.
2. Select largest $\frac{f_{e,m}}{c_e}$ from all the links.
3. Assign $X_{i,j}^{m,\tau} = 1$ for all unassigned values.
4. Assign $X_{i,j}^{m,\tau} = 0$ for all links interfering with e.
5. Repeat step 2-4 until all flows are met.
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Figure 4. Proposed time sharing algorithm.

Initially, the linear programming problem will be solved out using the simplex-II method. Then the optimized flow values will be obtained. The optimized flow values are not valid if there is no optimized time scheduling completed. We select the largest $\frac{f_{e,m}}{c_e}$ from all the links. The flow values $f_{e,m}$ can be obtained, i.e., $f_{e1,m}$, $f_{e2,m}$, and $f_{e3,m}$, in the same channel under conditions of ideal time scheduling. Link *e1*, *e2*, and *e3* are different links. If links are within the interference range, they interfere with each other. We select the largest value $\frac{f_{e,m}}{c_e}$ and assign $X_{i,j}^{m,\tau} = 1$ for all unassigned values, and we assign $X_{i,j}^{m,\tau} = 0$ for all links which interfere with *e*. We repeat these steps until all flows are met. After we apply this algorithm, we can get optimized time scheduling information and this will be an interference free link scheduling for the time slots. These flows can be transmitted throughout channel 1, because the time slot is allocated differently, i.e., $X_{2,1}^{1,1} = 1$ and $X_{8,5}^{1,2} = 1$ using the suggested algorithm. $X_{4,1}^{3,2} = 1$ and $X_{5,2}^{3,1} = 1$. Also, $X_{7,4}^{2,1} = 1$ and $X_{9,8}^{2,2} = 1$ are within the interference range.

Using the above steps, we can calculate $\frac{1}{T}\sum_{1\le\tau\le T} X_{i,j}^{m,\tau}$ and get $\sum_{e\in E}\sum_{m\in M}\frac{1}{T}\sum_{1\le\tau\le T} X_{i,j}^{m,\tau}$ from (12). We also can compare $\sum_{e\in E}\sum_{m\in M}\frac{f_{e,m}}{c_e}$ with $\sum_{e\in E}\sum_{m\in M}\frac{1}{T}\sum_{1\le\tau\le T} X_{i,j}^{m,\tau}$ to evaluate the suggested algorithm.

IV. SIMULATION RESULTS

In this section, we show simulation results for the suggested cross-layer optimization including the time scheduling optimization by the suggested algorithm.

We considered *N*=36, 49 and 64 mesh routers in a 500 m by 500 m area. For simplicity, we assumed that link rates depended only on the distance between the two mesh routers. We assumed a link rate of 54 Mbps where the distance was within 30 meters. The data rate was 48 Mbps within the distance of 32 meters, 36 Mbps within 37 meters, 24 Mbps within 45 meters, 18 Mbps within 60 meters, 12 Mbps within 69 meters, 9 Mbps within 77 meters, and 6 Mbps within 90 meters. The maximum transmission range R_T was 90 m and the maximum interference range R_I was 180 m in this simulation. We considered grid and random topologies for the simulation. For grid topology, the distance between two adjacent mesh routers was $0.65 \cdot R_T$. The number of gateways is varied randomly from 2 to 16 in this simulation. We assumed that the total number of channels was 8 in the CR-based WMNs and the channels, which could be used by the secondary user, were randomly selected. The mesh routers should have at least one common channel to communicate to each other. A data set of 100 was generated for simulation in this paper. For every data set, generated traffic by the mesh router, location of the gateway, available frequency channels at each mesh router and maximum number of time slots *T* were randomly generated.

A. *Normailzed Costs*

The normalized cost was defined to evaluate the performance of the suggested algorithm. Normalized cost is the ratio between the flow optimization value and the time scheduling optimization value.

Fig. 5 shows the normalized costs for 36 mesh routers in the CR-based WMNs. The topology of the CR-based WMNs was grid. The average normalized cost was 1.0062 and the standard derivation was 0.02. From the results, we saw that the ratio of the two optimization values, i.e., flow and scheduling optimization values, was close to 1. Thus the suggested algorithm is also close to the optimal solutions.

B. *Per Node Throughput*

In this section, we show the per node throughput performance. The number of gateways and the size of the topology of the network were varied in this simulation. In this per node throughput was calculated as $\frac{\sum_{e\in E}\sum_{m\in M}\sum_{1\le\tau\le T}\left|f^{in}_{e,m,\tau} - f^{out}_{e,m,\tau}\right|}{N_G}$, where $f_{e,m,\tau}$ is the rate at which traffic is transmitted through link e in slot τ on channel m. The superscripts, *in* and *out*, represent incoming traffic and outgoing traffic, respectively. N_G represents the number of mesh routers except for the number of gateways. Results of the per node throughput is given for the grid topology as shown in Fig. 6.

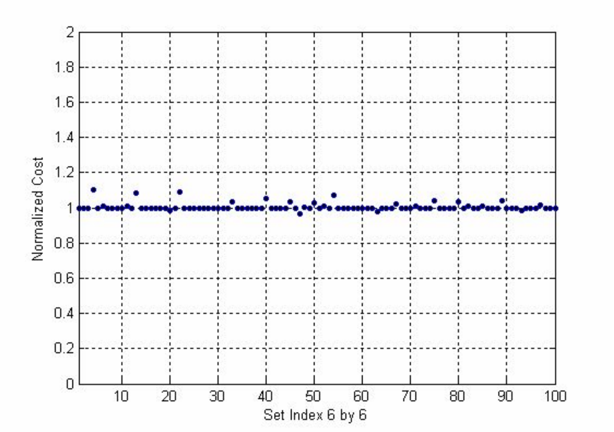

Figure 5. Normalized costs 6 by 6 router networks.

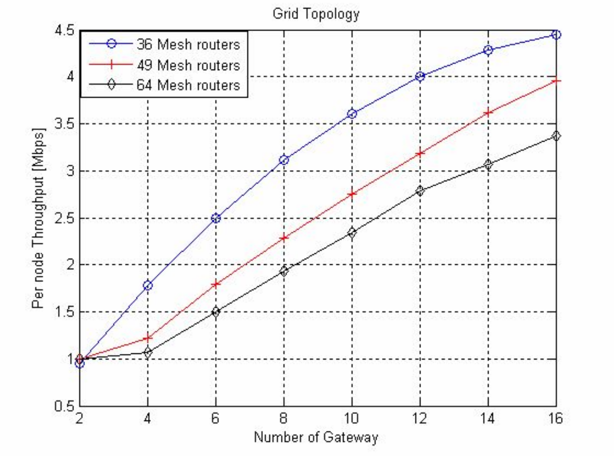

Figure 6. Per node throughput vs. the number of gateways with different numbers of mesh routers for a grid topology.

Results of the per node throughput vs. the number of gateways are shown for different numbers of mesh routers in these figures. As expected, we observe that the per node throughput significantly increased while the number of gateways increased. Also, the per node throughput is decreased with large numbers of mesh routers due to the fixed number of gateways.

V. CONCLUSION

In this paper, we suggested a cross-layer optimized algorithm for opportunistic frequency and time sharing between scheduling for MAC and network flow in CR-based WMNs. The problem was formulated using linear programming and solved by the simplex-II method. First, the flow optimization problem was developed for CR-based WMNs. Results showed that the network flow was optimized in CR-based WMNs with ideal interference free link scheduling. Secondly, we suggested the practical interference free link scheduling algorithm. Simulation results showed that the normalized cost of the optimized algorithm was close to 1, the optimal value, and offered a cross-layer optimized solution between scheduling and network flow in the CR-based WMNs. Throughput of the CR-based WMNs using the suggested algorithm was optimally enhanced.

The suggested a joint optimized algorithm for opportunistic frequency and time sharing and the suggested algorithm can be applied to centralized wireless multi-hop relay networks as well as distributed WMNs. Cross-layer protocols need to be studied for practical implementation of the suggested scheme for CR-based WMNs in the future.

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