Cross-Layer Design for Multi-Channel Wireless Mesh Networks Based on a Graph-Theoretic Approach

Ching-Ju Lin
Graduate Institute of Networking and Multimedia
National Taiwan University, Taipei, Taiwan
cjlin@cmlab.csie.ntu.edu.tw

Cheng-Fu Chou
Dept. of Computer Science and Information Engineering
National Taiwan University, Taipei, Taiwan
ccf@csie.ntu.edu.tw

Abstract— **Multi-channel wireless mesh networks (WMNs) aim to perform the ubiquitous wireless broadband network access. In WMNs, the problem of how to efficiently utilize multiple orthogonal channels and multiple communication interfaces to enhance the network capacity and the aggregate throughput has attracted much attention. Moreover, the interference problem in the wireless channels has made such problem more difficult. Since the routing and channel assignment in WMNs are highly correlated and significantly determine the performance of the system, in this paper we propose a cross-layer framework, which uses a linear programming approach to jointly solve the traffic-aware routing and interference-minimized channel assignment problems based on the traffic characteristics of different layers. Given the traffic demand of each mesh router, the linear programming approach constructs the flow-based routing to optimally distribute the traffic demand. Next, based on the flow scheduled on the routes, we assign the channel and schedule the traffic load for each interface card to balance the workload and minimize the interference effect among channels. The simulation results show that, exploring the traffic-aware routing and interference-minimized channel assignment, our cross-layer framework can achieve higher aggregate throughput compared with the WMNs using the non-traffic-aware channel assignment.**

I. INTRODUCTION

Due to the advance of the wireless technology, many interesting applications, such as wireless video streaming, neighboring gaming and VoIP, have the urgent requirement on broadband access over the ubiquitous wireless environment. Recently, the multi-hop city-wide wireless mesh networks (WMNs) have been developed for providing the last-mile ubiquitous broadband Internet access over the extensive coverage range [1]-[3]. The ubiquitous wireless environment helps to provide the Internet access for the area out of the coverage of the cable and DSL, and avoid the cost on deploying the cabal and DSL. Even with the capability of accessing the wired network, the devices have been increasingly equipped with multiple communication interfaces to efficiently utilize alternative wireless bandwidth and robustly access the seamless services. Moreover, the mesh topology allows the users to locally communicate with each other in the peer-to-peer manner without going through a service provider and the Internet, and thus relieves the traffic load of the wired networks.

In WMNs, there are three components, i.e. gateways, mesh routers, and end mobile devices. The gateways connect to the wired networks and provide the conduit to the external networks for the mobile nodes in WMNs. The mesh routers act like the fixed routers used to relay packets for other mesh routers or end devices, but the connection between two mesh routers is the wireless link. The end devices, which are not able to relay data for others, can associate with one of the mesh routers to communicate with the nodes in WMNs or access the Internet through the gateways by multi-hop forwarding. Since the nodes in WMNs usually behave like ones in the wired networks, the topology of WMNs and the traffic load of each router do not change frequently. Therefore, the channel resources are expected to be efficiently managed and utilized to optimize the system performance.

The WMNs aim to efficiently use the aggregate bandwidth of multiple orthogonal channels to enhance the network capacity and throughput. However, the problem of the channel assignment in the multi-radio multi-channel WMNs is proved a NP-hard problem in [9]. In addition, it becomes more difficult to solve the channel assignment problem when we further consider the interference effect, which is one of the major factors that degrade the system throughput in the wireless networks. We note that, in WMNs, the channel assignment correlates closely with the traffic load on each communication link, which can be determined by the routing of data transmission. Hence, the intuition of our approach is to figure out the traffic flow on each link, and assign the proper channel for each link based on the flow information to minimize the interference effect of close-by transmissions.

In this paper, we present a cross-layer framework including two procedures: traffic-aware routing and interference-minimized channel assignment. The goal of this work is to improve the aggregate throughput of WMNs and balance the load among orthogonal channels. In the traffic-aware routing scheme, we use the linear programming (LP) approach to figure out the best routing for maximally delivering the traffic demand subject to the capacity of each interface card. Next, interference-minimized channel assignment scheme associates each group of channel-depend interfaces with a wireless channel to satisfy the *Channel Dependency Constraint* and *Channel Number Constraint*, and meanwhile minimize the maximal interference per channel. Therefore, based on the LP model, our cross-layer framework is able to maximally transmit the traffic demand due to the optimal traffic routing and minimum performance degradation caused by the interference effect.

The rest of this paper is organized as follows. In section II, we briefly introduce several works which also investigate the channel assignment and the routing problems in the wireless mesh networks. The explicit description of our cross-layer routing and channel assignment algorithm is presented in section III. The performance evaluation via simulations is shown in section IV. Finally, section V gives a conclusion and refers to our future works.

II. RELATED WORKS

Recently, there have been many works [8][6][13] adapting the IEEE 802.11 standard for the multi-channel ad hoc networks. These works exploit multiple orthogonal channels to increase the capacity of ad hoc networks. However, considering the mesh network environment, the system should also take the routing into account, since the channel assignment and routing are heavily interdependent and jointly determine the interference effect and system performance.

Other research [5][7][12][14] separately considers the routing and channel assignment problems. Tang *et al.* in [7] greedily allocate the least used channel for each mobile node, and propose a Bandwidth-Aware Routing (BAR) algorithm to indicate the QoS-guaranteed routing. Draves *et al.* in [12] propose a Multi-Radio Link-Quality Source Routing protocol, which is similar to the DSR but uses a new metric called Weighted Cumulative Expected Transmission Time (WCETT). In the multi-channel environment, the traffic between two successive hops will not interfere with each other as two links use orthogonal channels. Hence, the WCETT metric explicitly accounts for the impact of both the path length and the channel diversity, and thus figures out the better route.

Some works [9][10][11] jointly solve the routing and channel assignment problems. Raniwala *et al.* [9][10] did the initial study on jointly considering these problems. They construct a multiple spanning tree-based structure to balance the traffic load dynamically, and also design a greedy algorithm to iteratively re-configure the channel assignment and routing that can improve the aggregate throughput. Alicherry *et al.* in [11] also jointly solve the channel assignment and routing problems based on the linear programming model. Their work conservatively finds an interference-free routing under the assumption that each node has infinite number of interface cards (NICs), and then uses a heuristic algorithm to fix the channel assignment for satisfying the NIC constraint of each node and the connectivity constraint. Nevertheless, our work, assuming there is infinite number of channels, finds the best routing and channel assignment subject to the NIC constraint and connectivity constraint, and next combines some groups of interfaces using different channels until the configuration satisfies the channel constraint. Another distinction between their works and ours is that all these works [9][10][11] assume that most of the WMNs nodes primarily communicate with the gateways to access the wired networks, while our approach considers a more realistic scenario, where allows not only the traffic going through the gateways but also the peer-to-peer communication without wired nodes involved. Hence, our framework is able to be applied to wide range of applications.

III. PROBLEM FORMULATION AND SYSTEM MODEL

A. Problem Formulation and System Overview

We consider the WMNs environment with finite number of orthogonal channels and with several mesh routers equipped with multiple interface cards. In this work, we assume there are K channels in the WMNs and the traffic demands of each router are given[1]. Thus, we are able to model this WMN as a directed graph $G_m(V_m, E_m)$. In the graph G_m, each mesh router $u \in V_m$ equips multiple interface cards (NICs), denoted as $N^u = \{n_i^u : 1 \leq i \leq |N^u|\}$, and each NIC n_i^u has the bandwidth capacity c_i^u. We let V_g denote the set of the gateways, and hence $V_g \subseteq V_m$. A directed link $e_{u,v} \in E_m$ if the distance between node u and node v is less than the maximal transmission range R_t. In our work, the communication can take place either between the router and the gateway or between two routers in the peer-to-peer manner. Our work aims to maximally route the aggregate traffic demand and take the fairness into account as well for each mesh router in the context of the NIC constraint and the channel constraint. For achieving this goal, we propose a cross-layer algorithm, composed of the traffic-aware routing and the interference-minimized channel assignment, to interdependently consider the problems of the routing and channel assignment.

We model the traffic-aware routing as a multi-commodity flow problem, and then use the linear programming model to construct a flow-based routing structure and schedule the network flow for each $e \in E_m$. Taking the fairness into consideration, the LP model solves the maximal π so that all of traffic sources can route the proportion π of their aggregate demands. The interference-minimized channel assignment associates each wireless link $e_{u,v}$ with some of given K channels based on the flow scheduled on each link. The objective of the interference-minimized channel assignment is to guarantee the connectivity of the routes, balance the load among channels and minimize the interference effect per channel under two constraints, *Channel Dependency Constraint* and *Channel Number Constraint*, which will be specifically defined latter. In the following, we describe the traffic-aware routing and interference-minimized channel assignment in our cross-layer framework, respectively.

B. Linear Programming Based Traffic-Aware Routing

We consider the flow-based routing structure as a directed graph G_m with the traffic flow carried by each $e_{u,v} \in E_m$. Each router $u \in V_m$ can simultaneously have multiple traffic demands, including the Internet traffic demand to the gateways and the peer-to-peer traffic demand to other routers $v \in V_m$. The problem of finding the max flow for several concurrent transmissions between different pairs of nodes can be described as the *Multi-commodity Flow Problem*. We collect all pairs of traffic demands as the set

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[1] Since the traffic pattern in WMNs does not change frequently, the traffic demand of each router could be obtained through online monitoring the traffic load or tracing the log file. However, the issues of how to get the traffic pattern and how to dynamically re-configure under a dynamic environment are out of the scope of this paper and will be our ongoing efforts.

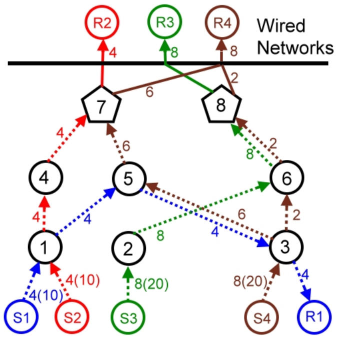

Fig. 1. LP-based Routing

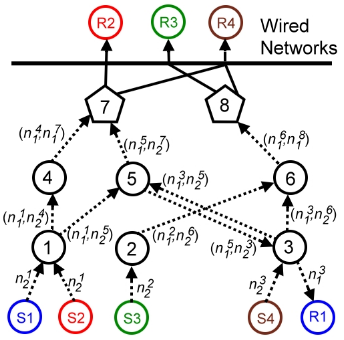

Fig. 2. NIC-Flow Association

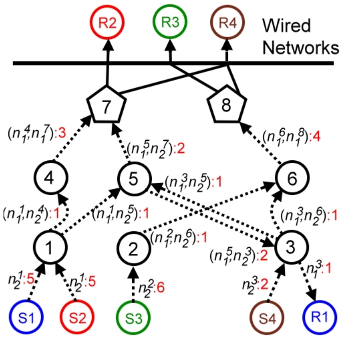

Fig. 3. Channel Dependency Constraint

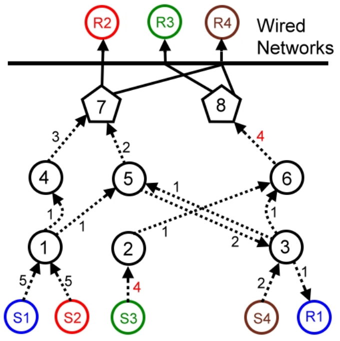

Fig. 4. Channel Number Constraint

$T = \{(s_1,r_1,d_1),\cdots,(s_k,r_k,d_k),\cdots,(s_{|T|},r_{|T|},d_{|T|})\}$ for $1{\le}k{\le}|T|$. For each traffic demand between the source and the destination, s_k in $(s_k,r_k,d_k){\in}T$ acts as a sending agent to generate the traffic demand d_k for the source node, and r_k is a receiving agent to receive the traffic sent to the destination. To involve these agent nodes in the linear programming model, we form a graph $G = (V,E)$ with $V = V_m{\cup}\{s_1,\cdots,s_k,\cdots,s_{|T|},r_1,\cdots,r_k,\cdots,r_{|T|}\}$ and E initialized to E_m. For the traffic demand $(s_k,r_k,d_k){\in}T$, if it is a peer-to-peer traffic from the source u to the destination v, $u,v{\in}V_m$, we add two edges $e_{s_k,u}$ and e_{v,r_k} to E. However, if it is an Internet traffic from the source u to the gateways, we add the edges $e_{s_k,u}$ and $e_{v,r_k}\forall v{\in}V_g$ to E to allow the traffic demand to be flexibly routed to any (or some) of all available gateways. We use $f^k_{u,v}$ to denote the flow traversing the edge $e_{u,v}{\in}E$ for k_{th} traffic demand in T, and the total flow $f_{u,v}$ carried by $e_{u,v}$ is the sum of all $f^k_{u,v}$ for $1{\le}k{\le}|T|$. Concerning the fairness, our model-based routing aims to route $\pi * d_k$ traffic for each demand $(s_k,r_k,d_k){\in}T$. Therefore, for k_{th} demand (s_k,r_k,d_k), $f^k_{s_k,u}$ means the actual traffic load, i.e. $\pi * d_k$, forwarded by the source node u, and $\sum_{\forall v\in V} f^k_{v,r_k}$ means the total flow received by the destinations. Note that the router $v{\in}V$ will be the only destination if (s_k,r_k,d_k) is a peer-to-peer traffic demand from the node u to the node v, while all gateways $v{\in}V_g$ are the possible destinations if (s_k,r_k,d_k) is an Internet traffic demand. Therefore, we use the summation of f^k_{v,r_k} for all destinations v to denote the total received flow of traffic demand (s_k,r_k,d_k). We now formulate a linear programming model to solve π and find the optimal routing for each traffic demand $(s_k,r_k,d_k){\in}T$.

$$maximize\ \pi \tag{1}$$

$Subject\ \ to:$

Capacity Constraint :

$$\sum_{\forall v\in V,1\le k\le|T|}(f^k_{u,v}+f^k_{v,u})\le\sum_{1\le i\le|N^u|}c^u_i \qquad ,\forall u{\in}V \tag{2}$$

Flow Constraint :

$$\sum_{\forall v\in V} f^k_{u,v} = \sum_{\forall v\in V} f^k_{v,u} \qquad \forall u{\in}V, 1{\le}k{\le}|T| \tag{3}$$

Fairness Forwarding Constraint :

$$f^k_{s_k,u} = \pi * d_k \qquad \forall(s_k,r_k,d_k){\in}T, \forall e_{s_k,u}{\in}E \tag{4}$$

Capacity Constraint (2) guarantees the total traffic going through the router will not exceed the total capacity provided by multiple interfaces. In Capacity Constraint, we ignore the interference problem and assume the capacity of interface cards can be fully utilized. We will discuss the interference problem in the channel assignment. Flow Constraint (3) makes sure that total incoming flow equals to total outgoing flow. Fairness Forwarding Constraint (4) promises all traffic demands to route the same proportion π of their requests d_k for $1{\le}k{\le}|T|$. Finally, the objective (1) is to maximize the π to ensure each node can optimally forward its traffic demand.

Figure 1 illustrates an example of our traffic-aware routing. There are 8 mesh routers, and the router 7 and 8 are designated as the gateways. Each router is equipped with 2 NICs with the bandwidth capacity 10. Router 1 has a peer-to-peer traffic demand 10 to the router 3 and an Internet traffic demand 10 to the gateways, respectively. Both of router 2 and 3 have traffic demand 20 to the gateways. Therefore, we create a traffic set $T = \{(s_1,r_1,10),(s_2,r_2,10),(s_3,r_3,20),(s_4,r_4,20)\}$, where first and second elements are the peer-to-peer traffic and the Internet traffic demands for router 1 and third and fourth elements are the Internet traffic demands for router 2 and router 3. For the Internet traffic demand $(s_4,r_4,20)$ from the source node 3, we create a sending agent s_4 and a receiving agent r_4. Then, we add edge $e(s_4,3)$ to generate the traffic for the source 3, and add edges $e(7,r_4)$ and $e(8,r_4)$ to receive the traffic sent to the gateways. The value of each flow in Figure 1 is calculated by the linear programming model. All of routers can forward 40% of their traffic demands. In our model-based routing, there may be multiple routes for a pair of traffic demand, and, hence, the traffic load can be shared by two gateways, i.e. 7 and 8. Figure 1 shows that the source node 3 can actually forward traffic load $f_{s_4,3} = 8$ for its demand $d_4 = 20$ to the gateways, and the gateways 7 and 8 receive traffic load 6 and 2 from the source node 3, respectively.

Before associating each NIC with a channel, we aggregate all flows $f^k_{u,v}$ for $1{\le}k{\le}|T|$ over edge $e_{u,v}$ to $f_{u,v}$, shown in Figure 2. Next, the flows associated with a node u are balancedly allocated to its interfaces $N^u = \{n^u_i : 1{\le}i{\le}|N^u|\}$. Figure 2 shows the flow-interface association in the example mentioned above. To avoid the collision between two successive hops, we separate the incoming flow from the outgoing flow on different interfaces using non-overlapped channels. In

id	$GroupNic_i$	Channel Dependency
1	$n_2^4, n_1^1, n_2^5, n_1^3, n_2^6, n_1^2$	$n_2^4 \leftarrow f_{1,4} \rightarrow n_1^1 \leftarrow f_{1,5} \rightarrow n_2^5 \leftarrow f_{3,5} \rightarrow n_1^3 \leftarrow f_{3,6} \rightarrow n_2^6 \leftarrow f_{2,6} \rightarrow n_1^2$
2	n_2^3, n_1^5, n_2^7	$n_2^3 \leftarrow f_{5,3} \rightarrow n_1^5 \leftarrow f_{5,7} \rightarrow n_2^7$
3	n_1^4, n_1^7	$n_1^4 \leftarrow f_{4,7} \rightarrow n_1^7$
4	n_1^6, n_1^8	$n_1^6 \leftarrow f_{6,8} \rightarrow n_1^8$
5	n_2^1	$f_{s_2,1} \rightarrow n_2^1 \leftarrow f_{s_1,1}$
6	n_2^2	$n_2^2 \leftarrow f_{s_3,2}$

TABLE I

CHANNEL-DEPENDENT INTERFACES

Figure 2, the notation (n_i^u, n_j^v) on $f_{u,v}$ means the node u and v associate with $f_{u,v}$ by i_{th} NIC and j_{th} NIC to communicate with each other. In Figure 2, we use the pair (n_1^1, n_2^4) on $f_{1,4}$ to denote that the traffic travelling on $e_{1,4}$ is handled by first NIC of node 1, n_1^1, and second NIC of node 4, n_2^4.

C. Interference-minimized Channel Assignment

If there are infinite number of channels and NICs, each flow can greedily associate with an unique orthogonal channel to perfectly avoid the interference with other communication links. However, the channel assignment will be restricted by the *Channel Dependency Constraint* and *Channel Number Constraint*. Therefore, we propose a two-phase interference-minimized channel assignment to satisfy two constraints in order, and to minimize the increasing interference effect per channel.

Channel Dependency Constraint: *Channel dependency* means that the flows associated with the same interface should be assigned the identical channel. For example shown in Figure 2, $f_{1,4}$ and $f_{1,5}$ should use the same channel, since both of them associate with NIC n_1^1. That is, the interfaces n_2^4, n_1^1 and n_2^5 associated with $f_{1,4}$ and $f_{1,5}$ should use the identical channel. Also, both of flows $f_{1,5}$ and $f_{3,5}$ associating with n_2^5 should use the identical channel. Due to the channel dependency constraint, the interfaces, including $\{n_2^4, n_1^1, n_2^5, n_1^3\}$, associated with $f_{1,4}$, $f_{1,5}$ and $f_{3,5}$ are called the channel-dependent interfaces and have to associate with the same channel. Table I presents six groups of channel-dependent interfaces for the example shown in Figure 1. We use $K^g = 6$ to denote the number of groups, and use $GroupNic_i$ to denotes the group of channel-dependent interfaces for $1 \leq i \leq K^g$. To satisfy the *Channel Dependency Constraint*, in the first phase of the channel assignment we assign an unique orthogonal channel i to all interfaces in the group $GroupNic_i$ for $1 \leq i \leq K^g$. Figure 3 shows the NICs associated with each flow and what channel they use.

Channel Number Constraint: *Channel Number Constraint* means that the number of allocated channels K^g can not be greater than the total number of channels K in WMNs. When the channel assignment still violates the *Channel Number Constraint* after the first phase, we attempt to iteratively merge two groups until the number of groups equals to K. For each NIC $n \in GroupNic_i$, we use the $IntfLoad_i^n$ to denote the total traffic load within the interference range R_i of interface n over channel i. $MaxIntfLoad_i$ is defined as $Max_{\forall n \in GroupNic_i}(IntfLoad_i^n)$ to indicate the maximal interference effect of $GroupNic_i$ over channel i. To reduce the number of groups, we greedily merge two groups $GroupNic_i$ and $GroupNic_j$ to minimize $MaxIntfLoad$ of the merged group. Next, we re-assign the channel i to each interface $n \in GroupNic_j$ and let $GroupNic_i = GroupNic_i \cup GroupNic_j$ be the merged group, and delete the $GroupNic_j$. Figure 4 shows the result of first merging from Figure 3 as the number of available channels is less than 6. $GroupNic_4$ and $GroupNic_6$ are merged because of the minimal $MaxIntfLoad$ of the merged group. Therefore, NIC $n_2^2 \in GroupNic_6$, associated with $f_{s_3,2}$, changes the channel assignment from 6 to 4. The procedure of merging will continue until satisfying the *Channel Number Constraint*, i.e. $K^g = K$. Merging two groups every iteration allows each channel to keep maximal interference effect minimized, and, hence, balances the load among all channels.

IV. PERFORMANCE EVALUATION

The performance of our cross-layer algorithm is evaluated by the simulation implemented in NS2 modified by Raniwala *et al.* [9] for the multi-radio multi-channel 802.11-based wireless networks. The linear programming model is solved by CPLEX [4]. In the following, we introduce the simulation environment and metrics, and finally show the simulation results.

Simulation Setup and Performance Metrics: The base-rate of a wireless channel is $2Mbps$, and there are 12 non-overlapped channels in the simulation environment. The transmission range of all mobile nodes is set to $250m$, and the ratio of the interference range to the transmission range is 2. 70 routers are uniformly distributed over a $1000m$ by $1000m$ square field, and 5 of 70 nodes are randomly designated as the gateways. Each node equips 2 IEEE 802.11b radios. For each topology, 30 nodes are chosen at random to generate traffic flow. We assume each source node has maximal aggregate traffic demand $4Mbps$, which equals to total capacity of interfaces, i.e. $2 * 2Mbps$. For 30 source nodes, 25 of them have the total traffic demand $4Mbps$ to the gateways, while the rest 5 of them have two demands: $2Mbps$ to the gateways and $2Mbps$ to a sink router randomly selected from all other routers. The evaluation metrics are (1) aggregate throughput, which is defined as the sum of the throughput of all flows, and (2) Jain's Fairness Index [15].

Comparison algorithms: We compare the performance of our cross-layer algorithm with three different algorithms and the upper bound solved by LP model as follows.

- Single-radio single-channel scheme (SRSC): SRSC is similar to the traditional ad hoc networks. Each node equips only one NIC and all nodes share the single channel.
- Multi-radio multi-channel scheme (MRMC): Each node has the same number of interface cards. MRMC just naively assigns first channel to first interface and assigns second channel to second interface.
- Non-traffic-aware greedy scheme (NON-TRAF): We compare our traffic-aware algorithm with the scheme

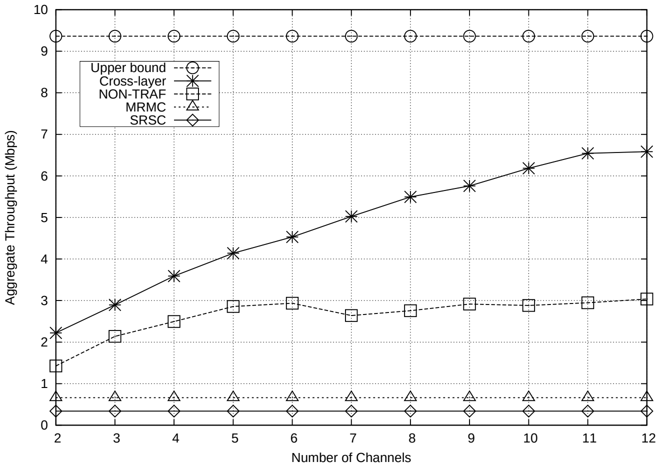

Fig. 5. Comparison among all schemes

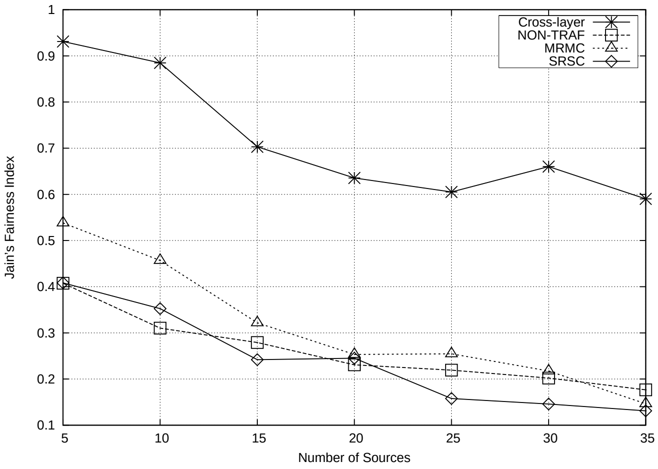

Fig. 6. Fairness among all flows

also used as the baseline in [9]. In NON-TRAF, each interface greedily selects the least-used channel, but does not take the traffic load of the channel into account.

- Model-based upper bound (Upper bound): We use the expected aggregate forwarded traffic load, i.e. $\pi * \sum_{\forall(s_k,r_k,d_k)\in T} d_k$, solved by LP model as the upper bound to compare with the actual aggregate throughput that our algorithm can achieve.

A. Improvements due to cross-layer design

Figure 5 shows the aggregate throughput of all schemes under various number of channels. Because the algorithms including SRSC, MRMC and Upper bound are independent of the number of channels, we extend the results of these schemes as straight lines. The results in Figure 5 shows that, even with more available channels in WMNs, the naive MRMC performs only twice better than the traditional single-channel environment (SRSC), because the channel utilization is restricted by the number of interfaces. However, our cross-layer algorithm and NON-TRAF scheme can have the increasing improvement with the number of the channels. In addition, our cross-layer algorithm can even outperform NON-TRAF by a factor of 2. The NON-TRAF greedily selects the least-used channel for each interface, but, however, the number of interfaces associated the channel can not exactly reflect the traffic load of this channel. Due to the benefit of the flow-based routing solved by LP model, our cross-layer algorithm can perceptively calculate the interference effect during the channel assignment, and optimally utilize the available orthogonal channels. Compared with the upper bound, SRSC only has about $350Kbps$ aggregate throughput because of the poor channel utilization caused by the severe interference effect in the single channel, while our algorithm can achieve 70% of the upper bound as there are 12 channels. The upper bound solved by the model is only restricted by the capacity of the interfaces, but, however, the actual aggregate throughput will be less than upper bound due to the interference problem. Therefore, as there are more channels, the increasing improvement on the aggregate throughput shows our algorithm can intelligently balance the load among channels and significantly alleviate the interference problem.

B. Fairness among all flows

We use Jain's Fairness Index [15], which is defined as $\frac{(\sum_{0<i<n} f_i)^2}{n\sum_{0<i<n} {f_i}^2}$, to evaluate the fairness among all flows f_i. Jain's Fairness Index gives a normalized number between 0 and 1, where 0 indicates the absolute unfairness and 1 indicates the absolute fairness. We vary the number of sources from 5 to 35 to observe the fairness under various traffic loads. Figure 6 shows that because the inherent contention problem in IEEE 802.11, all schemes have worse fairness when there are heavy traffic load. In SRSC, only one pair of the transmission wins the contention within the interference range. In addition, due to the backoff mechanism in IEEE 802.11, the node lost the contention should double its backoff interval and has lower probability to win the next contention. That is, the unfairness takes place because the node won the contention may get better chance to win the following contentions. Since MRMC just distributes the traffic load of each node on two interfaces over two channels, it performs slightly better than SRSC in terms of the fairness. In NON-TRAF, the channel assignment without considering the traffic load of channels results in the load-imbalanced problem among all channels. The interfaces using the light-loaded channel have less contention and thus perform higher throughput, but, however, the interfaces using heavy-loaded channel can not get satisfied QoS. Therefore, NON-TRAF sometimes has worse fairness than SRSC does. Our model-based algorithm optimally schedules the traffic load on each wireless link to fairly forward the traffic demand for all source nodes, so provides fairness among all flows. In addition, our channel assignment takes the interference effect into account so that the load among channels can be balanced.

C. Impact of system parameters on the aggregate throughput

To focus on the effect of the number of interfaces and the number of gateways on the performance, we ignore the peer-to-peer traffic demand and let all source nodes only have $4Mbps$ Internet traffic demand. We vary the number

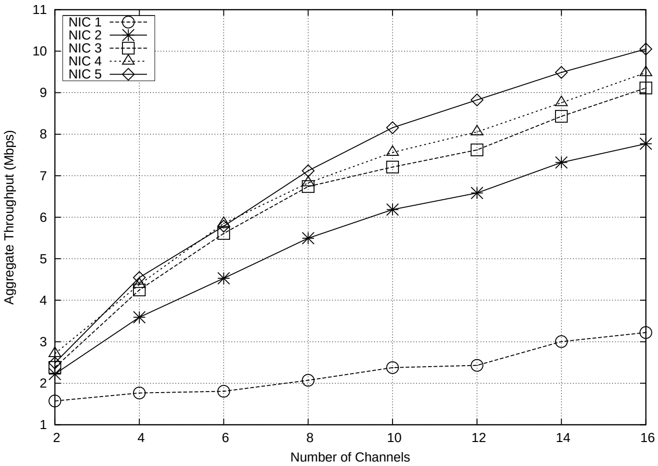

Fig. 7. Number of Interfaces vs. Aggregate Throughput

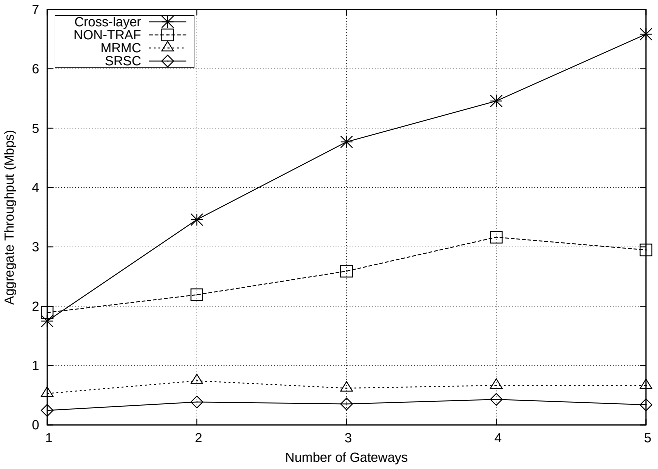

Fig. 8. Number of Gateways vs. Aggregate Throughput

of orthogonal channels from 2 to 16 and change the number of interfaces equipped in each node from 1 to 5 to evaluate the benefit of multiple interfaces. Figure 7 shows that, in general, the aggregate throughput increases with the number of channels. There is a significant improvement on the aggregate throughput from one radio environment to two radios environment. The throughput almost saturates when each node has 3 NICs. When there are more than 8 channels, the throughput still slightly increases as each node equips one more interface. This simulation shows that the WMNs can benefit from multiple interfaces even if each node only has 2 NICs.

The gateways connected with the wired Internet are in charge of relaying the data for the mesh routers, and usually have heavier traffic load. The results are shown in Figure 8 under varying the number of the gateways from 1 to 5. In the multi-channel environment, i.e. our algorithm and NON-TRAF, the network performs higher throughput because the gateways can use non-overlapped channels to share the traffic load. Moreover, with one more gateway using different channels, the network can increase the capacity to relay the data to the Internet. Our algorithm can outperform NON-TRAF because the model-based method optimally schedules the traffic load on multiple available gateways and assigns appropriate channels to their interfaces for balancing the load among gateways.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, we investigated the issues of routing and channel assignment in the wireless mesh networks. The cross-layer framework mutually considers the routing and channel assignment problems to minimize the interference effect among channels and enhance the aggregate throughput. The traffic-aware routing finds the paths for optimally delivering the traffic demand. Based on the flow on each link, the system assigns the channel for each NIC to minimize the interference effect and, meanwhile, subject to the *Channel Dependency Constraint* and *Channel Number Constraint*. The performance evaluation shows that our cross-layer algorithm can have significant improvement on the aggregate throughout and promise the fairness for each mesh router. Finally, our future work will focus on the distributed dynamic re-configuration, i.e. rerouting and channel re-assignment, to confront the transient traffic load fluctuation or the performance degradation.

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