Joint Routing and Channel Assignment in Multi-Radio Wireless Mesh Networks

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***Abstract*— This paper considers the problem of how to maximize throughput in multi-radio multi-channel wireless mesh networks. With mathematical model based on radio and radio-to-radio link, we introduce a *scheduling graph* and show that the feasibility problem of time fraction vector is equal to the problem of whether the scheduling graph is $\lfloor M \rfloor$-colorable, where M is the number of slots in one period. We use this equivalence property to derive a sufficient condition of feasibility, and then, using this sufficient condition, we mathematically formulate the joint routing and channel assignment problem as a linear programming problem. Finally, we use vertex coloring to get a feasible schedule and lift the resulting flows. We prove that the optimality gap is above a constant factor. The numeric results demonstrate the effectiveness of our proposed algorithm.**

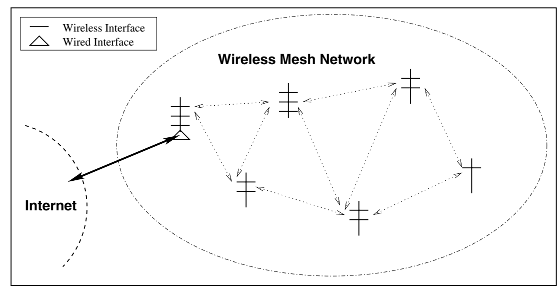

Fig. 1. A Multi-Radio Wireless Mesh Network

I. Introduction

With the spur of modern broadband wireless technologies, wireless mesh networks increasingly gain more attention in academy as well as in industry. Wireless mesh networks are stationary multihop wireless networks that provide an alternative way for the last-mile Internet access, as shown in Fig. 1. One of the popular deployment of wireless mesh network is to use standard commercial hardware, e.g. IEEE 802.11(a/b/g). With cheaper hardware, it is expected that multiple radio interfaces can be installed on one mesh node, so that simultaneous transmissions are allowed if radios are tuned in different orthogonal channels. However, interference in such a multi-radio multi-channel wireless mesh network still restricts the throughput, due to the limited number of available orthogonal channels or radios per node. Therefore, effective approaches to achieve the maximal throughput are highly demanded.

In this paper, we address the question of how to jointly perform channel assignment, routing and scheduling to maximize the throughput in a multi-channel multi-radio wireless mesh network. There are many works that consider the routing, channel assignment and scheduling in such networks. However, most of them only consider a subset problem. For example, some of them only consider finding better routes [1]; some consider routing and scheduling [2]; and some others consider channel assignment and scheduling [3]. Raniwala [4] *et. al.,* proposed an architecture for joint channel assignment and routing. Their work is based on heuristics and does not address the optimality.

The most closely work related to ours is proposed by Kodialam *et. al.* [5] that computes the capacity region of multi-channel multi-radio wireless mesh networks. Although this piece of work and ours have similar goals, they take different approaches. As we will elaborate in detail in Section II, we believe our approach is simple but powerful in solving this throughput maximization problem. In summary, we make the following contributions:

1) We develop a network model for multi-channel multi-radio mesh networks that provides a unified framework for both homogeneous and heterogeneous radios. We use an extended *conflict graph* to model the interference among different radio interfaces, which has the great flexibility of specifying arbitrary interference patterns. We also establish a *scheduling graph* that can directly map the link scheduling to vertex coloring problem. This way, we can directly take advantage of well developed vertex-coloring algorithms to obtain a feasible schedule. We believe our model is simple yet powerful for throughput maximization in multi-channel multi-radio mesh networks.
2) Due to the hardness of the joint channel assignment, routing and scheduling, we develop a *linear sufficient condition* of a feasible schedule of wireless links. Using this sufficient condition, we relax the original throughput maximization problem to a Linear Programming (LP) problem. Therefore, we can obtain a feasible solution in polynomial time. We prove that the obtained result is a

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constant factor approximation to the optimal one. With the scheduling graph we developed, we find, even with simple polynomial time greedy coloring algorithm, we can obtain an effective schedule based on the feasible solution. Since the feasible solution is computed based on sufficient condition, the actual resultant schedule may lift the rate of each flow by a same factor.

3) We conduct extensive simulations, which confirm the effectiveness of our algorithms. Our results reveal that with only a small portion of multi-radio nodes, the throughput of wireless mesh networks can be greatly improved. Our conclusions are coherent to these of existing works [6].

The rest of this paper is organized as follows. We start by presenting related works in Section II, and then state the radio based system model and the joint channel assignment and routing problem in Section III. Section IV studies the feasibility of a schedule in multi-radio wireless mesh networks. We further show the detailed formulation and solution of the joint routing and channel assignment problem in Section V. Numerical results are shown in Section VI. Section VII concludes the paper.

II. Related Works

Gupta and Kumar studied the capacity of wireless networks in [7]. They proposed two interference models, the protocol model and the physical model, mainly for single-channel single-radio case. And they showed how the capacity changes with the increase of the node density. Various other works have been done to compute the capacity problem under different scenarios. In [6], Kyasanur and Vaidya showed the capacity of multi-radio wireless networks and drew the impact of number of channels and radios. They showed that it was possible to reach the optimal throughput with as few as one interface per node in wireless multi-channel networks.

Raniwala *et. al.* proposed a centralized channel assignment and routing algorithm in [8]. They use a heuristic approach to obtain a static channel assignment. And in [4], Raniwala and Chiueh proposed an improved, distributed channel assignment algorithm, considering load-balance routing. In [9], Kyasanur and Vaidya proposed an channel assignment strategy, which fixes a channel on one radio and switches channels on other radios. This strategy permits communication without a global coordinator. The heuristic methods presented in these papers are not based on mathematical formulations. Nor is optimality discussed.

Kodialam *et. al.* considered a similar problem in [10] with a simple interference model, in which transmissions between two distinct pairs of nodes never results in a collision. They mapped the scheduling problem to edge coloring problem and proved that, based on theory of edge coloring, their solution is within $\frac{2}{3}$ of the optimal solution. But this interference model is derived from CDMA based multi-hop networks, which doesn't suit wireless mesh networks with multi-hop interference.

In [11], Alicherry *et. al.* studied the throughput maximization problem in multi-radio wireless mesh networks. They considered channel switching delay of current hardware and then provided a static channel assignment method, which is a constant approximation algorithm. Since our work is to approximate the maximal throughput in theoretical way, and the switching delay is expected to be a negligible overhead in near future, we assume that there is no channel switching overhead in our model, and a dynamic channel assignment method is used to approximate the maximal throughput.

The most closely related work to ours is Kodialam *et. al.* [5]. They proposed a relaxation of the original problem to an LP problem, and used the result as an oracle to derive schedule for feasible flows by a heuristic method. However, their model is based on node-to-node link, not radio-to-radio. Therefore, in order to reduce to an LP problem, they have to relax the node-radio constraint (i.e. the number of simultaneously active links should be less than the number of radios at a node), and later re-enforce it when computing a feasible schedule. This, not only complicates the algorithm design, but also makes it difficult to perform quantitative evaluation in theory. In contract, in this paper, we define a link with the radio-to-radio basis. The radio-to-radio link model characterizes both the node-radio constraint and the interference constraint, by using an extended conflict graph. Moreover, with a scheduling graph, we naturally map the scheduling problem to vertex coloring. Therefore, we can take advantage of well developed coloring algorithms, which make scheduling much easier and reliable. We prove that the optimality gap of our result is above a constant factor.

III. System Model and Problem Statement

We start this section by making some assumptions that we work on, and then we show the notations used in radio based model and discuss the contention in multi-radio wireless mesh networks. Lastly, we state the problem of joint channel assignment and routing that maximizes the throughput.

A. Assumptions

Let us consider a wireless mesh network with each node equipped with multiple radios. The wireless protocols used by radios may vary, e.g. IEEE 802.11 and IEEE 802.16. Each wireless protocol has several orthogonal channels while radios have fast channel switching abilities. We assume that each radio is compatible with only one wireless protocol, and channels belonging to different protocols do not interfere. We also assume that, among the radios using the same protocol, the transmission range and the interference range are both constants. Suppose that the system works in periodical slotted mode, where the time of one slot is a constant.

B. Radio Based Model

Our model is based on radios and radio-to-radio links. Let V denote the set of radios in a wireless network. The set of channels used in all protocols is C, which also includes a "virtual channel" ∞, which we will define later. And let L be the set of links. We say a link $l = (s, t, c) \in L$ if radio $s \in V$ could send data to radio $t \in V$ using channel c. In other words, t is in the transmission range of s and they are

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compatible with a wireless protocol using channel c. Noting that if radio s and radio t are plugged into the same node, there would be a link (s, t, ∞) with infinite bandwidth. Given a link $l = (s, t, c) \in L$, let $s(l) = s, t(l) = t$ and $c(l) = c$. We assume that the bandwidth of link l is b_l, and $b_\infty = \infty$. We define a multi-graph $G = (V, L)$, the connectivity graph, to present the topology of the wireless network. And we note that, if we assume that "virtual link" has infinite bandwidth, the capacity of a multi-radio wireless network is equivalent to that of a single-radio wireless network with these "virtual links" connecting between some node pairs. See Fig. 2 for an example. For simplicity, we only draw a single-channel case.

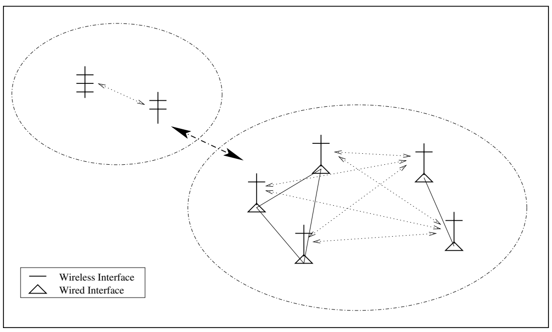

Fig. 2. Node Based $\Longleftrightarrow$ Radio Based

We consider the protocol interference model, which is similar to the model used in IEEE 802.11, based on Data/ACK or RTS/CTS/Data/ACK sequence. A transmission on link l is successful when all other links using channel $c(l)$, in whose interference area the sender $s(l)$ or the receiver $t(l)$ resides, are silent during the transmission. We note that our framework also suits *Receiver Conflict Avoidance* model [12], which only requires the receiver be clear to hear the signal.

The contention in multi-radio wireless networks comes from not only the wireless interference but also the radio resources limits. The radio based model can handle both causes in the same manner. We denote by I_l^R the set of links which, other than l, also use radio $s(l)$ or $t(l)$, and by I_l^C the set of links that interfere with l due to the wireless protocol model. Therefore, $I_l = I_l^R \cup I_l^C$ is the set of links which cannot simultaneously transmit while link l is active.

C. Joint Channel Assignment and Routing Problem

Suppose that there are several elastic source-destination flows in the network. We denote by $\mathcal{F}$ the set of flows, and by r_f the rates of flow $f \in \mathcal{F}$. We assume that the source of flow f is $o_f \in V$ and the destination is $d_f \in V$. Easy to see that the source of flow f could be any other radio on the same node of o_f since there is a link with infinite bandwidth between each two. So is the destination radio. Our goal is to maximize the total throughput of existing flows $\sum_{f \in \mathcal{F}} r_f$. And to reach the maximal throughput, multi-path routing is used for routing these flows. We use $r_{f,l}$ to denote the rate of flow f on link l and then get a formulation of our problem. We assign a time fraction $t_l \in [0, 1]$, which is schedulable, to each link l to meet the requirements of flows. We denote by T the required time fraction vector which consists of all t_l. Therefore, this problem can be presented as follows.

$$Z^* = \quad \max \textstyle\sum_{f \in \mathcal{F}} r_f, \tag{1}$$

$$\text{s.t.} \quad \begin{cases} T \text{ is feasible,} \\ \text{Flow conservation holds,} \\ \sum_{f \in F} r_{f,l} \le b_l \, t_l, & \forall \, l \in L. \end{cases} \tag{2}$$

Since flow conservation under multi-path routing can be presented by linear equations(See Section V), the hardest part in this problem is how to characterize the feasibility of a given time fraction vector T. We will discuss the feasibility problem in next section.

IV. Feasibility Problem

In this section we study the problem of determining the feasibility of required time fraction vector T. T is feasible if and only if we can find an interference free schedule which meets the time fraction requirements. We show equivalence between the scheduling problem and vertex coloring problem by introducing a *scheduling graph*. Due to the hardness of coloring problem, we use a linear sufficient condition to characterize the feasible region so that we can obtain a restricted form of the original problem. In other words, we find a ployhedra kernel of the feasible region.

A. Scheduling Graph

We define a *scheduling graph* based on a connectivity graph with each edge weighted by required time fraction, and a conflict graph. The *conflict graph* is used to specify the wireless interference. We define a conflict graph F, whose vertices correspond to the links L in the network. There is an edge between l and l' in F if and only if the links l and l' can not be active simultaneously. Note that the conflict graph is also adopted by Jain *et. al.* [2]. However, in our case, the wireless link is extended to have different channels. Therefore, we term the conflict graph defined here as *extended* conflict graph.

A scheduling graph is introduced to make a feasible schedule. We take Fig. 3 as an example to illustrate how to obtain a scheduling graph. For simplicity, we only consider single-channel single-radio case here. The upper left figure shows a network's connectivity graph with links indexed by $1, 2, 3, 4, 5$ and required time fractions following each link index. The lower left figure gives the conflict graph of this network. To obtain a scheduling graph, we suppose there are M slots per period first, e.g. $M = 5$ in our case. Therefore, each link needs at least $\lceil t_l M \rceil$ slots. We construct the scheduling graph $G_S(M)$, corresponding to the conflict graph F, by representing a vertex in F by $\lceil t_l M \rceil$ vertices in $G_S(M)$, between each two of which there exists an edge. And if $(l, l') \in Edge(F)$, then $(l_S, l'_S) \in Edge(G_S(M))$, for all l_S corresponds to l and l'_S corresponds to l'. The right figure in Fig. 3 shows the resulting scheduling graph of our example.

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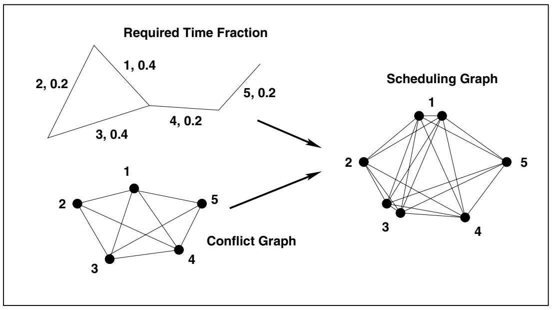

Fig. 3. Scheduling Graph, $M = 5$

We note that, Wu *et. al.* used a similar approach in [13], called *usage conflict graph* to bound the power rate function.

It is easy to see that, in a slotted system, any legal M-coloring of the scheduling graph $G_S(M)$ gives a feasible schedule of the wireless network, and vice-versa. Thus, if the chromatic number of $G_S(M)$ is more than M, which means the optimal schedule needs more than M slots in one period, the required time fractions are infeasible under this scheduling setup. Therefore, we can find an equivalence property between chromatic number of the scheduling graph and feasibility of the required time fractions, which is represented by the following theorem.

Theorem 1: In a slotted system, the required time fraction t_l on each link l is feasible if and only if $\exists M \in \mathbb{N}$ such that the scheduling graph $G_S(M)$ is M-colorable.

We still use Fig. 3 for example. Obviously, we need at least 6 colors to give a vertex coloring of $G_S(M)$. Because $6 > 5$, the required time fraction is not feasible with period length $M = 5$. Notice that in this case, since $t_l M$ are integers for all l, there is no truncation loss in construction of $G_S(M)$. Thus, for any other period length $M' \in \mathbb{N}$, the resulting scheduling graph must has chromatic number greater than M'. Therefore, the required time fractions in our example is not feasible.

B. A Sufficient Condition

We assume that all the numbers appeared in our paper are rational. Under this assumption, we can establish this linear sufficient condition of feasibility:

Theorem 2: The required time fractions must be feasible if

$$t_l + \sum_{l' \in I_l} t_{l'} \leq 1, \quad \forall\, l \in L. \tag{3}$$

Proof: Because the time fractions are all rational numbers, we can choose a $M \in \mathbb{N}$ such that $t_l M$ is an integer for all $l \in L$. And we use this M to construct a scheduling graph $G_S(M)$. If the inequality (3) is satisfied, multiply both sides by M, we have

$$t_l M + \sum_{l' \in I_l} t_{l'} M \leq M, \quad \forall\, l \in L. \tag{4}$$

Obviously, in the scheduling graph $G_S(M)$, the degree of a vertex l_S generated from l is

$$D(l_S) = t_l M - 1 + \sum_{l' \in I_l} t_{l'} M \leq M - 1. \tag{5}$$

Thus, from *Brook's theorem*, the scheduling graph $G_S(M)$ must be M-colorable. And from theorem 1, we know that the required time fractions must be feasible. ■

C. Optimality Gap

Due to the fact that the sufficient condition only present a polyhedra in the feasible region, there may exist feasible flows which do not satisfy the sufficient condition. We prove that, there exists a constant factor λ, such that, if required time fraction vector T is feasible, T/λ must satisfy the sufficient condition.

We know that links using the same radio cannot be active simultaneously. Then, given any feasible time fraction vector, we have

$$\sum_{l: v \in \{s(l), t(l)\}} t_l \leq 1, \quad \forall\, v \in V. \tag{6}$$

And with (6), we get, for any feasible time fraction vector,

$$\begin{aligned} t_l + \sum_{l' \in I_l} t_{l'} &\leq (2t_l + \sum_{l' \in I_l^R} t_{l'}) + (t_l + \sum_{l' \in I_l^C} t_{l'}) \\ &\leq 2 + (t_l + \sum_{l' \in I_l^C} t_{l'}). \end{aligned} \tag{7}$$

In [11], Alicherry *et. al.* proved that, for any feasible time fraction vector, we have,

$$t_l + \sum_{l' \in I_l^C} t_{l'} \leq C(q), \quad \forall\, l \in L, \tag{8}$$

where $q = R_I/R_T$. R_I is the interference range and R_T is the transmission range. The proof is based on geometry arguments. We denote the interference area of link l by A_l. Then $C(q)$ denotes an upper bound on how many links in region $R(l)$ do not pair-wise interfere with each other. The problem is the same as asking how many maximum circles of radius $0.5R_I$ can be packed into the region obtained by expanding A_l by $0.5R_I$. For example, we show that, $C(q) = 10, 8, 8$ for $q = 1, 2, 2.5$ respectively, whose bounds are tight.

Together with (7) and (8), we get, for any feasible time fraction vector,

$$t_l + \sum_{l' \in I_l} t_{l'} \leq 2 + C(q^*), \tag{9}$$

where $q^* = \arg\max C(q)$ for q in all protocols. Thus, we have, if required time fraction vector T is feasible, $T/(2 + C(q^*))$ must satisfy the sufficient conditions. This gives the optimality gap of the sufficient condition. We note that, in the case that there exist heterogeneous radios, the optimality gap may be very large.

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V. Joint Channel Assignment and Routing

In this section, we mathematically formulate the joint routing and channel assignment problem, using the sufficient condition of feasibility given above and taking into account the flow conservation. We then find a schedule which satisfies the required time fractions. We show that, the resultant schedule, can be used to lift the flows by a constant factor.

A. Problem Formulation

If we replace the constraint of feasibility in (2) by the linear sufficient condition (3), we can mathematically formulate our problem as follows.

$$\hat{Z} = \max \sum_{f\in F} r_f,$$

subject to:

$$t_l + \sum_{l'\in I_l} t_{l'} \le 1, \qquad \forall\, l \in L, \tag{10}$$

$$\sum_{l:s(l)=o_f} r_{f,l} = r_f, \qquad \forall\, f \in F, \tag{11}$$

$$\sum_{l:t(l)=o_f} r_{f,l} = 0, \qquad \forall\, f \in F, \tag{12}$$

$$\sum_{l:s(l)=d_f} r_{f,l} = 0, \qquad \forall\, f \in F, \tag{13}$$

$$\sum_{l:s(l)=v} r_{f,l} = \sum_{l:t(l)=v} r_{f,l}, \quad \forall\, v \in V - \{o_f, d_f\}, f \in F, \tag{14}$$

$$\sum_{f\in F} r_{f,l} \le b_l\, t_l, \qquad \forall\, l \in L, \tag{15}$$

$$t_l \ge 0, \qquad \forall\, l \in L,$$

$$r_{f,l} \ge 0, \qquad \forall\, f \in F,\ \forall\, l \in L.$$

Inequality (10) is the sufficient condition of feasibility. Equations (11), (12), (13) and (14) present the law of flow conservation. Constraint (11) shows that the total rate of flow f on outgoing links from o_f is equal to r_f. Equation (12) restricts that there is no flow belonging to f on incoming links to source o_f, and equation (13) holds that there is no flow belonging to f on outgoing links from destination d_f. Constraint (14) represents that, on any radio, except the source o_f and destination d_f, the amount of incoming flow is equal to the amount of outgoing flow. Constraint (15) indicates that the total rates of all flows in F on a link cannot exceed the capacity of the link. And the last two constraints restrict both $r_{f,l}$ and t_l be non-negative, for all l in L and f in F.

Remember that we denote by Z^* the maximal throughput of the given wireless network. From Section IV, we know that, there exists a solution of throughput no less than $Z^*/(2 + C(q))$ which satisfies the sufficient condition. Thus, we have, $\hat{Z} \ge Z^*/(2+C(q))$.

B. Scheduling and Lifting Flows

An optimal solution under sufficient condition may not be global optimal. After we apply an LP solver and obtain a feasible time fraction vector T. We can color the scheduling graph with period length $M \in \mathbb{N}$ arbitrarily chosen, and get a chromatic number N, which means a legal schedule with period N. Now we can scale the flows by M/N times and the resulting flows are still feasible.

Since the required time fractions, obtained from an LP problem with rational coefficients, are all rational numbers. We can find a $M \in \mathbb{N}$ such that $t_l M$ are all integers. From the proof of sufficiency, we know that, $G_S(M)$, with maximum degree of $M-1$, is M-colorable. We note that, coloring a graph G with $\Delta(G)+1$ colors is a trivial task, where $\Delta(G)$ is the maximum degree of G. Then we can always expect that $M/N \ge 1$. Therefore, the optimality gap will still be held even if we choose a simple greedy vertex coloring algorithm. Certainly, a better coloring algorithm will result better throughput, with computational cost trade-off. In practice, we can arbitrarily choose a relative large M, which will only result tiny truncation loss.

VI. Numerical Results

In this section, we present the numerical results. We show the throughput increments with multi-radio and multi-channel. We use a 5×6 grid topology with 30 nodes to test our method. We assume that each node has two slots for 802.11g or 802.11a radios. Corresponding to standards, there exist 3 orthogonal channels in 802.11g protocol and 12 in 802.11a. We also set the link speed of 802.11a/g radio to 54Mbps. The transmission range is fixed at 250m and the interference range is 500m, both for IEEE 802.11g and 802.11a protocols. The grid length is 200m, which results two-hop and three-hop interferences in our model.

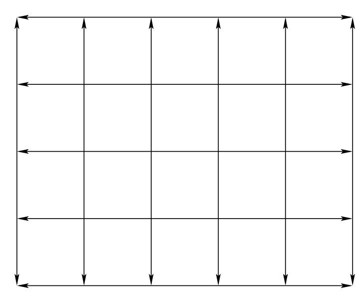

Fig. 4. Grid topology and flow pattern

We use lp_solve 5.1 [14] as our LP solver, and we choose the DSATUR algorithm of Brelaz [15] as our vertex coloring program, which is a sequential coloring algorithm with polynomial complexity. We always choose the period length $M = 100$ in generating the scheduling graph.

Our first experiment is to show the throughput increments due to multiple radio interfaces equipped on nodes. We assume that each node has an 802.11g radio plugged already, and leave an empty slot for 802.11a radio. Firstly, we fix a flow pattern and start with applying our algorithm to a single-radio wireless mesh network, i.e. each node of which only has an 802.11g radio. Then, we increasingly add 802.11a radios to the nodes in the network and watch the throughput gain. We repeat the

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above step until all the nodes are equipped with two radios. There is a total of elevens flows in our flow pattern, with five of them from the left to the right and six from top to the bottom, as shown in Fig. 4. The results are shown in Fig. 5.

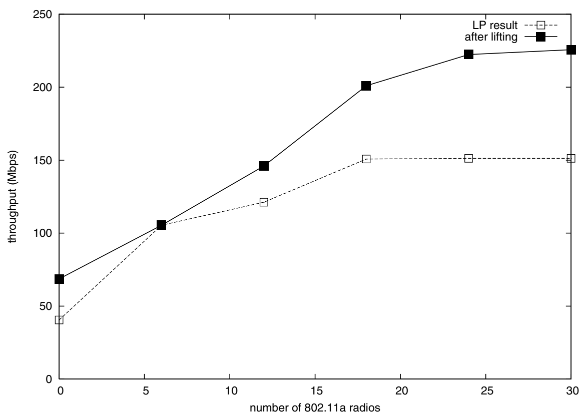

Fig. 5. Throughput increments due to multi-radio

From the above results, we can observe a substantial throughput gain when the fraction of multi-radio nodes is less than 60%. When using 60% multi-radio nodes, the throughput becomes three times as much as that of single-radio case. It illustrates the benefits of multi-radio networks. We also find that very small increments are obtained when we add even more 802.11a radios. Under this circumstances, increasing the number of radios will not increase the spatial utilization due to interference, which limits the throughput increments. Our results agree with the theoretical results made by Gupta *et. al.* in [7] and Kyasanur *et. al.* in [6].

The second experiment is designed to show the throughput increments with increasing orthogonal channels. We assume that each node has been equipped with two homogeneous radios. We still use the grid topology as that in the first experimet. However, this time, we use a flow pattern with four flows. Two flows traverse from left to right and the other two traverse from top to bottom. We increase the number of available orthogonal channels from 1 to 5 and observe the throughput increments. The results are shown in Fig. 6.

We can see the prominent throughput increments at the beginning of adding orthogonal channels. And the growth rate declines rapidly after the number of orthogonal channels reaches a relative small number (four in this case). This suggests that we can obtain considerable throughput with only limited orthogonal channels. This is coherent to the results that Kyasanur *et. al.* acclaimed in [6].

VII. CONCLUSION

In this paper, we propose a mathematical model of multi-radio wireless mesh networks, which is based on radio and radio-to-radio link. With this model, we provide a unified way to characterize the node-radio constraint as well as the wireless interference constrain. We develop a linear sufficient condition for a feasible schedule in multi-channel multi-radio wireless

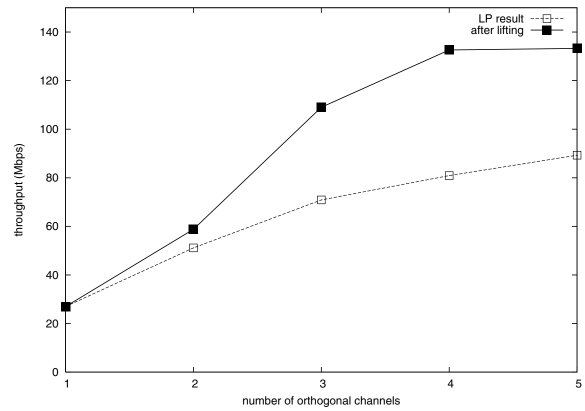

Fig. 6. Throughput increments due to multi-channel

mesh networks. With this sufficient condition, we formulate the joint routing and channel assignment problem as a linear programming problem that will compute the optimal routes for the given set of flows. Then with a scheduling graph, we obtain flow schedule on wireless links with vertex coloring algorithms. We prove that, in worst case, our solution is above a constant factor of the optimal throughput.

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