# Resource Planning and Packet Forwarding for Next-generation Multi-hop Wireless Mesh Networks

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***Abstract*—Most earlier works in the area of wireless mesh network assume a single interface being equipped in each node. In this paper, we consider the next-generation wireless mesh networks in which each node may be equipped with multiple radio interfaces, each capable of running in one of several modes, one of several channels, and each capable of supporting multiple modulations. For example, from off-the-shelf components, one can easily construct a mesh node with multiple IEEE 802.11a/b/g radio interfaces. Our goal is to address the resource planning and packet forwarding issues in such an environment. The proposed methodology is based on linear programming with network flow principles and radio channel access/interference models. Given a network topology, traffic requirements, and gateway capacities, we show how to allocate network interface cards and their channels to fully utilize channel bandwidths. The results can be used by a wireless Internet service provider to plan their networks under a hardware constraint so as to maximize their profits. To the best of our knowledge, this is the first work addressing resource planning in a wireless mesh network. Our numerical results show significant improvement in terms of aggregate network throughput with moderate network-layer fairness.**

**Keywords:** linear programming, resource planning, routing, channel assignment, wireless ad hoc network, wireless mesh network.

## I. Background and Related Work

The wireless mesh network (WMN) is a promising solution to the last-mile wireless Internet access problem. It can complement the limitation of WLAN coverage. Applications of WMN include enterprise wireless backbones and community networks [14]. In [4], two mesh hierarchies are defined: *infrastructure mesh* and *client mesh*, where the former has much less mobility than the latter. Reference [13] points out that a WMN may suffer from the scalability problem as the network grows due to the contention and interference among hosts. To mitigate the scalability problem, one may explore advanced transmission technologies (such as smart or MIMO antennas [10], [16], [21]) or layer-2 or layer-3 solutions based on commodity radio modules [2], [5], [7], [8], [11], [15], [17], [18], [20]. Several works show how to increase WMN capacity by adaptively adjusting the data rates [3], [6], [12], [19].

In this work, we adopt the latter approach based on commodity components. We explore the possibility of multi-interface, multi-channel model. For example, IEEE 802.11a/b/g has 12/3/3 non-overlapping channels available. One can easily make a multi-interface mesh node by off-the-shelf components. Several works have addressed the related issues. In [9], [22], [23], the authors propose to use a dedicated interface running on a control channel to negotiate the data channels to be used by other interfaces. References [2], [5], [7], [11], [15], [17], [18] propose to treat interfaces equally and some channel assignment techniques are used to exploit spatial reuse.

The above works all assume that the number of interfaces in each mesh node is given. In this paper, we address the resource planning problem in a Multi-radio Multi-mode Multi-channel Multi-rate wireless mesh network. Our approach is based on linear programming. Based on the well-known IEEE 802.11 channel contention model, we compute the near-optimal number of radio modules that should be equipped in each node and the channel that should be bound with each interface. We present two resource management and channel assignment algorithms: Decremental Interface Management (DIM) and Incremental Interface Management (IIM).

Our ultimate goal is to maximize the traffic volume in/out of Internet gateways of the mesh network, under the restrictions of network topology (connectivity status), available resources, and user's traffic needs. We summarize our contributions as follows:

- Instead of considering only a single factor, our approach addresses all practical characteristics of wireless communications, including the available non-overlapping radio channels and the interference factors among neighboring mesh nodes.
- Resources are allocated to mesh nodes based on user's traffic requirements, available hardware/radio modules, and gateway capacities. We allow nodes to have different numbers of radio interfaces. Not only addressing the related multi-channel issues, we also provide a guideline to wisely distribute the deployment costs considering an optimized network system. To the best of our knowledge, this is the first work addressing resource planning in wireless mesh networks.
- In order to enable simultaneous traffic incoming/outgoing through different radio modules of the same mesh host, we propose to perform multi-path packet forwarding (data flow splitting) to further exploit the benefits of having multiple transceivers. This idea will be elaborated in more detail in Section II-D.

The remaining paper is organized as below. In Section II, we introduce the proposed network architecture, our linear programming model for network optimization, two resource management and channel assignment algorithms, and our packet

This work of Ting-Yu Lin is sponsored by the NSC of Taiwan under Grant number NSC96-2218-E-009-006.
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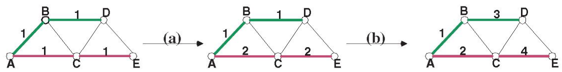



Fig. 1. Illustration of the multi-radio benefits (the number associated with each edge indicates the channel number used): (a) enabling simultaneous transmissions between routes (*inter-route* contention removed); (b) further enabling simultaneous transmissions between consecutive hops along a route (*inter-hop* contention eliminated).

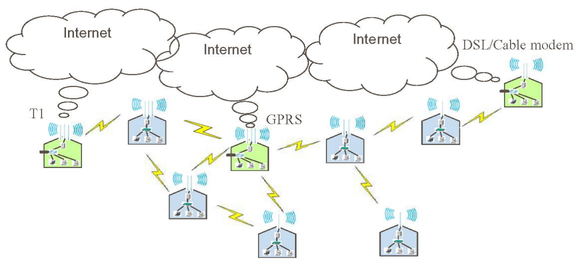



Fig. 2. A mesh network with heterogeneous Internet gateways.

forwarding strategy. Section III presents the network settings and detailed numerical results. Finally Section IV draws our conclusions and future plans.

## II. Resource Planning in a Wireless Mesh Network

This section first defines the architecture of our proposed wireless mesh network. Then we propose a linear programming model to allocate radio interfaces to mesh nodes and bind channels to these radio interfaces. Two schemes called Decremental Interface Management (DIM) and Incremental Interface Management (IIM) are proposed. In Section II-D, we re-visit the contention problems as depicted in Fig. 1, and propose a multi-path packet delivery function ($m$PDF) to further exploit the advantage of having multiple radios and channels.

### A. Network Architecture

We consider a next-generation network as shown in Fig. 2. Each mesh node is equipped with one or multiple wireless interfaces. Each interface can operate in one of several modes. In this work, we consider IEEE 802.11 a/b/g. Each antenna can be either omni-directional or directional. Also, an interface can support multiple modulations with different transmission rates. It is assumed that an interface is capable of selecting the best modulation depending on the channel quality. We consider link asymmetry, in the sense that the transmission rate in one direction of a link could be different from that of the other. The mesh network may have multiple heterogeneous Internet gateways with different bandwidths.

### B. Linear Programming Model

To construct a cost-efficient WMN, we need to allocate interfaces to nodes, assign channels to them, and balance traffic loads among gateways. The network is modeled by a directed graph $G = (V, E)$, where $V$ is the set of mesh nodes and $E$ the set of wireless links. Note that $E$ is determined by how we allocate interfaces. We make the following assumptions and define some notations:

- There are totally $N$ interfaces available.
- The maximal number of non-interfering channels is $C$.

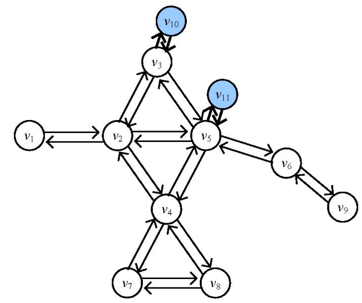



Fig. 3. An example wireless mesh network graph with separate mesh hosts and Internet gateways.

- All user traffic is destined to the Internet. We assume that each mesh node $v_i$ is associated with an uplink load upper bound $u_i^u$, a downlink load upper bound $u_i^d$, an uplink load lower bound $l_i^u$, and a downlink load lower bound $l_i^d$.
- A subset $V^g \subseteq V$ of mesh nodes are designated as Internet gateways and the remaining subset $V^h$ are designated as hosts, that is, $V = V^h \cup V^g$. We assume that only hosts in $V^h$ generate traffic. In case gateways in $V^g$ have some traffic demand, we can re-define the node set $V$. For instance, we can formulate an example network architecture as a bidirectional graph illustrated in Fig. 3. We create two virtual gateway nodes, $v_{10}$ and $v_{11}$, which deal with traffic relaying without generating traffic and have unlimited bandwidth to/from neighboring hosts, $v_3$ and $v_5$. In addition, for each $v_m \in V^g$, we use $B_m^u$ and $B_m^d$ to denote its uplink and downlink bandwidths, respectively, to the Internet.
- For each pair of neighboring hosts $v_i$ and $v_j$, the best bit rates from $v_i$ to $v_j$ and from $v_j$ to $v_i$ on channel $k$, $k = 1 \ldots C$, are denoted by $f_{ij}[k]$ and $f_{ji}[k]$, respectively. Note that the existence of such wireless links between $v_i$ and $v_j$ depends on how we allocate interfaces to $v_i$ and $v_j$. If any of $v_i$ and $v_j$ does not have an interface on channel $k$, we simply let $f_{ij}[k] = f_{ji}[k] = 0$. The best rates may depend on factors such as signal quality, transmission distance, etc. For link asymmetry, it is not necessary that $f_{ij}[k] = f_{ji}[k]$.
- Depending on how interfaces are allocated, we define the set of wireless links operating on channel $k$ as $E^k = \{e_{ij} | f_{ij[k]} > 0\}$. As a result, the set of all wireless links is $E = \cup_{k=1}^{C} E^k$.
- In order to represent how interfaces are allocated and how channels are bound, we define a *channel vector* $c_{i[k]}$ for each host $v_i$:

$$c_{i[k]} = \begin{cases} 1 & \text{if } v_i \text{ have an interface operating on channel } k \\ 0 & \text{otherwise.} \end{cases}$$

Note that it makes no sense to bind multiple interfaces of a host to the same channel. So the number of interfaces owned by $v_i$ is the cardinality of $c_i[k]$. In Section II-C, we will discuss how to determine these vectors. Then we can define the *connectivity vector* $c_{ij[k]}$ between $v_i$ and $v_j$:

$$c_{ij[k]} = \begin{cases} c_{i[k]} \times c_{j[k]} & \text{if } e_{ij} \in E^k \\ 0 & \text{otherwise.} \end{cases}$$

- To formulate the channel contention behavior, we define $IE_{ij}^k$ to be the set of links in the interfering range of link

$e_{ij}$ that also use channel $k$: $IE_{ij}^k = \{e_{pq} | e_{pq} \in E^k$ and one of $v_p$ and $v_q$ is in the interfering range of $v_i$ or $v_j\}$. For example, one simple definition of interfering range is to include all $v_i$'s and $v_j$'s two-hop neighbors.

- From now on, we introduce some unknown variables in our linear programming model. We define $\lambda_i^u$ as the actual uplink traffic load delivered from node $v_i$, and similarly $\lambda_i^d$ as the actual downlink traffic load destined to node $v_i$.
- Next, we define $x_{ij[s,k]}^u$ as the actual uplink traffic generated by source node $v_s$ over wireless link $e_{ij}$ using channel $k$, and similarly $x_{ij[d,k]}^d$ as the downlink traffic forwarded to destination node $v_d$ over wireless link $e_{ij}$ using channel $k$. Moreover, we define $x_{ij[0,k]}$ as the aggregate traffic load on wireless link $e_{ij}$ using channel $k$, where $x_{ij[0,k]} = \sum_{v_s \in V} (x_{ij[s,k]}^u \times c_{ij[k]}) + \sum_{v_d \in V} (x_{ij[d,k]}^d \times c_{ij[k]})$.
- For each gateway host $v_m \in V^g$, we define the aggregate uplink/downlink traffic via $v_m$ to be $g_m^{out}$/$g_m^{in}$ to be:

$$g_m^{out} = \sum_{v_s \in V} g_{s,m}^{out}, \quad g_m^{in} = \sum_{v_d \in V} g_{d,m}^{in}.$$

Our ultimate goal is to maximize the mesh network capacity such that the traffic flowing in/out of the set of gateway is the largest, without violating the traffic requirement (upper and lower bounds) of each mesh node. Our approach is based on linear programming. The objective function can be written as

$$Maximize \sum_{v_m \in V^g} (g_m^{out} + g_m^{in}),$$

subject to the following constraints: (1) general constraints:

$$\lambda_i^u \geq l_i^u, \lambda_i^u \leq u_i^u, \lambda_i^d \geq l_i^d, \lambda_i^d \leq u_i^d, x_{ij[s,k]}^u \geq 0, x_{ij[d,k]}^d \geq 0,$$

$$\sum \lambda_i^u = \sum_{v_m \in V^g} g_m^{out}, \sum \lambda_i^d = \sum_{v_m \in V^g} g_m^{in},$$

(2) gateway constraint:

$$\begin{cases} g_m^{out} + g_m^{in} \leq B_m & \text{if uplink and downlink share the bandwidth} \\ g_m^{out} \leq B_m^u, g_m^{in} \leq B_m^d & \text{otherwise.} \end{cases}$$

Due to the fact that radio channel bandwidth is shared by all wireless links within the interfering range of edge $e_{ij}$, we add one more constraint to reflect the channel model based on IEEE 802.11 DCF contention protocol:

$$\sum_{e_{pq} \in IE_{ij}^k} (x_{pq[0,k]} / f_{pq[k]}) \leq 1.$$

The above constraints, along with flow conservation equations successfully formulate our linear programming model.

### *C. Resource Allocation and Channel Assignment Techniques*

In this section, we present two algorithms to distribute available radio modules and perform channel arrangement: Decremental Interface Management (DIM) and Incremental Interface Management (IIM). Our goal is to derive the channel vector $c_{i[k]}$, $\forall v_i \in V^h$, and feed it back into our linear programming (LP) model introduced in Section II-B to maximize network throughput. Based on the two strategies, we decrease/increase network interfaces step by step until all available modules are used up, solving the linear model repetitively. At the end of these algorithms, we can obtain $n_i$, the required number of IEEE 802.11a/b/g radios associated with host $v_i$ (under the $N$ limitation), in the following way:

$$\sum_{k=1}^{C} c_{i[k]} = n_i,$$

where $\sum_{\forall v_i \in V^h} n_i = N$.

**Input:** Bounds of host traffic $\{u_i^u\}, \{u_i^d\}, \{l_i^u\}, \{l_i^d\}$, capacity of links $\{f_{ij[k]}\}$, bounds of gateway traffic $\{B_m\}, \{B_m^u\}, \{B_m^d\}$, number of available channels $C$, number of available NICs $N$.

**Output:** Channel boolean vector $\{c_{i[k]}\}$.

**Variable:** Actual host traffic $\{\lambda_i^u\}, \{\lambda_i^d\}$, actual link traffic from/to host $v_{s'}/v_{d'}$ $\{x_{ij[s',k]}^u\}, \{x_{ij[d',k]}^d\}$, actual gateway traffic $\{g_m^{out}\}, \{g_m^{in}\}$, actual number of NICs $N'$.

Fig. 4. Summary of inputs, outputs, and variables used in both the DIM and IIM procedures.

Before we describe the two algorithms in more detail, Fig. 4 summarizes the inputs, outputs, and variables used in the proposed DIM and IIM mechanisms.

The first proposed technique is Decremental Interface Management (DIM), which starts from equipping each mesh host with the maximal number of radio interfaces, i.e. $C$ NICs, since $C$ is the total number of non-overlapping channels. Assume that the number of available radio modules $N$ is insufficient to support $C$ NICs on each mesh host. In addition, as we will observe in Section III, it is not necessary to use all the $C$ interfaces equipped on each host in order to achieve the maximal network throughput. Instead, several interfaces can be removed without degrading the system, for there exist several wireless links over certain channels with zero traffic flows based on our LP calculation. In the proposed DIM algorithm, we first remove those useless interfaces and check if the total number of NICs used satisfies the $N$ limitation. If so, the algorithm terminates and returns the channel vector $c_{i[k]}$ along with corresponding traffic distribution patterns for our packet delivery function ($m$PDF), which will be presented later in Section II-D. Otherwise, we need to evaluate each NIC and find out a least useful interface for removal from the system. This process is repeated until the total number of used NICs meets the $N$ requirement.

Now we present the interface evaluation strategy adopted by DIM. For each NIC operating on channel $k$ equipped on mesh host $v_i$, we calculate the aggregate traffic (both uplink and downlink) $a_{i[k]}^n$ handled by the interface as follows:

$$\begin{aligned} a_{i[k]}^n \; = \; & \sum_{i \neq j, v_j \in V, v_{s'} \in V^h} (x_{ij[s',k]}^u + x_{ji[s',k]}^u) + \\ & \sum_{i \neq j, v_j \in V, v_{d'} \in V^h} (x_{ij[d',k]}^d + x_{ji[d',k]}^d), \end{aligned} \tag{1}$$

$\forall v_i \in V^h, 1 \leq k \leq C$. We hope to remove the NIC with the smallest $a_{i[k]}^n$. However, to avoid removing the only interface that a mesh host has, we calculate the aggregate traffic $a_i^h$ experienced by $v_i$ via all interfaces equipped on the host in the following equation:

$$a_i^h = \sum_{k=1}^{C} a_{i[k]}^n,$$

$\forall v_i \in V^h$, and define $w_{i[k]} = a_{i[k]}^n / a_i^h$. Only those NICs with $w_{i[k]} < 1$ will be considered for removal. Among those

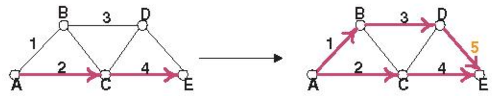



Fig. 5. The idea of traffic splitting for communication flow from sender A to receiver E in the proposed multi-path packet delivery function (mPDF): (a) original single-path and (b) multi-path delivery by adding one more radio module on each of nodes D and E binding to channel 5.

candidate NICs, we remove the interface which yields the minimum value of $a^n_{i[k]} \times w_{i[k]}$. All interfaces are evaluated and removed one by one until the number of total used NICs becomes equal to $N$.

Next, we introduce the Incremental Interface Management (IIM) strategy. Initially, we deploy one NIC on each mesh host, and bind the interface to operate on the best-condition channel. In other words, we test on all available channels, and choose the best channel, which produces the maximal network capacity based on our LP calculation. We then use the selected channel to construct a single-channel wireless mesh backbone as the initial phase in our IIM algorithm to avoid any performance bias due to bad initial channel selection.

Assume that $N$ is larger than the network size $|V^h|$, so as to realize a multi-radio system. Once the initial single-radio mesh has been optimized by our LP model, we start to add interfaces one by one based on the LP results. This process will be repeated until all $N$ available NICs have been distributed out.

Note that during the process of adding interfaces, we may be unable to find a feasible LP solution due to insufficient number of deployed NICs for supporting required user traffics. In this case, we repetitively reduce the traffic lower bounds ($l_i$) for both uplink and downlink at each mesh host $v_i$ in a exponential way ($l_i \rightarrow l_i/2 \rightarrow l_i/4 \rightarrow \cdots$) until a feasible LP solution is discovered. The lower bounds are restored to obtain a new LP solution, after wireless links are evaluated and more interfaces are added in.

Now we present the criteria for adding interfaces. We hope to characterize the most congested wireless link so as to add interfaces binding to another channel for traffic relief. For more accurate judgement, we recall the set $IE^k_{ij}$ of interfering links for edge $e_{ij}$ using channel $k$, and define $n_{ij[k]} = |IE^k_{ij}|$. We choose the edge $e_{ij}$ with the maximum value of $(x_{ij[0,k]}/f_{ij[k]}) \times n_{ij[k]}$ (refer to Section II-B for the definitions of $x_{ij[0,k]}$ and $f_{ij[k]}$) for adding interfaces on communicating hosts $v_i$ and $v_j$.

Once the most congested link is decided, we intend to select a channel with the lightest traffic load within the neighborhood of selected edge $e_{ij}$. Obviously, we want to avoid choosing the channel that both hosts $v_i$ and $v_j$ already have. As a result, for each candidate channel, we calculate the aggregate link traffic $a^x_{ij[k]}$ for all links in $IE^k_{ij}$, where

$$a^x_{ij[k]} = \sum_{e_{pq} \in IE^k_{ij}} x_{pq[0,k]},$$

and the aggregate link capacity $a^f_{ij[k]}$ of all links in $IE^k_{ij}$ as follows:

$$a^f_{ij[k]} = \sum_{e_{pq} \in IE^k_{ij}} f_{pq[k]}.$$

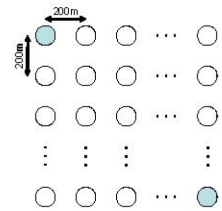



Fig. 6. The mesh grid with Internet gateways located at the upper-left and bottom-right corners.

The IIM algorithm chooses the channel with the minimum value of $a^x_{ij[k]}/a^f_{ij[k]}$, and add interfaces on hosts $v_i$ and $v_j$ binding to the selected channel accordingly.

### D. Multi-path Packet Delivery Function (mPDF)

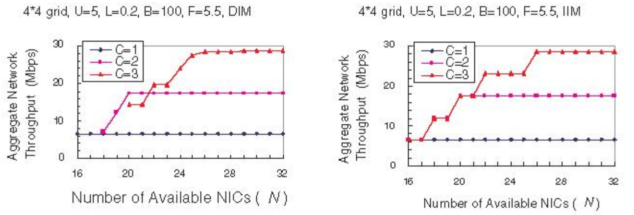
As one may notice that, in the proposed linear programming model, we maximize the network throughput by enabling simultaneous transmissions/receiving over non-interfering channels. As explained previously in Fig. 1, the adoption of multiple radio modules on mesh hosts can effectively mitigate the inter-route and inter-hop contention problems. In this section, we revisit the concept of simultaneous communication actions, and point out that our proposed methodology can further exploit the advantage of having multiple radios and channels to achieve an optimized WMN infrastructure.

In traditional single-radio single-channel WMNs, multi-path packet forwarding is not favorable since multiple interference-disjoint paths are difficult to discover due to the single-channel inter-route contention problem. As characterized in Fig. 1, by utilizing multiple radio modules on mesh hosts, the inter-route contention problem can be alleviated, making the multi-path packet forwarding become feasible. As a result, in addition to enabling simultaneous communications between two flows, we propose to further split traffic loads over multiple paths for a single flow. Fig. 5 (a) shows the resulting radio and channel configuration. Suppose that route A-C-E is the original single path. We observe that, by adding one more radio on each of nodes D and E binding to channel 5, we can enable two non-interfering forwarding paths for simultaneous transmissions for a single flow, as illustrated in Fig. 5 (b). The routing solution provided by our proposed LP model is actually a multi-path forwarding mechanism, to which we refer as the multi-path packet delivery function ($m$PDF).

Note that the multi-path problem is a subset of the inter-route contention problem. Multiple routes whether belonging to multiple flows or a single flow are possible to be made active simultaneously in a multi-radio multi-channel environment. Though several upper-layer challenges, including packet re-ordering problem, still remain questionable, in the proposed WMN architecture, we observe the potential of multi-path packet forwarding mechanism. We plan to investigate more on the feasibility of implementing our $m$PDF protocol by performing traffic engineering techniques in a real testbed.

## III. Performance Evaluation

This section provides selected performance results derived from performing our proposed resource allocation, channel




(a) DIM (b) IIM

Fig. 7. Aggregate network throughput vs. number of available radio interfaces for maximal 3 orthogonal channels in the IEEE 802.11b environment using (a) DIM and (b) IIM algorithms.

arrangement algorithms, and multi-path packet delivery function ($m$PDF) in a WMN. We describe the network environment settings in Section III-A, followed by detailed numerical results reported in Section III-B.

### A. Network Environment Settings

We generate a WMN in grid topology as illustrated in Fig. 6. All mesh nodes are assumed to be stationary and spaced 200 meters apart from each other. We assume that the transmission range is 250 meters and the interference range is 550 meters in our network. The IEEE 802.11 MAC protocol with RTS/CTS four-way handshaking mechanism is adopted in our channel contention model.

### B. Numerical Results

This subsection presents the numerical results. We adopt a mixed integer linear programming (MIP) solving tool [1] to perform the LP calculation. In the following presentation, we vary several critical parameters, including available number of channels and radio interfaces, network sizes and configurations, gateway capacities, and effective link data rates to observe the feasibility of our proposed methodology.

*1) Varying Number of Available Channels and Interfaces:* In this subsection, we experiment on a $4 \times 4$ grid mesh with 2 Internet gateways located at the upper-left and bottom-right corners separately. The IEEE 802.11b environment with 3 orthogonal (non-interfering) channels is considered. Assume that all mesh hosts have the same traffic requirement for both uplink and downlink data flows. Denoted as $U$ and $L$, the traffic upper bound and lower bound are set to be 5 Mbps and 0.2 Mbps, respectively. In addition, suppose that symmetric gateways are used, each with bandwidth capacity $B$ equal to 100 Mbps, and that all wireless links have the same bit rate $F$ equal to 5.5 Mbps. Fig. 7 shows the results for the DIM and IIM strategies. As we can see from this figure, the aggregate network throughput grows as $N$ and $C$ increase. An interesting observation is that, when 3 orthogonal channels are being used ($C = 3$), both DIM and IIM yield 4 times the throughput of a single-channel system ($C = 1$) by adding only 10 more (16+10=26 in total) network interfaces (i.e., 1.625 NICs per mesh host in average). In other words, to achieve the maximal network capacity with 3 channels available, it is not necessary to equip each mesh host with 3 NICs for utilizing all available radio bandwidths. Furthermore, as shown in Fig. 7, once the throughput saturates at its maximum point, adding network interfaces contribute little

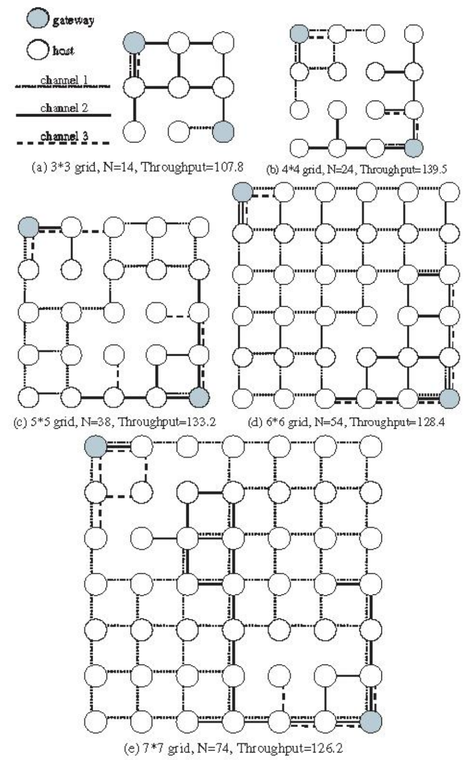



Fig. 8. The interface distributions and channel configurations for different network sizes in the IEEE 802.11g environment using the proposed DIM algorithm.

to the performance, since the bottleneck now lies in the number of orthogonal channels $C$. We have other sets of experiments on 802.11a with 8 orthogonal channels available. we observe that by using 54 network interfaces in total, averagely 3.4 NICs per mesh host, we can maximize the network throughput, but the details are omitted here due to page limit.

*2) Varying Network Configurations:* Next, we investigate the impacts of different network configurations on aggregate throughput. We vary the network configuration by changing $F$ function, network size, and gateway bandwidth capacities. Due to space limitation, below we only report the results for various network sizes.

We focus on the DIM algorithm, and vary network size from $3 \times 3$ to $7 \times 7$ to verify the scalability of our proposed strategy. We experiment on the IEEE 802.11g system with 3 orthogonal channels. The rest of parameter settings is the same as the previous experiment. Fig. 8 illustrates the derived network interface deployment and channel bindings for different network sizes. As we observe from the figure, hosts close to gateways (including gateway itself) are usually equipped with more radio interfaces, since Internet access is the main purpose of our data packets. Because the two gateways have identical bandwidth, the number of radio modules deployed at the two gateways is almost the same. In addition, the network throughputs are kept above 100 Mbps whether it is a small ($3 \times 3$) or large ($7 \times 7$) grid, suggesting that the proposed strategy is adaptable. Adaptability is critical for WMNs in designing

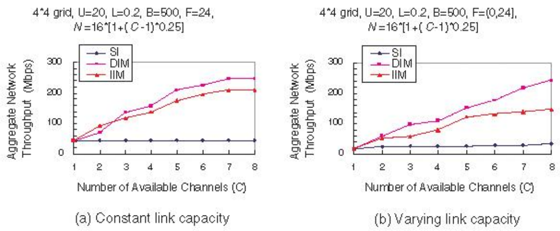



Fig. 9. Throughput comparisons between single-radio and multi-radio systems in the IEEE 802.11a environment with (a) constant and (b) varying link bit rates.

an easy-to-deploy high-performance wireless mesh bakcbone without paying much unnecessary attention to the network size and routing path length.

*3) Single-radio versus Multi-radio Systems:* In the final experiment, we go back to the $4 \times 4$ grid, and study the performance improvement provided by multi-radio multi-channel systems. We denote the Single-Interface strategy as SI, which is adopted in the single-radio system. For single-radio networks with varying link capacities, SI performs our LP calculations for all available channels, and selects the best channel producing the maximal throughput as our comparison base. For multi-radio networks, we perform the proposed DIM and IIM algorithms to manage available NICs and arrange channel bindings. Fig. 9 shows the throughput comparisons between single-radio and multi-radio systems. The setting of $N$ function is based on the observations from our previous experiments in the $4 \times 4$ grid, making $N$ to increase by 4 every time one more channel is available to the network. As we can see from Fig. 9, the advantage of using multiple radio interfaces on mesh hosts is obvious, as the throughput performance can be easily boosted up to 5 times that of the single-radio systems by equipping reasonable number of NICs ($< 3$) on each mesh host.

## IV. Conclusions

In this work, we propose an next-generation wireless mesh architecture and design related resource allocation and channel assignment mechanisms to maximize the possible network capacity at the deployment stage. The numerical results show encouraging potential in terms of network throughput improvement. We plan to investigate on the optimal arrangement by letting the channel vector $c_{i[k]}$ unknown and solving the non-linear programming model in the near future, so that we can observe how close our proposed linear methodology is to the optimal non-linear solution. The results will be reported in our future paper. In addition, we are interested in the fairness problem in WMNs. In this work, we realize the network-level fairness by setting reasonable user traffic bounds ($u_i$ and $l_i$) in our linear programming model and performing flow control in the packet forwarding function. However, there is still short of a link-level technique to prevent bandwidth occupancy from favoring those users closer to Internet gateways. This MAC-layer fairness issue will also be directed into our future work.

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