國 立 交 通 大 學

電信工程學系

碩 士 論 文

次世代無線網狀網路最佳化設計

Optimizing Next-generation Multi-hop Wireless Mesh Networks

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中 華 民 國 97 年 9 月

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國 立 交 通 大 學
電信工程學系
碩 士 論 文

A Thesis

Submitted to Department of Communication Engineering

College of Electrical Engineering and Computer Science

National Chiao Tung University

in partial Fulfillment of the Requirements

for the Degree of

Master

in

Communication Engineering

June 2008

Hsinchu, Taiwan, Republic of China

中華民國九十七年九月

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摘　　要

早期在無線網狀網路這方面的研究工作大多數都是假設每一個節點都只有單一的介面。在此份論文中，我們視下一代的無線網狀網路為每個節點都有著多重的無線電介面，每個介面都有能力支援多重模式並且執行一種，支援多重通道並使用其中一個，而且有能力支援多重的調變技術，我們把這種網路叫做 M^4（多重無線電，多重模式，多通道，多重速率）無線網狀網路。舉例來說，使用現成的零組件，人們可以輕易的建構一個有著多重無線電介面（支援IEEE 802.11 a/b/g）網狀網路的節點，我們的目標就是去處理在這樣一個環境中的資源分配規劃以及封包傳送的問題。

我們提出的方法是建立在以網路流量原則以及無線電通道 存取/干擾 模型為前提的線性規劃技術基礎上，當給定一個網路拓樸，運輸量的需求，以及閘道的容量，我們展示了如何去分派網路介面卡數目以及他們所使用的通道以便可以充分的使用整個頻寬。這些結果可以讓無線網路的提供者在硬體層面的限制下可以利用以上的方法來分配計畫他們的網路以達到最大的收益效率。這份論文最值得一提的就是，這是在無線網狀網路領域中第一份去處理資源計畫的工作。我們的一些數據上的結果顯示了在不影響網路層公平性下的網路總和流量有著大量顯著的改進。與其他假設固定無線電介面數量的多重無線電系統在模擬上的比較也進一步證實了網路規劃的重要性。

Optimizing 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 thesis, 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 (IEEE 802.11 b/g 2.4GHz or 802.11a 5GHz mode), one of several channels, and each capable of supporting multiple modulations. We call such a network an M^4 (multi-radio, multi-mode, multi-channel, multi-rate) wireless mesh network. 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 utilized 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. The importance of network planning is further corroborated by the simulative comparisons with other multi-radio systems assuming a known and fixed number of interfaces at each mesh router.

誌謝

能夠完成此篇論文，首先要感謝我的指導教授－林亭佑博士，老師在我碩士階段兩年的時間當中，很有耐心的持續指導以及從旁協助我研究，尤其是在最近準備論文以及口試期間，更是全心全力的投入在我們身上；除此之外，在生活中與課業方面，也有相當程度的幫助以及開導，老師將所有的資源都全部投注在我們身上，讓我們能夠無憂無慮的專注在研究上，為此，深深的感謝老師。

再來，實驗室同學們 – 冠勳、威旭、安智、子庭、信雄，大家一起經歷過許多草創時期所遭遇的困境以及辛勞；在研究方面，能夠互相討論給予意見，大家能夠實行團隊合作的精神；在生活方面能夠在需要幫助的時候伸出援手，雪中送炭。此外，也感謝其他所有 Bun Lab 的成員。

此外，要感謝電信工程學系的諸多老師，在修課以及日常生活方面，能夠提供優良的教學品質及環境，讓我們在研究之虞，能夠學習更多電信領域的相關知識，無論是與本身領域相關以及非相關的科目都能夠有一定程度的涉獵以及學習，對此後的發展相信是一股正面的力量。

最後，特別感謝我的母親 – 施美霞女士，辛苦提拔我至碩士畢業，感謝！也感謝姑姑范小玫、弟弟范育綸，在家庭生活給予我援手。謝謝！

誌於 2008.06 新竹 交大

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Chapter 1

Introduction

The wireless mesh network (WMN) is a promising solution to the last-mile wireless Internet access problem. It can effectively complement the limitation of WLAN coverage. Applications of WMN include enterprise wireless backbones and community networks [15]. In [5], two mesh hierarchies are defined: *infrastructure mesh* and *client mesh*, where the former has much less mobility than the latter. Reference [14] 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 [11,17,22]) or layer-2 or layer-3 solutions based on commodity radio modules [3, 6, 8, 9, 12, 16, 18, 19, 21]. Several works show how to increase WMN capacity by adaptively adjusting the data rates [4, 7, 13, 20].

In this thesis, 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.[1] Several works have addressed the related issues. In [10, 24, 25], the authors propose to use a dedicated interface running on a

[1] With the advance of communication hardware technology, and cost-reduced networking modules, nowaday computing devices are often capable of operating/communicating on/through different radio frequencies (e.g., WiFi/Bluetooth/WCDMA possibly readily available at a single laptop, which may be installed with another WiFi card via the PCMCIA interface). Hence, equipping multiple wireless interfaces at a single host is getting affordable and its popularity can be expected in next-generation wireless-enabled computers.

control channel to negotiate the data channels to be used by other interfaces. References [3,6,8,12,16,18,19] 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 thesis, we address the resource planning problem in a Multi-radio Multi-mode Multi-channel Multi-rate (M^4) 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 Chapter 3.4.

The remaining thesis is organized as below. Chapter 2 reviews past related work in M^4 wireless mesh networks. In Chapter 3, we introduce the M^4 network architecture, our linear programming model for network optimization, two resource management and channel assignment algorithms, and our packet forwarding strategy. Chapter 4 presents the numerical and simulation comparison results. Finally Chapter 5 draws our conclusions and future plans.

Chapter 2

Related Work

The design of multi-channel WMN has been investigated in several works [3, 8, 9, 12, 16, 18, 19, 21]. These works treat all channels equally based on the IEEE 802.11 MAC mechanisms and have a goal of minimizing the contention among wireless links. A *single-transceiver* model is assumed in [9, 21], while a *multi-transceiver* model is adopted in [3, 6, 8, 12, 16, 18, 19]. For a single-transceiver system, the radio interface in each node needs to switch among channels. This will results in the *multi-channel hidden-terminal problem* [21]. So the authors in [21] proposed to embed a negotiation phase in the ATIM (Ad Hoc Traffic Indication Map) window that is periodically sent under the Power Save Mode (PSM). Every node has to go to a pre-defined control channel when entering the ATIM window. The negotiation phase is to determine data channel to be used after the ATIM window finishes. The Slotted Seeded Channel Hopping (SSCH) mechanism [9] divides the time axis into virtual channels. Each virtual channel's hopping sequence is determined by a (channel, seed) pair. Whenever a sender wishes to communicate with a neighbor, it changes its hopping schedule to the receiver's in the corresponding virtual channel. SSCH requires a looser time synchronization than [21], but its channel switching overhead is high.

References [3, 8] pointed out the advantage of equipping multiple radio interfaces on a

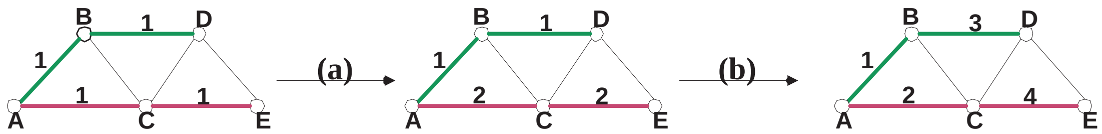


Figure 2.1: Illustration of the multi-radio benefits (the number associated with each edge indicates the channel number used): (a) enabling simultaneous transmissions between routes (*inter-route* contention removed); (b) further enabling simultaneous transmissions between consecutive hops along a route (*inter-hop* contention eliminated).

single mesh node. Such system can alleviate both *inter-route* and *inter-hop* contentions. As shown in Fig. 2.1, two data paths A-B-D and A-C-E both operating on channel 1 cannot be active at the same time, due to inter-route contention. The two data flows can be made active simultaneously by adding one more interface binding to channel 2 on node A and switching nodes C, E to operate on channel 2, removing the inter-route contention (Fig. 2.1 (a)). However, since wireless links A-B and B-D use the same channel 1 along the A-B-D route, the contention between consecutive hops remains. By adding another radio modules on nodes B, C and switching nodes D, E to channels 3, 4 respectively, the inter-hop contention problem can be further eliminated, so that links A-B, B-D, A-C, and C-E now become interference-disjoint and can be made active simultaneously (Fig. 2.1 (b)). Note that designing multi-radio multi-channel protocols is non-trivial, requiring not only methods to assign channels intelligently, but also cautions to take care of network connectivity. Furthermore, in case that interface switching between channels is necessary in any proposed protocols, the multi-channel hidden-terminal problem, as characterized in [9], should be treated carefully to avoid degrading performance due to packet collisions.

Several works have addressed multi-channel MAC/routing protocols based on IEEE 802.11 [6, 12, 16, 18, 19]. In [16], the authors suggested to associate a radio interface to a fixed channel and use the remaining interfaces to switch among other channels. The fixed channel is determined by each mesh node so as to evenly distribute all available channels in a neighborhood. Whenever a sender wishes to communicate, it tunes one of its switchable interfaces to operate on the receiver's fixed channel. In addition to interface assignment strategy, reference [16] also proposed a multi-channel routing protocol (MCR) considering the costs of interface switching and channel diversity when selecting a route. Ideally, the MCR protocol assigns the most cost-efficient route to each communication flow, so that multiple wireless links operating on different channels along the selected route can be active simultaneously (inter-hop contention problem considered). However, since routes are determined independently in MCR, the inter-route contention problem, as explained in Fig. 2.1, remains unaddressed.

In [12], a Multi-Radio Link-Quality Source Routing (MR-LQSR) protocol is proposed. The goal of this protocol is to discover a high-throughput route between communicating entities in a multi-radio multi-hop wireless mesh network. The authors defined a Weighted Cumulative Expected Transmission Time (WCETT) metric for path selection. Using WCETT, one may predict the transmission efficiency considering packet data rates and channel diversity along a single route. As a result, the inter-hop contention problem as characterized in Fig. 2.1 is handled by the proposed routing protocol. However, since routes are evaluated individually, contention between communication flows (inter-route contention) is also ignored in this thesis, lacking a global optimization for the inherently cooperative wireless network system.

In [18, 19], also targeting on a multi-radio multi-channel wireless mesh environment, the authors proposed a set of centralized [19] and distributed [18] channel assignment and routing algorithms. Since channel assignment and routing tend to affect each other, the proposed protocol repeats the two processes periodically to check if the current settings, including channel binding and route selection, meet the requirements of traffic loads and inherent wireless link capacities. The load-aware channel assignment algorithm does not require any specific routing algorithm. Whenever no feasible route can be found by the routing protocol, the procedure will go back to re-perform the channel assignment algorithm, so as to find a reasonable route for the data flow that fits in all wireless link capacities along the path. This thesis considered both the inter-route and inter-hop contention problems. However, there is no guarantee of finding an optimal channel setting for arbitrary routing protocols, especially in real environments where asymmetric links are common, transmission rates vary a lot, and link quality is often different from channel to channel. In addition, like the previous two works [12, 16], proposals in [18, 19] also ignore the problem of optimizing the number of radio modules assigned to a mesh host.

In a recent work [6], the authors proposed a joint channel assignment and routing protocol to optimize the network throughput subject to fairness constraints. The optimization methodology is also based on linear programming. Given the interference model, number of available channels, aggregate user traffic demands, and number of radios at each mesh router, [6] addresses the interference-free link scheduling, routing, and channel assignment problems (RCL algorithm). We share the similar idea of traffic splitting over multiple routing paths to achieve load balancing by performing traffic engineering techniques as proposed by [6]. In RCL, all wireless channels are assumed to have equally maximal data rate and gateways assumed to have unlimited capacity, which are different from our assumptions in this thesis. Additionally, [6] also uses an equal and given number of interfaces at each mesh router as most previous works do, ignoring the problem of optimizing radio numbers for heterogeneous (forwarding) traffic requirements at mesh routers. We will report and discuss the performance comparison results through simulation experiments in Chapter 4.3.

Chapter 3

Resource Planning in an M^4 Wireless Mesh Network

This chapter first defines the architecture of our M^4 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 Chapter 3.4, we re-visit the contention problems as depicted in Fig. 2.1, and propose a multi-path packet delivery function (mPDF) to further exploit the advantage of having multiple radios and channels.

3.1 Network Architecture

We consider an M^4 network as shown in Fig. 3.1. Each mesh node is equipped with one or multiple wireless interfaces. Each interface can operate in one of several modes. In this thesis, 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

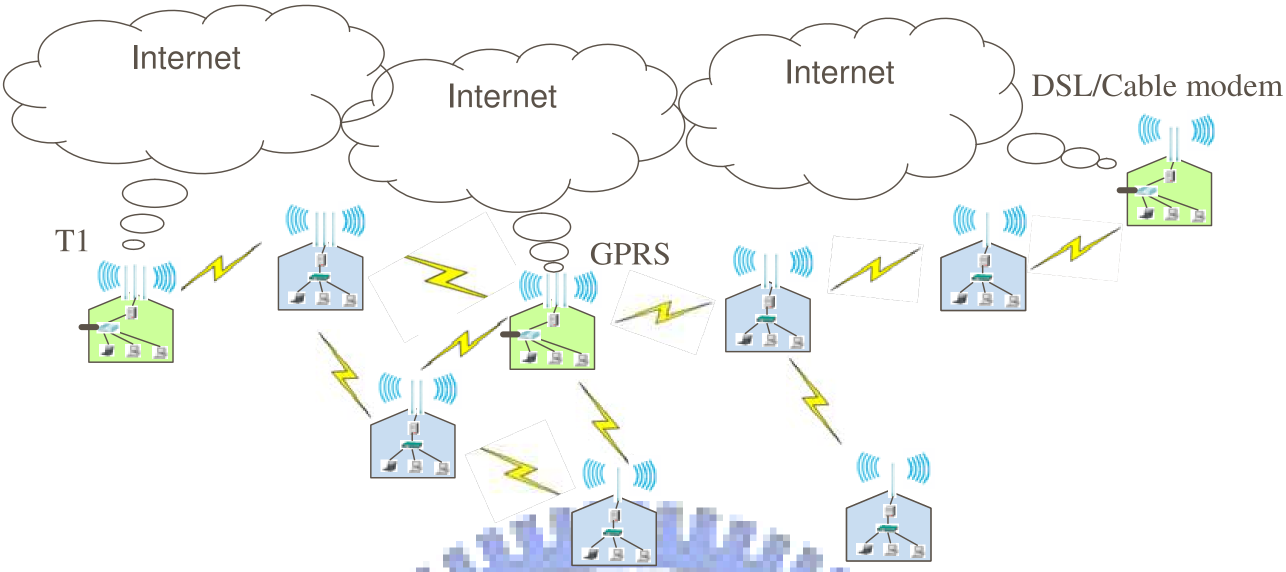


Figure 3.1: An M^4 mesh network with heterogeneous Internet gateways.

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.

3.2 Linear Programming Model

To construct a cost-efficient M^4 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 several notations:

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

- 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 example, we can transform the original network architecture as Fig. 3.2 into a new graph as Fig. 3.3. 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. Note that the two figures have the same network architecture. 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

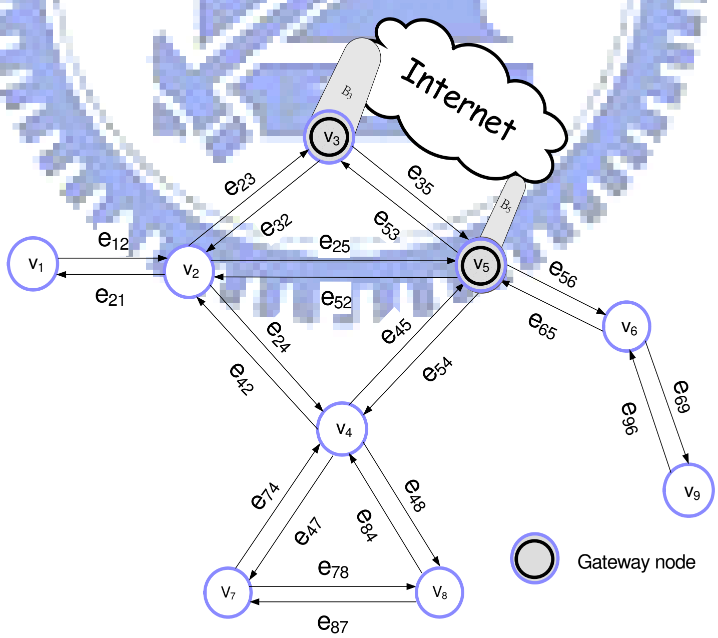


Figure 3.2: An example wireless mesh network architecture in graph representation.

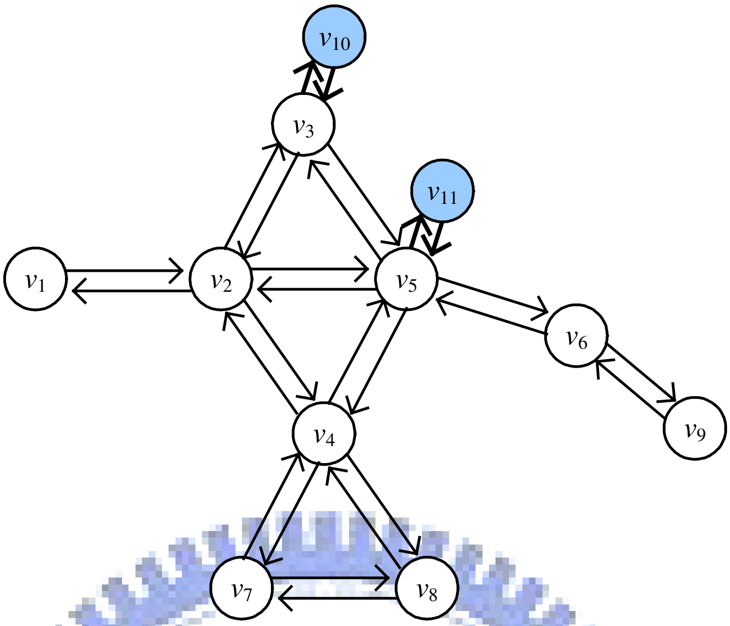


Figure 3.3: A simplified example graph with separate mesh hosts and Internet gateways.

v_j to v_i on channel k, $k = 1 \ldots C$, are denoted by $f_{ij}[k]$ and $f_{ji}[k]$, respectively.[1] 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

[1] On measuring the best achievable bit rate from one mesh node to the other, one may utilize probing-based quality evaluation by testing all available physical channel rates and tracking the respective packet loss ratios. In this thesis, we adopt the methodology proposed by [4] to obtain the best bit rate for a wireless link.

define a *channel vector* c_i for each host v_i. For each element k in c_i, $k = 1 \ldots C$:

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

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 channel vector c_i. In Section 3.3, we will discuss how to determine this vector for each mesh node. Then we can define the *connectivity vector* c_{ij} as an indication of connection status between v_i and v_j. For each element k in c_{ij}, $k = 1 \ldots C$:

$$c_{ij[k]} = c_{i[k]} \times c_{j[k]}$$

- 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.[2]

- Now, we introduce some unknown variables in our linear programming model. We define λ_i^u as the actual uplink traffic load delivered from node v_i, and similarly λ_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 $x_{ij[0,k]} = \sum_{v_s \in V}(x_{ij[s,k]}^u \times c_{ij[k]}) + \sum_{v_d \in V}(x_{ij[d,k]}^d \times c_{ij[k]})$.

[2]Alternatively, some separate algorithm may be devised to establish the interfering link set for every node pair.

- 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}, where:

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

A summary of notations is given in Table 3.1.

Our ultimate goal is to maximize the mesh network capacity such that the traffic flowing in/out of the set of gateways 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:

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

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

Table 3.1: Summary of notations: (a) parameters that are given and (b) parameters that are to be determined.

(a)

u^u_i	Maximum uplink traffic load allowed at node v_i (upper bound)
l^u_i	Minimum uplink traffic load required at node v_i (lower bound)
u^d_i	Maximum downlink traffic load allowed at node v_i (upper bound)
l^d_i	Minimum downlink traffic load required at node v_i (lower bound)
$f_{ij[k]}$	Capacity of directional wireless link e_{ij} over channel k
B_m	Capacity of (Ethernet/T1/T3) gateway node v_m
B^u_m	Uplink capacity of (xDSL/cable modem) gateway node v_m
B^d_m	Downlink capacity of (xDSL/cable modem) gateway node v_m
C	Number of available non-interfering channels
$c_{i[k]}$	Channel boolean vector of node v_i ($c_{i[k]} = \{0,1\}$)
N	Number of available sets of communication equipment

(b)

λ^u_i	Actual uplink traffic load delivered from node v_i
λ^d_i	Actual downlink traffic load destined to node v_i
$x^u_{ij[s,k]}$	Uplink traffic flow generated by source node v_s over wireless link e_{ij} using channel k
$x^d_{ij[d,k]}$	Downlink traffic flow forwarded to destination node v_d over wireless link e_{ij} using channel k
g^{out}_m	Traffic flow out of gateway node v_m
g^{in}_m	Traffic flow back into gateway node v_m

based on IEEE 802.11 DCF contention protocol:

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

(a)

Constraints

Constraints of hosts

$$\lambda_i^u \le u_i^u \quad \forall v_i \in V^h$$
$$\lambda_i^d \le u_i^d \quad \forall v_i \in V^h$$
$$\lambda_i^u \ge l_i^u \quad \forall v_i \in V^h$$
$$\lambda_i^d \ge l_i^d \quad \forall v_i \in V^h$$

Constraints of links (interference model)

$$x_{ij[0,k]} = \sum_{v_s \in V^h} x^u_{ij[s,k]} + \sum_{v_d \in V^h} x^d_{ij[d,k]} \quad \forall v_i \in V^h, v_j \in V^h, k, c_{ij[k]} > 0$$
$$\sum_{e_{pq} \in IE^k_{ij}} \frac{x_{pq[0,k]}}{f_{pq[k]}} \le 1 \quad \forall v_i \in V^h, \forall v_j \in V^h, k, c_{ij[k]} > 0$$
$$x^u_{ij[s,k]} \ge 0 \quad \forall v_i \in V, v_j \in V, v_s \in V^h, k, c_{ij[k]} > 0$$
$$x^d_{ij[d,k]} \ge 0 \quad \forall v_i \in V, v_j \in V, v_d \in V^h, k, c_{ij[k]} > 0$$

Constraints of gateways

$$g^{out}_m + g^{in}_m \le B_m \quad \forall v_m \in V^g \quad \text{(for Ethernet/T1/T3)}$$
$$g^{out}_m \le B^u_m \quad \forall v_m \in V^g \quad \text{(for xDSL/cable modem)}$$
$$g^{in}_m \le B^d_m \quad \forall v_m \in V^g \quad \text{(for xDSL/cable modem)}$$
$$g^{out}_m = \sum_{v_s \in V^h} g^{out}_{s,m} \quad \forall v_m \in V^g$$
$$g^{in}_m = \sum_{v_d \in V^h} g^{in}_{d,m} \quad \forall v_m \in V^g$$
$$g^{out}_{s,m} \ge 0 \quad \forall v_s \in V^h, v_m \in V^g$$
$$g^{in}_{d,m} \ge 0 \quad \forall v_d \in V^h, v_m \in V^g$$

(b)

Uplink flow conservation

Among hosts and links

$$\lambda^u_{s'} = \sum_{\substack{v_j \in V, k \\ c_{s'j[k]}>0}} x^u_{s'j[s',k]} \quad \forall v_{s'} \in V^h$$

Among links

$$\sum_{\substack{v_j \in V^h, k \\ c_{ji[k]}>0}} x^u_{ji[s',k]} = \sum_{\substack{v_j \in V, k \\ c_{ij[k]}>0}} x^u_{ij[s',k]} \quad \forall v_i \in V^h, v_{s'} \in V^h, i \ne s'$$
$$\sum_{\substack{v_i \in V^h, k \\ c_{is'[k]}>0}} x^u_{is'[s',k]} = 0 \quad \forall v_{s'} \in V^h$$

Among links and gateways

$$\sum_{\substack{v_i \in V^h, k \\ c_{im[k]}>0}} x^u_{im[s',k]} = g^{out}_{s',m} \quad \forall v_{s'} \in V^h, v_m \in V^g$$

Downlink flow conservation

Among hosts and links

$$\lambda^d_{d'} = \sum_{\substack{v_j \in V, k \\ c_{jd'[k]}>0}} x^d_{jd'[d',k]} \quad \forall v_{d'} \in V^h$$

Among links

$$\sum_{\substack{v_j \in V, k \\ c_{ji[k]}>0}} x^d_{ji[d',k]} = \sum_{\substack{v_j \in V^h, k \\ c_{ij[k]}>0}} x^d_{ij[d',k]} \quad \forall v_i \in V^h, v_{d'} \in V^h, i \ne d'$$
$$\sum_{\substack{v_i \in V^h, k \\ c_{d'i[k]}>0}} x^d_{d'i[d',k]} = 0 \quad \forall v_{d'} \in V^h$$

Among links and gateways

$$\sum_{\substack{v_i \in V^h, k \\ c_{mi[k]}>0}} x^d_{mi[d',k]} = g^{in}_{d',m} \quad \forall v_{d'} \in V^h, v_m \in V^g$$

Figure 3.4: Re-formatted linear programming (a) constraints and (b) flow conservation equations.

Finally, the linear programming constraints and flow conservation equations are summarized in Fig. 3.4 (a) and (b), respectively.

3.3 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 3.2 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 $\sum_{\forall v_i \in V^h} n_i = N$.

Before we describe the two algorithms in more detail, Fig. 3.5 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 4, 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

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 $v_{s'}/v_{d'}$ $\{x^u_{ij[s',k]}\},\{x^d_{ij[d',k]}\}$, actual gateway traffic $\{g_m^{out}\},\{g_m^{in}\}$, actual number of NICs *N'*.

Figure 3.5: Summary of inputs, outputs, and variables used in both the DIM and IIM procedures.

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 (mPDF), which will be presented later in Section 3.4. 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) $a^n_{i[k]}$ handled by the interface as follows:

$$
\begin{aligned}
a^n_{i[k]} &= \sum_{i \neq j, v_j \in V, v_{s'} \in V^h} (x^u_{ij[s',k]} + x^u_{ji[s',k]}) + \\
&\sum_{i \neq j, v_j \in V, v_{d'} \in V^h} (x^d_{ij[d',k]} + x^d_{ji[d',k]}),
\end{aligned}
\tag{3.1}
$$

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

$$a^h_i = \sum_{k=1}^{C} a^n_{i[k]},$$

$\forall v_i \in V^h$, and define $w_{i[k]} = a^n_{i[k]}/a^h_i$.

Only those NICs with $w_{i[k]} < 1$ will be considered for removal.

Among those 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. Fig. 3.6 provides a pseudo-code for the DIM algorithm.

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-

begin

Set $\{c_{i[k]}\}$ such that each host has C NICs operating on the corresponding channels;

Count the total number of used NICs N'; // currently $N' = C*|V^h|$

while true **do**

Solve the LP (input: $\{u_i^u\},\{u_i^d\},\{l_i^u\},\{l_i^d\},\{f_{ij[k]}\},\{B_m\},\{B_m^u\},\{B_m^d\},C,N,\{c_{i[k]}\}$,

output: $\{\lambda_i^u\},\{\lambda_i^d\},\{x_{ij[s',k]}^u\},\{x_{ij[d',k]}^d\},\{g_m^{out}\},\{g_m^{in}\}$);

if not feasible **then**

return NO_SOLUTION;

else {

remove all interfaces involving with *no* traffic loads;

if $N' \leqq N$ **then**

return $\{c_{i[k]}\}$;

}

endif;

Compute the aggregate traffic (uplink and downlink) handled by each NIC $i[k]$: $\{a_{i[k]}^n\}$;

Compute the aggregate traffic (uplink and downlink) experienced by each host v_i : $\{a_i^h\}$;

For each host v_i and channel k, compute $\{w_{i[k]} := a_{i[k]}^n / a_i^h\}$;

Choose the interface with <u>minimum</u> ($a_{i[k]}^n * w_{i[k]}$) where $w_{i[k]} < 1$; suppose i', k' satisfy;

$c_{i'[k']}$:= false; // reset $c_{i'[k']}$

$N' := N' - 1$; // interface binding to channel k' on host $v_{i'}$ has been removed

endwhile;

end.

Figure 3.6: Decremental Interface Management (DIM) algorithm pseudocode.

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_{ij}^k of interfering links for edge e_{ij} using channel k, and define $n_{ij[k]} = |IE_{ij}^k|$. 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 3.2 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 $a_{ij[k]}^x$ for all links in IE_{ij}^k, where

$$a_{ij[k]}^x = \sum_{e_{pq} \in IE_{ij}^k} x_{pq[0,k]},$$

and the aggregate link capacity $a_{ij[k]}^f$ of all links in IE_{ij}^k as follows:

$$a_{ij[k]}^f = \sum_{e_{pq} \in IE_{ij}^k} f_{pq[k]}.$$

begin

half := 0;

Set $\{c_{i[k]}\}$ such that each host has 1 NIC and all NICs are on the same best condition channel;

Count the number of NICs N'; // currently $N' = |V^h|$

while true **do**

Solve the LP (input: $\{u_i^u\},\{u_i^d\},\{l_i^u\},\{l_i^d\},\{f_{ij[k]}\},\{B_m\},\{B_m^u\},\{B_m^d\},C,N,\{c_{i[k]}\}$,

output: $\{\lambda_i^u\},\{\lambda_i^d\},\{x_{ij[s',k]}^u\},\{x_{ij[d',k]}^d\},\{g_m^{out}\},\{g_m^{in}\}$);

if not feasible **then**

if $N' = N$ **then** **return** NO_SOLUTION;

half := *half* + 1;

for each i **do**

$l_i^u := l_i^u / 2$; // reduce traffic bounds in order to obtain a feasible solution

$l_i^d := l_i^d / 2$; // when the number of interfaces is insufficient to support

endfor; // required traffic needs

else

if *half* = 0 **and** $N' = N$ **then** **return** $\{c_{i[k]}\}$;

while *half* > 0 **do**

half := *half* – 1;

for each i **do**

$l_i^u := l_i^u * 2$; // restore the required traffic bounds

$l_i^d := l_i^d * 2$; // as more interfaces are going to be added

endfor;

endwhile;

Count the number of interfence links for edge e_{ij} over channel k, let $\{n_{ij[k]}=|IE^k_{ij}|\}$

Choose the pair (i,j) with maximum $(x_{ij[k]} / f_{ij[k]}) * n_{ij[k]}$; suppose i', j', k' satisfy;

For each channel $k \in \{\hat{k} \mid c_{i'[\hat{k}]} \text{ is false} \vee c_{j'[\hat{k}]} \text{ is false}\}$,

compute the aggregate link traffic $\{\sum a^x_{i'j'[k]}\}$ for all links in $IE^k_{i'j'}$;

compute the aggregate link capacity $\{\sum a^f_{i'j'[k]}\}$ for all links in $IE^k_{i'j'}$;

Choose the channel with minimum $(\sum a^x_{i'j'[k]} / \sum a^f_{i'j'[k]})$; suppose k'' satisfies;

if $c_{i'[k'']}$ = false **then**

$c_{i'[k'']}$:= true;

$N' := N' + 1$; // add one more NIC binding to channel k'' on host $v_{i'}$

endif;

if $c_{j'[k'']}$ = false **and** $N' < N$ **then**

$c_{j'[k'']}$:= true;

$N' := N' + 1$; // add one more NIC binding to channel k'' on host $v_{j'}$

endif;

endif; **endwhile**; **end.**

Figure 3.7: Incremental Interface Management (IIM) algorithm pseudocode.

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. A detailed pseudo-code for IIM algorithm is illustrated in Fig. 3.7.

3.4 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. 2.1, the adoption of multiple radio modules on mesh hosts can effectively mitigate the inter-route and inter-hop contention problems. In this section, we re-visit 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 M^4 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. 2.1, 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. 3.8 (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. 3.8 (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 (mPDF).

Note that the multi-path problem is a subset of the inter-route contention problem.

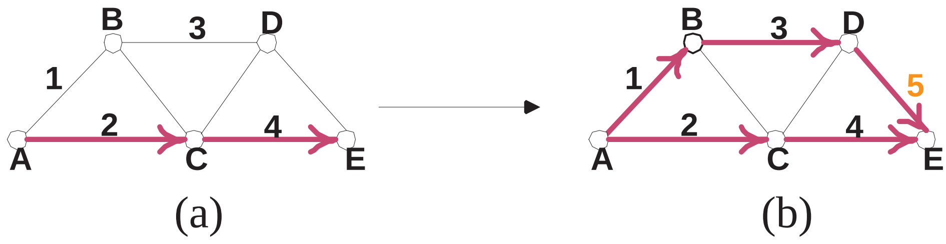


Figure 3.8: The idea of traffic splitting for communication flow from sender A to receiver E in the proposed multi-path packet delivery function (mPDF): (a) original single-path and (b) multi-path delivery by adding one more radio module on each of nodes D and E binding to channel 5.

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 M^4 WMN architecture, we observe the potential of multi-path packet forwarding mechanism. The benefit of utilizing multiple routing paths in multi-channel environments has been verified in our previous work presented in [23]. We plan to investigate more on the feasibility of implementing our mPDF protocol by performing traffic engineering techniques in a real testbed.

Chapter 4

Performance Evaluation

This chapter provides performance results derived from performing our proposed resource allocation, channel arrangement algorithms, and multi-path packet delivery function (mPDF) in an M^4 WMN. We describe the network environment settings in Section 4.1, followed by numerical and simulation comparison results reported in Section 4.2 and Section 4.3 respectively.

4.1 Network Environment Settings

We generate an M^4 WMN in grid topology as illustrated in Fig. 4.1. 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.

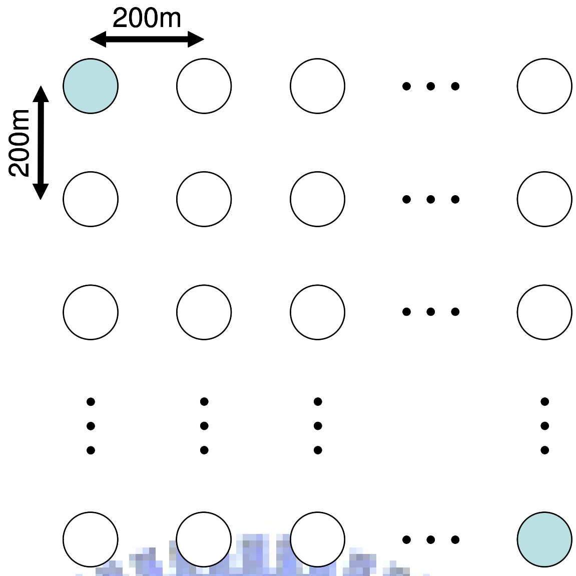


Figure 4.1: The mesh grid with Internet gateways located at the upper-left and bottom-right corners.

4.2 Numerical Results

This section 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.

4.2.1 Varying Number of Available Channels and Interfaces

In this section, we first experiment on a 4×4 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. 4.2 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. 4.2, once the throughput saturates at its maximum point, adding network interfaces contribute little to the performance, since the bottleneck now lies in the number of orthogonal channels C.

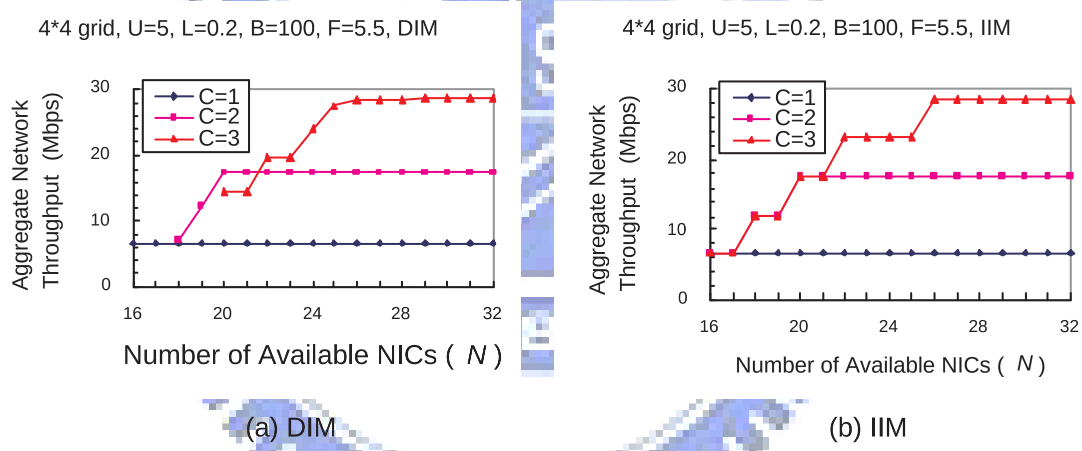
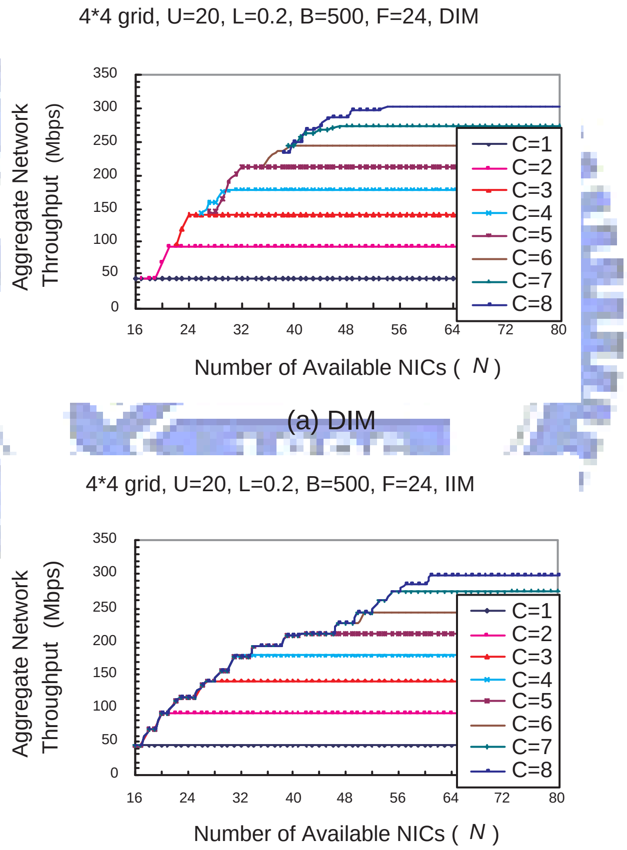


Figure 4.2: Aggregate network throughput vs. number of available radio interfaces for maximal 3 orthogonal channels in the IEEE 802.11b environment using (a) DIM and (b) IIM algorithms.

We conduct another experiment considering the IEEE 802.11a environment, also in a 4×4 grid topology having 2 Internet gateways. Though with 12 non-overlapping channels, IEEE 802.11a is conceived to have maximal 8 orthogonal (non-interfering) channels available in many areas around the world. As a result, we adopt this assumption and define related parameters U and L to be 20 Mbps and 0.2 Mbps respectively, B and F

to be 500 Mbps and 24 Mbps respectively. Fig. 4.3 plots the results. In this figure, we observe that by using 54 network interfaces in total, averagely 3.4 NICs per mesh host, we can maximize the network throughput and fully utilize the total radio bandwidths that 8 orthogonal channels can provide. This result is encouraging for we do not need to deploy a large number of 8 NICs on each mesh host, in order to take advantage of all channel bandwidths. Note that different network configurations and parameter settings will produce various values of required N. In real WMN systems, given user traffic requirements, network connectivity function, gateway capacities, and wireless link data rates, an optimal value for N should exist to achieve a reasonable deployment cost.



(a) DIM

(b) IIM

Figure 4.3: Aggregate network throughput vs. number of available radio interfaces for maximal 8 orthogonal channels in the IEEE 802.11a environment using (a) DIM and (b) IIM algorithms.

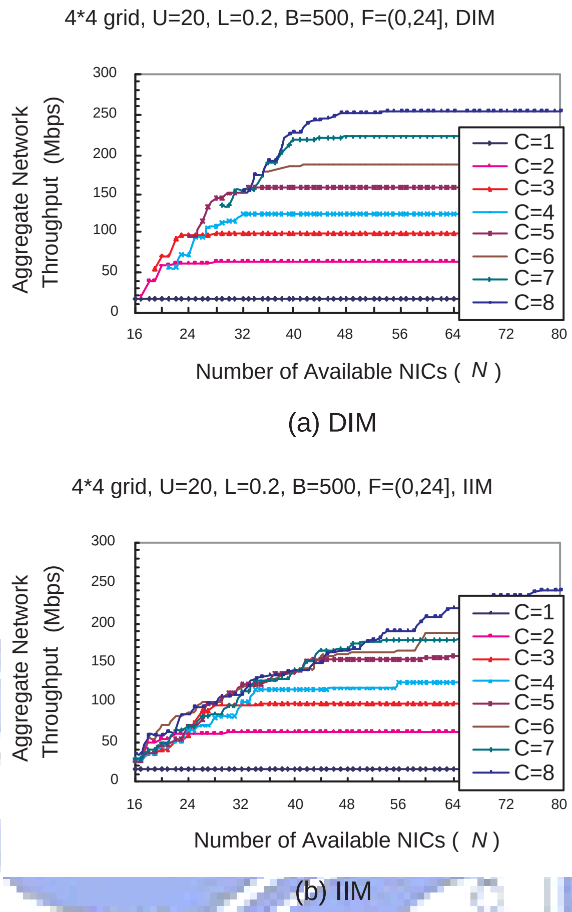


Figure 4.4: Aggregate network throughput vs. number of available radio interfaces in the IEEE 802.11a environment with varying link bit rates (uniformly distributed over (0,24]Mbps) using (a) DIM and (b) IIM algorithms.

4.2.2 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. Below we report the results in order.

Since in real environments, data rate differs from link to link due to distinguished surroundings and channel conditions, we now remove the constant link capacity assumption, and let F uniformly distribute over the range of (0,24] Mbps. The rest of parameter settings is the same as in Fig. 4.3. Fig. 4.4 illustrates the results. Though with lower network throughput due to imperfect link data rates, Fig. 4.4 shows similar trends and phenomena as we observed from Fig. 4.3. As we can see from the figure, DIM outperforms IIM as C increases by keeping N at a lower number, which suggests that the proposed DIM strategy is more adaptive than IIM when dealing with varying link bit rates.

Now we focus on the DIM algorithm, and vary network size from 3×3 to 7×7 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. 4.5 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

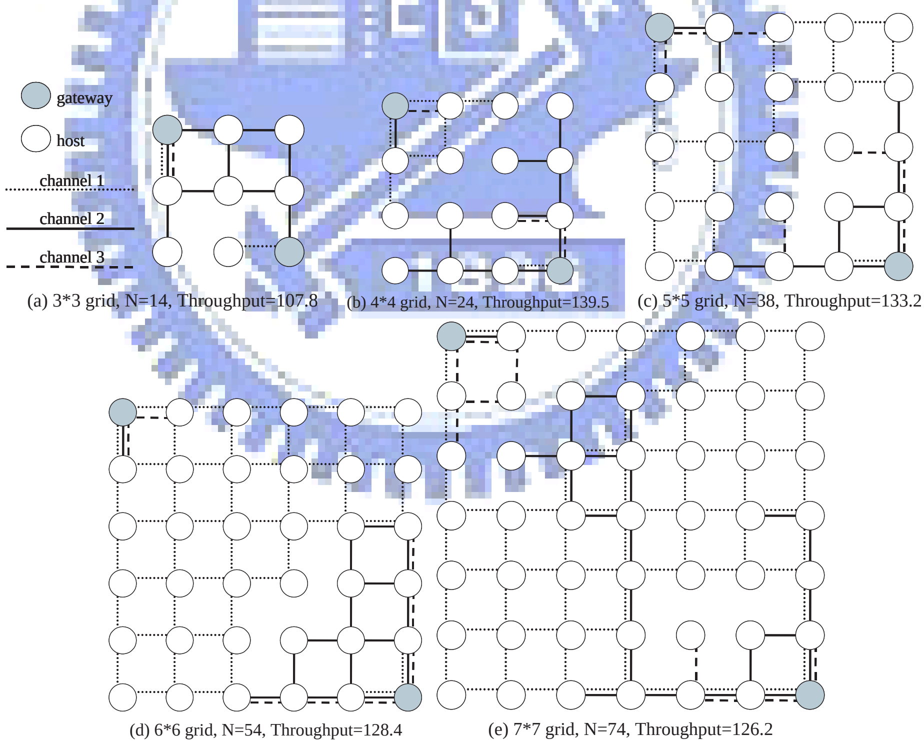
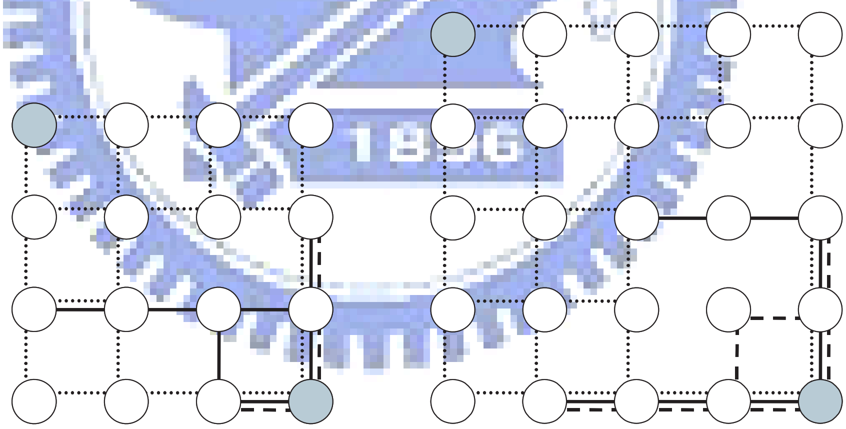


Figure 4.5: The interface distributions and channel configurations for different network sizes in the IEEE 802.11g environment using the proposed DIM algorithm.

almost the same. In addition, the network throughputs are kept above 100 Mbps whether it is a small (3×3) or large (7×7) grid, suggesting that the proposed strategy is scalable. Scalability property is critical for WMNs in designing an easy-to-deploy high-performance wireless mesh backbone without paying much unnecessary attention to the network size and routing path length.

Also focusing on the DIM strategy, in the next experiment, we enable heterogeneous gateways by setting the upper-left gateway capacity to be 5 Mbps and the bottom-right one to have 500 Mbps bandwidth capacity. The rest of parameter settings is the same as the previous experiment. We test on the 4×4 and 5×5 grids. Fig. 4.6 depicts the resulting network configurations. Due to distinguished gateway capacities, most traffic is directed toward the bottom-right gateway for load balancing. As a result, more interfaces will be assigned to the bottom-right gateway. Furthermore, Fig. 4.6 (a) and Fig. 4.6 (b) show similar throughput performance despite their different network sizes, which once again validates the scalability of our proposed methodology.

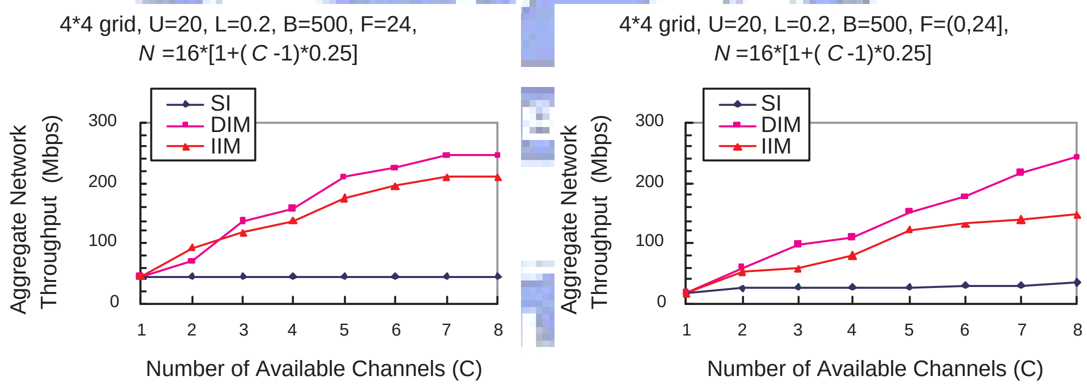


(a) 4*4 grid, N=24, Throughput=75.9 (b) 5*5 grid, N=38, Throughput=74.6

Figure 4.6: The interface distributions and channel configurations for (a) 4×4 and (b) 5×5 grids in the IEEE 802.11g environment with unbalanced gateway capacities using DIM algorithm.

4.2.3 Single-radio versus Multi-radio Systems

In the final experiment, we go back to the 4×4 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. 4.7 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 4×4 grid, making N to increase by 4 every time one more channel is available to the network. As we can see from Fig. 4.7, 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.



(a) Constant link capacity (b) Varying link capacity

Figure 4.7: Throughput comparisons between single-radio and multi-radio systems in the IEEE 802.11a environment with (a) constant and (b) varying link bit rates.

4.3 Simulation Results and Comparison

In this section, we report the simulative performance comparison with the RCL algorithm proposed in [6]. The simulator used for experiments is ns-2 [2] with multi-radio extension. Two-ray ground model is adopted for the radio propagation path loss. Note that to the best of our knowledge, our work is the first to address the optimization of the number of equipped radios at each mesh router. As described in Section 2, we have a different problem scope from the RCL algorithm. To provide a fair comparison, let us make the following assumptions in the simulations for both the RCL and our algorithms. First, up-link and down-link traffics are assumed to be symmetric, though our algorithm handles asymmetric up- and down-link traffics. Second, we also adopt the protocol model of interference, and assume the interference sources consist of 2-hop neighbors of both the sender and receiver (with RTS/CTS enabled). Third, equal data rate (capacity) for all channels and links is assumed. Fourth, gateway capacity is limited. Fifth, given a fixed total number of available radios, RCL will allocate equal number to each mesh router, while our proposed algorithm will assign heterogeneous numbers to nodes in order to balance the loads.

To demonstrate the importance of network planning, we use the same parameter settings as in Fig. 4.2 with total available number of orthogonal channels $C = 2$. Experiments are performed using three different grid topologies: 3×3, 4×4, and 5×5. Table 4.1 summarizes the aggregate network throughput yielded by the three algorithms under different network sizes. Here N denotes the total number of required radio interfaces by each algorithm. As we can see from this table, to achieve comparable network throughput, our proposed DIM and IIM approaches always result in a smaller total number of radio interfaces needed. Under the 5×5 topology, our IIM algorithm even requires only half as many as the number of radio interfaces used by RCL ($N = 27$ vs. $N = 50$) to achieve similar throughput performance, thus saving deployment costs. Consequently, network planning by distributing available radios based on different (forwarding) traffic requirements at mesh routers has been effectively exercised by the proposed DIM and IIM algorithms.

Table 4.1: Comparison of the RCL algorithm equipping two radio interfaces at each mesh router with our proposed approaches having the capability of distributing radio interfaces based on load-sensitivity.

	3x3	4x4	5x5
RCL (Mbps)	18.0341 N=18	17.2148 N=32	15.7682 N=50
DIM (Mbps)	18.0341 N=15	17.1631 N=21	15.5473 N=31
IIM (Mbps)	18.0593 N=13	17.1902 N=20	15.7504 N=27

Chapter 5

Conclusions

In this thesis, we propose an M^4 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 $c_{i[k]}$ become 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. On the other hand, due to the relatively high computational complexity incurred by the linear programming calculations, we only perform this optimization task at the WMN deployment stage as an initialization setup. Once mesh nodes are well configured, the LP modeling will be re-evaluated periodically in an infrequent basis. Based on the current insights observed from this work, we plan to explore a sub-optimal tree-induced flow designation strategy, which requires less computational complexity. These results and possible improvements will be reported in our future research. In addition, we are interested in the fairness problem in WMNs. In this thesis, 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 research.

Bibliography

[1] lp-solve: a Mixed Integer Programming (MIP) solver. *http://www.geocities.com/lpsolve*.

[2] ns-2: The Network Simulator. *http://www.isi.edu/nsnam/ns/*.

[3] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou. A Multi-Radio Unification Protocol for IEEE 802.11 Wireless Networks. In *Proc. IEEE BroadNets*, pages 25–29, Oct. 2004.

[4] D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris. Link-level Measurements from an 802.11b Mesh Network. In *Proc. ACM SIGCOMM*, pages 121–131, Aug. 2004.

[5] I. F. Akyildiz, X. Wang, and W. Wang. Wireless Mesh Networks: A Survey. *Elsevier Computer Networks*, 2005.

[6] M. Alicherry, R. Bhatia, and L. Li. Joint Channel Assignment and Routing for Throughput Optimization in Multi-radio Wireless Mesh Networks. In *Proc. ACM Int'l Conf. Mobile Computing and Networking (MobiCom)*, Sep. 2005.

[7] B. Awerbuch and D. H. H. Rubens. High Throughput Route Selection in Multi-Rate Ad Hoc Wireless Networks. In *Proc. First Working Conference on Wireless On-demand Network Systems (WONS)*, Jan. 2004.

[8] P. Bahl, A. Adya, J. Padhye, and A. Wolman. Reconsidering Wireless Systems with Multiple Radios. *ACM SIGCOMM Computer Communications Review (CCR)*, 34(5):39–46, Oct. 2004.

[9] P. Bahl, R. Chandra, and J. Dunagan. SSCH: Slotted Seeded Channel Hopping for Capacity Improvement in IEEE 802.11 Ad-Hoc Wireless Networks. In *Proc. ACM Int'l Conf. Mobile Computing and Networking (MobiCom)*, pages 216–230, 2004.

[10] C.-Y. Chang, P.-C. Huang, C.-T. Chang, and Y.-S. Chen. Dynamic Channel Assignment and Reassignment for Exploiting Channel Reuse Opportunities in Mobile Ad Hoc Wireless Networks. *IEICE Transaction on Communicaton*, pages 1234–1246, Apr. 2003.

[11] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya. Using Directional Antennas for Medium Access Control in Ad Hoc Networks. In *Proc. ACM Int'l Conf. Mobile Computing and Networking (MobiCom)*, pages 59–69, Sep. 2002.

[12] R. Draves, J. Padhye, and B. Zill. Routing in Multi-Radio Multi-Hop Wireless Mesh Networks. In *Proc. ACM Int'l Conf. Mobile Computing and Networking (MobiCom)*, pages 114–128, 2004.

[13] G. Holland, N. Vaidya, and P. Bahl. A Rate-Adaptive MAC Protocol for Multi-Hop Wireless Networks. In *Proc. ACM Int'l Conf. Mobile Computing and Networking (MobiCom)*, pages 236–251, Jul. 2001.

[14] J. Jun and M. L. Sichitiu. The Nominal Capacity of Wireless Mesh Networks. *IEEE Wireless Communications*, 10(5):8–14, Oct. 2003.

[15] R. Karrer, A. Sabharwal, and E. W. Knightly. Enabling Large-scale Wireless Broadband: The Case for TAPs. In *Proc. 2nd Workshop on Hot Topics in Networks (HotNets-II)*, 2003.

[16] P. Kyasanur and N. H. Vaidya. Routing and Interface Assignment in Multi-Channel Multi-Interface Wireless Networks. In *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, 2005.

[17] R. Ramanathan, J. Redi, C. Santivanez, D. Wiggins, and S. Polit. Ad Hoc Networking with Directional Antennas: A Complete System Solution. *IEEE Journal on Selected Areas in Communications (JSAC)*, pages 496–504, Mar. 2005.

[18] A. Raniwala and T.-C. Chiueh. Architecture and Algorithms for an IEEE 802.11-Based Multi-Channel Wireless Mesh Network. In *Proc. IEEE INFOCOM*, 2005.

[19] A. Raniwala, K. Gopalan, and T.-C. Chiueh. Centralized Channel Assignment and Routing Algorithms for Multi-Channel Wireless Mesh Networks. In *Mobile Computing and Communications Review*, pages 50–65, Apr. 2004.

[20] S.-T. Sheu, Y. Tsai, and J. Chen. MR2RP: The Multi-Rate and Multi-Range Routing Protocol for IEEE 802.11 Ad Hoc Wireless Networks. *ACM/Kluwer Wireless Networks*, 9(2):165–177, 2003.

[21] J. So and N. Vaidya. Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver. In *Proc. ACM MobiHoc*, pages 222–233, May 2004.

[22] K. Sundaresan, R. Sivakumar, M. A. Ingram, and T.-Y. Chang. A Fair Medium Access Control Protocol for Ad-hoc Networks with MIMO Links. In *Proc. IEEE INFOCOM*, Mar. 2004.

[23] W.-H. Tam and Y.-C. Tseng. Joint Multi-Channel Link Layer and Multi-Path Routing Design for Wireless Mesh Networks. In *Proc. IEEE INFOCOM*, 2007.

[24] S.-L. Wu, C.-Y. Lin, Y.-C. Tseng, and J.-P. Sheu. A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Net-

works. In *Proc. Int'l Symposium on Parallel Architectures Algorithms and Networks (I-SPAN)*, pages 232–237, Dec. 2000.

[25] S.-L. Wu, Y.-C. Tseng, C.-Y. Lin, and J.-P. Sheu. A Multi-channel MAC Protocol with Power Control for Multi-hop Mobile Ad Hoc Networks. *The Computer Journal*, 45(1):101–110, 2002.