國立交通大學

電機學院　電信學程

碩士論文

提升使用端效能之異質無線技術整合研究

On Synergizing Heterogeneous Wireless Technologies to Improve User Experiences

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中華民國 99 年 1 月

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碩士論文

A Thesis
Submitted to College of Electrical and Computer Engineering
National Chiao Tung University
in partial Fulfillment of the Requirements
for the Degree of

Master of Science
in

Communication Engineering

January 2010

Hsinchu, Taiwan, Republic of China

中華民國九十九年一月

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摘要

在整合異質無線技術上所需要考慮包括無線協定中各層的不同技術問題。在路徑選擇協定上也是都要考慮各種不同無線技術的能力跟功能，而目前最關鍵的就是針對網路層設計。

在此份論文中，我們考慮網路下載的流量，設計一個協力合作架構包括各種異質無線平台，多重模式(多重無線介面)的行動裝置和固定的裝置，這些裝置都有能力支援多重通道，並且實現提升使用端更好的下載使用效能。在此架構上提出一個協力合作的路徑選擇協定，此協定利用線性方法去計算出最佳路徑。所以我們最主要的目地就是在此架構上利用協力合作的路徑選擇方法提升使用端的下載速度。而我們的模擬實驗也證明此方法在協力合作架構上可以得到有效的效能提升。

On Synergizing Heterogeneous Wireless Technologies To Improve User Experiences

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ABSTRACT

Integrating heterogeneous wireless technologies involves various technological challenges at all layers of the protocol stack. Designing at the networks layer is perhaps the most critical, while the most challenging for different capabilities and functionalities of various wireless access models should be all taken into account in a unified routing process.

In this thesis, considering downloading traffic from the Internet, we propose a synergized framework (SF), consisting of heterogeneous wireless platforms, multi-mode (multi-interface) mobile and fixed wireless hosts capable of operating over multiple orthogonal (non-overlapping) radio channels, to realize better downloading experiences for users via cooperation between different wireless technologies. An SNG routing protocol is devised to enable the proposed framework. Given perceived network information, SNG performs computations based on linear formulations, and obtains an optimized route for packet delivery. Our main objective is to improve effective user downlink throughput via the cooperative (synergized) communication model and its corresponding SNG routing mechanism. Simulation results demonstrate the benefits brought by the unified architecture and corroborate the efficacy of the proposed routing technique.

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，老師在我碩士階段三年的時間當中，很有耐心的持續指導。而我有時因工作關係無法跟老師討論研究內容，老師也都能額外配合我的時間，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；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，實驗室學弟妹們 – 昆儒、葳庭、承穎、境宜、泰乙、冠樺、廣淳、凱全，大家都給予我滿大的幫助，尤其泰乙在研究上幫忙很多，並且大家也常幫我分擔一些有時因工作無法到校處理學校事務的事情，讓我可以安心的在這三年裡完成我的學業；真的由衷感謝所有 Bun Lab 的成員。

此外，要感謝在工作上的主管，他可以讓我在不影響份內工作下，給予最大方便讓我可以有多餘時間在研究上。今天能夠順利畢業真的感謝主管給予最大的鼓勵及支持。

另外特別感謝我的父母親，一直在人生道路上給予最大的支持與鼓勵，讓我不用擔心家裡，可以全心在工作上及學業上。

最後，感謝我的老婆 – SAN，在我工作又邊唸書這段時間，把家裡的大小事處理好不讓我擔心，真是辛苦你了，謝謝，我愛你。

誌於 2010.01 新竹 交大

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Contents

List of Tables

List of Figures

Chapter 1

Background

In the past decade, we have witnessed a multitude of communication technologies evolved into mature wireless Internet access options. Wireless wide-area networks (WWANs), wireless metropolitan-area networks (WMANs), and wireless local-area networks (WLANs) possess complementary characteristics in terms of transmission range and attainable data rate. Table 1.1 summarizes respective features of those state-of-the-art wireless communication systems (statistics excerpted partially from the empirical data documented in [2, 7, 11, 19, 21]). Among those technologies, IEEE 802.11 family standards are traditionally classified as WLAN systems, while WCDMA/HSDPA, LTE, and WiMAX are usually recognized as WWAN or WMAN cellular communication platforms. Furthermore, according to the attainable data rates, cellular standards are further categorized into 3G (WCDMA), 3.5G (HSDPA), and 4G (LTE and WiMAX) systems. Generally speaking, WLAN systems have limited transmission distances (normally in tens of meters), but achieve higher data communication rates (in tens of even hundreds of Mbps). Infrastructure access to the IP network in WLANs is via access points (APs). Due to its limited communication range, the IEEE 802.11-based WLAN systems have developed a multi-hop relaying mode (termed as the ad hoc multi-hop mode) to extend effective AP coverage. On the other hand, 3G WWAN systems, such as WCDMA, are capable of transmitting

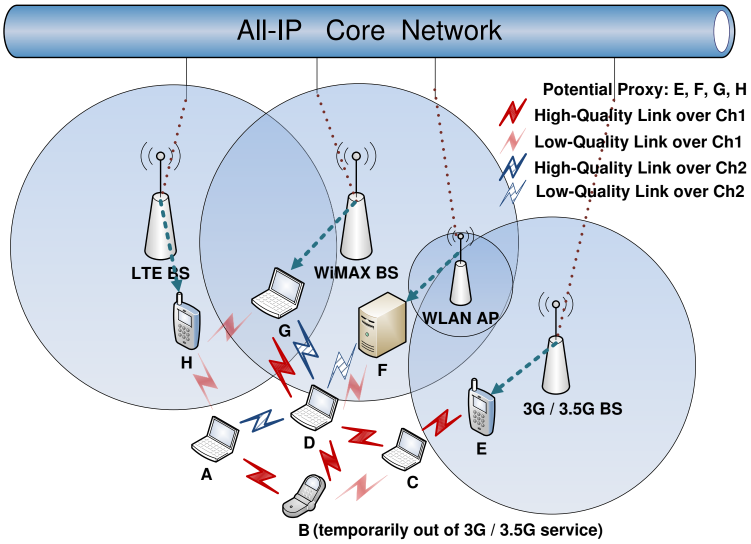

Figure 1.1: Illustration of the proposed synergized framework (SF) to enable seamless internetworking between (mobile) wireless devices.

data for long distances (several kilometers), but have relatively low data rates (in hundreds of Kbps to at most 2 Mbps). Access to the IP core network in WWAN/WMAN systems is via base stations (BSs). Researchers have observed the complementary characteristics between WLANs and 3G WWANs, along with the usefulness offered by the ad hoc multi-hop relaying mode. Some have proposed to integrate these heterogeneous systems in order to provide an integrated wireless environment capable of serving ubiquitous connections with high data rates. Such integration issues and the benefits of enabling cooperation (interworking) between 3G, WLAN, and ad hoc multi-hop communication models have been extensively studied in [5, 8, 9, 12, 13, 15, 17, 18].

The integration of various wireless technologies is a non-trivial task, involving designs at all layers of the protocol stack. We observe that designing at the network layer is perhaps the most critical yet challenging in the sense that different capabilities and functionalities of heterogeneous wireless access platforms need be considered in a unified routing process. Most past integration solutions tap into the aforementioned complementary characteristics (long/short transmission distance accompanied by low/high data rate) possessed by respective wireless systems when designing their routing algorithms.

Table 1.1: Comparison of wireless technologies

Technology / Attribute	IEEE 802.11a, b, g	IEEE 802.11n	WCDMA / HSDPA	LTE	WiMAX
Frequency band	2.4 ~ 2.497 GHz (b, g, n) 5.15 ~ 5.35 GHz (a, n) 5.725 ~ 5.285 GHz (a, n)		700 ~ 2100 MHz		2.3 ~ 2.4 GHz 2.496 ~ 2.69 GHz 3.4 ~ 3.6 GHz 3.4 ~ 3.8 GHz
Standard specified data rate	54 Mbps (a, g) 11 Mbps (b)	600 Mbps	2 Mbps (WCDMA) 14 Mbps (HSDPA)	300 Mbps (2 x 2 MIMO)	75 Mbps (2 x 2 MIMO)
Commercial data rate	~ 27 Mbps (a) ~ 22 Mbps (g) ~ 5 Mbps (b)	50 ~ 144 Mbps	384 Kbps ~ 2 Mbps (WCDMA) 1~10 Mbps (HSDPA)	10 ~ 100 Mbps	2 ~ 10 Mbps
Transmission range	30 ~ 45 m (a) 30 ~ 100 m (b) 30 ~ 100 m (g)	50 ~ 300 m	3 ~ 12 km	5 ~ 100 km	2 ~ 10 km

However, with the emergence of high-speed 4G technologies (LTE and WiMAX), the complementarity becomes no longer salient, making the integration task even more challenging. In this thesis, we try to address this new challenge by proposing a synergized framework (SF), considering various state-of-the-art wireless access technologies, and design an optimized routing process for such a generic hybrid networking environment.

Fig. 1.1 illustrates the concept of a synergized framework (SF), where clients E, F, G, and H have direct Internet connections via BS/AP and can act as potential proxies (gateways) for other clients. In this framework, participating clients may have multiple interfaces operating over orthogonal (non-overlapping) radio channels. For instance, there are 3 non-overlapping channels in IEEE 802.11 b/g, while 8 (up to 12) non-overlapping channels are available in IEEE 802.11a. With the prevalence of inexpensive wireless hardware components, it becomes affordable to equip multiple radio interfaces on a communication host (client). As shown in Fig. 1.1, clients A, D, F, and G are capable of transmitting simultaneously over orthogonal channels, Ch1 and Ch2, with different link qualities with their own neighboring clients. Imagine a routing protocol designed to synergize the cooperation between participating clients. Take client A in Fig. 1.1 for example, what attribute(s) should act as the metric(s) in determining the best route to access the Internet? Obviously, among the four proxy (gateway) options, theoretically LTE BS can provide the highest downlink data rate for client A via direct link with proxy H (1 relaying hop). However, the radio link quality over Ch1 between clients A and H is weak, unfortunately invalidating the high downlink bandwidth provided by LTE BS. On the other hand, since radio link qualities between A-D (over Ch2) and D-G (over Ch1 and Ch2) are both good, client A may instead consider selecting WiMAX BS as the downlink provider via proxy G, despite the fact of having to travel 2 relaying hops. In addition, by leveraging the multiple interfaces available on clients A, D, and G, the routing protocol can possibly enable multi-path flow by simultaneously taking route G-D-A over high-quality Ch2 and route G-D-B-A over high-quality Ch1 to further increase the effective downlink rate for client A. Consequently, the best route in this case does not necessarily involve proxy with the highest downlink capacity, neither proxy with the shortest relaying path. In other words, either proxy (gateway) capacity or relaying hop distance alone no longer serves as the single metric for selecting the best route in such a synergized (integrated) framework. Rather, those factors, together with ad hoc multi-hop link qualities, should all be taken into consideration in a holistic manner. Motivated by the interacting tradeoffs, we design a routing protocol that tries to optimize the foregoing factors when selecting the best routes. Another observed benefit shown in Fig. 1.1 is that client B, while temporarily out of direct connection with its BS, can select another route via multi-hop relaying to reach the core network and still enjoy the Internet services (with possibly better quality than its original downlink quality) under this cooperative model. Such hybrid network combining centralized access model and distributed ad hoc multi-hop communication behavior is generally beneficial in terms of reduced deployment costs for infrastructure providers and increased connectivity opportunities for end users (clients).

The remainder of this thesis is organized as follows. In Section 2, we review related earlier research efforts in the area of integrating heterogeneous wireless technologies, and point out the unique contributions of our work. Section 3 presents the SNG protocol, elaborating on network neighborhood discovery process, route optimization details, and packet forwarding procedures. We conduct extensive simulations to validate the routing performance and exhibit the benefits brought by the proposed synergized framework in

Section 4. Finally, Section 5 draws our conclusion and maps out future plans.

Chapter 2

Related Work

Due to the availability of dual-mode terminals and popularity of ad hoc networking technologies, several pioneering works have been proposed to explore the multi-hop relaying possibility in a cellular system [3, 20, 23–27]. In [3], an ad hoc Global System for Mobile Communications (A-GSM) architecture is presented to provide connectivity for users in dead spots. The proposed architecture intends to increase cellular capacity and link robustness. With the similar idea in mind, the authors in [20] devise an opportunity-driven multiple access (ODMA) mechanism to support multi-hop connections. Specifically, ODMA breaks down a single CDMA transmission into a number of smaller radio hops to relay the packets. Due to reduced transmit power and co-channel interference, the cellular coverage-capacity tradeoffs can be optimized. However, ODMA does not support communications for users outside the cellular coverage. Also exploiting dual-mode terminals capabilities, the iCAR authors in [23] introduce the ad hoc relay stations (ARSs) to be deployed by the network operator at cell boundaries with limited mobility under the control of cellular mobile switching center (MSC). The deployed ARSs have two interfaces capable of communicating with the cellular base station and, simultaneously, communicating with other ARSs in ad hoc mode via WLAN interface. ARSs in iCAR can divert excess traffic from a congested cell to other lightly-loaded neighboring cells. With the traffic adaptations performed by ARSs, iCAR aims to balance traffic load between cells. Furthermore, iCAR also increases cellular coverage by enabling users out of cellular coverage to access the system through the assistance of deployed relay stations (ARSs). Since mobile hosts (MHs) in iCAR have only one air interface for communicating with the cellular system, in [26], the authors extend iCAR by including another ad hoc network interface (A-interface) into MHs (so that MHs can participate in the relaying procedure as well). An adaptive routing protocol, entitled as ARFA, is introduced to facilitate flexible access (FA) in the extended iCAR-FA architecture. Another proposal to achieve cellular load balancing can be found in [24, 25], where a mobile-assisted data forwarding (MADF) mechanism is introduced to forward part of the traffic in a crowded (hot) cell to some free (cold) cells. Different from the usage of stationary ARSs adopted by iCAR, MADF utilizes mobile stations (MSs) that are located between hot and cold cells as relaying nodes. By implementing MADF in Aloha and TDMA networks, the authors show that the throughput in a hot cell, which is surrounded by several cold cells, can be significantly improved. In [27], the self-organizing packet radio ad hoc network with overlay (SOPRANO) project is another effort to incorporate the ad hoc relaying capability in a cellular system. Several aspects, including bandwidth allocation, access control, routing, traffic control, and profile management, have been investigated in the proposed SOPRANO architecture. Focusing on connection establishment and self-organization issues, the SOPRANO authors investigate the optimal transmission strategy in the multi-hop network with the objective of enhancing cellular capacity. All of the aforementioned research works belong to earlier efforts in the area of integrating cellular and ad hoc multi-hop networks. However, those previous works do not consider integration with WLAN APs, let alone those state-of-the-art broadband cellular systems, emerging in the past years. In light of this, we intend to consider a more generic networking paradigm that contains heterogeneous wireless Internet access technologies in a unified architecture by proposing a synergized framework

(SF) to enable interoperability between those communication platforms.

Motivated by the idea of incorporating ad hoc multi-hop relaying mode into infrastructure-based single-hop cellular communication, a number of follow-up research works have been proposed to integrate 2.5G/3G/3.5G WWAN with IEEE 802.11-based WLAN [4, 16, 22]. In [16], a unified cellular and ad hoc network (UCAN) architecture is proposed to enhance cellular throughput by providing low data-rate users with better downlink channel quality through proxy clients (acting as Internet gateways). A mobile client in UCAN has dual interfaces connecting to both 3G infrastructure and IEEE 802.11 ad hoc multi-hop network. The basic rationale behind UCAN is to find proxy clients with higher downlink data rates for users experiencing poor cellular channel qualities, where selected proxy client should perform the downloading on behalf of requesting user and then forward received packets in ad hoc multi-hop relaying mode via IEEE 802.11 interface to the intended destination (requesting user). Two proxy discovery mechanisms are introduced: greedy and on-demand protocols. The greedy protocol is proactive and tries to locate possible proxy client with better downlink quality, starting the search from immediate neighbors, 2-hop neighbors, 3-hop neighbors, and so on, in a greedy manner until no better neighbor can be found. This approach is simple but comes with one attendant drawback: such a greedy path may not always locate the proxy with the best cellular channel rate, due to possible local minimum occurring in the neighborhood of the requesting client. In order to address this problem, another on-demand protocol is proposed to perform proxy discovery in UCAN. Instead of greedily reaching out from the requesting client, on-demand protocol searches for the best proxy by propagating requesting message through the ad hoc network (with a limited number of hops controlled by a time-to-live, TTL, field). The UCAN authors evaluate the performance in a simulated HDR cell, with IEEE 802.11b as the simulated ad hoc interface. Also utilizing dual-mode terminals as relay proxies, the authors in [22] include WLAN APs as possible Internet gateways to provide seamless roaming between

WWANs and WLANs. The proposed integrated WWAN/WLAN two-hop-relay architecture intends to enhance cellular system capacity and extend WLAN coverage for up to two hops. More recently, a cross-layer study over integrated 3G and WLAN systems has been presented to enable interoperability between heterogeneous communication environments [4]. The suggested cross-layer algorithm jointly performs 3G resource allocation and ad hoc routing in order to increase 3G system performance. With a slightly different design metric from the previous attempts, the authors in [4] also try to select relaying route without disturbing existing WLAN background traffic. We observe that the underlying goal of foregoing research works mainly focuses on improving (downlink) capacity in cellular systems. Moreover, no specific proxy (gateway) load balancing strategy is available to judiciously divert user traffic to another possible candidate when the downlink bandwidth of selected proxy (gateway) is partially occupied by existing users. In this thesis, we aim to improve effective user downloading throughput, and perform gateway load balancing among requesting users in order not to exhaust some high-capacity proxies (gateways), which are commonly favored by proxy (gateway) selection algorithms. In addition, as the development of upcoming broadband 4G systems, such as WiMAX and LTE standards, progresses aggressively, we observe that Internet gateways may no longer be the communication bottleneck. On the contrary, communication bottleneck may exist in the ad hoc relaying domain. However, none of the above works considers the ad hoc bottleneck, where wireless link qualities vary and medium contentions dominate the effective throughput. Furthermore, the channel diversity provided by multiple orthogonal (non-overlapping) radio channels has not been leveraged to further increase the ad hoc network capacity either.

We summarize our unique contributions as follows. First, the proposed SF is a generic framework including all kinds of contemporary wireless Internet access technologies. Considering various gateway options and available ad hoc connection status, our SNG protocol distributes traffic loads across the synergized network to avoid exhausting certain ”hot” gateways. By participating in the unified framework and sharing radio resources, users out of BS/AP coverage can still be served via ad hoc relaying model and users originally having low-quality channels can be served better. Second, we model varying link qualities and wireless co-channel contentions to reflect realistic ad hoc communication behavior. Since communication bottleneck may exist in the ad hoc domain, our SNG protocol takes this factor into account when computing the best routes for requesting users. Third, the proposed SNG protocol further exploits channel diversity to enable multi-path routing flows.

Chapter 3

SNG Routing Protocol

In this section, we present our SNG routing protocol, which is customized to operate over the proposed synergized framework (SF). As explained and illustrated in Fig. 1.1, the SF is an integrated network containing heterogeneous wireless Internet access technologies (with distinct downlink capacities), a variety of communication devices (with different numbers of interfaces), and various ad hoc links (with varying channel qualities). In order to obtain the best route for a downloading request made by a participating client (user) in such a hybrid network, the SNG protocol takes a holistic approach by considering available proxies (gateways), remaining downlink capacities, and ad hoc link connection qualities, when making an optimized routing decision. Below we describe the necessary components that are included in the SNG mechanism. In Section 3.1, a network construction procedure based on periodical table exchange is introduced. The obtained network information is then used to compute the best (optimized) route for the requested downloading flow based on linear programming methodology. We provide the detailed optimization formulations in Section 3.2. Once the best route and corresponding link flows are determined, the data downloading can be performed via the selected proxy (gateway). Section 3.3 describes the signaling process and packet forwarding strategy. Finally, we summarize the SNG routing protocol in Section 3.4.

3.1 Network Information Construction

Since the SNG routing protocol tries to take both the infrastructure downlink capabilities and ad hoc connectivity status into account, a moderate amount of network information is necessary in determining a good route. In the ad hoc multi-hop network domain, SNG requires every participating client (node) to estimate and periodically update the average data rates for wireless links originating from its immediate neighbors. The estimation can be achieved using certain packet-pair probing mechanism [6]. By counting the number of successfully received broadcast advertisements, a node can obtain the packet delivery ratio from a neighbor to approximate the effective link rate. More details for improving the estimation accuracy can be found in [6]. The estimated data rates are kept by a node in the **C-Table** (capacity table) to reflect the ad hoc wireless link capacities over certain channels. In addition to the link capacities from neighbors, a node should also include the information regarding proxy (gateway) availability and attainable downlink bandwidth (if capable of acting as a gateway) in the C-Table. Specifically, the **Gateway Bit** (set to *true* or *false*) and **Gateway Capacity** fields should be provided in the C-Table as well.

Whenever receiving a C-Table with new entries from others, a node learns and records those new entries in its own C-Table. In this way, the network knowledge perceived by a node can be effectively expanded. To ensure the freshness of received C-Table, a node is required to attach and increase the **Sequence Number** whenever advertising a new C-Table. In addition, we incorporate a **TTL** (time-to-live) field to limit how far (how many hops) the C-Table can travel. This limitation intends to impose a scoped neighborhood discovery on the table exchange process. Although a more complete network knowledge can lead to a better optimized routing decision (as one may soon observe from the computation models presented in Section 3.2), too many C-Table exchanges pose significant communication overhead, possibly trading off the optimized benefit that can be achieved. We investigate this design issue in Section 4.1. In fact, the simulation results show that the proposed SNG protocol only needs a moderate amount of discovered neighborhood information to outperform other routing approaches.

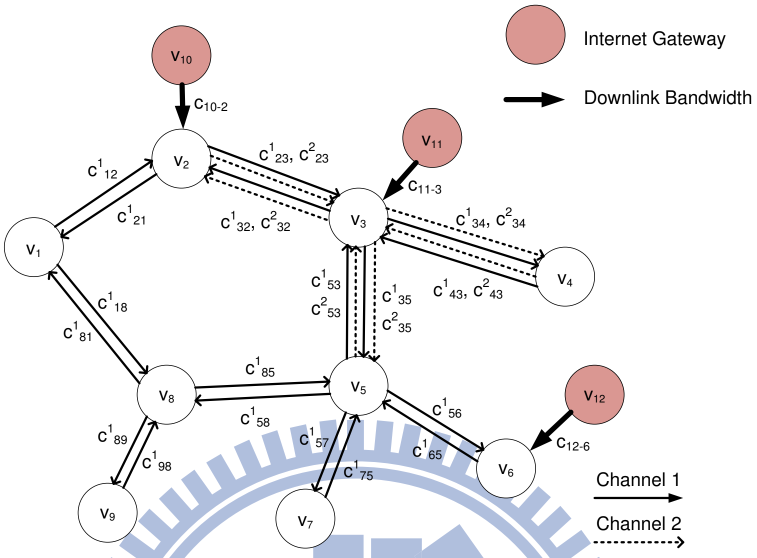

Figure 3.1: Constructed network topology, along with corresponding link capacities, potential gateways, and available Internet downlink bandwidths within 3-hop neighborhood of client node v_1.

Fig. 3.1 illustrates an example 3-hop neighborhood discovered by client (node) v_1. Potential proxy clients for v_1 downloading request include v_2, v_3, and v_6, connecting to Internet gateways v_{10}, v_{11}, and v_{12}, respectively. Note that nodes v_{10}, v_{11}, and v_{12} represent BSs/APs capable of providing downlink bandwidths from the IP infrastructure. In our routing modeling (presented in Section 3.2), Internet gateways are special clients that do not generate downloading requests. Two interfaces (operating on non-overlapping Channel 1 and Channel 2) are available at nodes v_2, v_3, v_4, and v_5, making communications simultaneously over both channels are possible. Furthermore, wireless link asymmetry is considered in our route computation to reflect realistic wireless radio channel conditions. As shown in Fig. 3.1, link capacity from node v_3 to v_5 over Channel 1 (c^1_{35}) is not necessarily identical to link capacity in the reverse direction (c^1_{53}). Similarly, c^2_{35} is not always equal to c^2_{53} when Channel 2 is used.

3.2 Downlink Flow Routing Computation

Given the neighborhood information obtained by limited C-Table exchanges, a requesting client (node) computes the best route and corresponding traffic flow distributions based on linear optimization. Define a directed graph $G = (V, E)$, where set V contains all nodes (clients), and set E includes all edges (wireless links). Below we introduce the notations to be used in our optimization formulations.

- As explained in Fig. 3.1, there are two types of clients: clients that request for downloading services (mobile clients), and clients that do not generate downloading requests (Internet gateways). We use V^m to denote the set of mobile clients, and V^g to indicate the set of Internet gateways. Consequently, V^m and V^g are disjoint sets and their union equals to set V ($V = V^m \cup V^g$).

- For wireless link originating from node v_i to node v_j over channel k, we denote the edge as e^k_{ij}, while e^k_{ji} is used to represent the edge in the reverse direction over the same channel. Assume there are totally K non-overlapping channels in the network. In case of interface k ($1 \leq k \leq K$) not being equipped on either node v_i or v_j or both nodes, the edges e^k_{ij} and e^k_{ji} simply do not exist.

- Set N_i contains all immediate neighbors of node v_i.

- To model the medium contention behavior in the 802.11-based ad hoc network domain, we define I^k_{ij} as the set of interfering links that interfere with communication from node v_i to node v_j over channel k. One may define this set differently based on various interference models. In our modeling, we adopt to include all wireless links within two hops of nodes v_i and v_j in set I_{ij}^k, considering RTS/CTS four-way handshaking is used in the 802.11 DCF access mode.

- Define c_{ij}^k as the estimated link capacity (rate) from node v_i to node v_j over channel (interface) k. In case of interface k $(1 \leq k \leq K)$ not being equipped on either node v_i or v_j or both nodes, we simply let $c_{ij}^k = c_{ji}^k = 0$. Furthermore, wireless link asymmetry is considered, so that c_{ij}^k is not necessarily equal to c_{ji}^k. However, if either c_{ij}^k or c_{ji}^k is zero, while the other is not $(\forall v_i, v_j \in V^m)$, we should avoid such links by letting $c_{ij}^k = c_{ji}^k = 0$, in order for the 802.11 acknowledgement mechanism to work correctly (bi-directional link required).

- Finally, f_{ij}^k denotes the optimized traffic flow distribution from node v_i to v_j over channel (interface) k that we intend to obtain through our computations.

A brief summary of notations is provided in Table 3.1.

Table 3.1: Summary of notations used in our optimization model

Notation	**Description**
V^g	Set of potential gateways (proxies)
V^m	Set of mobile clients
N_i	Neighbor set of node v_i
I_{ij}^k	Set of interfering links for communication between node v_i and v_j over channel k
c_{ij}^k	Estimated link capacity from node v_i to v_j over interface k
f_{ij}^k	Downlink traffic flow from node v_i to v_j over interface k (to be computed)

For each potential gateway candidate $v_g \in V^g$, a requesting node $v_r \in V^m$ evaluates the maximum downlink throughput attainable by current gateway capacity and routing flow distributions. The evaluation is based on linear optimization by setting the objective function as

$$Maximize \ \ \lambda = \sum_{k=1}^{K} \sum_{v_j \in N_g} f_{gj}^k, \tag{3.1}$$

where λ represents the effective downlink throughput injected into the ad hoc multi-hop network, while satisfying the following constraints.

Flow Conservation Constraint:

For requesting node $v_r \in V^m$

$$\sum_{k=1}^{K} \sum_{v_j \in N_r} f_{jr}^k = \sum_{k=1}^{K} \sum_{v_j \in N_g} f_{gj}^k, \tag{3.2}$$

while for other nodes $v_i \in V^m$, $v_i \neq v_r$

$$\sum_{k=1}^{K} \sum_{v_j \in N_i} f_{ij}^k = \sum_{k=1}^{K} \sum_{v_j \in N_i} f_{ji}^k, \tag{3.3}$$

ensuring equal incoming and outgoing flows.

Capacity Constraint:

For reasonable non-negative flow computations, the estimated link capacities represent the upper bounds for feasible f_{ij}^k values, thus we have

$$0 \leq f_{ij}^k \leq c_{ij}^k, \quad \forall e_{ij}^k \in E. \tag{3.4}$$

MAC Contention Constraint:

In 802.11-based ad hoc multi-hop networks, wireless medium is shared and contended by all links within the interference range of each other. Such contention behavior can be modeled as

$$\sum_{e_{pq}^k \in I_{ij}^k} \frac{f_{pq}^k}{c_{pq}^k} \leq 1, \forall v_i, v_j \in V^m. \tag{3.5}$$

After evaluating each gateway candidate based on the above optimization procedures, requesting node v_r selects the gateway with the maximum λ value computed by the linear programming model. The client connected to the selected gateway should then be notified to serve as downloading proxy for v_r, and calculated flow distributions should be provided to corresponding relaying nodes (clients).

3.3 Packet Forwarding Strategy

Once the proxy (gateway) client is determined, a requesting client sends out the **Gateway Request (GREQ)** packet to notify the proxy. The GREQ packet should contain computed λ value, so that the gateway downlink capacity can be refreshed to reflect the occupied bandwidth by the current requesting client. In addition, all corresponding relaying nodes are expected to receive the **Relay Request (RREQ)** packets for initiating the relaying process. Each sent RREQ packet should include computed flow distributions to facilitate routing performed by a relaying node. Like the refreshed gateway downlink capacity, all involved link capacities need be updated to reflect the current bandwidth occupancy. Both the GREQ and RREQ are unicast packets (acknowledgement mechanism used) to provide transmission reliability.

Based on the optimized flow computation results, multi-path packet delivery routes are possibly obtained to leverage channel diversity brought by multiple interfaces. The benefits and feasibility of exercising multi-path packet forwarding have been discussed in previous works [10, 14]. In this thesis, we also implement the multi-path packet forwarding by distributing traffic flows according to the calculations obtained from our linear formulations.

3.4 SNG Routing Protocol Summary

Below we provide the pseudo-code for our proposed SNG routing algorithm. In a nutshell, whenever there is a downloading request (DLRequest == *true*) issued, the SNG routing daemon computes an optimized route based on discovered neighborhood information, which includes network configurations, available gateways, attainable downlink capacities from the IP network, and estimated ad hoc link rates. The ultimate goal is to maximize the perceived downlink data rate for a requesting client that participates in the synergized framework (SF).

Algorithm 1 SNG Routing Algorithm

```
while (!exit) do
    Periodically estimate neighboring link capacities;
    Periodically exchange SNG C-Table;
    if DLRequest == true then
        Construct the network graph $G = (V, E)$;
        for each gateway candidate $v_g \in V^g$ do
            Solve LP (input: $c_{ij}^k$, $I_{ij}^k$, $K$, $V^g$, $V^m$, $E$);
            output: $f_{ij}^k$, $\lambda$;
        end for
        Send GREQ to selected gateway node with the max $\lambda$;
        Send RREQ to all relaying nodes;
        Refresh all link & gateway capacities;
        Perform downloading;
    end if
end while
```

Chapter 4

Performance Evaluation

To validate the performance of the proposed routing mechanism in the hybrid network, we implement our SNG protocol in the ns-2 simulator. The IEEE 802.11 MAC protocol with RTS/CTS four-way handshaking is used, and 3 802.11b non-overlapping channels are simulated. Default transmit power and Two-Ray Ground propagation model are adopted, leading to 250m transmission distance and 550m interference range. For each client running the SNG routing optimization, the *lpsolve* tool is utilized for the computation [1]. As presented in Section 3.1, SNG does not intend to collect a global network information. Instead, a TTL field is used to limit how far the C-Table can propagate. In the simulations, we use the parameter h to indicate how many hops the C-Table can travel. Two other routing mechanisms, Greedy and On-demand (introduced in [16]), are also implemented for comparison with SNG. The Greedy protocol searches for proxy client with better downlink quality, starting from the immediate neighbors, in a greedy manner until no better neighbor can be found. On the other hand, the On-demand protocol selects the proxy with the highest downlink capacity within h-hop neighborhood.

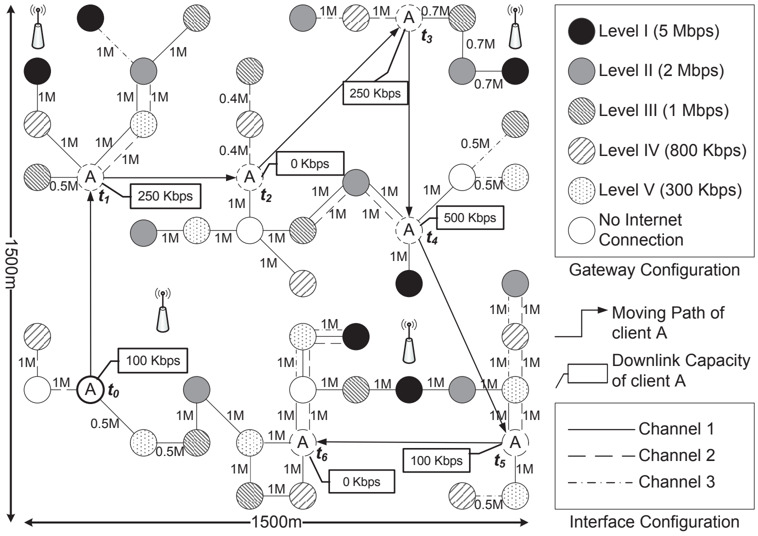

Figure 4.1: Simulation environment with 45 nodes randomly deployed in a $1500m \times 1500m$ network topology, along with corresponding Internet connection status, interface (channel) configurations, and ad hoc wireless link rates.

4.1 Impact of Network Information Scope

In this section, we investigate the impact of parameter h, and compare different routing strategies with respect to obtained downlink throughput. Fig. 4.1 shows the simulated network environment. Colored nodes represent potential gateways, which are classified into five levels in terms of downlink capacities. Channel (interface) configurations and estimated link rates are also illustrated in Fig. 4.1. In order not to further complicate the network environment, symmetric links (with equal link rate in both directions) are modeled in the simulations (note that this simplification does not affect the performance justification). We generate a mobile client A, which has two 802.11 interfaces operating on Channel 1 and 2 respectively and one cellular interface connecting to the IP network, to observe the attainable downlink throughputs at different time snapshots (t_0-t_6). As client A roams across the network, its cellular channel qualities vary depending on its locations.We implement four approaches for client A to obtain downlink services: Without Relay (using its own cellular connections), Greedy, On-demand, and our SNG.

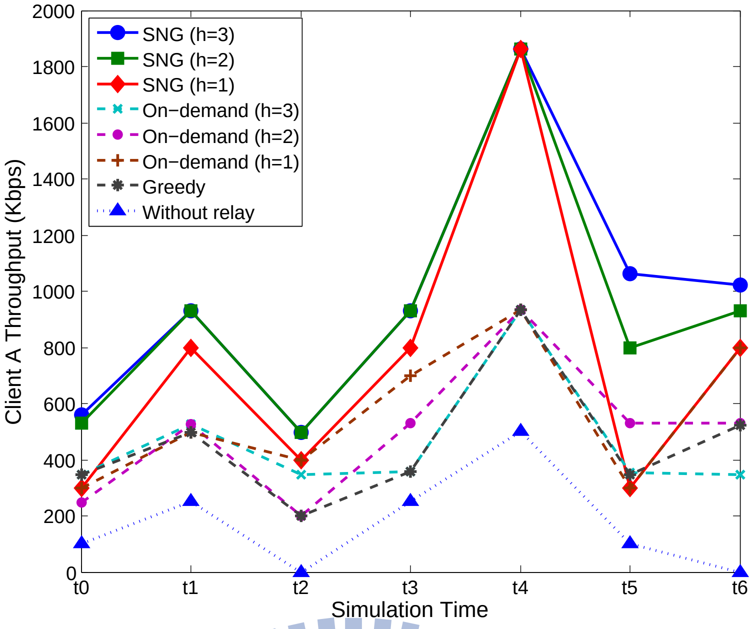

Figure 4.2: Throughput performance obtained by using different routing strategies as client A roams across the simulated network.

Fig. 4.2 shows that SNG outperforms other strategies when reasonable neighborhood information ($h \geq 2$) can be utilized for route optimization, while Without Relay provides the lowest downlink throughput due to no cooperation with other clients. We also experiment on SNG ($h = 4$, $h = 5$), but the throughput improvement is insignificant compared to SNG ($h = 3$), thus omitted from the figure. The results indicate that SNG only needs a moderate amount of neighborhood knowledge to outperform other strategies. In order to have a better understanding of how each routing mechanism determines the best route, we compile the downlink paths selected by respective protocol at t_2, t_3, and t_6 in Fig. 4.3. Interestingly, the best route (leading to the highest downlink throughput) does not always involve the best gateway (SNG at t_2, t_3), or the shortest hop distance (SNG at t_6). Moreover, at t_2, Greedy gives lower throughput with shorter route (2-hop) than the On-demand strategy with longer route (3-hop), due to weak link quality over Ch2 (0.4 Mbps) used by Greedy. This phenomenon also reveals that the hop distance factor alone cannot act as the single metric for a good route. In addition, downlink throughput can

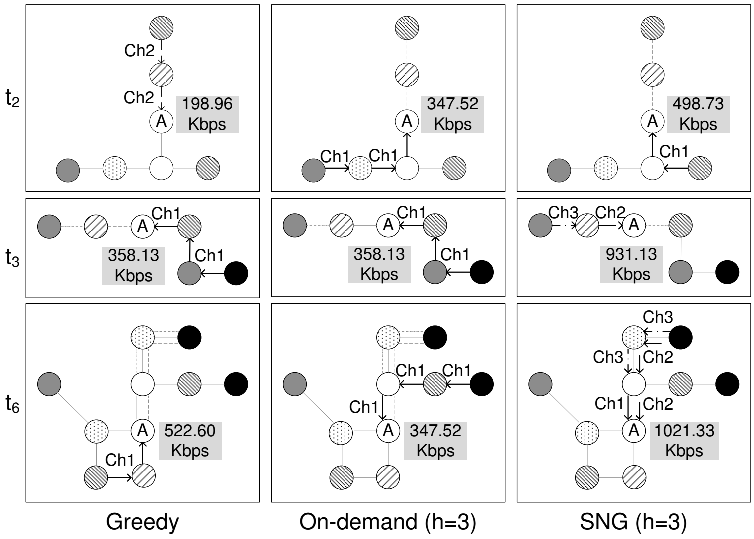

Figure 4.3: Downlink flow paths selected by different routing strategies at respective time snapshot. Note that selecting Internet proxy (gateway) with the highest downlink rate does not necessarily yield the best throughput for client A, since the communication bottleneck may exist in the ad hoc network domain.

be further increased by enabling multi-path packet delivery (SNG at t_6). From the above observations, we conclude that a good routing protocol in such a hybrid network should take various factors into a unified consideration, thus validating the SNG optimization strategy.

4.2 Importance of System Load Balancing

Another essential problem for the heterogeneous multi-hop network is the system load distribution. We investigate this issue by observing the aggregate throughput produced by respective routing technique. Fig. 4.4 shows the simulated network, with five potential gateways, and up to 15 user requests made in order. The aggregate network throughputs under different routing strategies are plotted in Fig. 4.5. The SNG protocol is able to yield significantly higher throughput than the other two routing mechanisms. Since SNG refreshes gateway capacities and ad hoc link rates to reflect current bandwidth

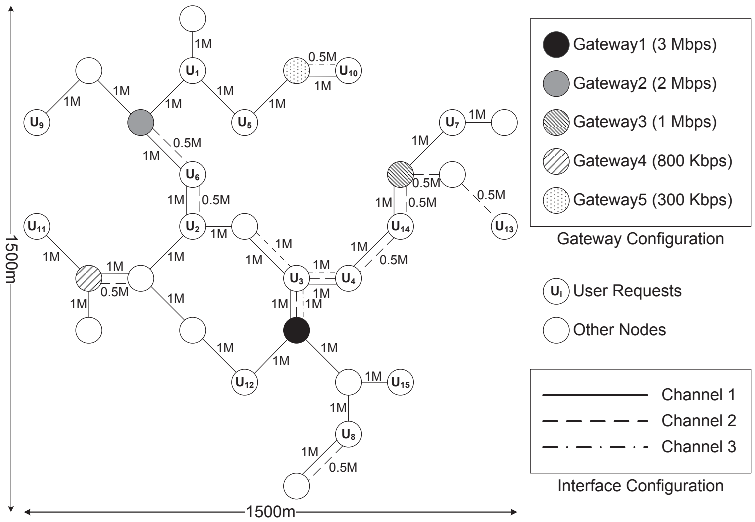

Figure 4.4: Network configuration with 30 clients and 5 potential proxies (gateways) randomly placed in a 1500m × 1500m topology.

occupied by existing users, the routing process has better knowledge to distribute the downloading requests correctly. In addition, we analyze the gateway utilization status, shown in Fig. 4.6, under different routing strategies. With the same user requesting patterns (U_1 request, followed by U_2 request, followed by U_3 request, and so on), we observe that G1 is under-utilized in Greedy and On-demand. In fact, G1 is selected by several users, such as U_3 and U_4, as downlink gateway. However, because of ad hoc channel contentions, U_3 and U_4 seldom get the chance to use G1 capacity. On the other hand, SNG avoids such adversary effect by distributing traffic to other non-interfering channels, leading to high G1 utilization. Two important design issues are revealed from the above experiments. First, both gateway and ad hoc link capacities should be refreshed to reflect up-to-date bandwidth allocation. Second, channel diversity should be leveraged.

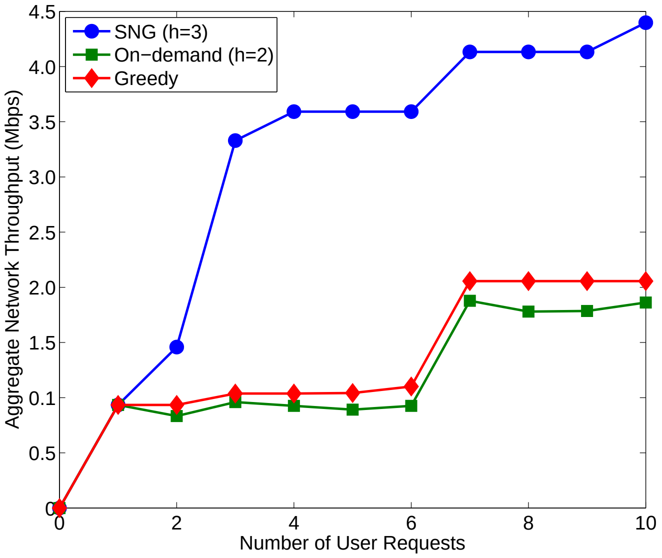

Figure 4.5: Aggregate network throughput increases as user demands grow, and saturates at varying points under different routing strategies (without limiting per-user traffic amount).

4.3 Restricting Per-user Traffic to Accommodate More Users

From Fig. 4.5, we further analyze the distributions of per-user traffic flows under different routing strategies. Fig. 4.7 indicates the unevenly distributed flow occupancy, leading to unfair network capacity sharing among users. Only 6, 8, and 5 users are effectively served (with non-zero percentage) using the SNG, On-demand, and Greedy mechanisms, respectively. In this set of experiments, we impose a 500 Kbps limitation on per-user downlink flow allowed by available gateway capacity. The results are shown in Fig. 4.8 with slightly reduced throughputs (compared to Fig. 4.5). By imposing the per-user flow restriction, the aggregate throughputs gradually reach the saturation points (in contrast to the sharp saturations in Fig. 4.5). Fig. 4.9 illustrates the improved flow distributions, where more users can be supported by the available system capacity. Due to

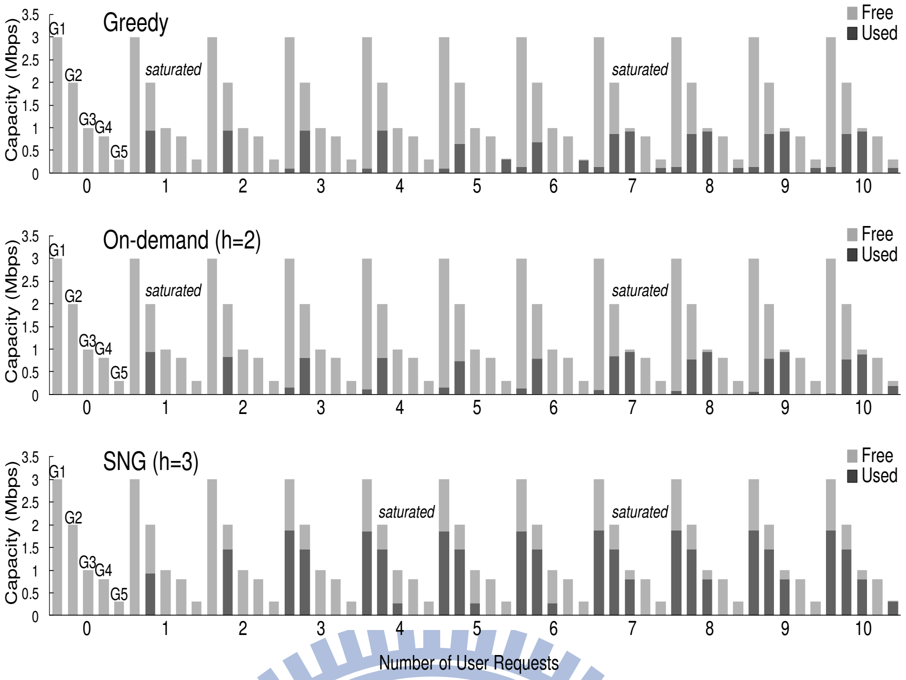

Figure 4.6: Proxy (gateway) capacity utilization status under Greedy, On-demand, and our SNG routing strategies, respectively.

better balanced bandwidth allocations, 12, 9, and 9 effective requests can now be served by the SNG, On-demand, and Greedy protocols, respectively.

Based on a series of simulative experiments targeted on the heterogeneous multi-hop networking environment, among the three routing techniques, our proposed SNG protocol is demonstrated to be capable of offering the best downlink rate through its optimized routing intelligence.

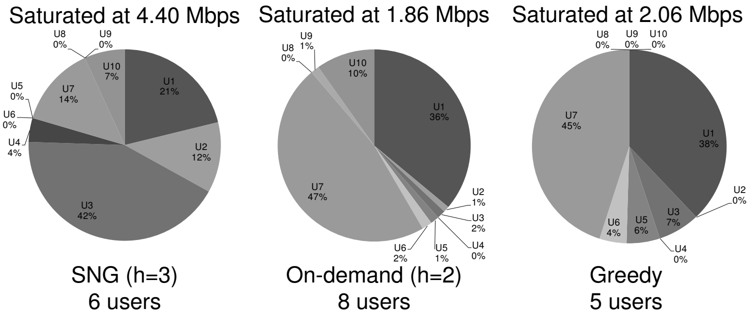

Figure 4.7: Unevenly distributed per-user traffic flow occupancy among saturated throughput obtained by respective routing strategy.

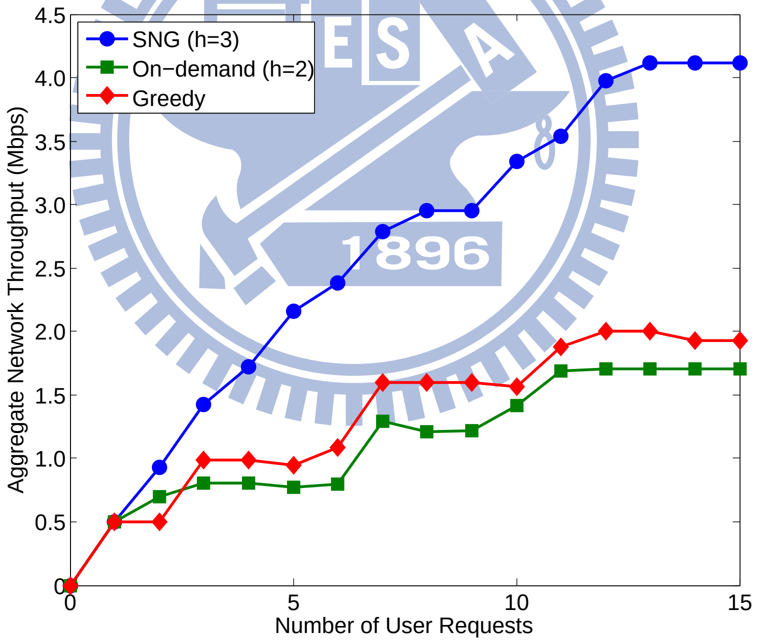

Figure 4.8: Aggregate network throughput against number of user requests (with 500 Kbps restriction on per-user traffic amount). More user requests can be accommodated by the overall system capacity.

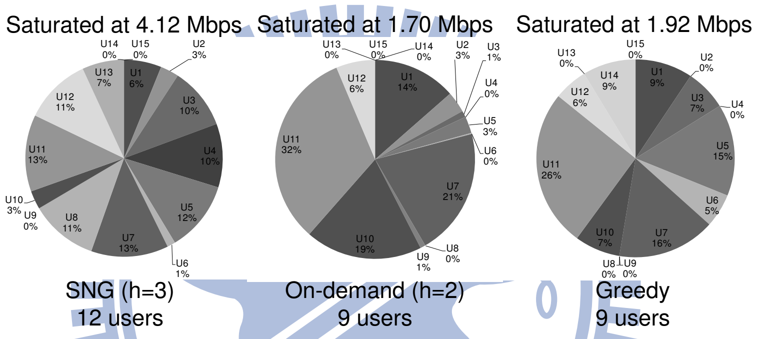

Figure 4.9: Improved per-user traffic flow distributions to allow more user requests at the cost of slightly reduced system saturated throughputs (compared with Fig. 4.7).

Chapter 5

Conclusion and Future Work

In this thesis, we propose a synergized framework (SF), and design a network-layer SNG routing protocol to enable the proposed communication model. The SNG protocol determines the best route for a downloading request in an optimized manner. Simulations show that the SNG mechanism is able to outperform other routing strategies based on moderate amount of neighborhood information without incurring much computation/communication overhead. The results encourage us to initiate a prototyping project. In the near future, we plan to set up a heterogeneous multi-hop networking testbed, containing various wireless devices, and implement the SNG protocol to perform packet routing. With the availability of open-source Android-based platforms, we may be able to incorporate such routing intelligence into smart phones as well, making them even smarter. Those prototyping experiences will be reported in our future publication. Although we only consider the Internet downloading traffic in the current SNG routing process, the optimization strategy can be easily extended to support peer-to-peer communication within the ad hoc network domain, finding the best route between arbitrary source and destination node pair. Such extension will also be directed into our future study.

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自傳

我來自嘉義的一個小康家庭，家境不算富裕。家中有五名成員，父母親、二個妹妹、我。小時候在父母親的諄諄教誨之下，完成了小學、國中及高中的學業。高中畢業後大學沒考上、重新補習一年考上義守大學資訊工程系，並由那時開始接觸了電腦，並慢慢對電腦產生興趣，因此在學校期間，參加了電腦研習社，多方的學習電腦技能。

大學畢業後即入伍當兵，退伍後第一份工作是到神達電腦公司當 BIOS 軟體助理工程師，但因發現自己不是很有興趣在 BIOS 開發上，所以三個月後就換了另一份工作，總算找到自己有興趣的工作，在廣聯國際股份有限公司當測試工程師，後來一直對測試很有興趣，所這份工作做的很不錯，之後在同事介紹下到光寶公司的通訊事業群當手機的測試工程師，負責 Nokia CDMA 案子的 field trial，去過印度、美國、印尼等國家。後來因光寶結束通訊事業群，所以跟著在光寶時的主管一起轉職到華冠通訊股份有限公司，一樣負責產品的測試驗證工作。

在華冠這期間公司陸續參與幾個 project， 如一開始的 3G feature phone，及後來的 Windows mobile 手機，負責了 Windows mobile 6.1 LTK 的測試認證工作，並且第一支通過 Windows Mobile 6.1 LTK 認證的手機，此手機是跟 Asia 02 合作的案子。另外也有跟倚天合作的有 GPS 的 Windows Mobile 的手機，並且去過香港 field trial。並於今年的五月內轉到 protocol 部門，參與 Qualcomm 的案子，負責 Qualcomm 平台的 protocol 測試，所以在手機通訊這塊領域已累積相當的經驗。

對於職場工作上，自己所負責的工作、任務都會盡心去完成，並且從中一直學習。並且為了希望能多學習加強自己技能，在華冠期間利用時間再進修，考上交通大學電信在職研究所，並且已順利畢業。期望將來能在職場上更能發揮所長。