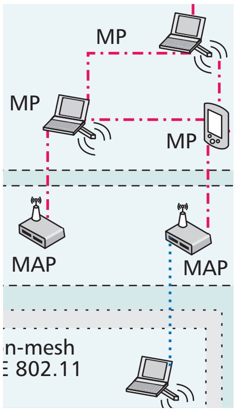
ACCEPTED FROM OPEN CALL

DESIGN ISSUES AND EXPERIMENTAL STUDIES OF WIRELESS LAN MESH

YING-DAR LIN AND SHIAO-LI TSAO, SHUN-LEE CHANG, SHAU-YU CHENG, AND CHIA-YU KU,
NATIONAL CHIAO TUNG UNIVERSITY



The authors present the design and development of a WLAN mesh system conforming to the latest IEEE 802.11s draft amendment.

ABSTRACT

Wireless mesh networking, as a low-cost and reliable technology for rapid network deployment, has attracted considerable attention from academia and standardization in the industry. The IEEE 802.11s standard defines a wireless LAN mesh using the IEEE 802.11 medium access control and physical layers, and is one of the most active standards with increasing commercial opportunities. This study presents the design and development of a WLAN mesh system conforming to the latest IEEE 802.11s draft amendment. Without costly hardware modifications, the proposed solution is a pure software extension for commercial off-the-shelf WLAN chipsets. This study constructs an experimental testbed, and evaluates issues such as the transmission reliability of mesh broadcast-type control messages and multichannel transmissions. Experimental results demonstrate that the delivery of mesh broadcast-type control messages, such as routing construction frames, using the multiple acknowledged unicast scheme improves mesh stability from an 86 to a 98 percent success ratio in a 16-node grid. Transmitting packets using a single radio interface switching between multiple channels reduces inter-flow interference and doubles the throughput in our testbed.

INTRODUCTION

Infrastructure-based wireless networks provide convenient access to the Internet, and are becoming increasingly popular in spite of their costly *wired* deployment. On the other hand, mobile ad hoc networks (MANETs) eliminate the need for infrastructure, decreasing deployment time and alleviating network construction costs. However, having routing functions on *all* nodes in a MANET complicates the design of networking devices [1]. The fact that MANET usage is typically limited to military and specialized civilian applications also hinders its growth [2]. By combining an infrastructure-based wireless network and a MANET, a wireless mesh network (WMN) presents a *low-cost* and *fast-deployment* solution compared to an infrastructure-based wireless network, and a *reliable* and *less complicated* solution compared to a MANET. A WMN is similar to a multihop cellular network (MCN) [3], which has been proved to improve aggregated throughput *linearly* due to spatial division.

In [1] the authors classify the WMN architecture into three types: infrastructure, client, and hybrid. An infrastructure WMN is organized as a hierarchical network, functionally consisting of mesh *gateways*, *relay points*, *access points*, and *terminals*.[1] A mesh gateway is a device capable of bridging the wireless mesh and wired infrastructure. A relay point implements a routing algorithm to relay packets in a mesh. To support non-mesh terminals, the mesh uses access points to bridge the WMN and non-mesh terminals. In a client mesh there is no gateway and non-mesh terminal because this kind of mesh emphasizes flat peer-to-peer communications. A hybrid mesh includes both infrastructure and mesh terminals that provide interfaces for end users and mesh routing capability. Figure 1a gives an example of a hybrid WMN, while Fig. 1b shows the corresponding wireless local area network (WLAN) mesh using IEEE 802.11s terminology.

Diverse mesh architectures result in various usage scenarios [1, 2], and a considerable number of challenges for designing and realizing a WMN [1, 4–6]. Industrial organizations have also prepared standards and recommended practices for existing wireless technologies, such as IEEE 802.15.5 for low-rate wireless personal area networks (WPANs). Among these efforts, IEEE 802.11s [7], which defines a WLAN mesh using IEEE 802.11 medium access control (MAC) and physical (PHY) layers, is one of the most active standards and has increasing commercial opportunities.

This study is the first publicly reported work that exploits the system design issues of an IEEE 802.11s mesh system. Prior studies, such as the mesh on XO-laptop for One Laptop per Child (OLPC) [8] and the *open80211s* project for Linux,[2] evaluated the network performance of the IEEE 802.11s mesh. However, no studies examine system architectures and mesh stability. The system proposed in this study is developed

---

[1] *The organization is based on the operating functions, so multiple roles, such as the terminal and relay point, may be implemented on the same physical device.*

[2] *Project open802.11s; http://www.open80211s.org/*

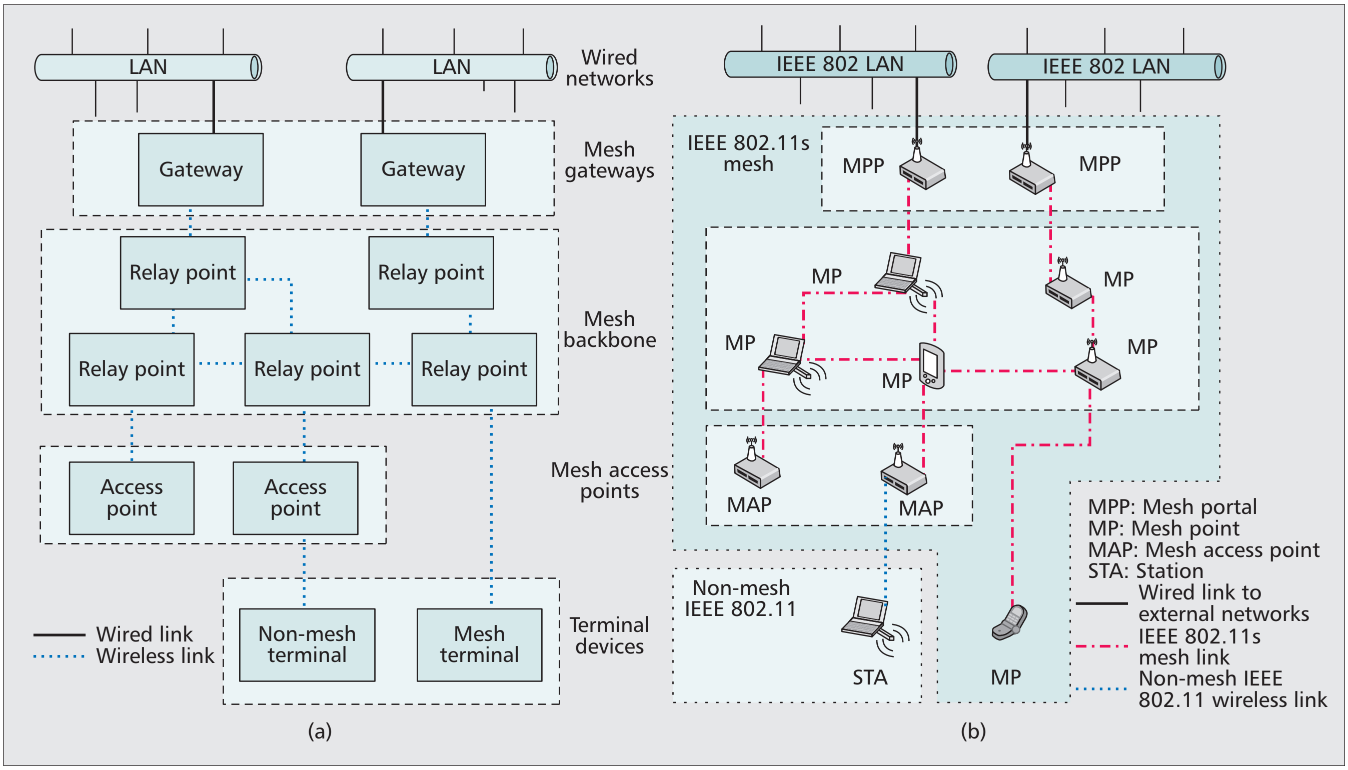


Figure 1. *A logical view of a wireless mesh network and its mapping to IEEE 802.11s: a) a generic mesh network; b) an IEEE 802.11s mesh network.*

based on the latest draft amendment of IEEE 802.11s, and extends the functions of commercial off-the-shelf WLAN chipsets. The proposed extension is a pure software solution that integrates with a WLAN driver. Considering the portability of the proposed solution and the stability of the software during the system development phase, this study proposes a *modularized* design that separates mesh functions into a driver and a user-space program.

Using this system prototype, this study establishes a real testbed and further investigates design and implementation issues that influence system performance. Results show that transmitting mesh broadcast-type control frames over a multihop wireless mesh without acknowledgment can cause network stability problems. In a 16-node interference-intensive grid topology, for example, 14 percent of path request messages are lost, and not all routing paths are found even when broadcasting at the most reliable data rate (i.e., 1 Mb/s). Therefore, this study evaluates the feasibility of replacing unacknowledged broadcast with multiple acknowledged unicasts for mesh broadcast-type control messages. Another issue is the serious interference between mesh nodes sharing the same channel. To reduce this interference, the study also examines the effectiveness of transmitting packets using a single radio interface switching between multiple channels.

The rest of this article is organized as follows. The next section briefly presents the key features of IEEE 802.11s. We then discuss the design and implementation issues of a WLAN mesh. We then present the experimental results, and the final section offers the conclusion.

IEEE 802.11S

This section overviews IEEE 802.11s. The first part presents the architecture of an IEEE 802.11s mesh network, and the second part describes mesh functions, including the network link construction, routing algorithm, data delivery, and flooding control.

NETWORK ARCHITECTURE

IEEE 802.11s [7] defines an IEEE 802.11-based WMN that supports broadcast and unicast delivery over a *self-configured multihop link-layer* topology. As Fig. 1b shows, an IEEE 802.11s mesh network contains three types of nodes: the mesh point (MP), mesh access point (MAP), and mesh portal (MPP). The MP is the basic mesh unit that provides topology construction, routing, and data forwarding. This type of node can also be designed as a terminal device for end users to directly connect with peer MPs and access the mesh. Non-mesh IEEE 802.11 stations (STAs) must first associate with a MAP, which is an MP capable of IEEE 802.11 access point (AP) functions, before accessing a mesh. An MPP is an MP integrated with gateway functions to interoperate with external IEEE 802 LANs. The MP, MAP, and MPP are all logical components, and some of them can be physically collocated.

MESH FUNCTIONS

Network Link Construction — The IEEE 802.11s standard specifies the *boot sequence* procedure for an MP joining a mesh network based on the procedure for an STA associating with an AP in a conventional non-mesh WLAN. First, an MP performs an active or passive scan to obtain a

When forming a new mesh, the initial MP randomly decides a channel precedence value and embeds that value in the management frames. After the channel scan, other MPs select the channel with the highest precedence as their operating channels.

list of existing MPs in each channel. Next, the MP uses the *mesh peer link management* protocol to associate with an MP matching its own preferences. This protocol behaves like the conventional IEEE 802.11 association procedure. The only difference is that the mesh peer link management protocol uses several new management frames. These frames encapsulate mesh-specific information, such as a mesh identifier, while removing unrelated parameters, such as a service set identifier (SSID). After a successful association with a neighboring MP, the MP becomes a member of an IEEE 802.11s mesh network.

IEEE 802.11s introduces the unified channel graph (UCG), which presents one mesh sharing the same preferences in the same channel, to handle several meshes spanning different channels. When forming a new mesh, the initial MP randomly decides a channel precedence value and embeds that value in the management frames. After the channel scan, other MPs select the channel with the highest precedence as their operating channels. This procedure forms a UCG called the *simple channel unification* protocol. To resolve multiple UCGs in different channels due to spatial division and the needs of channel switching, such as radar detection, IEEE 802.11s proposes a *channel graph switch* protocol. In this protocol an MP sets a waiting timer and broadcasts a mesh channel switch announcement. The announcement contains the waiting period and a precedence value of the candidate channel. When the timer expires, the MPs receiving the announcement switch to a candidate channel with the highest precedence.

Routing — IEEE 802.11s defines a *path selection* framework that flexibly allows vendors to implement proprietary routing metrics and protocols to meet special needs. The communication between two MPs begins with the construction of a routing path. Then the data frames are transmitted along with the routing path via neighboring MPs.

Hybrid Wireless Mesh Protocol (HWMP) is the mandatory routing protocol recommended by IEEE 802.11s. This protocol comprises an *on-demand* routing procedure to construct a path between two arbitrary nodes and a *proactive* extension to speed up the initial connection. The on-demand routing procedure is derived from Ad Hoc On-Demand Vector (AODV) [9], but it works on the link layer and adopts a radio-aware metric called the airtime link metric. This metric considers the actual transmission quality in terms of transmission error and data rate. To construct a routing path from one node to another (e.g., from node *s* to node *t*), *s* broadcasts a path request message (PREQ) into the mesh. Upon receiving the PREQ, *t* responds to *s* with a path response message (PREP) through unicast transmission. The reverse routing path from *t* to *s* is first built after *t* receives the PREQ, and the desired routing path from *s* to *t* is created after *s* receives the PREP. Once established, this path can be used before it times out.

The proactive extension of HWMP actively forms a *routing tree* rooted at an MP by periodically broadcasting root announcement messages. Under the HWMP, a unicast packet without a valid on-demand routing path can be transmitted to the root first. The root then forwards the packet along the tree to its destination. Meanwhile, an on-demand routing procedure is performed between the source and destination to create a direct routing path. This help from the root may reduce latency before the direct on-demand routing path is established [10].

Interworking — IEEE 802.11s also defines an *interworking* procedure to handle the communication between two terminals in which at least one is bridged by an MPP. A terminal bridged by the MPP is called a *proxied entity*. IEEE 802.11s assumes that an MPP can learn all proxied entities it bridges. In addition, every mesh node has a proxy table that maintains the relation between a proxied entity and its MPP.

To transmit a packet from a mesh node *s* to a proxied entity *t*, the interworking procedure on *s* first performs the HWMP to issue a PREQ to request the path to *t*. If no MP responds to the query (e.g., the proxied entity has not been learned), the packet is forwarded to one or more MPPs and then bridged to their attached external networks. Otherwise, the corresponding MP, *b*, replies to *s* with the PREP. Then *s* inserts the relation, *b* bridges *t*, into its proxy table. Once the relation exists, the packet can be delivered from *s* to *b*, and then *b* bridges the packet to *t*.

Data Frame Format — IEEE 802.11s introduces a mesh header subfield in the beginning of the frame body to address multihop transmissions. When convoying packets whose source and destination are both inside the mesh, the subfield indicates that the 4-address format in the frame header is used. The frame header includes the MP addresses of the next-hop receiver, transmitter, destination, and source, and is processed by MPs as it would be in a wireless distribution system (WDS). Otherwise, the subfield contains two additional addresses to encapsulate the addresses of proxied entities. When a packet enters or leaves a mesh, the sender and receiver addresses are enveloped into or recovered from the subfield.

Flooding Control — The fact that an MP blindly retransmits broadcast frames to its neighbors may cause endless flooding due to the loop structure of a mesh topology. To avoid infinite rebroadcasting, the source MP first tags a 32-bit incremental sequence number, called the Mesh Sequence Number field, on each frame before transmitting it. Other MPs can use this field and the source MP address as a unique signature to avoid duplication. The source MP also transmits the Mesh Time to Live field, a counter decreased per hop with each frame to limit its longevity. This field acts as a backup mechanism to detect duplication for rollover sequence numbers and limited recording space.

DESIGN AND IMPLEMENTATION ISSUES OF AN IEEE 802.11S MESH

This section first presents the software architecture that considers both portability of the proposed solution and system stability for future extensions. Second, this section discusses the design and implementation issues including the transmission reliability of mesh broadcast-type control frames and multichannel transmissions.

SOFTWARE ARCHITECTURE

To improve the portability of the IEEE 802.11s software package, a modularized design is required. The proposed design separates *platform-independent* functions such as HWMP routines from the kernel and implements them as a Linux daemon program, called a path selection daemon. This approach simplifies the development of HWMP algorithms and provides greater flexibility in changing routing algorithms. The user-space daemon also improves system stability since it reduces the chance of kernel crash during the system development stage.

Time-critical functions are implemented in the kernel and *hooked* in the IEEE 802.11 driver. The *boot sequence module* performs the boot sequence procedures to associate the device with an IEEE 802.11s network. The *data forwarding module* relays multihop data and triggers the path selection daemon to construct a routing path when necessary. Last, the *action frame handler module* translates the MAC-layer control frames into module-specific commands and activates other modules to process these commands. Figure 2 illustrates the proposed software architecture for the IEEE 802.11s nodes. Only MPPs have the IEEE 802.3 part, and only MPPs and MAPs have the bridge part.

The proposed design handles the control and data planes separately. Figure 2 shows that when a control frame such as a routing message is received, it is passed to the action frame handler module to check if the frame comes from an associated neighbor. If the frame is from a validated neighbor, it is then forwarded to the user-space path selection daemon. The daemon updates the routing tables, including the path selection table and proxy table in the kernel space, and issues the corresponding control frames to its neighbors via the action frame handler module and transmission (TX) handler if necessary.

For the data plane, the data forwarding module either dispatches a received data frame to the upper layers of the protocol stack while the node is the destination, or relays it to the next hop. To relay a data frame, the data forwarding module updates the next-hop MAC addresses of the frame by referencing the path selection table, and then the proxy table if the destination is not inside the mesh. The TX handler then transmits the data frame. If not found in both tables, the frame is forwarded to the root and invokes on-demand routing.

TRANSMISSION STRATEGIES FOR MESH BROADCAST-TYPE CONTROL FRAMES

In the wireless environment, a sender has difficulty detecting a collision on the receiver side. This results in the need for acknowledgment (ACK) and retransmission mechanisms to reduce the packet loss side-effect. However, the IEEE 802.11 broadcasting scheme, called conventional broadcasting in this article, has no ACK. As a result, conventional broadcasting is unreliable and packet loss is high in an interference-prone environment. Packet loss is cumulative in multihop transmissions, which brings a new challenge to the wireless mesh since some of the IEEE 802.11s control frames are broadcast-type. Thus, the frequent loss of these broadcast-type control frames may result in unstable mesh topology and network.

To improve the transmission reliability of broadcast-type control frames, possible IEEE 802.11-compatible solutions either blindly broadcast the same frame multiple times, called the multiple-broadcast scheme, or unicast it to each neighbor individually,[3] called the multiple-unicast scheme. Both schemes reduce packet loss at the expense of using more wireless resources. The multiple-broadcast scheme might use less wireless resources than the second scheme because it does not require ACK frames, certain inter-frame spaces (IFSs), and retransmissions. However, it must use more robust coding and modulation (i.e., a lower transmission rate) [12] so that the broadcast frames are more likely to be received by all neighbors. On the other hand, the multiple-unicast scheme is able to adopt a higher transmission rate for each individual neighbor. The ACK frames used by this approach also improve transmission reliability.

The proposed design handles the mesh broadcast-type control frames and other broadcast-type frames separately. The mesh broadcast-type control frames (e.g., the routing request frames) are directly generated by the mesh protocols. The other broadcast-type frames come from upper layers of the protocol stack (e.g., Dynamic Host Configuration Protocol [DHCP] discovery). The latter are normally less important, and may inherit different characteristics from applications and services. Therefore, this study leaves the response to the loss of these kinds of broadcast-type frames to upper-layer protocols and applies the conventional broadcasting approach.

The transmission reliability of mesh broadcast-type control frames significantly influences the construction and stability of a mesh network. In addition, the number of broadcast-type control frames depends on the scale of the mesh, and is relatively small compared to that of broadcast-type data frames. Therefore, this study applies and evaluates the multiple-broadcast and multiple-unicast schemes only for mesh broadcast-type control frames.

MULTICHANNEL WITH FEWER RADIOS

In a single-channel mesh network, nodes sharing the same channel may experience intra-flow interference in multihop transmissions and inter-flow interference in nearby data flows. A frequency multiplexing approach, which uses multiple radios to carry packets in separate channels, can be used to avoid this interference. However, low-cost devices are usually equipped with a limited number of radio interfaces, so multiple-radio schemes might not be adopted. Therefore, the mesh system in this study applies a low-cost solution that uses fewer radios switching between multiple channels for data transmission.

Several channel switching problems must be

The daemon updates the routing tables, including the path selection table and proxy table in the kernel space, and issues the corresponding control frames to its neighbors via the action frame handler module and transmission handler if necessary.

The transmission reliability of mesh broadcast-type control frames significantly influences the construction and stability of a mesh network. In addition, the number of broadcast-type control frames depends on the scale of the mesh, and is relatively small compared with that of broadcast-type data frames.

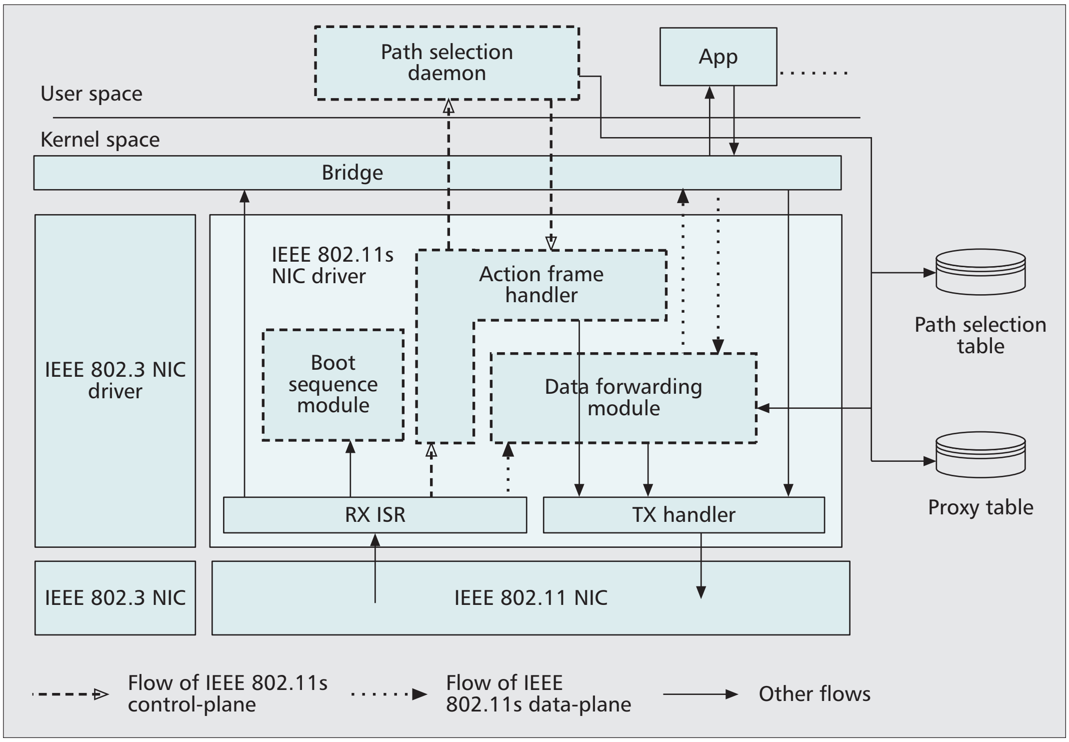


Figure 2. *The proposed software architecture and the control/data plane flows. The modules in bold text are the IEEE 802.11s extensions.*

solved. The first problem is that switching between channels without coordination can result in packet loss. To avoid this, a notification mechanism that notifies neighbors to buffer data before channel switching is necessary. Second, frequent switches cause a heavy switch overhead, while infrequent switches may result in prolonged latency and buffer overflow. Hence, a policy that manipulates radios to switch between multiple channels at suitable switch intervals must be decided.

Notification mechanisms compatible with the WLAN standards can be employed to avoid packet loss and link disruption caused by channel switching. Compatible mechanisms include, but are not limited to, the power-saving mechanism and the channel switch announcement in IEEE 802.11v. For example, an MP can use the power-saving mechanism to announce its sleep mode. When the MP enters sleep mode, its neighbors must buffer data for that MP. During the sleep period, the MP can switch to different channels for data transmissions and receptions.

In the proposed approach, with fewer radios and multiple channels, a mesh node where data flows merge, such as a gateway, could perform channel switching to serve separate data flows. The separation can reduce the inter-flow interference and improve the throughput. The switch node first uses a notification mechanism to announce its channel departure or return. While the node switches to a channel, how long the node stays in the channel should be determined. A suitable staying period is the time sufficient for transmitting queued packets on each channel. Therefore, it is important to know the channel resources each channel requires for transmitting queued packets. The desired channel resources are derived from the number of packets to exchange between mesh nodes, the channel quality (i.e., transmission rate) of a link, the average packet size, and so on. An unsuitable staying period might produce a high switching overhead or buffer overflow that degrades the throughput. Thus, the length of staying period should be investigated.

EXPERIMENTAL RESULTS

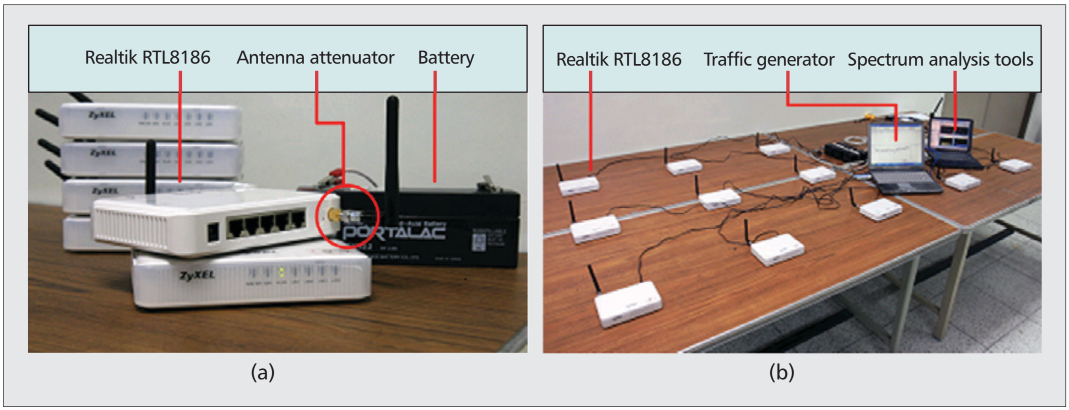
This study conducts a number of experiments to evaluate the proposed approaches for the design and implementation issues presented in the previous section. This section first describes the experimental testbed, and then the experimental results.

EXPERIMENTAL TESTBED

This study implemented a WLAN mesh system on the Realtek *RTL8186* platform, which is a commercial system-on-a-chip embedded with an Ethernet, a single-radio 802.11b/g controller, and a 180 MHz 32-bit MIPS processor. The platform runs an embedded Linux (v. 2.4.18) and integrates with an open source link-layer bridge module (called *Ethernet Bridge*) that bridges the Ethernet and IEEE 802.11 networks. By combining the Ethernet, bridge, and WLAN functions, this platform supports MP, MAP, and MPP functions. Figure 3a shows that the integrated testbed is powered by a battery, where a fixed attenuator is attached to the antenna to regulate its transmission power. This greatly reduces the actual space required for the experimental testbed, and makes it possible to conduct small-scale mesh experiments in the laboratory.[4] The traffic generator injects the desired experimental

---

[3] *Those two strategies appeared in the early version of IEEE 802.11s. However, the latest draft removes the part and states that the problem is beyond their scope. Besides, some literature, such as [11], also provides solutions that need to extend the IEEE 802.11 control frames.*



(a)

(b)

Figure 3. *Illustration of the testbeds: a) experimental mesh platforms where the Realtek RTL8186 is inside the ZyXEL P-330W product; b) an experimental deployment.*

Unlike the multiple-broadcast scheme, which has to broadcast packets using the minimal transmission rate, the multiple-unicast transmission may apply higher and different data rates for individual nodes.

patterns, and the data rate and testbed topology vary in different experiments. Figure 3b shows the testbed configuration.

EVALUATION OF BROADCASTING STRATEGIES

Both the multiple-broadcast and multiple-unicast schemes produce more reliable transmissions than conventional broadcasting. Unlike the multiple-broadcast scheme, which has to broadcast packets using the minimal transmission rate, the multiple-unicast transmission may apply higher and different data rates for individual nodes. The experiments in this section evaluate these two schemes in terms of reliability, routing construction success ratio, latency, and channel utilization.

Figure 4a depicts the packet error rate (PER) of a one-hop transmission under different IEEE 802.11b/g data rates. The results present the link quality baseline for the following experiments. The results are based on broadcasting 100-byte packets.[5] Both the sender and receiver are connected by a 20 dB attenuator, and the distance between each unit is fixed at 70 cm. The received signal strength of each MP ranges from –70 to –80 dBm, which is a common reference value for Wi-Fi network deployment.[6] During these tests, a spectrum analyzer detected two APs in the neighboring channels with received signal strengths of –71 and –75 dBm. The signal causes adjacent channel interference (ACI) and increases the PER in wireless transmissions.[7] Under the same channel quality, including signal strength and ACI, the 11b PHY delivers a slower data rate and also lower PER, while the 11g PHY gives higher ones, as Fig. 4a indicates. Thus, a common practice is to use 11b PHY when the channel quality drops and 11g PHY when it clears up. Experimental results also show that the PER increases significantly when the data rate exceeds 36 Mb/s. To help the multiple-broadcast and multiple-unicast schemes utilize wireless resources more efficiently, the following experiments manually select a maximum of 36 Mb/s for the data rate.

Figure 4b illustrates the degradation of broadcast reliability for increasing hop counts in a chain topology. Three schemes (i.e., conventional broadcast, multiple-broadcast, and multiple-unicast) are evaluated with various data rates. The packet arrival ratio measured in this experiment represents the percentage of broadcast packets successfully received by the measuring node. The conventional broadcast scheme at 36 Mb/s has the worst performance in all six configurations. The two-broadcast scheme significantly improves reliability when using the same data rate. The result of the multiple-broadcast scheme at 36 Mb/s is comparable to the conventional broadcast scheme at lower data rates (1 Mb/s and 11 Mb/s) when the broadcast repetition increases to three. Naturally, the multiple-unicast scheme presents the best reliability in all configurations, even at 36 Mb/s.

To determine the feasibility of these three schemes, this study investigates the routing construction success ratio in an $n \times n$ grid topology, as Fig. 5a shows. The routing construction is a typical function that uses mesh broadcast-type control frames in the IEEE 802.11s path selection framework. The success ratio is measured by counting successful routing trials, that is, when the source node (SRC) correctly receives a PREP from the destination node (DST). To reflect unicasting behavior in the real world, this study also measures the multiple-unicast scheme using the RTL8186 auto-rate mode, automatic rate fallback (ARF) [15]. Figure 5b shows these experimental results. The success ratio of conventional broadcast with the most reliable data rate (i.e., 1 Mb/s) lowers to 86 percent in the largest experimental grid. However, the multiple-unicast scheme at 36 Mb/s keeps above 90 percent success ratio in all network sizes. Furthermore, the same scheme using the auto data rate is superior to all other schemes. Even in the 16-node grid, it shows a 98 percent success ratio for routing construction. Examining the distribution of auto data rates reveals that only 40 percent successfully received frames are delivered with 11g data rates (12~54 Mb/s), and 60 percent of the frames are sent at more reliable 11b data rates (1, 2, 5.5, and 11 Mb/s). In other words, the high reliability of using auto data rate comes from transmitting many frames with more robust modulations.

To investigate the side-effects caused by these schemes, this study measures latency and channel utilization during the experiments above. This study defines latency as the time interval starting when SRC issues a broadcast-type PREQ and ending when it receives the corresponding PREP. The experimental results in Fig.

---

[4] *When using attenuators, some effects, such as the near-far problem [13], can be simulated, while the characteristics of multipath fading [14] are still different from the result obtained in a field test.*

[5] *Most of the mesh broadcast-type control messages are small but extensible, so we chose a small-size packet to represent them.*

[6] *Cisco Spectrum Expert Users Guide; http://www.cisco.com/en/US/products/ps9393/products_user_guide_list.html*

[7] *IEEE 802.11 regulates that the PER must be less than 10 percent when transmitting 1000 octets in a 10 dB noise environment, while the noise caused by ACI in our testbed is much higher than that.*

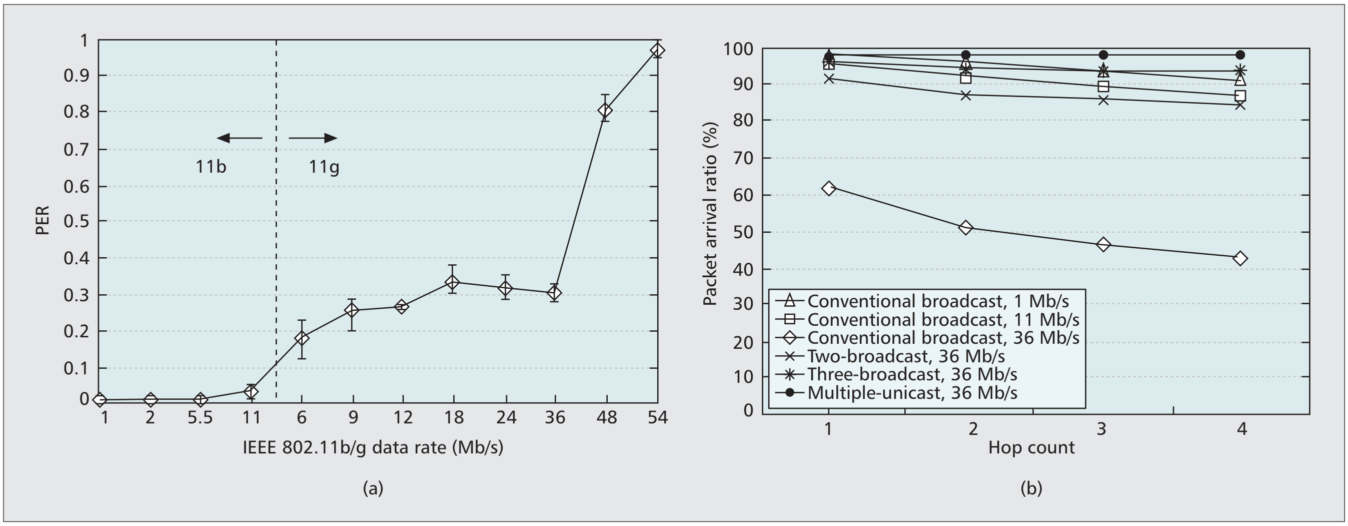


Figure 4. *a) The relation between PER and data rate during experiments: for each data rate, 5000 tests are conducted and the error bars indicate the maximum and minimum measured values; b) packet arrival ratio for different broadcasting strategies in chain topologies: for each data rate, 3000 tests are conducted.*

5c indicate that the latency curves of all configurations are similar, with only small differences. Even for the largest grid, the slowest routing construction time (the multiple-unicast scheme using the auto data rate) is only 8 ms slower than the fastest time, the conventional broadcast at 11 Mb/s, at 40 ms. These results demonstrate that an increased delay is acceptable for routing construction.

This study defines the channel utilization as the percentage of wireless media time occupied by all nodes on flooding the mesh broadcast-type control frames. This study investigates the root announcement messages, which are periodical mesh broadcast-type control frames maintaining a mesh routing tree, to assess the average channel utilization of mesh broadcast-type control frames in an IEEE 802.11s network. The total occupied media time includes the time spent on PHY layer headers, MAC layer headers, payload, and IFSs. Figure 5d depicts the calculated channel utilization. Due to the large proportion of low-speed 11b frames, the multiple-unicast scheme using auto data rate consumes more wireless resources than other configurations. However, since this is a small fraction (less than 3 percent), this overhead helps maintain the routing structure of a WLAN mesh.

The results above reveal that the multiple-unicast scheme is the most suitable scheme for the transmission of mesh broadcast-type control messages in our testbed. In real-world deployment, however, the PER can change unpredictably, and a larger mesh scale may lead to unacceptable latency. Therefore, a sophisticated broadcasting strategy considering actual runtime conditions deserves further study.

EVALUATION OF MULTICHANNEL WITH FEWER RADIOS

Utilizing multichannel with fewer radios enhances the total throughput of a mesh network. This study implemented three cases, including one channel with a single radio (1C1R), two channels with dual radios (2C2R), and two channels with a single switching radio (2C1R). Figure 6a shows the experimental topology, which consists of two paths beginning at two traffic generators and merging at a switch node. During the experiments, two saturated nonblocking UDP data streams were simultaneously generated and destined to the traffic sink. These experiments reveal the upper bound throughput of the examined topologies. In the case of 2C1R, the switch node is equipped with one radio to round-robin serve two paths which operate in non-overlapping channels. In the other cases, the switch node is equipped with a single radio (1C1R) and dual radios (2C2R) to serve two paths without switching.

Figure 6b depicts the experimental results. The 2C1R throughput is nearly twice as high as the 1C1R for a staying period of 240 ms (not including the 6 ms switch overhead). This demonstrates the improvement of using multichannel transmissions with fewer radios. The improvement is achieved by reducing the interflow interference between two paths. Although using 2C1R with a staying period of 240 ms maximizes the utilization of a single radio, the 2C2R results reveal the difference in capacity (i.e., the radio capacity served by single or dual radios) and the side-effect caused by the switching. The switch overhead, which is about 6 ms on the Realtek RTL8186, represents the time wasted during channel switching. Shorter staying periods incur *higher* switch overheads. However, long staying periods produce prolonged latency and possible buffer overflow, which deteriorates transmission quality. For example, buffer overflow can decrease throughput when the staying period is greater than 240 ms.

Obtaining an optimal staying period is more difficult in the real world than under the experimental environment above. A channel switching algorithm should be based on the switch overhead, queue size, traffic requirement, data rate, and channel status of each channel. The switch overhead is a burden for switching, but reducing

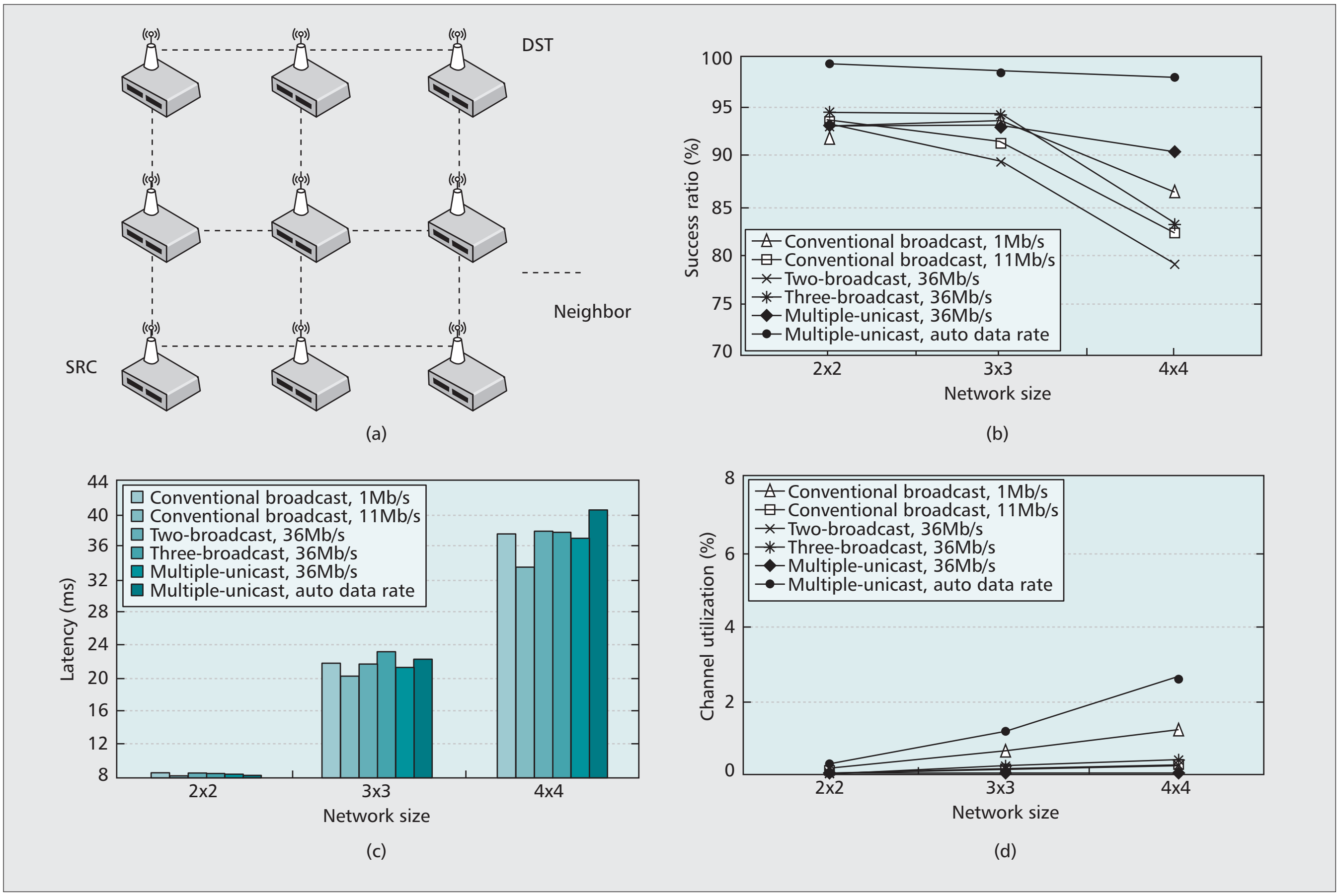


Figure 5. *Experiments for routing establishment: a) the* n × n *grid topology; b) the success ratio, which is 98 percent when adopting the multiple-unicast scheme using auto data rate during 600 trials; c) the latency to establish a routing path; d) the channel utilization to maintain the routing tree.*

it using a longer staying period causes prolonged latency. To prevent buffer overflow, the queue size constrains the maximum staying period. Switching strategies, such as adjusting the switching frequency or allocating different staying periods for each requirement, can be applied to deal with the different traffic requirements of each channel. The switching algorithm should also take the data rate and channel status into account, because the time spent on transmitting the same amount of data with different data rates and different channel status is distinct. Finally, an adaptive channel switching algorithm combining the above factors in the runtime to optimize the multichannel transmissions with fewer radios is worthy of development.

CONCLUSIONS AND FUTURE WORKS

This study presents the design and development of a WLAN mesh system, and discusses issues including the system design, reliable transmission of mesh broadcast-type control frames, and multi-channel transmissions. Experimental results show that the multiple-unicast scheme achieves a 98 percent routing construction ratio, acceptable latency, and channel utilization in our testbed. This study also demonstrates that multi-channel transmissions using a single switching radio improve effectively throughput without extra hardware costs.

Future studies should further investigate the conditions that affect the multiple-unicast scheme. An adaptive channel switching algorithm to optimize the multichannel transmissions with fewer radios is currently being developed and evaluated. Much larger-scale indoor and outdoor deployments are also planned, with the goal of finding the optimal number of mesh points, meshes, and channels in a specific deployment scenario.

ACKNOWLEDGMENTS

We would like to acknowledge the help from our colleagues, Jui-Hung Yeh, Cho-Hao Lee, and Yung-Sheng Chen. We also thank the anonymous reviewers for their fruitful comments.

REFERENCES

[1] I. F. Akyildiz, X. Wang, and W. Wang, "Wireless Mesh Networks: A Survey," *Comp. Net.*, vol. 47, no. 4, 2005, pp. 445–87.

[2] R. Bruno, M. Conti, and E. Gregori, "Mesh Networks: Commodity Multihop Ad Hoc Networks," *IEEE Commun. Mag.*, vol. 43, no. 3, Mar. 2005, pp. 123–31.

[3] Y-D. Lin and Y-C. Hsu, "Multihop Cellular: A New Architecture for Wireless Communications," *Proc. IEEE INFOCOM*, 2000.

[4] J. Bicket *et al.*, "Architecture and Evaluation of an Unplanned 802.11b Mesh Network," *Proc. ACM MobiCom*, 2005.

[5] A. Raniwala and T. Chiueh, "Architecture and Algorithms for an IEEE 802.11-based Multi-Channel Wireless Mesh Network," *Proc. IEEE INFOCOM*, 2005.

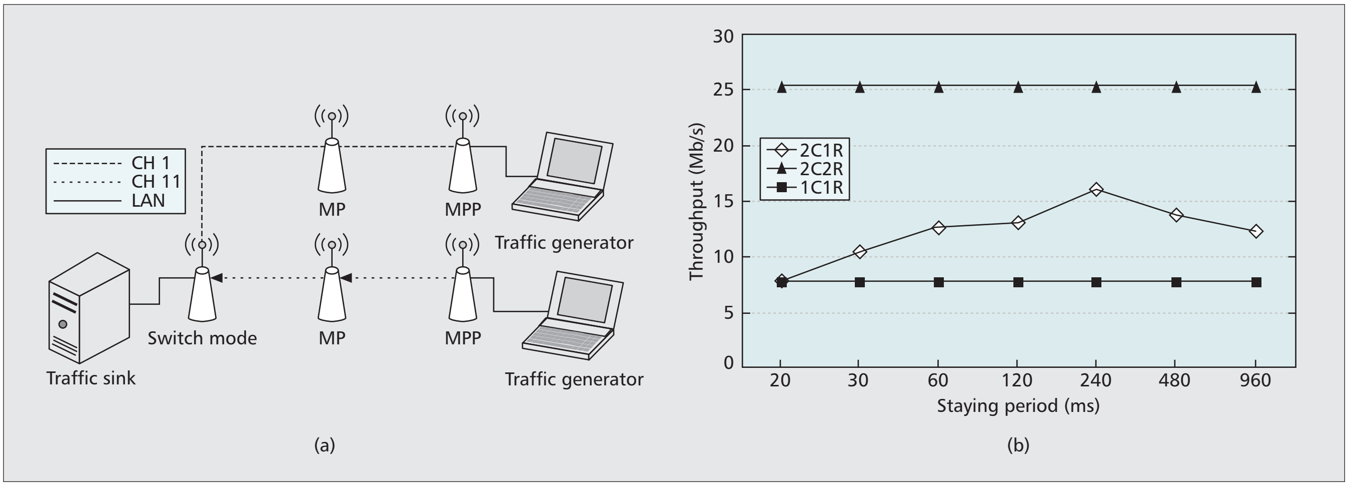


Figure 6. *Results of multi-channel transmissions: a) the experimental topology; b) impact of staying period for throughput. The period does not include the 6 ms switch overhead.*

[6] K. Ramachandran *et al*., "On the Design and Implementation of Infrastructure Mesh Networks," *Proc. IEEE Wksp. Wireless Mesh Net*., 2005.
[7] IEEE P802.11s/D2.03, "Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications — Amendment: Mesh Networking," Nov. 2008.
[8] L. Hideki *et al*., "Evaluating the Impact of RTS-CTS in OLPC's XOs' Mesh Networks," *XXV Simpósio Brasileiro de Telecomunicações*, 2007.
[9] C. Perkins and E. Royer, "Ad-Hoc On-Demand Distance Vector Routing," *Proc. 2nd IEEE Wksp. Mobile Comp. Sys. Apps*., 1999.
[10] M. Bahr, "Proposed Routing for IEEE 802.11s WLAN Mesh Networks," *Proc. 2nd Annual Int'l. Wksp. Wireless Internet*, 2006.
[11] K. Tang and M. Gerla, "MAC Reliable Broadcast in Ad Hoc Networks," *Proc. MILCOM*, 2001.
[12] A. Doufexi *et al*., "A Comparison of the HIPERLAN/2 and IEEE 802.11a Wireless LAN Standards," *IEEE Commun. Mag*., vol. 40, no. 5, May 2002, pp. 172–80.
[13] C. Ware *et al*., "Unfairness and Capture Behavior in 802.11 Ad Hoc Networks," *Proc. IEEE ICC*, 2000.
[14] A. Sheth *et al*., "Packet Loss Characterization in WiFi-Based Long Distance Networks," *Proc. IEEE INFOCOM*, 2007.
[15] A. Kamerman and L. Monteban, "WaveLAN-II: A High-Performance Wireless LAN for the Unlicensed Band," *Bell Labs. Tech. J*., 1997, pp. 118–33.

BIOGRAPHIES

YING-DAR LIN [SM] (ydlin@cs.nctu.edu.tw) received his Bachelor's degree in computer science from National Taiwan University in 1988, and his M.S. and Ph.D. degrees in computer science from the University of California, Los Angeles (UCLA) in 1990 and 1993, respectively. He joined the faculty of the Department of Computer Science at National Chiao Tung University (NCTU) in August 1993 and has been a professor since 1999. He spent his sabbatical year as a visiting scholar at Cisco, San Jose, California, in 2007–2008. He is also the founder and director of the Network Benchmarking Laboratory (NBL), co-hosted by Industrial Technology Research Institute (ITRI) and NCTU since 2002, which reviews the functionality, performance, conformance, and interoperability of networking products ranging from switches, routers, and WLAN to security and VoIP. In 2002 he co-founded L7 Networks Inc., which addresses the content networking markets with the technologies of deep packet inspection. His research interests include quality of service, network security, deep packet inspection, embedded hardware software co-design, WLAN mesh, and P2P networking. He has been on the editorial boards of *IEEE Communications Magazine*, *IEEE Communications Surveys & Tutorials*, *IEEE Communications Letters*, *Computer Communications*, and *Computer Networks*.

SHIAO-LI TSAO [M] (sltsao@cs.nctu.edu.tw) received his B.S., M.S., and Ph.D. degrees in engineering science from National Cheng Kung University, Taiwan, in 1995, 1996, and 1999, respectively. His research interests include mobile communication, wireless networks, and embedded software. He is currently an assistant professor with the Department of Computer Science at National Chiao Tung University. He has published more than 60 international journal and conference papers, and holds or has applied for 16 U.S. patents. He received the Research Achievement Award of the Industrial Technology Research Institute in 2000 and 2004, the Outstanding Project Award of the Ministry of Economic Affairs of Taiwan in 2003, Young Researchers Award of the Pan Wen-Yuan Foundation in 2007, and Young Engineer Award of the Chinese Institute of Electronic Engineering in 2008.

SHUN-LEE CHANG [M] (changsl@cs.nctu.edu.tw) received his B.S. and M.S. degrees in computer science from National Chiao Tung University, Taiwan, in 1997 and 1999, respectively. Currently, he is working toward his Ph.D. He worked for Formosoft Inc. and developed PKI products during 1999–2004. In 2006–2009 he participated in IEEE 802.11s-related research projects at the Realtek-NCTU joint research center. His research interests are the design, analysis, and implementation of wireless mesh networks.

SHAU-YU CHENG (shauyu.cheng@msa.hinet.net) received his B.S. degree from the Department of Computer Science and Engineering, Tatung University, Taipei, Taiwan, in 1995, and his M.S. degree from the Institute of Computer Science, National Chiao Tung University, Hsinchu, Taiwan, in 1999. In 1999 he joined the army for substitute service in Formosoft Inc. After retirement from the army, he is pursuing his Ph.D. degree at the Institute of Computer Science of National Chiao Tung University. He was the team leader in the Realtek-NCTU joint research center. His research mainly involves channel estimation and synchronization in wireless communications, multi-spec receiver designs, wireless mesh networks, and associated VLSI architectures.

CHIA-YU KU [M] (cyku@cs.nctu.edu.tw) received his M.S. degree from the Department of Computer Science, National Chiao Tung University, Taiwan, in 2008. He has been earning his Ph.D. degree since September 2007. His research interests include wireless mesh networking, multichannel multiradio, mobility management, integration of wireless networks, and performance evaluation.