A GATEWAY APPROACH TO MOBILITY INTEGRATION OF GPRS AND WIRELESS LANs

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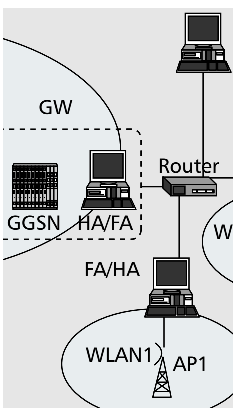

The authors present a gateway approach to the integration of GPRS and wireless LANs (WLANs). The proposed architecture leverages Mobile IP as the mobility management protocol over WLANs.

An early version of this paper was presented at IEEE PCM 2002.

ABSTRACT

This article presents a gateway approach to the integration of GPRS and wireless LANs (WLANs). The proposed architecture leverages Mobile IP as the mobility management protocol over WLANs. The interworking between GPRS and WLANs is achieved by a gateway that resides on the border of GPRS and WLAN systems. The design goal is to minimize the modifications in GPRS and WLANs as both systems are widely available in the market already. By deploying the gateway, users can seamlessly roam among the two systems. The proposed architecture and design principles have been implemented in a commercial GPRS network operated by the Taiwan Cellular Corporation. Empirical experiments with multimedia applications were conducted to analyze the performance in terms of handoff latency, packet delay, and throughput.

INTRODUCTION

The number of mobile users has grown rapidly in recent years. They not only require traditional voice service but also multimedia services with high bandwidth access. General Packet Radio Service (GPRS), a prelude to third-generation (3G) evolution, is designed to serve highly mobile subscribers with sophisticated high-power radio. Cell diameters in GPRS could exceed 10 km. The currently available data rate is in the range of 20–170 kb/s. On the other hand, by utilizing short-range low-power radio, wireless local area networks (WLANs) are mainly deployed for indoor environments for low-mobility high-speed applications. The bit rate of IEEE 802.11b can achieve 11 Mb/s, while IEEE 802.11a/g and European Telecommunications Standards Institute (ETSI) HIPERLAN/2 have defined standards with bit rates greater than 50 Mb/s. It is likely that both GPRS and WLANs will coexist and complement each other in the future. Users might want to use GPRS virtually anywhere to access the Internet. They nevertheless would like to leverage high-speed access of WLANs whenever possible. In addition, many organizations provide free WLAN access for their employees/students within their own buildings/campuses. However, GPRS and WLANs are based on different networking technologies. The integration of them, especially seamless roaming, thus becomes a critical issue.

Standards organizations have started standardization of the integration of WLANs and 3G/GPRS. In [1, 2] the 3G Partnership Project (3GPP) defines the requirements, principles, and interworking scenarios for integration of WLANs and 3GPP networks. The interworking between HIIPERLAN/2 and 3G systems is also specified by ETSI in [3]. The integration is categorized as *tight coupling* and *loose coupling*. In tight coupling, as specified in Fig. 1, a WLAN is connected to the GPRS core network as one of the radio access networks (RANs) with a standard GPRS interface G_b. Loose coupling, on the other hand, utilizes WLANs as complementary networks to 3G/GPRS systems. In this case, GPRS and WLANs could be two parallel networks and work independently. Reference [4] summarizes recent activities in WLAN-GPRS integration and provides an extensive comparison of the tight and loose coupling models. In tight coupling, the access point (AP) of a WLAN can be regarded as a base station and is connected to a serving GPRS support node (SGSN) through a GPRS interworking function (GIF) by the G_b interface, as shown in Fig. 1. Loose coupling, however, interfaces the GPRS and WLANs by the G_i interface and separates them as independent networks. It is expected that loose coupling will be deployed earlier than tight coupling due to the architecture complexity in tight coupling.

This article presents a *gateway approach* to integrating GPRS and WLAN systems. The proposed model is based on loose coupling. The premise is that the GPRS is owned by a licensed cellular operator, and the WLAN system is managed by a different provider such as a university. This reflects today's real-world deployment in which most GPRS and WLAN systems are run by different providers. They also work independently. This article emphasizes *mobility* integration based on Internet Protocol (IP), a promising universal network-layer protocol to integrate heterogeneous wireless systems. GPRS

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introduces two special nodes, the gateway GPRS support node (GGSN) and the SGSN, and GPRS Tunneling Protocol (GTP) to provide IP services [5, 61. WLAN systems, however, primarily focus on the physical and link layers without considering IP and above layers. To enforce mobility in WLANs among different IP subnets, Mobile IP (IETF RFC 3344 for IPv4 and RFC 3775 for IPv6), the protocol developed by the IETF to support IP mobility, is a natural choice. Based on this principle, the primary issue in the integration of GPRS and WLANs discussed in this article is the integration of Mobile IP with the mobility management defined in GPRS. Because the integration is based on Mobile IP, the underlying WLANs could be based on IEEE 802.11, HIPERLAN, or any other radio technologies.

As both GPRS and WLAN systems are mature and available in the market already, our design goal is to minimize modifications to both systems. Although there are many design alternatives [4, 7–10], our objective is to design a *practical* solution rather than an *optimal* solution so that service providers can realize the integration of GPRS and WLANs immediately without waiting for a lengthy standardization process. We propose to design a *gateway* that resides at the border of GPRS and WLAN systems. By simply deploying this gateway, the integration of GPRS and WLANs could be achieved without changing the existing infrastructures. Based on the design principles, we have implemented the gateway in a commercial GPRS network operated by the Taiwan Cellular Corporation (TCC), one of the biggest cellular operators in Taiwan. The gateway connects the GPRS network to an IEEE 802.1lb network with Mobile IPv4 running on top of it. Although IPv6 might be more efficient than IPv4, it is not yet widely deployed. The integration of GPRS and WLANs is a timely issue. As mentioned earlier, our main objective is to provide an immediate solution. Therefore, our design is based on IPv4. In addition, to demonstrate the feasibility of the proposed approach, empirical experiments are presented to analyze the testbed performance. The experiments based on a commercial GPRS system should be valuable for future reference.

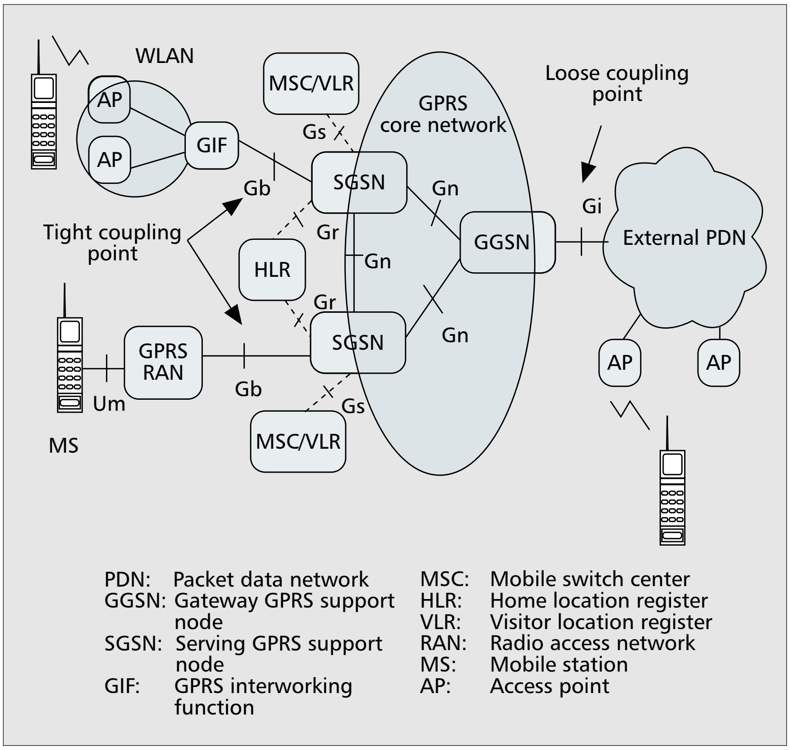


Figure 1. *Loose coupling vs. tight coupling.*

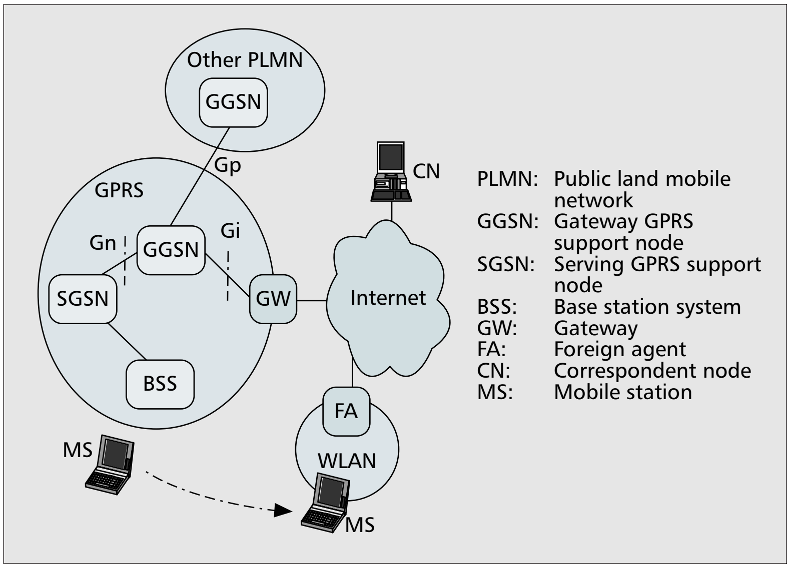


Figure 2. *Architecture of the gateway approach.*

GATEWAY APPROACH

The gateway approach presented in this article is based on loose coupling. The architecture is depicted in Fig. 2. We presume that GPRS and WLAN systems are independently owned and managed by two different providers. For instance, the GPRS system is provided by a cellular operator, while the WLAN system is deployed and administrated by a university. We consider the case that a GPRS subscriber who is not affiliated with the university hands off from a GPRS network to a WLAN domain. Therefore, the GPRS system is the subscriber's home network and the WLAN is the foreign network. In addition, the design also allows a WLAN user who is not a subscriber of the GPRS network to roam into the GPRS network. Hence, the home network is the WLAN and the GPRS is the foreign network. Compared to other loose coupling work [7–10], our design is closer to real-world deployment of GPRS and WLAN systems, in which both WLAN users and GPRS subscribers may roam into a system that is not owned by the same provider and does not have any subscription/registration information on the user.

Although the proposed design incorporates security and mobility management, this article mainly highlights mobility management, which is a primary task for the integration of heterogeneous wireless networks. *WLAN-centric authentication* that works with the gateway approach proposed in this article can be found in [11]. The

In 3GPP TS 29.061, it defines an architecture such that Mobile IP can be optionally supported to provide mobility management for intersystem roaming. In the architecture, a gateway GGSN is enhanced with FA functionality and is referred to as a GGSN/FA.

proposed WLAN-centric authentication leverages widely used WLAN-based authentication and requires the GPRS operator to install an authentication, authorization, and accounting (AAA) server. In order to filter proper messages to the GPRS AAA server, an additional *registration filter* is deployed between the base station system (BSS) and SGSN in the GPRS network. The registration filter is a logical entity and could be implemented inside the SGSN. Thus, WLAN users could execute WLAN-based authentication in GPRS networks as they do in WLANs. GPRS subscribers are authenticated by GPRS authentication in GPRS networks. They, however, perform WLAN-based authentication in WLAN systems.

In GPRS, GPRS mobility management (GMM) supports mobility management functions such as GPRS attach, GPRS detach, and routing area update. Tunneling is done using GTP. GPRS is built on GSM. Mobile IP, on the other hand, is designed for Internet-based architecture. To keep a session alive while handing off from one system to another, there are some possible solutions. Because both GPRS and WLANs are widely deployed already, an efficient way to integrate them should reduce the impact on existing systems as much as possible. The gateway (GW), which is placed on the conjunctional point of the GPRS and WLAN systems, is responsible for integration. Therefore, the mobility management in GPRS and WLANs (Mobile IP) can function as they are. The GW is a logical entity that could be implemented standalone or as an addition to the gateway GGSN, which connects GPRS to external networks. Because a user might have a home network in either the WLAN or GPRS network, the GW should function as both home agent (HA) and foreign agent (FA). Therefore, the GW essentially is a gateway GGSN combining HA and FA. The GW is referred to as GGSN/FA or GGSN/HA, depending on the context. The following sections present the cases when a user has a home network in a WLAN system and a GPRS system, respectively.

Home in a WLAN System

When the home network of a user is in WLAN system, the correspondent node (CN) sends its traffic to the WLAN system regardless of the mobile station's (MS's) anchor point. The home network should tunnel traffic to the MS's current location if the MS is not inside its home network. In this scenario, the gateway should function like an FA. In 3GPP TS 29.061 [12], it defines an architecture such that Mobile IP can optionally be supported to provide mobility management for intersystem roaming. In the architecture, a gateway GGSN is enhanced with FA functionality and referred to as a GGSN/FA. Although the location of HA is out of the scope of the specification of 3GPP TS 29.061, we envision that there is an HA for the MS in the WLAN domain. To process a Mobile IP (MIP) request after the MS roams into GPRS, the access point name (APN) [5] is utilized to select the specific network service. The MS sends a Packet Data Protocol (PDP) context activation request with *MIPv4FA* as the APN, which instructs the SGSN to forward the request to the GGSN with FA service (i.e., the GW). The MIP registration will be performed after the PDP context activation is completed. Once the MS is registered with its HA successfully, packets destined to the MS's home IP address in the WLAN domain will be intercepted by the HA and forwarded to the FA (the GW). The GW decapsulates the packets and transmits datagrams based on GTP tunneling to the target SGSN. Packets finally will reach the MS in the way defined in GPRS.

Figure 3 illustrates an example of a CN communicating with an MS roaming between GPRS and WLANs. In this example, the MS has its home network in the WLAN domain, and the CN is outside the GPRS. In Fig. 3, the MS first attaches to the GPRS system and activates its PDP context. This may be because an MS is powered up in GPRS or the MS just moves into GPRS. After MIP registration is successfully completed, packets from CN to MS are intercepted by the HA, which further delivers them to the GW (GGSN/FA). When the MS is performing a standard GPRS attach, the GW can extract the MS's home IP address and update the PDP context. It also remembers the mapping of the IP address and the tunnel endpoint ID (TEID) [5]. Therefore, the GW can decapsulate the packets received from the HA and tunnel them to the proper SGSN using standard GTP tunneling. If reverse tunneling is implemented, the reply from the MS would be transmitted along the same path to the HA and then the CN. Usually, a GPRS provider will place a firewall to protect the GPRS system. Thus, reverse tunneling is usually implemented.

Figure 3 also depicts that once the MS hands off back to the WLAN (i.e., its home network),[1] MIP deregistration[2] is performed because the HA does not need to tunnel packets for the MS now. Packets are then sent to the MS without going through the GPRS system. If the MS roams to GPRS again, it only needs to initiate MIP registration by issuing an MIP agent solicitation if the previous GPRS PDP context is still valid. The session can continue after MIP registration is completed.

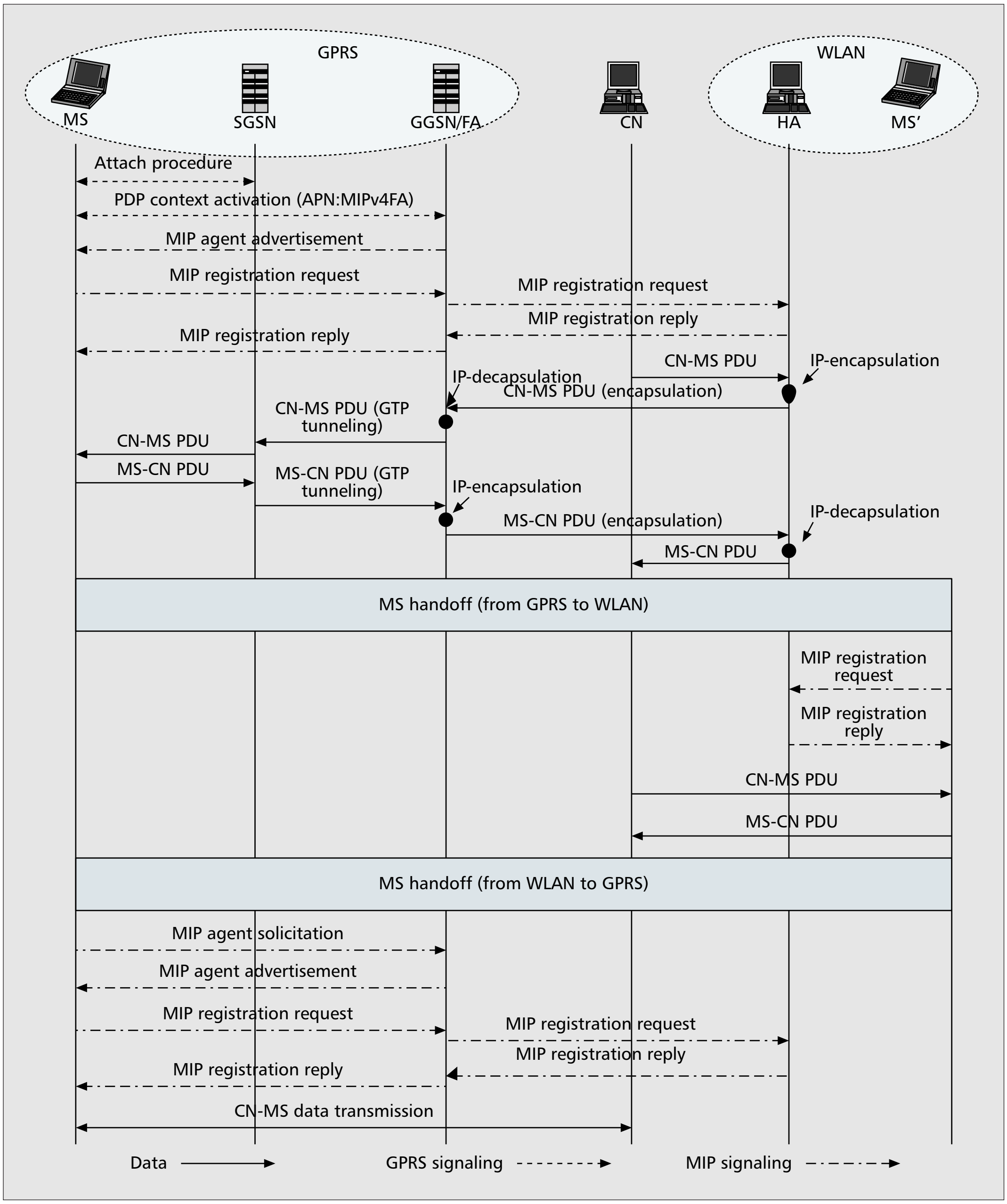
Although the case that CN is inside GPRS is not shown, it could be depicted easily based on Fig. 3.

Home in a GPRS Network

The GGSN/FA approach described above follows 3GPP TS 29.061 [12] for roaming between a public land mobile network (PLMN) and other packet data networks (PDNs). It presumes that there is an external network that is the home network of the MS. Many users, however, may have subscribed to GPRS services but are not affiliated with any WLAN provider. It is possible that this type of user will roam into a WLAN system but still want to be reachable by their home GPRS network. For this scenario, the gateway shown in Fig. 2 functions as a GGSN combined with an HA (GGSN/HA). It connects to other GGSNs through the standard G_i interface. Once moving into WLANs, an MS will send MIP registration messages to its HA (the gateway). Therefore, packets initiated from

[1] *The MS' in Fig. 3 represents the new location of the MS after roaming into a WLAN.*

[2] *In MIP, dcregistration is done by sending a registration request in which the lifetime field is set to zero.*



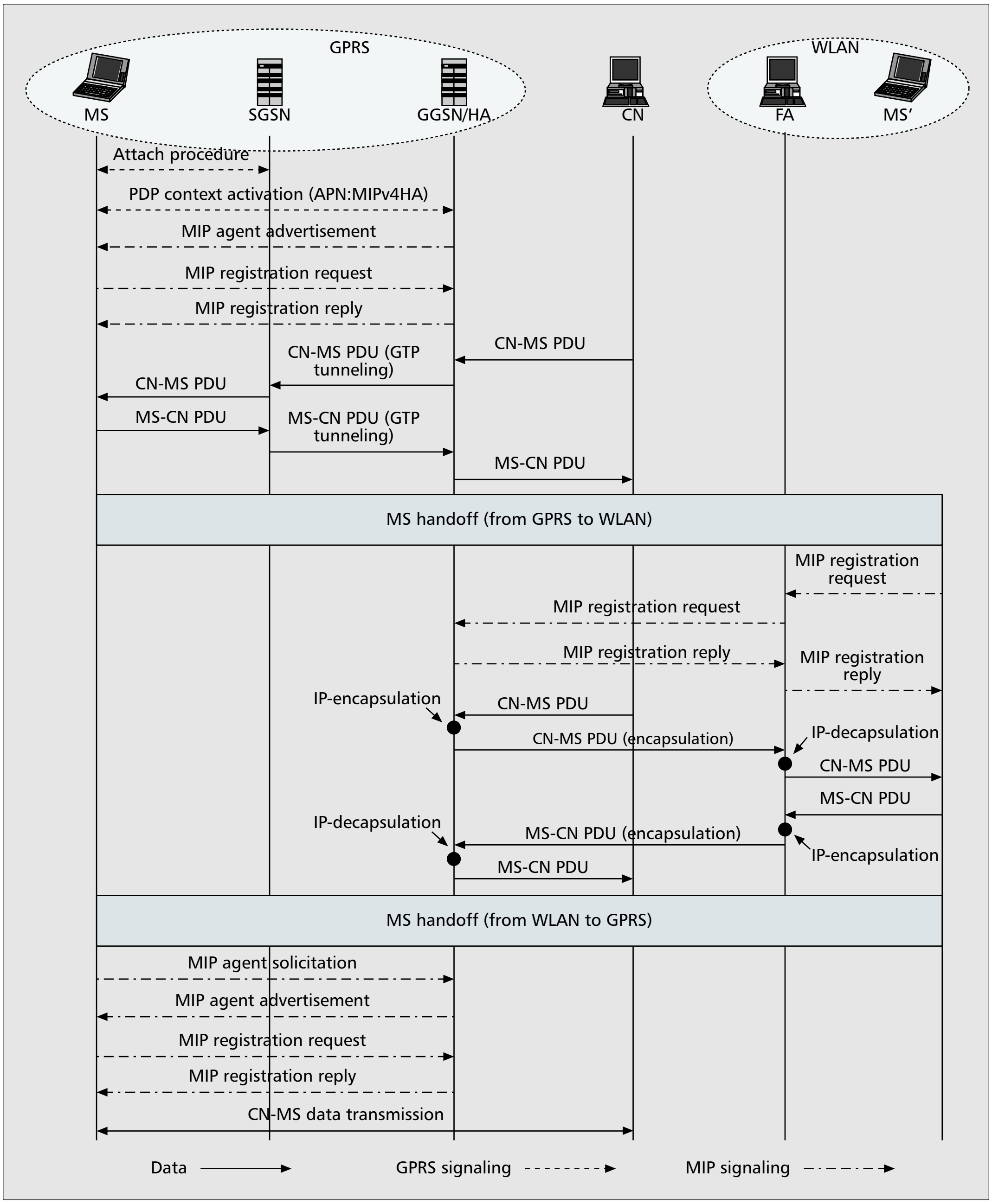
■ **Figure 3**. *Intersystem roaming: the home network is in a WLAN.*

The GGSN functionality in the gateway should also be aware of the change of the anchor point. Therefore, packets initiated inside the GPRS network will be passed to the HA part of the gateway and will be sent to the current location of the MS if the MS is in WLANs.

external PDNs (WLANs) will be intercepted by the gateway and tunneled to the MS. The GGSN functionality in the GW should also be aware of the change of anchor point. Therefore, packets initiated inside the GPRS network will be passed to the HA part of the GW and sent to the current location of the MS if the MS is in WLANs.

Figure 4 shows the flows when the CN is outside the GPRS network. As discussed earlier, the MS first needs to activate PDP context before it can utilize GPRS services. The activation request specifies the APN with *MIPv4HA*. Therefore, the activation request will be sent to the GW (GGSN/HA), which initiates an MIP agent advertisement after the PDP context is created. The MS may perform MIP deregistration by sending a registration request with zero lifetime if it has registered with the HA before. This is because the GPRS is the home network, and there is no need for the HA to intercept packets when the MS is in its home network. When a CN wishes to send packets to the MS, the packets will reach the GW. The GGSN functionality in the GW will tunnel packets to the SGSN currently serving the MS. Packets are delivered to the MS with standard GPRS procedures. The HA functionality in the GW will not function because there is no registration information on the MS. Once the MS moves into a WLAN, it performs MIP registration with the HA in the GW. Packets from the CN, therefore, will be intercepted and tunneled by the HA (GW) to the new location of the MS. Figure 4 assumes that reverse tunneling is implemented. Thus, packets from MS to CN will go through the HA. When the MS moves back to the GPRS, the MS deregisters with the HA (GW). If the PDP context created earlier is still alive, the MS can just

We propose that even when packet transmission is through WLAN interface, GPRS radio should be enabled for control messages, such as location update and paging, as long as the MS is under GPRS radio coverage.



■ **Figure 4**. *Intersystem roaming: the home network is in the GPRS.*

resume its transmission. Otherwise, a new PDP context will be created as discussed earlier. Similarly, one should easily comprehend the case when the CN is inside GPRS based on Fig. 4.

Handoff Management

Usually WLANs are used for indoor applications while GPRS is utilized for outdoor usage. The choice of radio interfaces may involve many factors such as availability of the radio, type of application, and billing. Normally WLANs would be a better choice if available. It is also possible to utilize both systems for data transmission simultaneously. Nevertheless, this article mainly considers the mobility management issues caused by switching between different radio interfaces, that is, handing off between different systems. Two policies are proposed and have been implemented in our testbed: *WLAN-preferred* and *user-triggered*. In WLAN-preferred mode, the link quality is tracked. It changes to WLAN connection automatically if a WLAN system is available. The link quality is tracked as well in user-triggered mode. On the other hand, the decision to switch between systems is based on user command and availability of the radio. Furthermore, we propose that even when packet transmission is through a WLAN interface, a GPRS radio should be enabled for control messages, such as location update and paging, as long as the MS is under GPRS radio coverage. The SGSN thus still regards the MS as reachable, so high cost and long latency for reattaching to GPRS could be minimized when the MS switches back to GPRS. Besides, circuit-switched network service is still available for voice phone

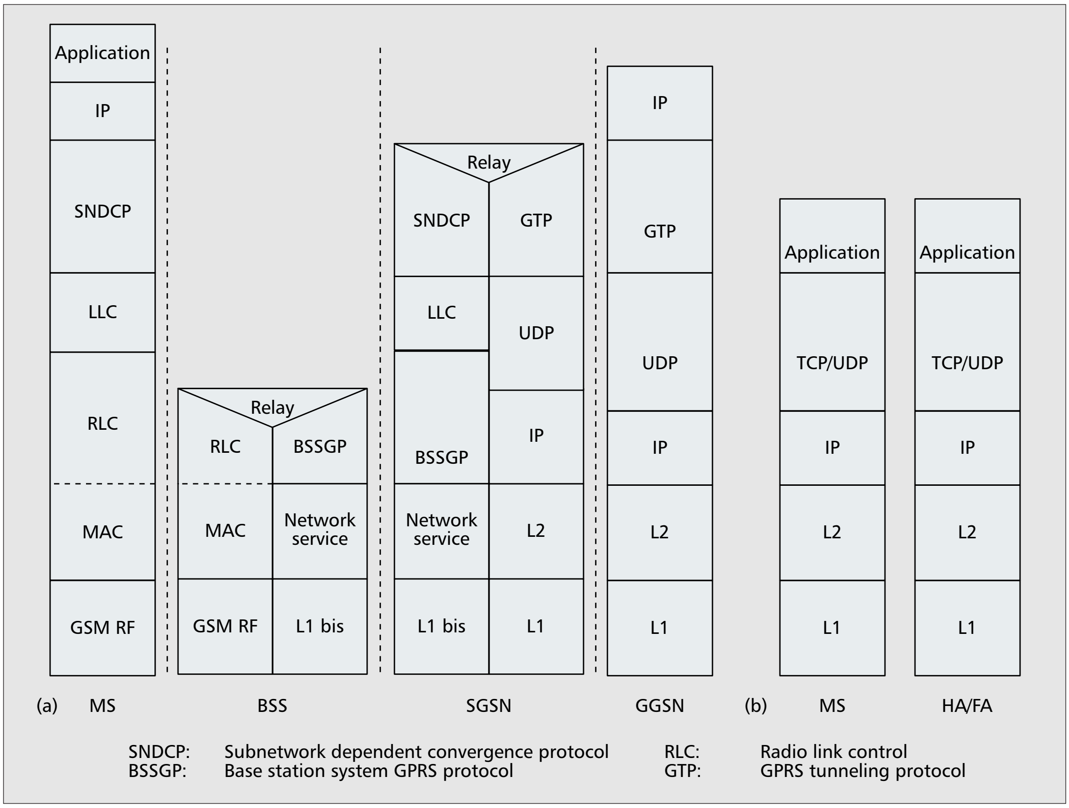


Figure 5. *Dual protocol stacks: a) GPRS user plane; b) IP stack.*

One can see that both GPRS and Mobile IP can work as what they are. The gateway functions as GGSN, HA, and FA. By deploying the gateway, the integration of mobility management in GPRS and WLAN systems could be achieved without any modification.

calls. Basically they do not interfere with each other because of different radio frequencies.

System Requirements

In order to deploy our design, some modifications to the network and terminal are necessary. This section discusses the system requirements for our design.

Requirements for GPRS and WLAN Systems

Based on the discussion earlier, one can see that both GPRS and MIP can work as what they are. The GW functions as GGSN, HA, and FA. By deploying the GW, the integration of mobility management in GPRS and WLAN systems can be achieved without any modification.

Requirements for MS

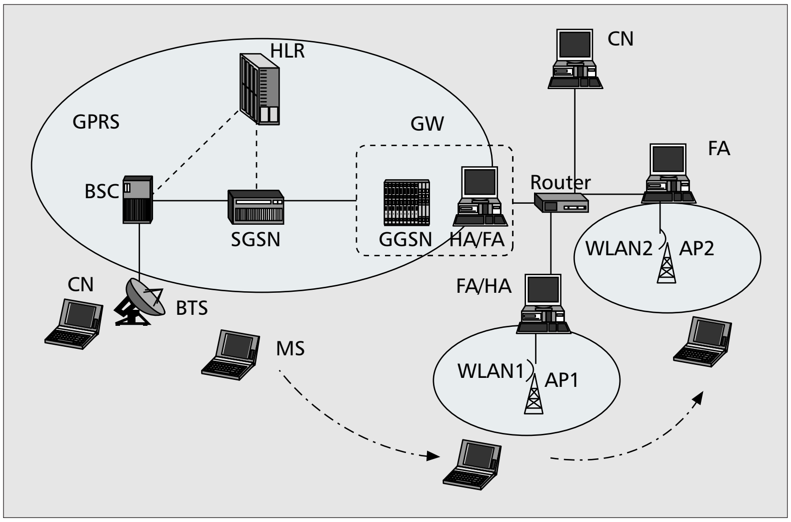
In addition to the GPRS radio interface, an MS must be equipped with a WLAN-compatible radio interface. Evidently, the MS should understand the protocol stacks of both systems, as illustrated in Fig. 5. Figure 5a represents the user plane of GPRS, while Fig. 5b shows a conventional IP stack, in which layers 1 and 2 should be based on a WLAN system. Please note the requirements of dual radios and dual protocol stacks in the MS are inevitable for integration. Because our design does not need to change anything in the network except in deploying the GW, the protocol stacks in the terminal do not need to be modified either. To deal with dual radios, the handoff management presented earlier should be implemented. However, other techniques could also be used as long as they can trigger higher layers to perform handoff.

Testbed and Experimental Analysis

The implementation of a testbed aims to realize the proposed idea and perform various experiments. Figure 6 shows the testbed architecture, in which a GPRS system is supported by TCC. Table 1 lists the nodes, including the BSS,[3] HLR, SGSN, and GGSN, in the system. The logical entity marked by a dotted rectangle in Fig. 6 is the proposed GW that provides GGSN, HA, and FA functionalities. When GPRS is the home network, there are two foreign networks in WLANs; thus, two FAs are presented. When the home network is the WLAN system, there is one HA deployed in the WLANs.

The MS is a laptop with two PCMCIA interfaces. One is for IEEE 802.1lb radio. The other one is equipped with a Nokia D211 GPRS radio, which provides three time slots downlink, two time slots uplink, and four total time slots simultaneously. Basically, the WLAN and GPRS interfaces can operate simultaneously. Theoretically, 64.2 kb/s is the maximum data rate for the Nokia D211. Because the TCC GPRS system supports GPRS-l and GPRS-2 only, the maximum data rate is 40.2 kb/s. In our experiments, a valid SIM card was inserted so that the MS could attach to the TCC GPRS system. In GPRS, the MS, which is usually referred to as user equipment (UE), consists of mobile terminal (MT) and terminal equipment (TE) [5]. The communication between MT and TE is based on Point-to-Point Protocol (PPP). When the MS wishes to connect to GPRS, the TE uses the AT command set to request the MT to create a PDP context. Our MS runs Linux, in which the AT command can be arranged in the *chat* file. The

[3] A BSS consists of base transceiver station (BTS) and base station controller (BSC).



■ **Figure 6**. *Testbed architecture.*

Node	Model
BTS	Siemens BS20
BSC	Siemens BSC
HLR	Siemens SR8
SGSN	Nokia DX200
GGSN	Nokia GN2500

■ **Table 1.** *Testbed components in the TCC GPRS system.*

script can be executed by calling a *pppd* daemon. A graphic user interface is also implemented in the MS to provide information on both networks so that the user may use *user-triggered* mode to initiate handoff, as discussed earlier.

We have also implemented a simplified Session Initiation Protocol (SIP, IETF RFC 3261) user agent in the testbed. The SIP user agent executes IP signaling to establish real-time multimedia sessions between two end hosts. Both MS and CN are equipped with cameras. Not only can they talk to each other, they can also see each other. There is also a *whiteboard* to exchange information. In addition, a traffic controller (TC) is implemented to control the maximum bandwidth of the video traffic going into the networks.

Based on the testbed architecture, various experiments were performed. The results based on the scenario shown in Fig. 3 are presented in Figs. 7 and 8. Figure 7 illustrates the results in which the CN was a fixed host outside the GPRS network. In Fig. 8 the CN was a mobile host inside the GPRS network. Similarly, results based on the scenario discussed in Fig. 4 are presented in Figs. 9 and 10. All experiments were conducted such that the MS moved from GPRS to WLAN 1 and WLAN 2, then followed the same path back to GPRS. Except for the MS and CN, there was no other user in the testbed.

Handoff Latency

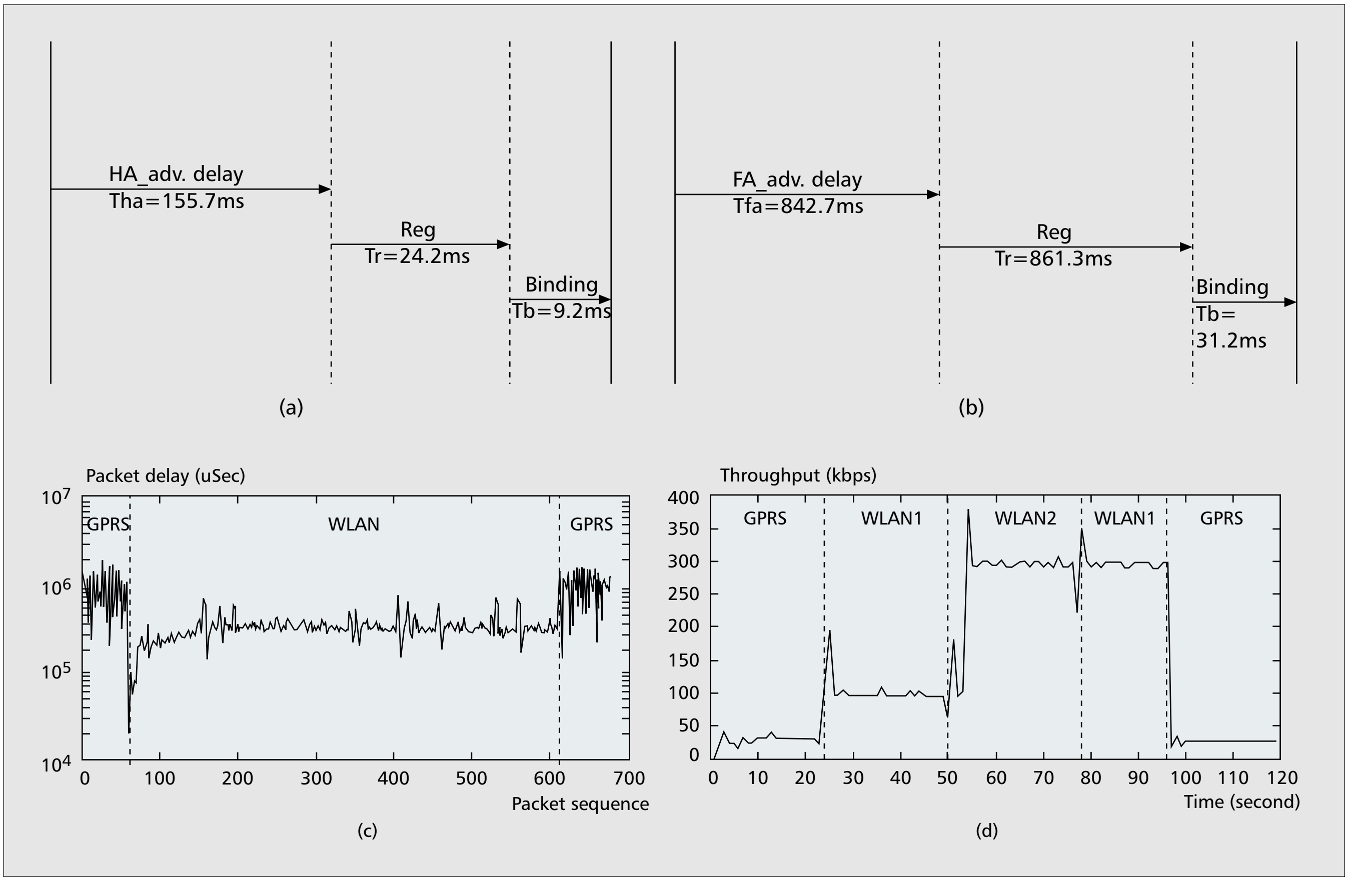
The handoff latencies between GPRS and WLAN are presented in parts a and b of Figs. 7–10. In our experiments, the CN continuously sent *ping* packets to the MS at 10 ms intervals. In the WLAN, the HA/FA would broadcast an agent advertisement periodically *every second*. Therefore, the MS did not need to send an agent solicitation. Because there is no broadcast in the GPRS core network, the agent advertisement can only be sent by unicast after the PDP context is created [12]. In our experiments, therefore, the MS would send an agent solicitation after roaming into GPRS to trigger the GGSN/FA or GGSN/HA to send an agent advertisement.

Figure 7a shows that the delay to detect an HA agent advertisement was 155.7 ms. Because the advertisements were sent every second, the maximum and minimum delay would be 1 s and 0 s, respectively. The time for the MS to receive an MIP registration reply from the HA after the MS sent an MIP registration request was 24.2 ms. Finally, it cost a delay of 9.2 ms for the MS to receive packets from the CN again after the binding update in the HA was done. The handoff latency from GPRS to WLAN totally cost 189.1 ms. Relatively, Fig. 7b indicates the handoff latency from WLAN to GPRS. First, the MS sent an MIP agent solicitation and waited for 842.7 ms to acquire the agent advertisement. The messages from the MS to the GGSN/FA would go through the BSS and SGSN in GPRS. The bandwidth in GPRS was also less than that in WLAN. Therefore, the delay to receive an agent advertisement in GPRS was much longer than that in WLAN. After that, it took 861.3 ms to receive the registration reply from the HA. For similar reasons as those discussed for agent advertisement, the registration delay in Fig. 7b was much longer than that in Fig. 7a. Finally, the delay was 31.2 ms to receive packets from the CN again for the MS. Because packets needed to go between WLAN and GPRS, the binding delay was longer than that shown in Fig. 7a. The total delay for roaming to GPRS from WLAN was 1735.2 ms, which was much longer than the handoff latency from GPRS to WLAN. Because GPRS employs much more complex radio technology and protocol stack, in a GPRS network packets need to go through several nodes with more complex protocol stacks to reach the HA. Therefore, the exchange of MIP signaling messages between MS and HA would take much more time. Thus, the handoff latency from WLAN to GPRS was longer than the handoff latency from GPRS to WLAN.

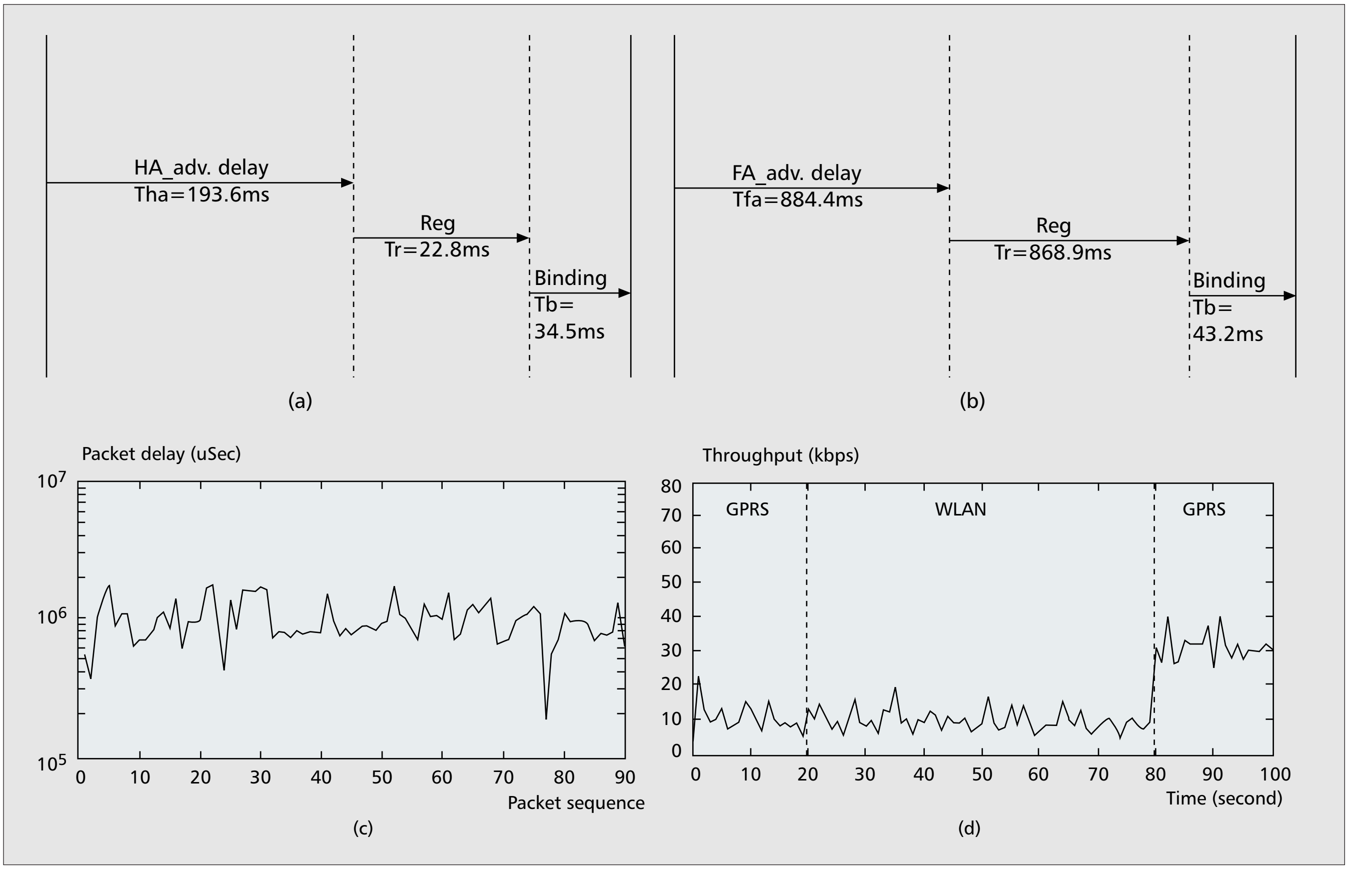
The other three cases illustrated in Figs. 8–10 show similar behavior. The handoff latency mainly depends on the delays of agent advertisement and registration rather than placement of the CN and home network.

TCP Packet Delay

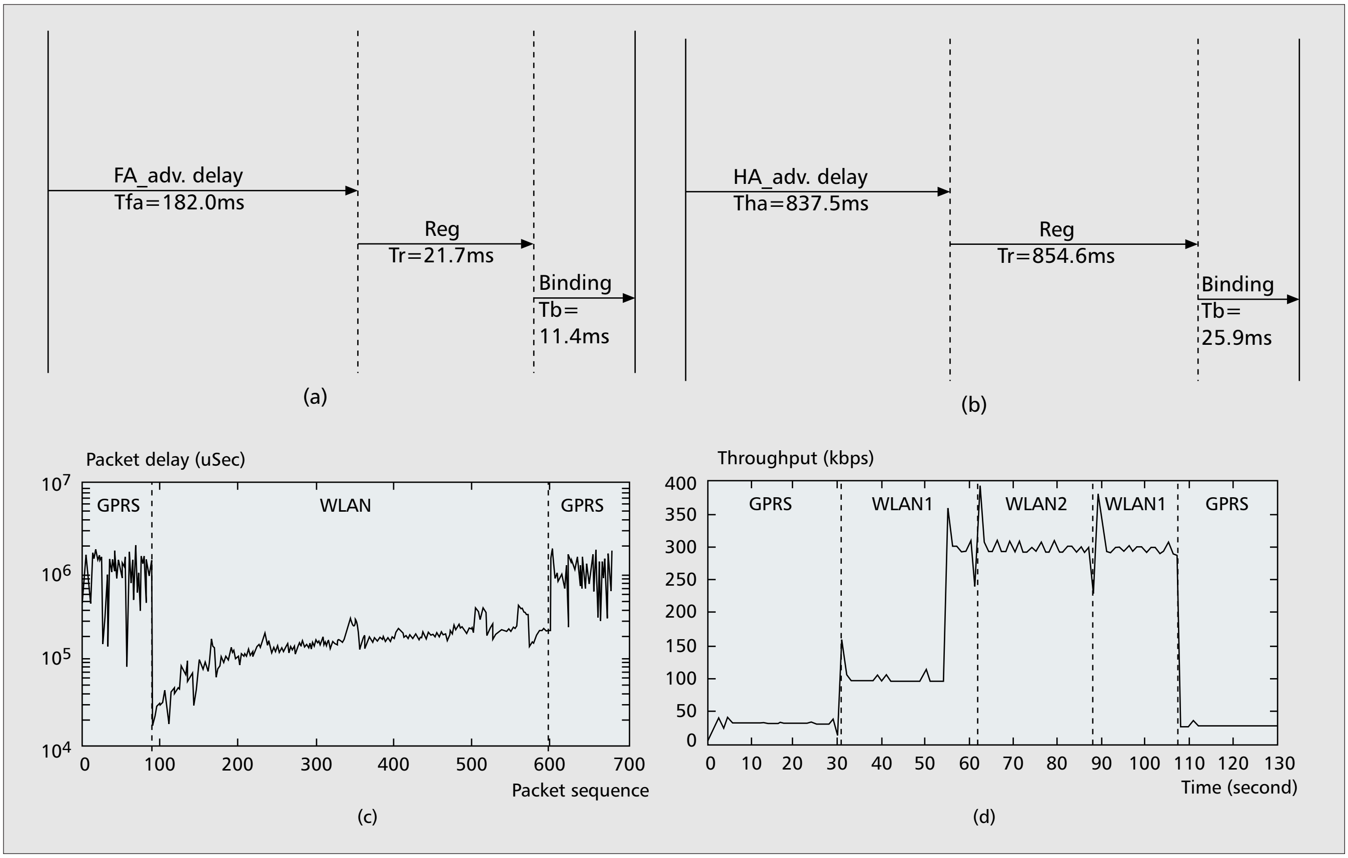
Part c of the figure sets indicates the TCP packet delay. The MS continuously generated TCP traffic to the CN by using *netperf* and waited for acknowledgment. The delay was calculated from the time the TCP packet was generated to the



■ **Figure 7**. *Experiment results: the home network is in a WLAN (CN: a fixed host outside GPRS): a) handoff latency from GPRS to WLAN; b) handloff latency from WLAN to GPRS; c) TCP packet delay; d) video throughput.*



■ **Figure 8**. *Experiment results: home network is in WLAN (CN: an MS inside GPRS) (a–d, see Fig. 7).*



■ **Figure 9**. *Experiment results: home network is in GPRS (CN: a fixed host outside GPRS) (a–d, see Fig. 7).*

time the acknowledgment was received. Compared to the 11 Mb/s in IEEE 802.11b, the maximum data rate of 40.2 kb/s in GPRS was much lower. Hence, the TCP packet delays in GPRS were higher than the TCP packet delays in WLAN as shown in Figs. 7c and 9c. Figures 8c and 10c show that the TCP packet delay remains around 1 s, which is the same as the packet delay in GPRS in Figs. 7c and 9c. This is because in Figs. 8c and 10c, the CN was inside the GPRS network, which was the bottleneck of the packet delay.

VIDEO THROUGHPUT

Part d of the figure sets presents the throughput of video traffic the MS received from the CN. Experiments discussed here were part of a multimedia conference initiated by SIP signaling. The video codec was based on H.263. Based on the feature of the GPRS medium access control and the hardware we adopted, the data rate in GPRS was around 32 kb/s, as shown in Figs. 7d and 9d. After roaming into WLANs, the traffic was conditioned by a traffic controller (TC) we implemented to enforce the maximum data rates with 100 kb/s and 300 kb/s, respectively. The TC was used as a simple form of quality of service (QoS) control. When the MS first moved from GPRS to WLAN, the video quality was drastically improved because of the high bandwidth of WLAN. The quality was further improved when the TC increased the data rate. However, the data rate dramatically dropped during handoffs, which are marked by vertical dotted-lines. Even though there was no retransmission due to UDP packets, the video coding techniques helped recover loss of small amounts of packets by other correctly received packets.

Similar to the TCP packet delay, we observe that the MS received 10 kb/s approximately from the CN when the CN was inside GPRS. Please refer to Figs. 8d and 10d. Around 32 kb/s incoming bandwidth was achieved when the MS moved back to GPRS because packets buffered in GPRS earlier were delivered at this moment.

SUMMARY

The integration of GPRS and WLANs should benefit both operators and users. From the operators' point of view, minimizing modifications to existing systems is a key factor for success. The *gateway approach* proposed in this article provides a solution to achieve this goal. A testbed based on a commercial GPRS system was constructed to validate the proposed approach. Various experiments were carried out to examine the design principles and analyze performance. The results show that the proposed gateway approach could achieve the design goal and provide a solution to integrate mobility management in GPRS and WLAN effectively.

ACKNOWLEDGMENTS

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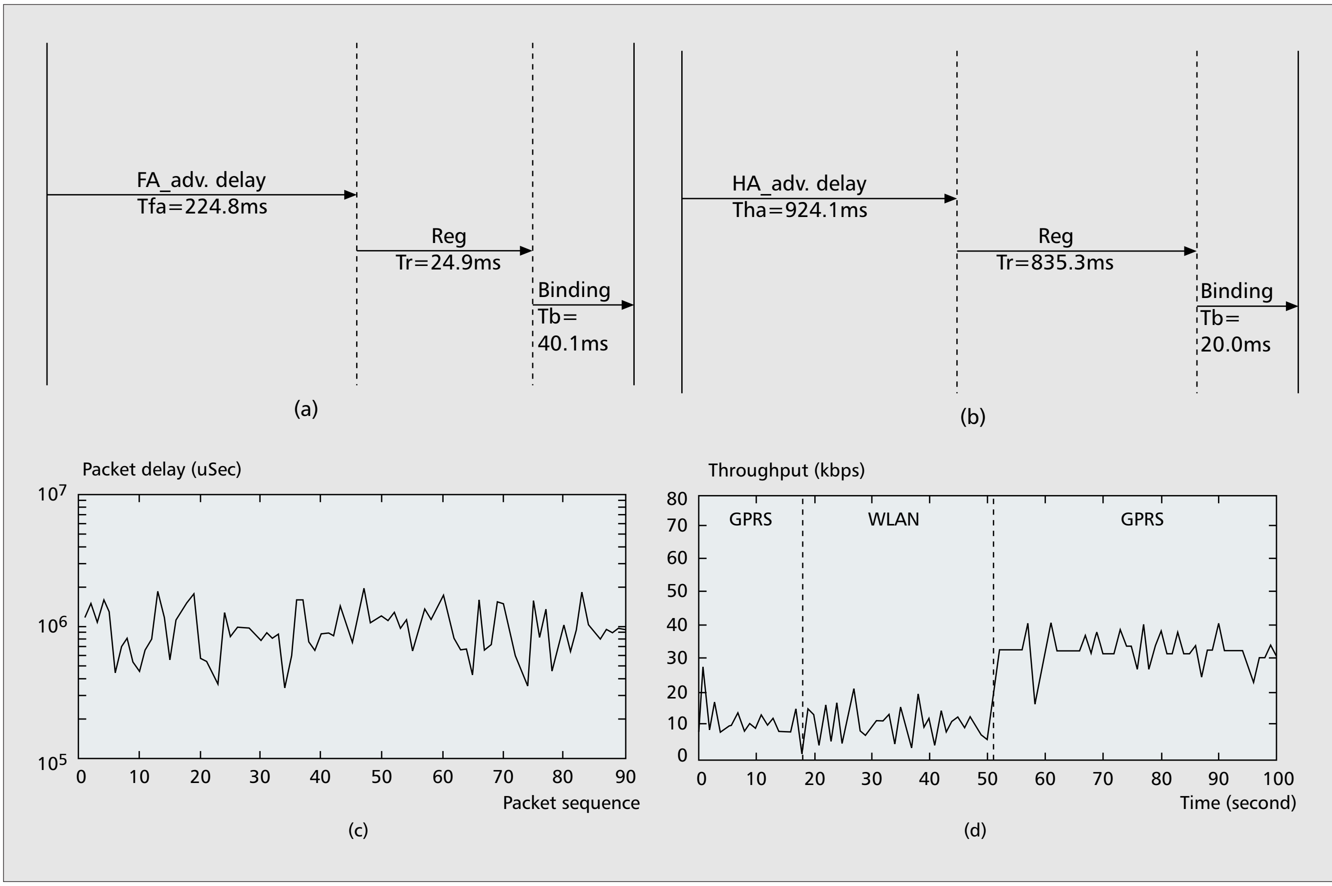

■ **Figure 10**. *Experiment results: home network is in GPRS (CN: an MS inside GPRS) (a–d. see Fig. 7).*

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References

[1] 3GPP TR 22.934, "Feasibility Study on 3GPP System to Wireless Local Area Network (WLAN) Interworking," Sept. 2003.
[2] 3GPP TR 23.234, "3GPP System to Wireless Local Area Network (WLAN) Interworking: System Description," Jan. 2004.
[3] ETSI TR 101957, "Requirements and Architectures for Interworking between HIPERLAN/2 and 3rd Generation Cellular Systems," Aug. 2001.
[4] A. K. Salkintzis, C. Fors, and R. Pazhyannur, "WLAN-GPRS Integration for Next-generation Mobile Data Networks," *IEEE Wireless Commun.*, vol. 9, Oct. 2002, pp. 112–24.
[5] 3GPP TS 23.060, "General Packet Radio Service (GPRS); Service Description; Stage 2," 2004.
[6] 3GPP TS 29.060, "General Packet Radio Service (GPRS); GPRS Tunneling Protocol (GTP) Across the Gn and Gp Interface," 2004.
[7] S. Aust *et al.*, "Design Issues of Mobile IP Handoffs between General Packet Radio Service (GPRS) Networks and Wireless LAN (WLAN) Systems," *Proc. 5th Int'l. Symp. Wireless Pers. Multimedia Commun.*, Honolulu, HI, Oct. 2002, pp. 868–72.
[8] M. Ylianttila *et al.*, "Optimization Scheme for Mobile Users Performing Vertical Handoffs between IEEE 802.11 and GPRS/EDGE Networks," *Proc. IEEE GLOBECOM*, San Antonio, TX, Nov. 2001, pp. 3439–43.
[9] L. Morand and S. Tessier, "Global Mobility Approach with Mobile IF in All IP Networks," *Proc. IEEE ICC*, New York, NY, Apr. 2002, pp. 2075–79.
[10] J. Ala-Laurila, J. Mikkonen, and J. Rinnemaa, "Wireless LAN Access Network Architecture for Mobile Operators," *IEEE Commun. Mag.*, vol. 39, Nov. 2001, pp. 82–89.
[11] M.-C. Jiang, J.-C. Chen, and Y.-W. Liu, "WLAN-Centric Authentication in Integrated GPRS-WLAN Networks," *Proc. IEEE VTC*, Orlando, FL, Oct. 2003, pp. 2242–46.
[12] 3GPP TS 29.061, "Interworking between the Public Land Mobile Network (PLMN) Supporting Packet-Based Services and Packet Data Network (PDN)," 2004.

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