Design and Analysis of a Mobility Gateway for GPRS-WLAN Integration

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***Abstract*— This paper presents the design and analysis of *GPRS-WLAN Mobility Gateway (GWMG)* for the integration of GPRS and wireless LANs (WLANs). The interworking between GPRS and WLANs is achieved by the GWMG 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 GWMG, users can seamlessly roam among the two systems. Unlike other related work, the proposed GWMG could be used when either the GPRS or WLAN is a user's home network. Both mathematical analysis and simulation are developed to analyze the performance. The proposed GWMG has also been implemented in a testbed comprising a commercial GPRS system. The results show that the GWMG could achieve the design goal to effectively integrate GPRS and WLANs.**

***Index Terms*— mobility management, GPRS, wireless LANs, interworking, all-IP wireless networks, performance analysis**

I. 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 current available data rate is in the range of $20 - 170\ Kbps$. 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 and high-speed applications. The bit rate of IEEE 802.11b can achieve $11\ Mbps$, while IEEE 802.11a/g/n and European Telecommunications Standards Institute (ETSI) HIPERLAN/2 have defined standards with bit rate greater than $50\ Mbps$. 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 to 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 the standardization for the integration of WLANs and 3G/GPRS. In [1], [2], the 3G Partnership Project (3GPP) defines the requirements, principles, and interworking scenarios for the integration of WLANs and 3GPP networks. The interworking between HIPERLAN/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 Figure 1, a WLAN is connected to the 3G/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 coupling 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 Serving GPRS Support Node (SGSN) through a *GPRS Interworking Function (GIF)*[1] by the G_b interface as shown in Figure 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 paper presents the design and analysis of a *GPRS-WLAN Mobility Gateway (GWMG)* to integrating GPRS and WLAN systems. The proposed model is based on loose coupling architecture. 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 paper emphasizes on *mobility* integration based on Internet Protocol (IP), a promising universal network-layer protocol to integrate heterogeneous wireless systems. GPRS introduces two special nodes, the Gateway GPRS Support Node (GGSN) and the SGSN, and GPRS Tunneling Protocol (GTP) to provide IP services [5], [6], [7]. 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

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[1] The name of the *interworking function* may be different in different proposals.

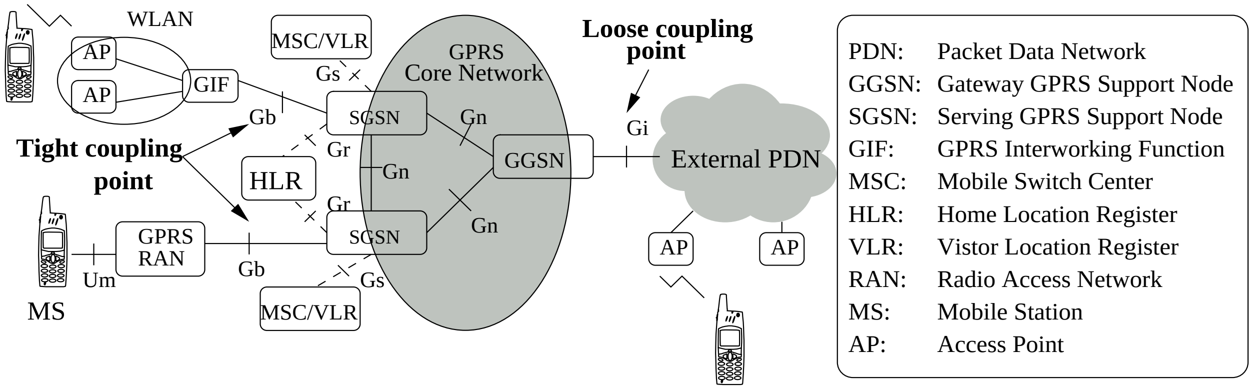

Fig. 1. Loose coupling vs. tight coupling

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 paper 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 systems and available in the market already, our design goal is to minimize modifications to both systems. Although there are many design alternatives, 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 lengthy standardization process. The proposed GWMG 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 GWMG in a commercial GPRS network operated by the Taiwan Cellular Corporation (TCC), one of the biggest cellular operators in Taiwan. The GWMG connects the GPRS network to an IEEE 802.11b network with Mobile IPv4 running on top of it. Although IPv6 might be more efficient than IPv4, it however is not 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 presenting the design of GWMG, this paper also constructs mathematical models to evaluate the performance. The analysis is validated by extensive simulation. The implementation and experimental results are reported in [8]. A list of acronyms in this paper can be found in Table I.

Section II discusses essential principles for the integration of GPRS and WLANs. Section III surveys related work. Section IV presents the design of GWMG. Section V develops mathematical models to quantify the performance. Numerical results are discussed in Section VI. Section VII summarizes the paper.

II. DESIGN PRINCIPLES

There could be different approaches for the integration of GPRS and WLANs. As mentioned above, our objective is to design an architecture and mobility management protocol so users can roam seamlessly between GPRS and WLANs. In this section, we delineate the essential principles of our design.

TABLE I
ACRONYMS

AP	Access Point
APN	Access Point Name
BSS	Base Station System
CN	Correspondent Node
FA	Foreign Agent
GGSN	Gateway GPRS Support Node
GIF	GPRS Interworking Function
GMM	GPRS Mobility Management
GPRS	General Packet Radio Service
GTP	GPRS Tunneling Protocol
GWMG	GPRS-WLAN Mobility Gateway
HA	Home Agent
IMS	IP Multimedia Subsystem
IP	Internet Protocol
MIP	Mobile IP
MMPP	Markov-Modulated Poisson Process
MS	Mobile Station
PDP	Packet Data Protocol
PSTN	Public Switched Telephone Network
RAN	Radio Access Network
SGSN	Serving GPRS Support Node
SIM	Subscriber Identity Module
TEID	Tunnel Endpoint ID
UE	User Equipment
WLAN	Wireless Local Area Network

1) *IP-layer integration:* The integration should be based on IP layer so the underlying WLANs could be based on IEEE 802.11, HIPERLAN, or any other radio technologies.
2) *Minimizing modifications to standards:* This paper considers the integration of WLANs with GPRS rather than 3G. GPRS has been in the market for a while. Although 3G systems have been deployed, it is expected that GPRS will still be operated for a certain time. Many operators have invested many equipments for GPRS. They will not obsolete GPRS equipments unless GPRS is not profitable. A solution which requires modifications to GPRS standards, thus GPRS equipments, is not likely to be accepted by operators. On the other hand, 3G is still evolving. Modifications to 3G systems may be

adopted by the standards bodies and realized in the future. Therefore, minimizing modifications to GPRS standards would be a key for success. Similarly, the design should minimize the modifications to IP and its mobility protocols.

3) *Easy to deploy:* Both GPRS and WLAN systems are in the market already. The integration is a timely issue. The solution should be easy to deploy and get into market quickly. Based on this principle, IPv4 is preferable than IPv6 because most of GPRS and WLAN systems are using IPv4.
4) *Independent of operator:* Currently, GPRS usually is owned by a licensed cellular operator. Many WLAN systems, however, are managed by a different provider, such as a university, company, or Internet Cafe. The solution should not require that a WLAN is owned and operated by the GPRS operator. Based on this principle, loose coupling may be more feasible.
5) *Independent of home network:* Because GPRS and WLAN systems may be owned and operated by different providers, they may have their own subscribers. A subscriber of a WLAN system is not necessary to be a subscriber of a GPRS system. The user profile and authentication information may be kept in the WLAN system only but not the GPRS. Similarly, the user profile of a GPRS subscriber may be kept in the GPRS only but not the WLAN. Therefore, the *home network* of a user may be in a WLAN or a GPRS system.
6) *Service continuity:* The solution should allow service continuity so users do not need to reestablish the service when handing off between GPRS and WLAN systems.

III. RELATED WORK

The paper [4] summarizes recent activities in WLAN-GPRS integration and provides an extensive overview of the tight coupling and loose coupling models. Various work based on loose coupling has been reported [9], [10], [11], [12]. In [9], the authors present a prototype for handoffs between GPRS and Mobile IP. In the proposed architecture, GPRS connects to the Internet by a special designed Foreign Agent (FA) and is considered as one of the *Foreign Networks* of the Mobile IP. Users affiliated with a Mobile IP Home Network could roam between the GPRS and other Mobile IP foreign networks. It, however, does not consider that a GPRS subscriber may not affiliate with any Home Agent (HA) in the Mobile IP network. In addition to the scenario presented in [9], our design also allows users to have a GPRS as their home network and roam from the GPRS to other Mobile IP networks. The network performance for handoffs between WLAN and GPRS/EDGE networks is investigated in [10]. The architecture studied is similar to that in [9]. In [11], the authors depict a mobility approach for all-IP networks in which various types of access networks such as WLAN, GPRS, PSTN, attach to an IP core network with Mobile IP as the mobility management protocol. This paper, again, assumes that the HA resides inside IP core network and GPRS connects to the IP core network through a Gateway Foreign Agent (GFA) as one of the foreign networks.

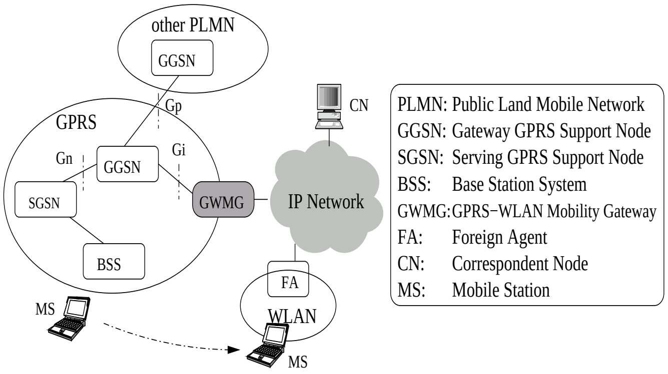

Fig. 2. Architecture of the proposed GWMG design

In real world, GPRS is an independent network which connects to other IP networks without relying on a Mobile IP backbone. [12] proposes a loose coupling architecture in which WLAN system is owned by cellular operator. Although roaming is discussed, this paper focuses more on how to utilize Subscriber Identity Module (SIM) card for authentication and secure access in WLAN system.

3GPP, on the other hand, assumes that the backbone is based on 3G/GPRS. A WLAN is simply a RAN attaching to the 3G/GPRS core network. 3GPP has defined the requirements, principles, and interworking scenarios for integration of WLANs and *3GPP networks*. 3GPP 22.934 [1] specifies that *"the intent of 3GPP-WLAN interworking is to extend 3GPP services and functionality to the WLAN access environment. Thus the WLAN effectively becomes a complementary radio access technology to the 3GPP system."* Similar statement is declared in 3GPP 23.234 [2] as well. In 3GPP, basically a WLAN device is a User Equipment (UE) utilized by a *3GPP subscriber* to access the WLAN [2]. Although a 3G subscriber is able to access to a WLAN, the 3G network is the home network of the user. The design principles are not necessary same as ours, in which either GPRS or WLAN can be a user's home network.

There are also some recent papers discussing the seamless interworking of WLAN and cellular networks. The framework proposed in [13] assumes there is a common IP core network for the integration. As discussed earlier, we consider that GPRS and WLAN are two independent networks and are connected to each other directly. [14] proposes a SIP-based approach. It utilizes the IP multimedia subsystem (IMS) which does not exist in GPRS. We aim to propose a way which can be realized in *GPRS* immediately. [15] proposes an architecture based on Mobile IPv6. Again, Mobile IPv6 is not widely deployed now. Our objective is to provide an immediate solution.

IV. DESIGN OF GPRS-WLAN MOBILITY GATEWAY (GWMG)

The gateway approach presented in this paper is based on loose coupling model. The architecture is depicted in Figure 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. The two systems connect to each other directly by a gateway. The *IP Network* shown in Figure 2 could be a university network that connects various WLANs together. We consider the case that a GPRS subscriber who is not affiliated with the university hands off from a GPRS network to the 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. When roaming between GPRS and WLAN, a session will be redirected to the new system so the session will not break. A service can continue without reestablishing the service, which essentially meets the requirements of the *Scenario 4* defined in 3GPP 22.934 [1]. Compared to other loose coupling work, 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 of the user. Although the proposed design incorporates security and mobility management, this paper 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 paper can be found in [16].

In GPRS, the GPRS Mobility Management (GMM) supports mobility management functions such as GPRS Attach, GPRS Detach, and Routing Area Update [7]. 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 GWMG, 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) could function as they are. The GWMG is a logical entity that could be implemented stand-alone 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 GWMG is designed to function as both Home Agent (HA) and Foreign Agent (FA). Therefore, the GWMG is a *gateway GGSN* combining HA and FA. In this paper, the GWMG is also referred to as GGSN/HA or GGSN/FA, depending on the context. Section IV-A and Section IV-B present the cases when a user has a home network in a WLAN system and a GPRS system, respectively.

A. 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 anchor point. The home network should tunnel traffic to the mobile station's current location if the mobile station (MS) is not inside its home network. In this scenario, the GWMG should function like a GGSN/FA. In 3GPP TS 29.061 [17], 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. Although the location of HA is out of the scope 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 PDP (Packet Data Protocol) Context Activation request with *MIPv4FA* as the APN, which instructs the SGSN to forward the request to the GGSN with FA service, that is, the GWMG. 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 GWMG). The GWMG 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 WLAN systems. In this example, the MS has its home network in the WLAN domain, and the CN is outside the GPRS. In Figure 3, the MS first attaches to the GPRS system and activates its PDP context. This may be because the 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 GWMG (GGSN/FA). When the MS is performing a standard GPRS attach, the GWMG 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 GWMG 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 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, that is, its home network[2], MIP de-registration[3] 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.

Figure 4 shows a similar example except that the CN is inside the GPRS system. Once CN and MS attach to GPRS successfully, packets from CN to MS will be tunneled to the

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[2] The MS' in Figure 3 represents the new location of the MS after roaming into a WLAN.

[3] In MIP, de-registration is done by sending a Registration Request in which the lifetime field is set to zero.

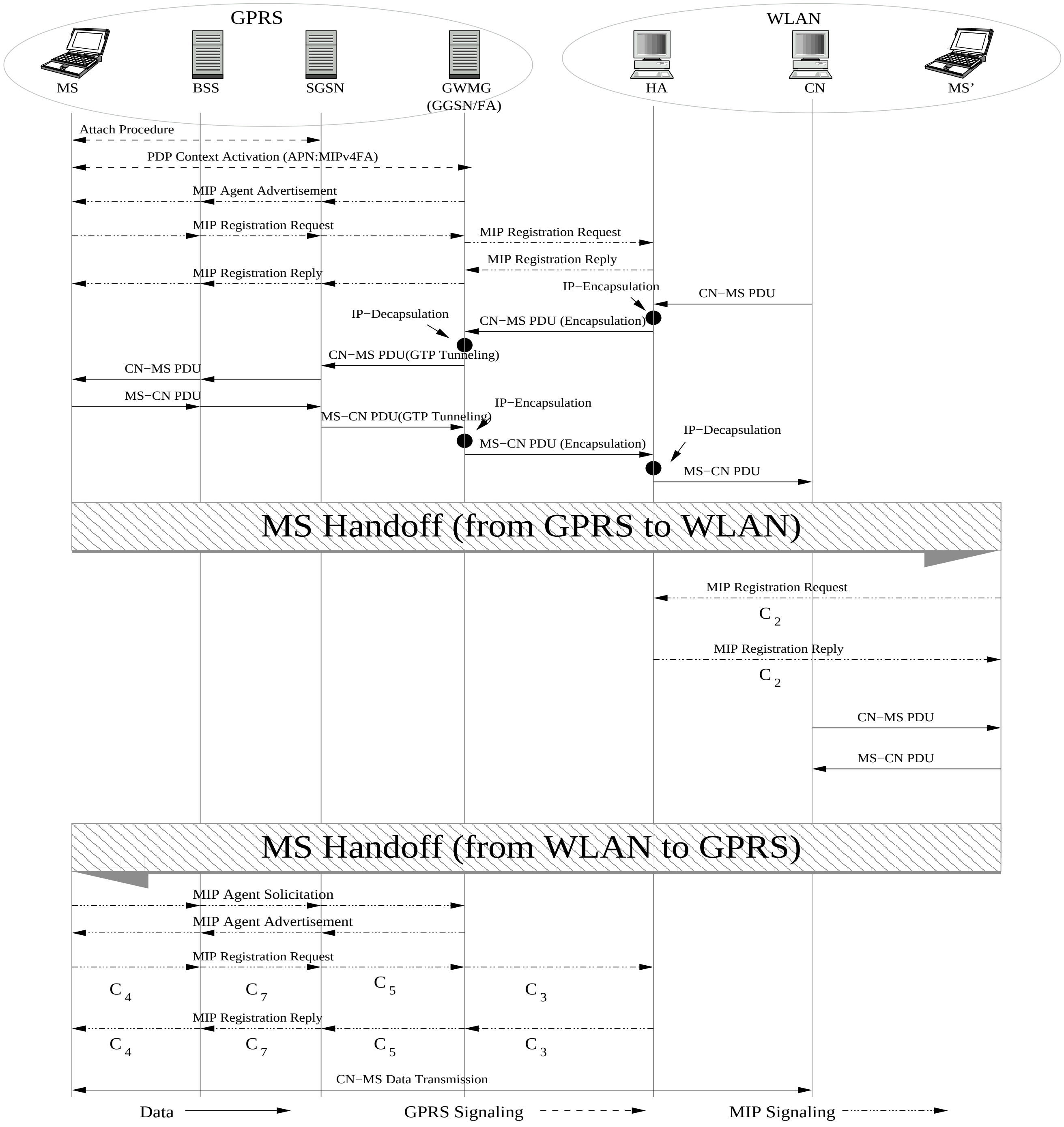


Fig. 3. Intersystem roaming: the home network is in a WLAN (CN is outside GPRS)

MS’s serving GGSN, which is the GWMG, as that defined in GPRS. The GWMG may tunnel packets to the proper SGSN if it knows the mapping between the IP address and the TEID. Otherwise, packets from CN will be sent to the HA in the home network then be delivered to the MS as shown in Figure 4. If reverse tunneling is implemented, the reply from the MS would be transmitted along the same path to the HA then the CN. When the MS moves into its home network (WLAN), the MS first de-registers with its HA. Other flows are standard transmissions between GPRS and external networks. Like that in Figure 3, the MS may reuse previous PDP context once it moves to GPRS again.

B. *Home in a GPRS Network*

The GGSN/FA approach described above presumes that there is a WLAN that is the home network of the MS. Many users, however, may have subscribed to GPRS services but will roam into a WLAN which the user is not affiliated with. The home network is the GPRS and there is no HA for the MS in the WLAN. It is possible that this type of users still want to be reachable by their home GPRS network after roaming into the WLAN. For this scenario, the GWMG shown

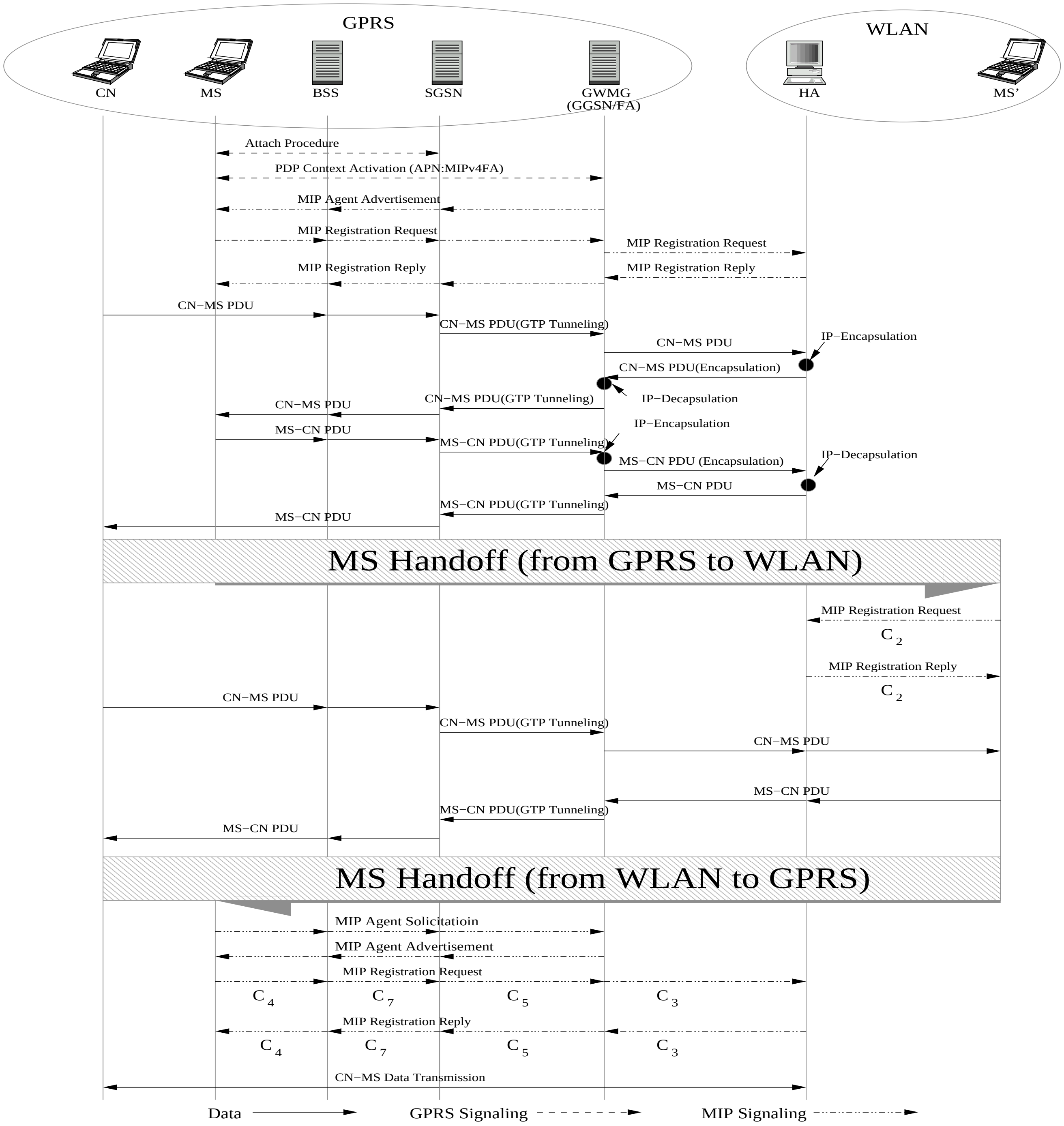


Fig. 4. Intersystem roaming: the home network is in a WLAN (CN is inside GPRS)

in Figure 2 functions as a gateway GGSN combining with HA (GGSN/HA). It connects to other GGSNs through the standard G_i interface. Once moving into a WLAN, an MS will send MIP registration messages to its HA (the GWMG). Therefore, packets initiated from external packet data networks (WLANs) will be intercepted by the GWMG and be tunneled to the MS. The GGSN functionality in the GWMG 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 GWMG and sent to the current location of the MS if the MS is in a WLAN.

Figure 5 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 GWMG (GGSN/HA), which initiates an MIP Agent Advertisement after the PDP context is created. The MS may perform MIP de-registration 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

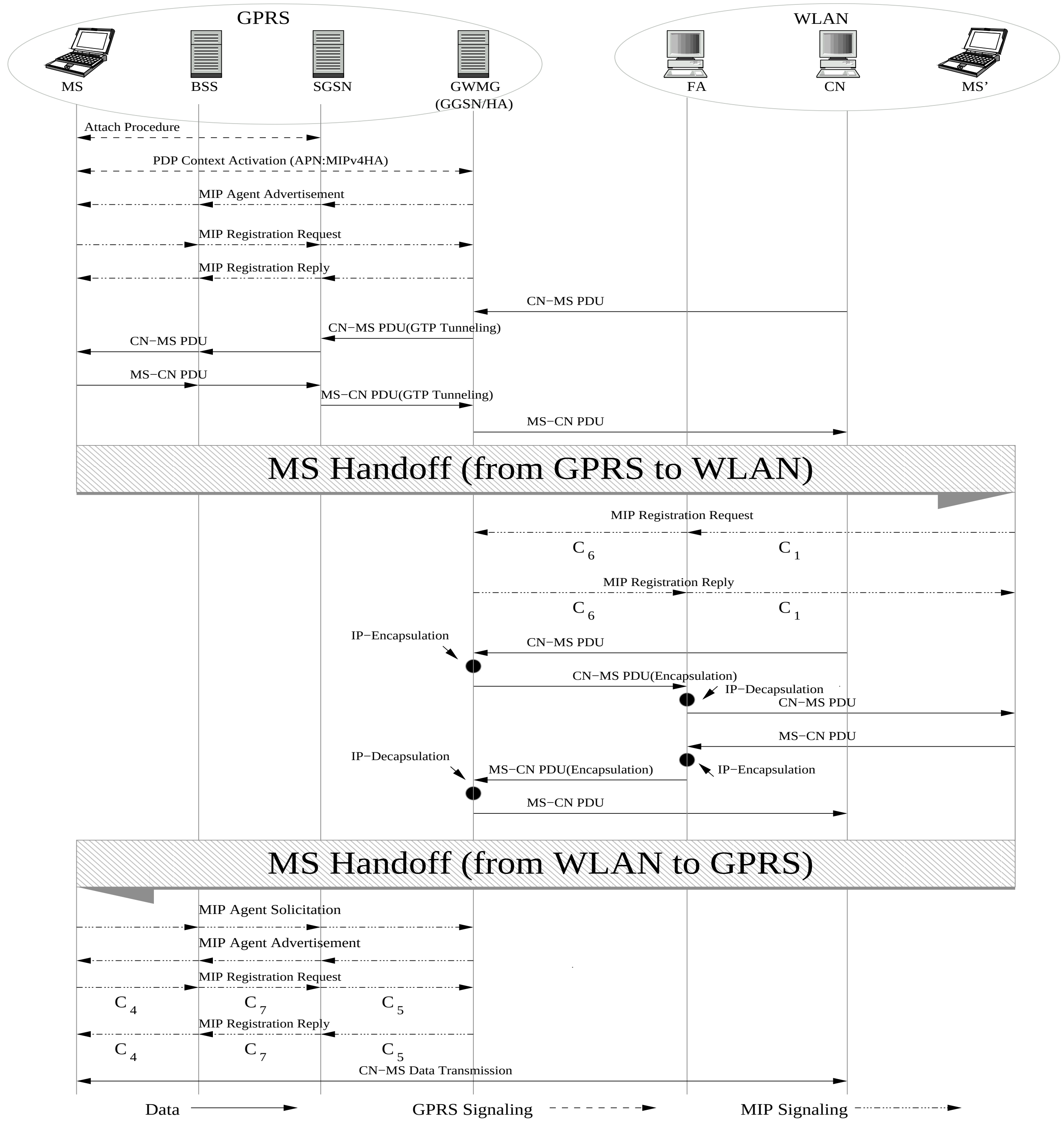


Fig. 5. Intersystem roaming: the home network is in a GPRS (CN is outside GPRS)

network. When a CN wishes to send packets to the MS, by default the packets will reach the GWMG because the GWMG is the MS's serving GGSN. The GGSN functionality in the GWMG 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 GWMG 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 GGSN/HA (GWMG). Packets from the CN, therefore, will be intercepted and tunneled by the GWMG to the new location of the MS. Figure 5 assumes that reverse tunneling is implemented. Thus, packets from MS to CN will go through the GGSN/HA. When the MS moves back to the GPRS, the MS de-registers with the HA (GWMG). If the PDP context created earlier is still alive, the MS can just resume its transmission. Otherwise, a new PDP context will be created as discussed earlier.

Figure 6 illustrates the case when the CN is inside GPRS network. As shown in the figure, packets from CN will arrive at the GWMG, which will tunnel packet to the MS by using GTP tunneling when both MS and CN are inside GPRS. This is a standard procedure in GPRS. Once the MS roams into a

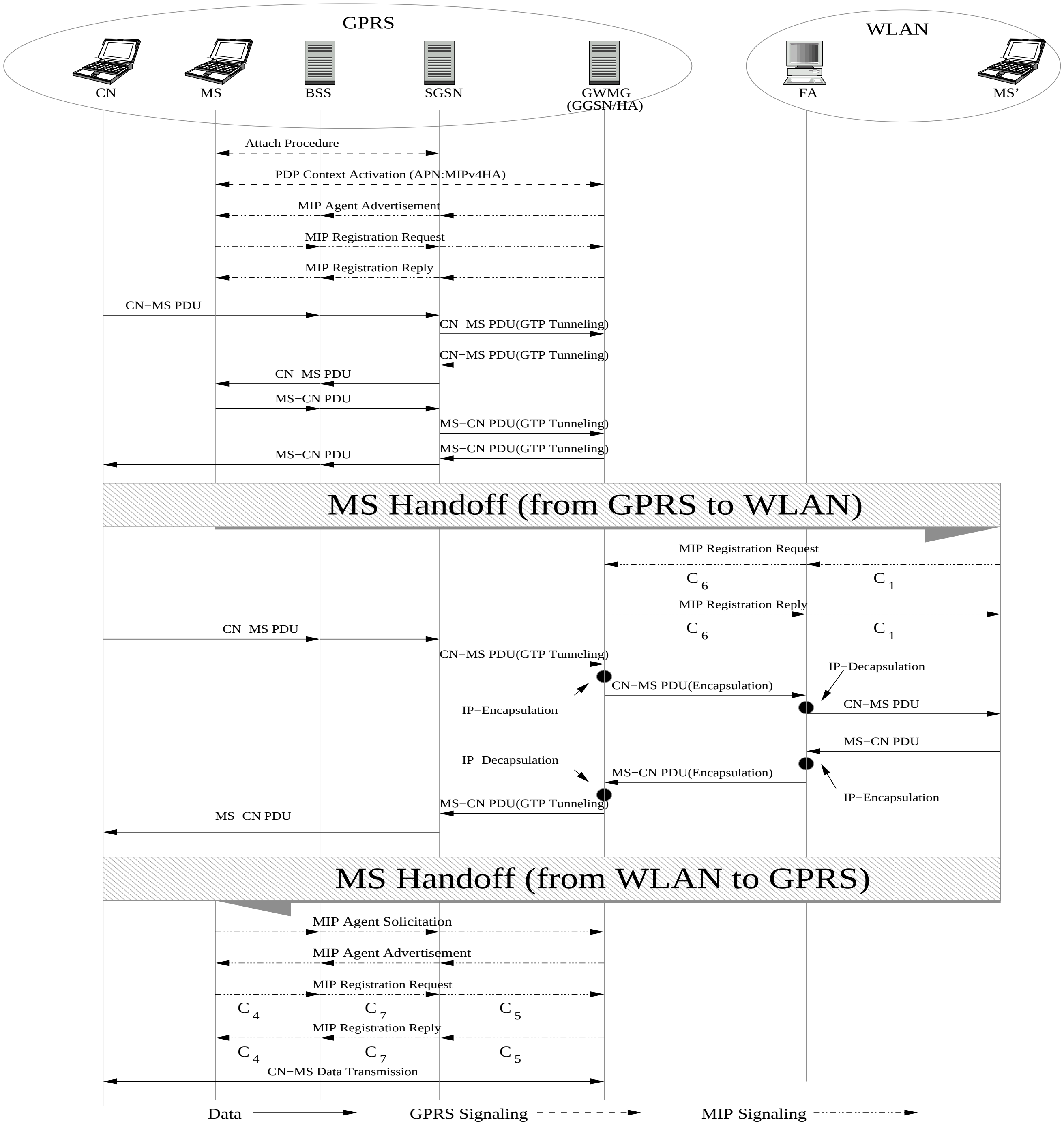


Fig. 6. Intersystem roaming: the home network is in a GPRS (CN is inside GPRS)

WLAN, the MS registers its new location with the GGSN/HA. The GGSN part in the GWMG then updates its routing policy. Instead of tunneling packets to any SGSN, the GGSN part of the GWMG will pass packets to the HA in the GWMG, which further tunnels packets to the MS. Therefore, packets from the CN will be tunneled by the GWMG to the MS in the WLAN. When the MS roams back to the GPRS network, it de-registers with the GGSN/HA. The MS can use the same PDP context created earlier or it will create a new one. Communications then are resumed by using GTP tunneling as discussed earlier.

C. 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, quality of service, and billing. Normally WLAN would be a better choice if available. It is also possible to utilize both systems for data transmission simultaneously. Some strategies for the selection of radio interfaces have been proposed [18], [19], [20]. The proposed architecture and GWMG should be able to work with any of them. This paper mainly considers the mobility management

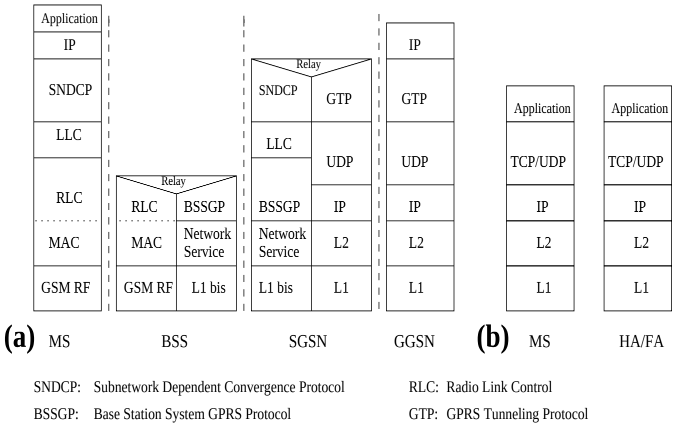


Fig. 7. Dual protocol stacks in MS

issues caused by switching between different radio interfaces, that is, handing off between different systems. Once a new interface is determined based on the interface selection algorithm, the mechanisms discussed in Section IV-A and Section IV-B will be used to deal with the handoff from one system to the other, and keep the session alive.

Two simple policies for interface selection have been proposed and implemented in our testbed: *WLAN-preferred* and *user-triggered* [8]. In WLAN-preferred mode, the link quality is tracked. It changes to WLAN interface automatically if a WLAN system is available. In user-triggered mode, the link quality is tracked and reported to the user. The decision to switch between systems, however, is based on user command.

D. System Requirements

This section discusses the system requirements of our design.

1) Requirements for GPRS and WLAN Systems: Based on above discussion, one can see that both GPRS and Mobile IP can work as they are. The GWMG functions as GGSN, HA, and FA. By deploying the GWMG, the integration of mobility management in GPRS and WLAN systems can be achieved without any modification. Compared to other approaches, our approach is easier to deploy and should be more preferable by GPRS and WLAN providers.

2) 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 Figure 7. Figure 7 (a) represents the user plane of GPRS, while Figure 7 (b) shows a conventional Internet protocol 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 GWMG, the protocol stacks in the terminal *do not* need to be modified either. To deal with dual radios, the handoff management presented in Section IV-C should be implemented to trigger the switch between different systems. This is also inevitable for any approach.

V. PERFORMANCE ANALYSIS

The proposed GWMG was initially implemented in a GPRS system we purchased from the Industrial Technology Research Institute (ITRI). It was then implemented in a commercial GPRS system operated by the Taiwan Cellular Corporation (TCC). The GPRS system connected to a 802.11b WLAN system. The implementation of a testbed aims to realize the proposed idea and perform various experiments. The testbed architecture and detailed experimental results are presented elsewhere [8]. The experiments were conducted to measure handoff latency, TCP packet delay, and video throughput in the testbed. For handoff latency, results show that the handoff latency from WLAN to GPRS was longer than the handoff latency from GPRS to WLAN. This is 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. The TCP packet delays in GPRS were higher than the TCP packet delays in WLAN because the maximum data rate in the GPRS testbed was $40.2\ Kbps$, which was much lower than the $11\ Mbps$ data rate in IEEE 802.11b. Similar to the TCP packet delay, we observe that the video quality was much better when the MS was in WLAN.

This section analyzes the performance of the proposed GWMG. Because this paper mainly considers the mobility management issues caused by handing off between different systems, *handoff latency* is an important performance metric. As shown in Figures 3–6, there are many signaling flows. Therefore, the other metric for the performance analysis is *signaling and database cost*. Because the integration of mobility management is based on IP layer, we ignore the cost and latency incurred in other layers. The objective of this section is to develop simple but effective models to quantify the performance of the proposed architecture and GWMG.

A. Signaling and Database Cost

In order to model *signaling cost*, we first label the transmission costs with c_i ($i = 1 \cdots 7$) between system nodes as indicated in Figures 3–6. Here we only consider the signaling cost directly related to handoff between two systems. The *database cost* refers to the cost for accessing the system node. The database cost for SGSN is denoted as a_{SGSN}. Similarly, a_{BSS}, $a_{GGSN/HA}$, $a_{GGSN/FA}$, a_{HA}, and a_{FA} represent the database costs for accessing the corresponding system nodes. Table II summarizes the parameters.

The signaling and database cost is denoted as:

$$\begin{aligned} C(\text{weight cost}) = \\ P_i[\alpha\ C_s(\text{signaling}) + \beta\ C_d(\text{database})] + \\ (1 - P_i)[\alpha\ C_s^{'}(\text{signaling}) + \beta\ C_d^{'}(\text{database})] \end{aligned} \tag{1}$$

where α and β are weight factors for signaling cost and database cost. P_i ($i = 1$ or 2) is the roaming probability defined in Table II. $C_s(.)$ and $C_d(.)$ represent the signaling cost and database cost, respectively, for the following four

TABLE II

SYSTEM PARAMETERS FOR SIGNALING AND DATABASE COST

c_1	signaling cost between MS and FA
c_2	signaling cost between MS and HA
c_3	signaling cost between HA and GGSN/FA (GWMG)
c_4	signaling cost between MS and BSS
c_5	signaling cost between SGSN and GGSN/FA (GWMG)
c_6	signaling cost between FA and GGSN/HA (GWMG)
c_7	signaling cost between BSS and SGSN
α	weight for signaling cost
β	weight for database cost
P_1	probability for moving to WLAN when MS is in GPRS
P_2	probability for moving to GPRS when MS is in WLAN
$C_s(.)$	signaling cost
$C_d(.)$	database cost

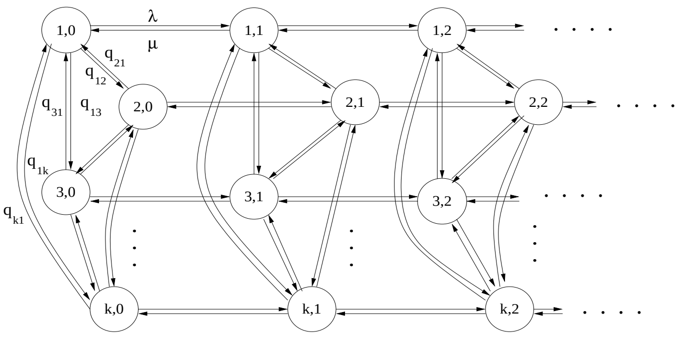


Fig. 8. State diagram

scenarios: (1) home network is in WLAN and MS moves from GPRS to WLAN; (2) home network is in WLAN and MS moves from WLAN to GPRS; (3) home network is in GPRS and MS moves from GPRS to WLAN; and (4) home network is in GPRS and MS moves from WLAN to GPRS. The cases of $1 - P_i$ represent the scenarios that the MS is moving inside the system the MS is current staying. Because this paper mainly considers the interworking between GPRS and WLAN systems, the cost for moving inside a same system is ignored. Therefore, $C^{'}_s(.)$ and $C^{'}_d(.)$ are 0. The $C_s(.)$ and $C_d(.)$ with $i = 1$ and 2 can be derived from Figures 3–6. For scenario (1): home network is in WLAN and MS moves from GPRS to WLAN, for example, the corresponding costs can be found in Figure 3. By looking at the center part of Figure 3 for handing off from GPRS to WLAN, we can see that the signaling cost is $2c_2$. From the figure, we can also see that only HA is accessed. Therefore, the database cost is a_{HA}. The results are put in row 1 of Table III. Results of other scenarios are listed in Table III as well. By replacing the signaling cost and database cost in Table III into Equation (1), one can derive the weight cost of the four scenarios listed above.

B. Handoff Latency

As shown in Figures 3–6, the MS needs to perform MIP registration and/or PDP context activation for handing off from one system to another. There are message exchanges between MS and several *system nodes* including GWMG, SGSN, BSS, HA, and FA. We first develop a generic model to calculate the average packet waiting time in each system node. Assuming the mean service rates of GWMG, SGSN, BSS, HA, and FA are μ_{GWMG}, μ_{SGSN}, μ_{BSS}, μ_{HA}, and μ_{FA}, respectively. Because the design is based on IP layer, we ignore the handoff latency incurred in other layers. The performance of the proposed mechanisms does not depend on the handoff delays in other layers.

Recent studies have shown that Markov-Modulated Poisson Process (MMPP) [21] is more realistic than traditional Poisson process to model packetized multimedia traffic. We therefore employ *MMPP/M/1* queuing model to derive average packet waiting time in each system node. A packet is generated based on two-state MMPP model. The two-state MMPP is specified by two-state Markov chain with the infinitesimal generator Q and the Poisson arrival rates λ_1, λ_2 of state 1 and state 2:

$$Q = \begin{pmatrix} -\sigma_1 & \sigma_1 \\ \sigma_2 & -\sigma_2 \end{pmatrix} \qquad \Lambda = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} \tag{2}$$

where σ_1 is the transition rate from state 1 to state 2. σ_2 is the transition rate from state 2 to state 1.

Assuming there are n numbers of mobile stations, each of them possesses the same MMPP behavior. The generator $\mathbf{Q}$ and rate matrix $\mathbf{\Lambda}$, therefore, are the superposition of the individual generators Q_i and rate matrices Λ_i:

$$\mathbf{Q} = Q_1 \oplus Q_2 \oplus \cdots \oplus Q_n \tag{3}$$

$$\mathbf{\Lambda} = \Lambda_1 \oplus \Lambda_2 \oplus \cdots \oplus \Lambda_n \tag{4}$$

where $\oplus$ represents the Kronecker-sum, which is defined as follows:

$$A \oplus B = (A \otimes I_B) + (I_A \otimes B) \tag{5}$$

where $\otimes$ represents the Kronecker-product:

$$C \otimes D = \begin{pmatrix} c_{11}D & c_{12}D & \cdots & c_{1m}D \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1}D & c_{n2}D & \dots & c_{nm}D \end{pmatrix} \tag{6}$$

I_A and I_B are identity matrices with the same dimension as A and B, respectively. If Q_i and Λ_i are $k_i \times k_i$ matrices, $\mathbf{Q}$ and $\mathbf{\Lambda}$ are $k \times k$ matrices, where $k = \prod_{i=1}^{n} k_i$.

Based on MMPP/M/1 queue, Figure 8 shows the states and state transitions in a node. The state (i, j) denotes a process of $\{J(t), N(t), t \geq 0\}$ which is a homogeneous continuous-time Markov chain. $J(t)$ and $N(t)$ denote the state of Markov chain and the number of arriving packets at time t, respectively. We can solve the steady-state vector π of the MMPP by the following equations:

$$\pi \mathbf{Q} = 0, \quad \pi e = 1 \tag{7}$$

where e is $[1, 1, \cdots, 1]^T$.

Let $p_{i,m}$ be the steady-state probability in which i represents the state and m is the number of packets in the queue. By employing the steady-state balance equations, we can solve $p_{i,m}$:

TABLE III

SIGNALING AND DATABASE COST

Home	Probability	C_s(signaling)	C_d(database)
WLAN	P_1	$2c_2$	a_{HA}
	P_2	$2c_4 + 2c_5 + 2c_3 + 2c_7$	$a_{BSS} + a_{SGSN} + a_{GGSN/FA} + a_{HA}$
GPRS	P_1	$2c_1 + 2c_6$	$a_{FA} + a_{GGSN/HA}$
	P_2	$2c_4 + 2c_5 + 2c_7$	$a_{BSS} + a_{SGSN} + a_{GGSN/HA}$

$$p_{i,m} = \pi_i(1-\rho_i)\rho_i^m \tag{8}$$

where ρ_i is λ_i/μ and π_i is the i'th element of π.

The average number of packets in the node and the average arrival rate, thus, can be derived as follows:

$$E[\text{number of packets}] = \sum_{i=1}^{k}\sum_{m=1}^{\infty}(m-1)\times p_{i,m} \tag{9}$$

$$\lim_{t\to\infty} E[N(t)]/t = \pi\lambda \tag{10}$$

Therefore, the average waiting time can be obtained based on the average number of packets and the average arrival rate:

$$E[\text{waiting time}] = E[\text{number of packets}]/\pi\lambda + 1/\mu \tag{11}$$

Section IV discusses two cases in which home network may be in a GPRS or WLAN system. First, let us consider the case when home network is in a WLAN and CN is outside GPRS. The handoff latency is the time from MS sends out the MIP registration message until the time MS registers with HA successfully. Let n be the total number of MSs in the integrated system. If there are m number of MSs in GPRS, there are $n-m$ number of MSs in WLAN, where $m = 0, 1, 2, ...n$. There are $(n+1)$ possibilities to represent the distribution of MSs in GPRS and WLAN systems. Thus, the handoff latency can be obtained by averaging the $(n+1)$ possibilities:

$$\begin{aligned} &D_g\{\text{average handoff latency from WLAN to GPRS}\} = \\ &\quad \frac{1}{n}\{d_g\{\text{0 user in GPRS, n users in WLAN}\} + \cdots \\ &\quad\quad +d_g\{\text{(n-1) users in GPRS, 1 user in WLAN}\}\} \end{aligned} \tag{12}$$

$$\begin{aligned} &D_w\{\text{average handoff latency from GPRS to WLAN}\} = \\ &\quad \frac{1}{n}\{d_w\{\text{n users in GPRS, 0 user in WLAN}\} + \cdots \\ &\quad\quad +d_w\{\text{1 user in GPRS, (n-1) users in WLAN}\}\} \end{aligned} \tag{13}$$

In Equation (12), $d_g\{x$ users in GPRS, y users in WLAN$\}$ represents the handoff delay that x users in GPRS and y users in WLAN and at this moment one user will roam to GPRS. $D_g\{$average handoff latency from WLAN to GPRS$\}$ is the average delay for users roaming from WLAN to GPRS. Similarly, d_w and D_w are functions when users roaming from GPRS back to WLAN. By using Equation (11), the average waiting time in a specific system node can be obtained. D_g and D_w, thus, can be derived by the superposition of the average waiting time in all intermediate nodes the registration message will traverse. All scenarios discussed in Section IV can be analyzed by the same model.

TABLE IV

PARAMETERS FOR SIGNALING COST AND DATABASE COST

Signaling cost							
c_1	c_2	c_3	c_4	c_5	c_6	c_7	α
1	1	1	1	1	1	1	0.5

Database cost						
a_{BSS}	a_{SGSN}	a_{HA}	a_{FA}	$a_{GGSN/FA}$	$a_{GGSN/HA}$	β
3	5	8	5	8	15	0.5

VI. NUMERICAL RESULTS

This section provides the numerical results for the analysis presented in Section V. The analysis is validated by extensive simulation.

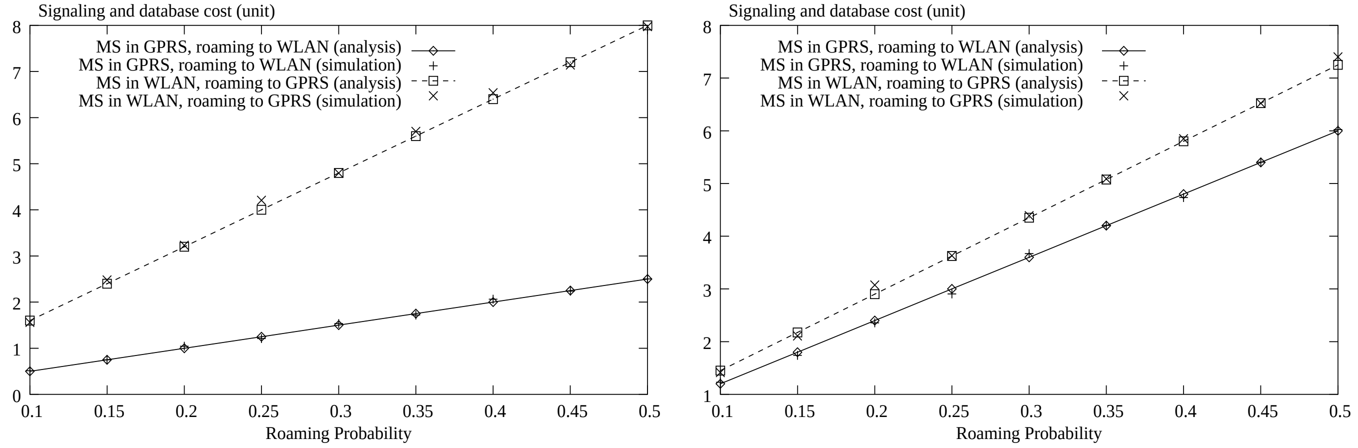
Figure 9 depicts the signaling and database cost. The x-axis represents the roaming probability P_i ($i = 1$ or 2). The y-axis is the weight cost of the singling and database cost. The analytical results in Figure 9 are based on Equation (1) and Table III. Table IV lists the values of the parameters which are reasonably chosen to illustrate the performance. The analytical model developed in Section V is independent of the values. Choosing other values will not change the conclusion drawn from the analysis.

Comparing Figure 9 (a) and (b), it shows that the cost for roaming to GPRS is higher than the cost for roaming to WLAN in either cases. This is because the signaling message in GPRS will pass more system nodes and the database cost in GPRS is higher than that in WLAN. The line of roaming to GPRS in Figure 9 (a) grows faster than that in Figure 9 (b). This is because in Figure 9 (a) the registration messages must be sent back to the MS's home network (WLAN). For the similar reason, the line of roaming to WLAN in Figure 9 (b) increases faster than that in Figure 9 (a).

Figure 10 shows the handoff latency for the scenarios shown in Figures 3–6. There are n MSs, each with roaming probability 0.5. That is, each MS has 0.5 probability to stay in the same system. We assume that traffic is sending from CN to MS. The traffic is generated based on the two-state MMPP. The parameters of Equation (2) are:

$$\mathbf{Q_i} = \begin{pmatrix} -\frac{1}{410} & \frac{1}{410} \\ \frac{1}{15} & -\frac{1}{15} \end{pmatrix} \qquad \mathbf{\Lambda_i} = \begin{pmatrix} 8 & 0 \\ 0 & 0 \end{pmatrix}$$

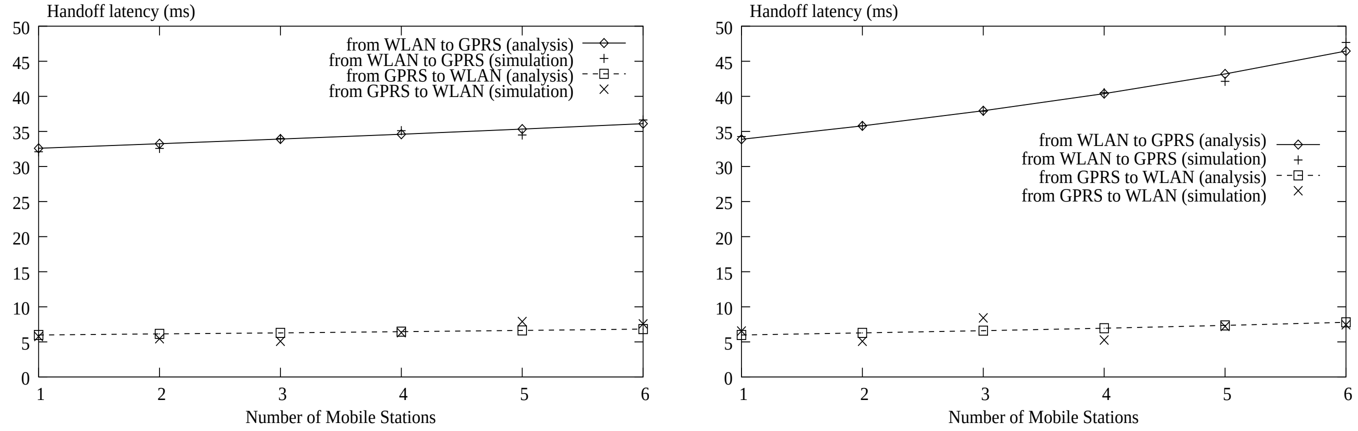
Because $\lambda_2 = 0$, the two-state MMPP represents an ON-OFF source. The service rates are indicated in Table V. Similarly, the values are reasonably chosen to illustrate the performance. The analytical model developed in Section V



(a) Home in WLAN

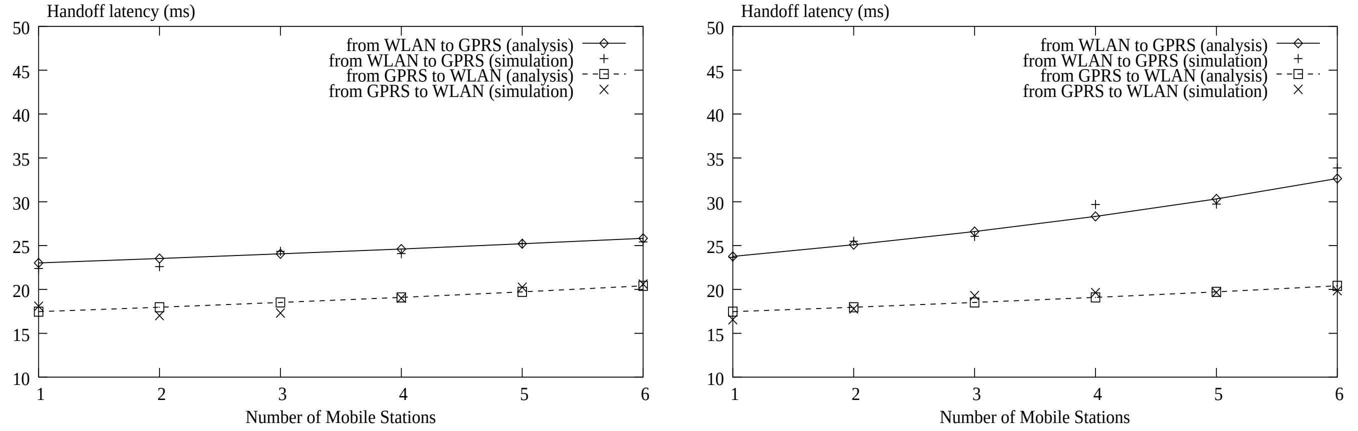
(b) Home in GPRS

Fig. 9. Signaling and database cost



(a) Home in WLAN and CN outside GPRS

(b) Home in WLAN and CN inside GPRS



(c) Home in GPRS and CN outside GPRS

(d) Home in GPRS and CN inside GPRS

Fig. 10. Handoff latency

is independent of the values. Choosing other values will not change the conclusion drawn from the analysis.

Figure 10 (a) depicts the handoff latency when the home network is in a WLAN and CN is outside GPRS, which is correspondent to Figure 3. Figure 10 (a) indicates that the handoff latency from WLAN to GPRS is higher than the handoff latency from GPRS to WLAN. This is because when roaming from WLAN to GPRS, the MIP registration messages need to traverse more system nodes than roaming from GPRS to WLAN. This can also be observed in Figure 3.

Similar to Figure 10 (a), Figure 10 (b) shows the handoff latency when the home network is in a WLAN and CN is

TABLE V

PARAMETERS FOR SERVICE RATE

Service rate (packet/second)				
u_{SGSN}	u_{GWMG}	u_{HA}	u_{FA}	u_{BSS}
225	250	175	150	200

inside GPRS. It is correspondent to Figure 4. In Figure 10 (b), the handoff latency from WLAN to GPRS is also higher than the handoff latency from GPRS to WLAN. Comparing with Figure 10 (a), however, the handoff latency from WLAN to GPRS in Figure 10 (b) grows faster than that in Figure 10 (a) when the number of MSs increases. This is because in Figure 10 (b), CN is inside GPRS. User packets from CN to MS will be delivered from GPRS to the HA in WLAN then be sent back to the MS inside GPRS. There are more packets which contend the resources with the MIP registration messages. When roaming from GPRS to WLAN, the handoff latency in Figure 10 (b) is slightly higher than that in Figure 10 (a). This is because in Figure 10 (a), both MS and CN are inside WLAN. Packets between MS and CN can be sent to each other without going through the HA. Basically, user packets will not compete with the MIP registration messages for the resources in the HA.

Figure 10 (c) is correspondent to Figure 5. Similar to that in Figure 10 (a), the handoff latency from WLAN to GPRS is higher than the handoff latency from GPRS to WLAN. Comparing Figure 3 with Figure 5, we can see that the MIP registration messages traverse more system nodes when roaming from GPRS to WLAN when the home network is in a GPRS. In addition, there are more user packets which tend to compete with the MIP registration messages. Thus, the handoff latency from GPRS to WLAN in Figure 10 (c) is higher than that in Figure 10 (a). With the similar reason, the handoff latency from WLAN to GPRS in Figure 10 (c) is lower than that in Figure 10 (a).

Figure 10 (d) is correspondent to Figure 6. The results are similar to Figure 10 (b). The comparison with other figures should be similar to the discussion above.

The analysis shows that the performance of the GWMG mainly depends on the deployment and service rates of the system nodes. Because there are more processes in GPRS, the handoff latency to GPRS is higher than the handoff latency to WLAN. In addition to exhibiting the characteristics of the design, the analysis quantifies the performance metrics in a systematic way. The conclusion obtained from the analysis and simulation is consistent with the experimental results from the testbed.

VII. SUMMARY

The integration of GPRS and WLANs should benefit both operators and users. However, both GPRS and WLAN systems are in the market already. From operators' point of view, minimizing modifications to existing systems would bring new services into market quickly. It would be a key factor for success. The GWMG proposed in this paper provides a solution to achieve this goal. Unlike other work, the GWMG could be used when either GPRS or WLAN is a user's home network. There are many issues needed to be resolved for the integration of GPRS and WLANs. This paper, by no means, could address all of them. In this paper, we focus on the architecture and mobility management. Generic mathematical models are developed to analyze the performance. It is validated by simulation. Although not discussed in this paper, a testbed based on a commercial GPRS system has been constructed to demonstrate the feasibility of the design. The results show that the proposed GWMG could achieve the design goal and provide a solution to integrate mobility management in GPRS and WLANs effectively.

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