

WGSN: WLAN-based GPRS Support Node with Push Mechanism

VINCENT W.-S. FENG, LIN-YI WU, YI-BING LIN AND WHAI-EN CHEN

*Department of Computer Science and Information Engineering, National Chiao Tung University,
Hsinchu, Taiwan 300, Republic of China*

Email: vincentfeng@itri.org.tw, {lywu, liny}@csie.nctu.edu.tw, cwe@pcs.csie.nctu.edu.tw

This paper proposes wireless LAN (WLAN)-based GPRS Support Node (WGSN), as a solution for integrating Third Generation (3G) and WLAN services. We show that the 3G mechanisms can be re-used for WLAN user authentication and network access without introducing new procedures and without modifying the existing 3G network components. We describe the WGSN features and show how they are designed and implemented. To reduce the power consumption and computation complexity of a mobile station (MS), the WGSN applications may not be activated in the MS if they are not used. For an MS-terminated application, a push mechanism is implemented in WGSN, which automatically activates the application at the MS side. An analytic model is proposed to investigate the requirements on the WGSN transmission delay of the push operation. A WGSN prototype has been implemented in the Industrial Technology Research Institute and National Chiao-Tung University Joint Research Center.

Received 16 June 2003; revised 16 September 2003

1. INTRODUCTION

The 3rd Generation Partnership Project (3GPP) Technical Report 22.934 [1] conducted a feasibility study on the Third Generation (3G) system and wireless LAN (WLAN) interworking that extends 3G services to the WLAN environment. In this interworking, WLAN serves as an access technology to the 3G system, which scales up the coverage of 3G services. Six scenarios were proposed for incremental development of 3G and WLAN interworking. Each scenario enhances interworking functionalities over the previous scenarios as shown in Table 1. The service and operational capabilities of each scenario are described as follows.

Scenario 1 provides common billing and customer care for both WLAN and 3G mobile operators. That is, a customer receives single monthly billing statements combining both 3G and WLAN services. The customer also consults the same customer care center about the problems for both services.

Scenario 2 re-uses 3G access control and charging mechanisms for WLAN services. The WLAN customers are authenticated by the 3G core network without introducing a separate procedure. In addition, the roaming mechanism between the 3G system and WLAN is supported. In this scenario, users can access traditional Internet services but cannot access 3G services (such as circuit-switched (CS) voice and GPRS data services) through WLAN.

Scenario 3 allows a customer to access 3G packet-switched (PS) services over WLAN. The PS services include short message service (SMS) [2], multimedia message service (MMS) [3] and IP multimedia subsystem service (IMS) [4]. Customers equipped with both a WLAN card and 3G module

can simultaneously but independently access WLAN and 3G networks.

Scenario 4 allows a customer to change access between 3G and WLAN networks during a service session. The system is responsible for re-establishing the session without user involvement. Service interruption during system switching is allowed in this scenario. Quality of service (QoS) is a critical issue for service continuity. Since 3G and WLAN networks have different capabilities and characteristics, the user would gain different QoS grades in different networks. Therefore, QoS adaptation is required during system switching.

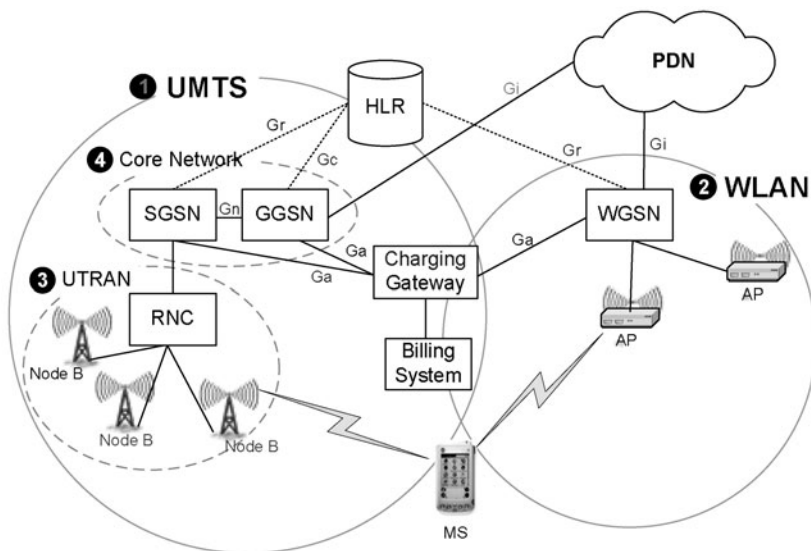
Scenario 5 provides seamless service switching (i.e. hand-over) between the 3G system and WLAN. Techniques must be developed to minimize data lost rate and delay time during switching so that the customer would not experience significant interruption during handover.

Scenario 6 supports 3G CS services in the WLAN environment. The seamless continuity feature described in Scenario 5 is also required to support CS services when customers roam between different networks.

Our survey with several mobile service providers indicates that the Scenario 3 features are essential for commercial operation of 3G/WLAN interworking in the first stage deployment. Depending on the business strategies, the Scenario 4 features may or may not be deployed in the long-term commercial operation. Scenarios 5 and 6 are typically ignored because the benefits of the extra features might not justify the deployment costs. This paper proposes a Universal Mobile Telecommunications System (UMTS) [5] and WLAN interworking solution called WLAN-based GPRS Support Node (WGSN). The features of WGSN are

TABLE 1. Interworking scenarios and service capabilities.

Service capabilities	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Common billing	✓	✓	✓	✓	✓	✓
Common customer care	✓	✓	✓	✓	✓	✓
3G-based access control		✓	✓	✓	✓	✓
3G-based access charging		✓	✓	✓	✓	✓
Access to 3G PS services			✓	✓	✓	✓
Service continuity				✓	✓	✓
Seamless service continuity					✓	✓
Access to 3G CS services with seamless mobility						✓

**FIGURE 1.** WGSN architecture (dashed lines: signaling; solid lines: data and signaling).

described in Section 2. The design and implementation of WGSN components are elaborated in Section 3. The WGSN authentication and network access procedures are given in Section 4. The WGSN push mechanism is analyzed in Section 5. Our approach has similar development goals to the approaches described in [6, 7]. However, we focus more on providing session initiation protocol (SIP) applications (i.e. SIP Application Level Gateway (ALG) and the SIP push mechanism) in the WGSN system.

2. THE WGSN APPROACH

This section describes the architecture and the features of the WGSN. WGSN interworks UMTS with WLAN to support Scenario 3 features described in Section 1.

2.1. WGSN network architecture

Figure 1 illustrates the inter-connection between a UMTS network and a WLAN network through WGSN. The UMTS network (Figure 1, label 1) provides 3G PS services. The WLAN network (Figure 1, label 2) provides access to the Internet. The customers are allowed to roam between the

two networks as long as the Mobile Station (MS) is equipped with both a 3G module and a WLAN card.

The UMTS network includes two sub-networks. The UMTS Terrestrial Radio Access Network (UTRAN; Figure 1, label 3) consists of Radio Network Controllers (RNCs) and Node Bs (i.e. base stations). The radio interface between a Node B and an MS is based on WCDMA radio technology [8]. The UMTS core network (i.e. GPRS network; Figure 1, label 4) consists of Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN), which provide mobility management and session management services to mobile users. An SGSN connects to the UTRAN by Asynchronous Transfer Mode (ATM) links, and communicates with the GGSN through an IP-based backbone network. The GGSN connects to the external Packet Data Network (PDN) by an IP-based interface Gi. Both SGSN and GGSN communicate with the Home Location Register (HLR) through the Gr and Gc interfaces, respectively. These two interfaces are based on the Mobile Application Part (MAP) [9]. The HLR is the master database containing all user-related subscription and location information.

The WLAN radio network includes 802.11-based access points (APs) that provide radio access for the MSs. The WGSN acts as a gateway between the PDN and the WLAN node, which obtains the IP address for an MS from a Dynamic Host Configuration Protocol (DHCP) [10] server and routes the packets between the MS and the external PDN. The WGSN node communicates with the HLR to support GPRS/UMTS mobility management following 3GPP Technical Specification 23.060 [11]. Therefore, the WLAN authentication and network access procedures are exactly the same as that for GPRS/UMTS.

The WGSN node integrates both SGSN and GGSN functionalities. Like an SGSN, the WGSN communicates with the HLR through the Gr interface. On the other hand, like a GGSN, the WGSN communicates with the external PDN via the Gi interface. Therefore, for other GPRS/UMTS networks, the WGSN node and the corresponding WLAN network are considered as a separate GPRS network. The WGSN node can be plugged in any 3G core network without modifying the existing 3G nodes. To integrate the billing system for both UMTS and WLAN, WGSN communicates with the Charging Gateway using the same UMTS protocols (the GPRS Tunneling Protocol (GTP') implemented in the Ga interface [11] or by FTP).

To access the WGSN services, the MS must be either a 3G-WLAN dual mode handset or a laptop/Personal Data Assistant (PDA) that is equipped with both a WLAN Network Interface Card (NIC) and a 3G module.

2.2. WGSN features

Based on the seven interworking aspects listed in 3GPP Technical Specification 22.934 [1], we describe the features implemented in WGSN [12].

Service aspects: WGSN provides general Internet access and Voice over IP (VoIP) services based on SIP [13]. Since a Network Address Translator (NAT) is built in the WGSN node, the VoIP voice packets delivered by the Real Time Transport Protocol (RTP) connection [14] cannot pass through the WGSN node. This issue is resolved by implementing a SIP ALG [15] in the WGSN node, which interprets SIP messages and modifies the source IP address and port contained in these SIP messages.

In UMTS, an MS must activate the Packet Data Protocol (PDP) [11] context for VoIP service before a caller from the external PDN can initiate a phone call to this MS. Also, for both UMTS and WLAN, a SIP User Agent (UA) must be activated in an MS before it can receive any incoming VoIP call. Therefore, a SIP-based Push Center (SPC) is implemented in the WGSN node to provide MS-terminated SIP services. The SPC is implemented on an SMS-based IP service platform called iSMS [16], where none of the UMTS/GPRS components is modified. SPC also provides a push mechanism through WLAN for a WGSN user who does not bring up the SIP UA. Therefore, the SIP terminated services (e.g. incoming VoIP calls) can be supported in WGSN.

Access control aspects: WGSN utilizes the standard UMTS access control for users to access WLAN services. Our mechanism re-uses the existing UMTS Subscriber Identity Module (SIM) card and the subscriber data records in the HLR. Therefore, the WGSN customers do not need a separate WLAN access procedure, and the maintenance for customer information is simplified. User profiles for both UMTS and WLAN are combined in the same database (i.e. the HLR).

Security aspects: WGSN utilizes the existing UMTS authentication mechanism [17], i.e. the WLAN authentication is performed through the interaction between an MS (using 3G SIM card) and the 3G Authentication Center. Therefore, WGSN is as secure as existing 3G networks. We do not attempt to address the WLAN encryption issue [18]. It is well known that WLAN based on IEEE 802.11b is not secure. For a determined attack, Wired Equivalent Privacy (WEP) is not safe, which only makes a WLAN network more difficult for an attacker to intrude. The IEEE 802.11 Task Group I is investigating the current 802.11 Media Access Control Address (MAC) security. WGSN will follow the resulting solution.

Roaming aspects: WGSN provides roaming between UMTS and WLAN. We utilize the standard UMTS mobility management mechanism without introducing any new roaming procedures.

Terminal aspects: A terminal for accessing WGSN is installed with a Universal IC Card (UICC) reader (a smart card reader implemented as a standard device on the Microsoft Windows platform). The UICC reader interacts with the UMTS SIM card (i.e. the UICC containing the SIM application) to obtain authentication information for the WGSN attach procedure.

Naming and addressing aspects: WGSN user identification is based on the Network Access Identification (NAI) format [19] following the 3GPP recommendation. Specifically, the International Mobile Subscriber Identity (IMSI) is used as WGSN user identification.

Charging and billing aspects: WGSN acts as a router, which can monitor and control all traffic for the MSs. The WGSN node provides both offline charging and online charging (for pre-paid services) based on the Call Detail Records (CDRs) delivered to the charging gateway.

Besides the seven aspects listed above, WGSN also provides automatic WLAN network configuration recovery. A WGSN MS can be a notebook, which is used at home or office with different network configurations. The network configuration information includes IP address, subnet mask, default gateway, WLAN Service Set Identifier (SSID) etc. When the MS enters the WGSN service area, its network configuration is automatically reset to the WGSN WLAN configuration if the MS is successfully authenticated. The original network configuration is automatically recovered when the MS detaches from the WGSN. This WGSN

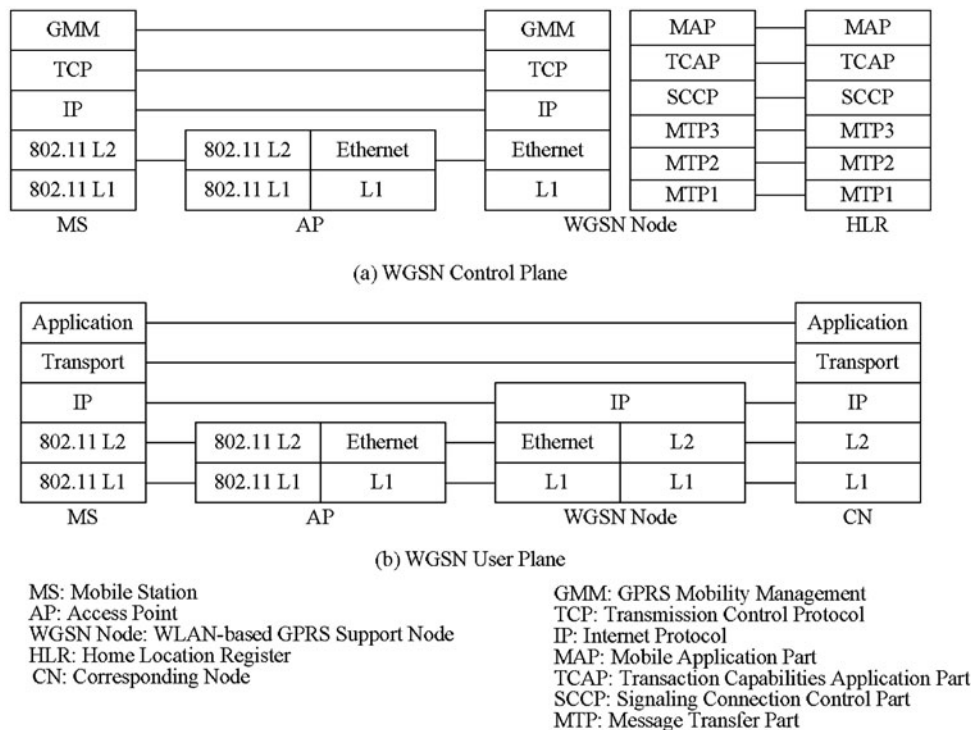


FIGURE 2. WGSN protocol stack. (a) WGSN control plane. (b) WGSN user plane.

functionality is especially useful for those users who are unfamiliar with network configuration setup.

3. IMPLEMENTATION OF WGSN

This section describes the implementation of WGSN. We first introduce the protocol stack among MS, AP, WGSN and HLR. Then we elaborate on the WGSN components for the WGSN network node and the MS. Figure 2 illustrates the WGSN protocol stack. In the current implementation, the lower-layer protocol between the MS and the WGSN node is IP over 802.11 radio (through WLAN AP). In the control plane, standard GPRS Mobility Management (GMM) defined in 3GPP Technical Specification 23.060 [11] is implemented on top of TCP/IP between the MS and the WGSN node. The standard UMTS Gr interface is implemented between the WGSN node and the HLR through Signaling System Number 7 (SS7)-based MAP protocol [18]. The layers of the SS7 protocol include Message Transfer Part (MTP), Signaling Connection Control Part (SCCP) and Transaction Capabilities Application Part (TCAP). Details of SS7 can be found in [18]. The WGSN node communicates with the charging gateway through the IP-based GTP' protocol which is not shown in Figure 2. In future, the TCP/IP layers in the control plan will be replaced by Extensible Authentication Protocol/EAP Over LAN (EAP/EAPOL) [20, 21]. EAP/EAPOL operates over the 802.11 MAC layer, which allows authentication of an MS before it is assigned an IP address. Therefore, the IP resource of the WGSN system can be managed with better security. Also, between the WGSN node and the HLR, the lower-layer SS7 protocols (i.e. MTP and SCCP) will be replaced by IP-based Stream

Control Transmission Protocol (SCTP) [22] to support all-IP architecture.

The WGSN user plane follows the standard IP approach, i.e. the MS and the WGSN node interact through the Internet protocol. The MS communicates with the CN in the external PDN using the transport layer over IP. In the user plane, the WGSN node serves as a gateway between the WLAN network and the external PDN.

The WGSN MS must be either a 3G-WLAN dual mode handset or a laptop/PDA that is equipped with both WLAN NIC and a 3G module. The UICC reader (which can be contained in the 3G module or a separate smart card reader) communicates with the standard SIM card to obtain the authentication information required in both the 3G network and WLAN. In the current WGSN implementation, we use the GPRS module instead of the 3G module because the 3G service is not available in Taiwan at the time of writing this paper. The WGSN UICC reader is implemented as a standard device on the Microsoft Windows platform. The WGSN software modules are implemented on the Windows 2000 and XP OS platforms for notebooks and WinCE for PDAs. A WGSN client is implemented to carry out tasks in the control plane. Several SIP user agents are implemented for SIP-based applications in the user plane. The modules for the WGSN client are described as follows.

SIM module (Figure 3, label 1): As in UMTS, a WGSN user is authenticated using the UMTS SIM card (or GPRS SIM card in the current implementation) before the user can access the WLAN network. Through the UICC smart card reader, the SIM module retrieves the SIM information (including

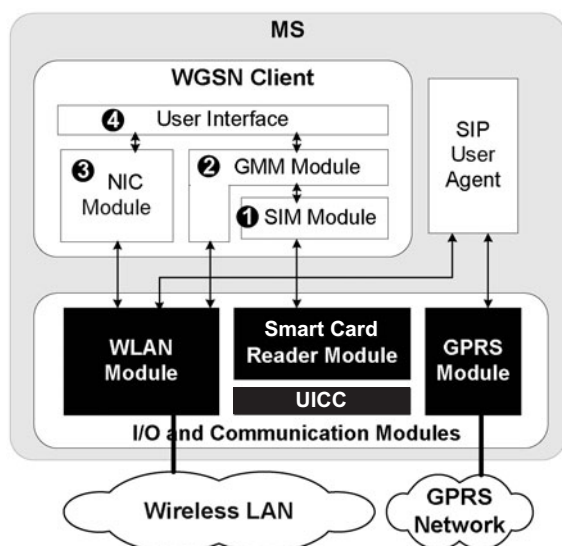


FIGURE 3. The MS architecture.

IMSI, SRES and Kc) [17] and forwards the information to the GMM module.

GMM module (Figure 3, label 2): Based on the SIM information obtained from the SIM module, the GMM module communicates with the WGSN node to perform MS attach and detach. The authentication action is included in the attach and detach procedures.

NIC module (Figure 3, label 3): The network configurations of different WLANs may be different. With the Operating System (OS) support, the NIC module dynamically sets up appropriate network configurations when a WGSN user moves across different WLAN networks. WGSN utilizes DHCP for IP address management. The WGSN MS must obtain a legal IP address and the corresponding network configuration through the DHCP lease request. On the other hand, when the MS terminates a WGSN connection, it should send the IP release message to the WGSN node, and the IP address is reclaimed for the next WGSN user. The NIC module then recovers the original network configuration for the MS. If the MS is abnormally terminated, the NIC module cannot immediately recover the network configuration. Instead, the NIC module offers a Window OS program called WGSN service. When the MS is re-started, this service will check if the network configuration has been recovered. If not, the configuration previously recorded by the NIC module is used.

User interface (Figure 3, label 4): A user interacts with the WGSN system through the MS user interface. As illustrated in Figure 4, the user types the Global System for Mobile communications (GSM)/General Packet Radio Service (GPRS) PIN number to initiate the WGSN connection. Like the usage of a GPRS handset, the pin number can be disabled. Based on the received command, the corresponding modules are instructed to carry out the desired tasks. During a WGSN session, the user interface indicates

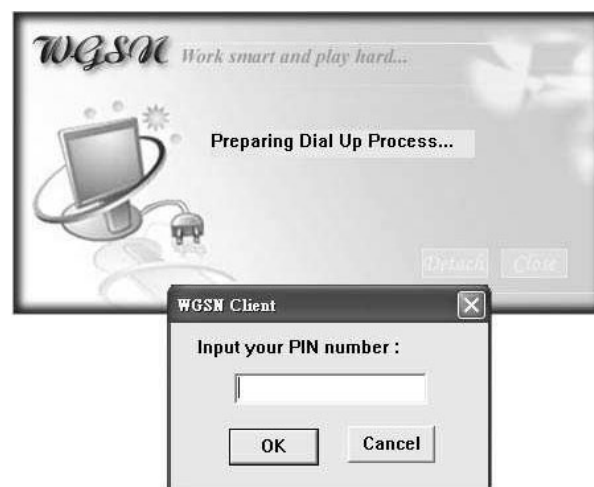


FIGURE 4. The WGSN user interface.

the status of the execution and displays the elapsed time of the WGSN connection.

On the network side, the WGSN node is implemented on the Advantech Industrial Computer platform S-ISXTV-141-W3. The black boxes in Figure 5 illustrate the WGSN communication modules, which include

- A SS7 module for communications with the HLR (through the SS7 network). In this module, the MTP, SCCP and TCAP layers (see Figure 2a) are based on Connect7 2.4.0-Beta version software developed by SS8 Networks Cooperation.
- An internal Ethernet module for communications with the WLAN APs.
- An external Ethernet module for communications with the external PDN.
- A GPRS module for communications with the MS (through the GPRS network).

The software architecture of the WGSN node includes four major components:

Authentication center (Figure 5, label 1) consists of the GMM and the Gr handlers. Through the internal Ethernet module, the GMM handler receives the GMM messages from the WGSN MS, and dispatches the corresponding tasks to the other WGSN modules (the details are described in Steps 4 and 8 under the attach procedure in Section 4). The Gr handler implements the standard MAP service primitives for the Gr interface [11]. Through the SS7 module, the Gr handler interacts with the HLR for MS network access and authentication. Specifically, it obtains an array of authentication vectors (including a random number Rand, a signed result SRES and an encryption key Kc) from the GPRS authentication center (which may or may not be co-located with the HLR). The size of the authentication array can be dynamically adjusted (see [17] for the details). Each time the WGSN MS requests for authentication, the Gr handler uses an authentication vector to carry out the task as specified in 3GPP Technical Specification 33.102 [23]. Furthermore, when an MS detaches, the Gr handler should inform the HLR to update the MS status. The

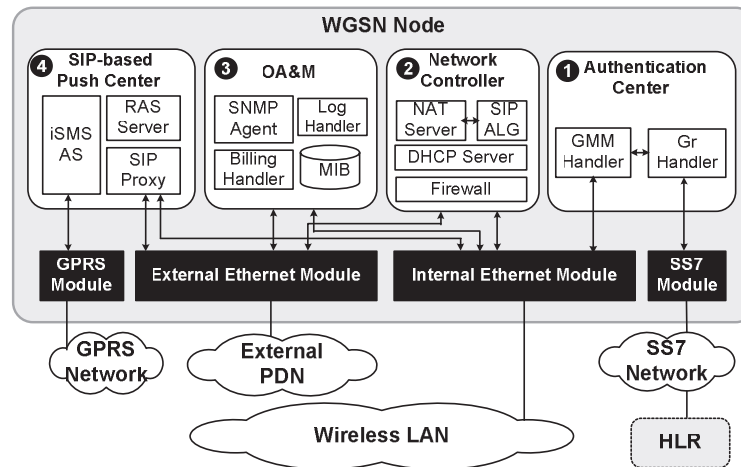


FIGURE 5. The WGSN node architecture.

current WGSN version has implemented two MAP service primitives: the MAP_SEND_AUTHENTICATION_INFO and MAP_PURGE_MS services. These primitives are implemented on MAP version 1.4 software developed by Trillium Digital Systems Inc.

Network controller (Figure 5, label 2) provides the following functions for Internet access:

- *IP address management*: A DHCP server is implemented in the WGSN node to distribute private IP addresses to the MSs. A NAT server performs address translation when the IP packets are delivered between the private (WLAN) and the public (external PDN) IP address spaces.
- *Internet access control*: The WGSN node only allows the authenticated users to access Internet services. Unauthorized packets will be filtered out by the firewall.
- *SIP application support*: To support SIP-based applications under the NAT environment, the WGSN node implements a SIP ALG that modifies the content of SIP packets so that these packets can be delivered to the WGSN MSs through the WGSN node.

Operation, administration and maintenance (OA&M; see Figure 5, label 3) controls and monitors individual WGSN user traffics. WGSN utilizes Simple Network Monitoring Protocol (SNMP) as the network management protocol. With Management Information Base (MIB), every managed network element is represented by an object with an identity and several attributes. An SNMP agent is implemented in the WGSN node, which interacts with the managed network element through SNMP. For example, the traffic statistics of an AP can be accessed by the OA&M (through the corresponding MIB object) and displayed in a web page using Multi Router Traffic Grapher (MRTG 2.9.22) [24]. The SNMP agent can also detach an MS through the MIB object of the MS. A log handler is implemented in the OA&M to record all events occurring in the WGSN node. A billing handler generates CDRs, which communicates with the billing gateway through the GTP' protocol or File Transfer Protocol (FTP).

SIP-based Push Center (SPC; see Figure 5, label 4) provides a push mechanism for GPRS networks that support private IP addresses. Since GPRS significantly consumes the MS power, a mobile user typically turns on GSM but turns off GPRS unless he/she wants to originate a GPRS session. In this case, services cannot be pushed to the users from the network side. For an MS that is GSM attached but GPRS detached, the SPC can push a SIP request to the MS through an SMS application server called iSMS AS [16]. Details of this GPRS push mechanism can be found in [25], which will not be discussed in this paper. SPC also provides a push mechanism through WLAN for a WGSN user who does not bring up the SIP UA. Therefore, the SIP-terminated services (e.g. incoming VoIP calls) can be supported in WGSN. We will elaborate more on SPC in Section 5.

4. ATTACH AND DETACH

In WGSN attach and detach procedures, the message flows between the WGSN node and the HLR are the same as that for the SGSN and the HLR in UMTS. The message flows between the MS and the WGSN node are specific to the WGSN network, which are not found in UMTS.

The attach procedure is illustrated in Figure 6, which consists of the following steps:

- Step 1: When the WGSN user brings up the MS user interface, the SIM module is invoked to configure the smart card reader and (optionally) requests the user to input the PIN number. The card reader authenticates the user through the PIN number just like a GPRS mobile phone.
- Step 2: The MS NIC module is invoked to store the current WLAN network configuration. To obtain the network configuration of WGSN, MS broadcasts a DHCP DISCOVER message on its subnet and looks for a DHCP server. The DHCP server in the WGSN node replies MS a DHCP OFFER message which includes an available IP address. Then, MS sends a DHCP REQUEST

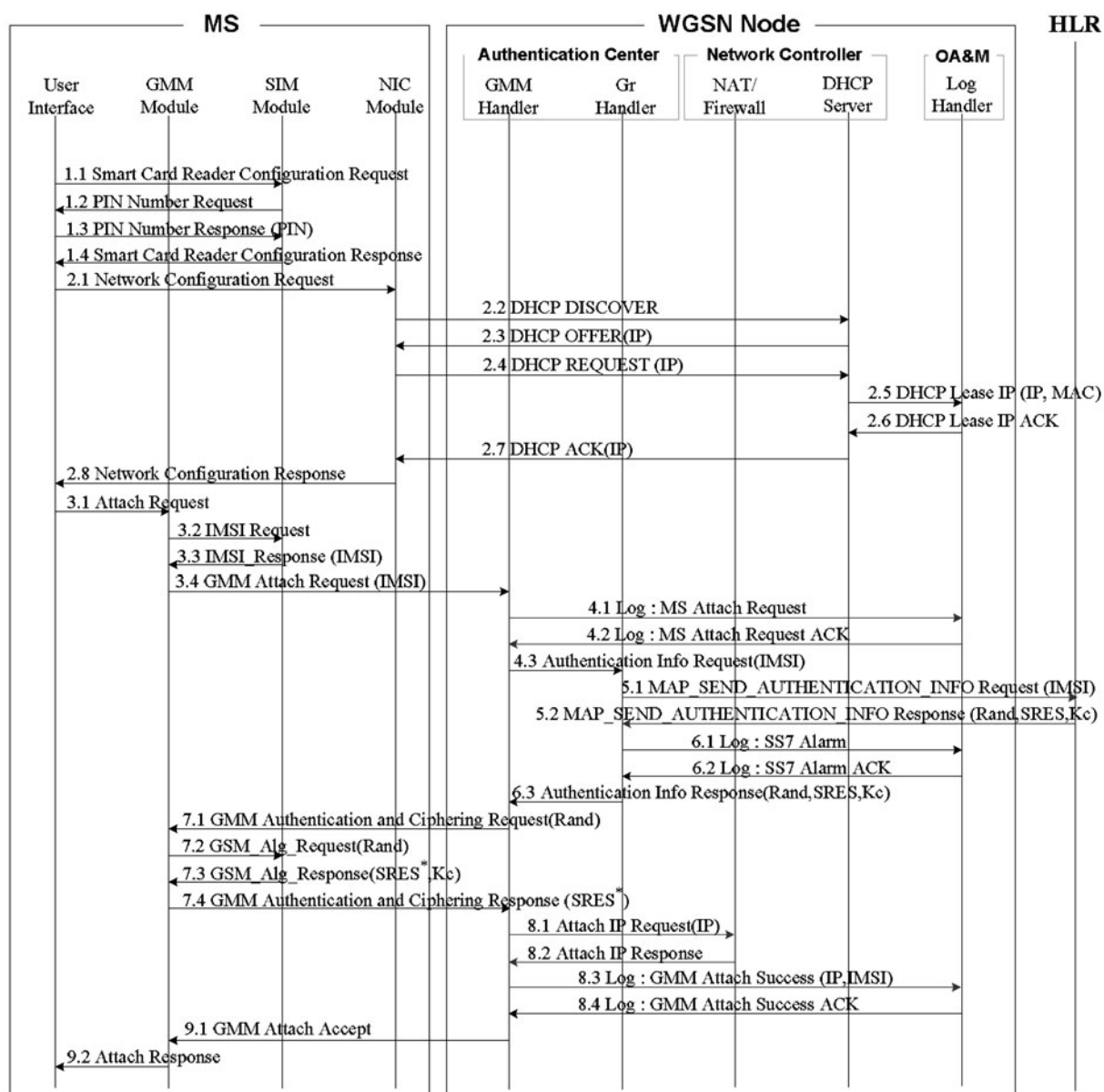


FIGURE 6. Message flow for the attach procedure.

message to DHCP server and asks for the usage of the available IP address contained in DHCP OFFER message. If the DHCP server accepts the request, it reports the IP lease event to the log handler and sends MS a DHCP ACK message with network configuration parameters. Finally, the MS NIC module sets up the new network configuration.

Step 3: The MS GMM module is invoked to perform the attach operation. The GMM module first obtains the IMSI from the SIM module. Then it sends the GMM Attach Request (with the parameter IMSI) to the WGSN node.

Step 4: When the GMM handler of the WGSN node receives the attach request, it reports this event to the log handler, and sends the Authentication Information Request to the Gr handler.

Step 5: The Gr handler sends the MAP_SEND_AUTHENTICATION_INFO Request (with the argument IMSI) to the HLR. The HLR returns the authentication vector (Rand, SRES, Kc) through the MAP_SEND_AUTHENTICATION_INFO Response message.

Step 6: The WGSN Gr handler issues the SS7 Alarm message to the log handler, and the event is logged. The Gr handler returns the authentication vector to the GMM handler.

Step 7: The GMM handler sends the GMM Authentication and Ciphering Request (with the parameter Rand) to the GMM module of the MS. The GMM module passes the random number Rand to the SIM module, and the SIM module computes the signed result SRES* and the

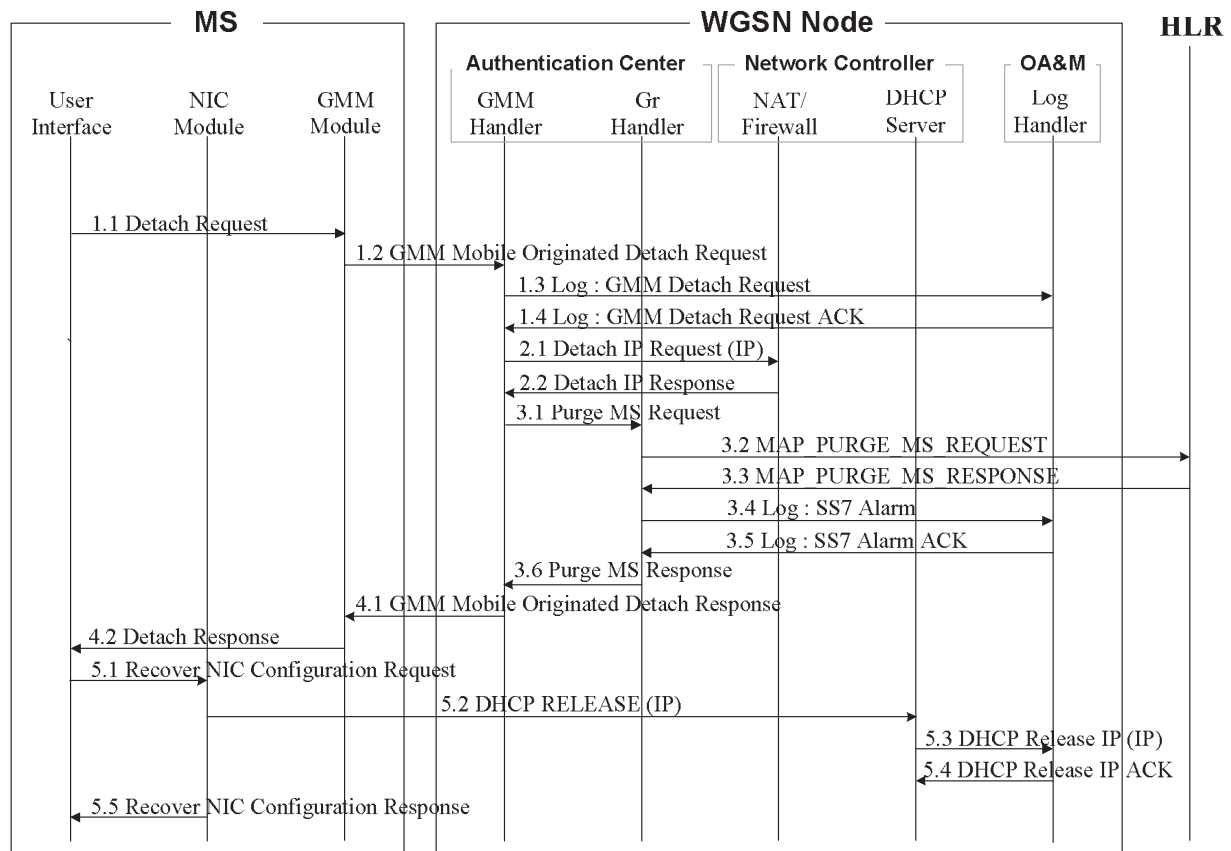


FIGURE 7. Message flow for the MS-initiated detach procedure.

encryption key K_c based on the received $Rand$ and the authentication key K_i stored in the SIM card. These results are returned to the GMM module. The GMM module returns the computed $SRES^*$ to the GMM handler of the WGSN node using the GMM Authentication and Ciphering Response (with the parameter $SRES^*$). The GMM handler compares $SRES$ with $SRES^*$. If they match, the authentication is successful.

- Step 8: The GMM handler sends the Attach IP request to the firewall, which will allow the packets of this IP address to pass the WGSN node. Then the GMM handler reports to the log handler that the attach is successful (with the corresponding IMSI and IP address).
- Step 9: The GMM handler sends the GMM Attach Accept message to the GMM module of the MS, and the GMM module passes the Attach Response message to the user interface. At this point, the attach procedure is completed.

The WGSN connection can be detached by the MS or by the network (the WGSN OA&M). The message flow for MS initiated detach is illustrated in Figure 7, and the steps are described as follows.

- Step 1: When the user presses the detach button in the user interface, the GMM module is invoked to send the GMM Mobile Originated Detach Request to the

GMM handler of the WGSN node. The GMM handler reports this detach event to the log handler.

- Step 2: The GMM handler sends the Detach IP Request to the firewall. From now on, the packets of this IP address will be filtered out by the firewall of the WGSN node.
- Step 3: The GMM handler invokes the Gr handler to send the MAP_PURGE_MS Request (with the parameters IMSI and the SSN address of the WGSN node) to the HLR. The HLR updates the MS status in the database and replies the MAP_PURGE_MS Response to the Gr handler. The Gr handler reports this event to the log handler.
- Step 4: Through GMM Mobile Originated Detach Response, the GMM handler informs the MS GMM module that the detach operation is complete.
- Step 5: The MS NIC module is instructed to recover the original network configuration. It sends the DHCP RELEASE message to the DHCP server in the WGSN node. The DHCP server reclaims the IP address and reports this event to the log handler. The NIC module then recovers the original network configuration (which was saved in Step 2 of the attach procedure).

The message flow for the network-initiated detach procedure is similar to that illustrated in Figure 7, and the details can be found in [12].

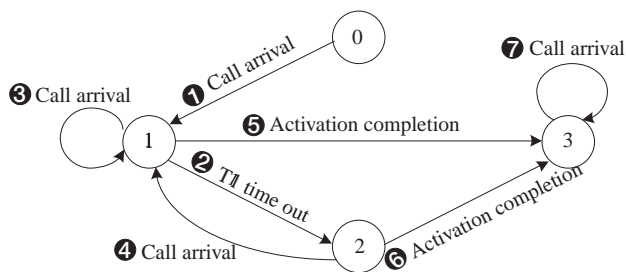


FIGURE 8. The FSM state transition diagram for the SPC status record.

5. PERFORMANCE OF THE WGSN PUSH MECHANISM

To reduce the power consumption and computation complexity of a WGSN MS, most WGSN applications are not activated at the MS until the user actually accesses them. This approach does not support ‘always-on’ or MS terminated services such as incoming VoIP calls. To address this issue, WGSN implements a push mechanism called SPC. Suppose that a SIP VoIP caller in the external PDN issues a call request to a WGSN user, which is first sent to the WGSN node. The WGSN node checks if the SIP UA of the called MS is activated. If so, the request is directly forwarded to the called MS. If not, the WGSN node sends a message to the MS to activate the corresponding SIP UA. After the SIP UA is brought up, the call request from the caller is then delivered to the SIP UA following the standard SIP protocol. We note that the VoIP call model is typically handled by the SIP UAs or a call server (or softswitch) that controls the call setup process and indicates whether the called party is busy or idle [26]. The WGSN SPC is only responsible for pushing the SIP requests to the MSs where the SIP UAs are not activated. For every SIP UA (an MS may have several SIP UAs for different applications), a status record is maintained in the SPC. A four-state Finite State Machine (FSM) is associated with the record. These states are

State 0: The SPC has not initiated the activation process.

State 1: The SPC has initiated the activation process, and one incoming call is waiting for setup.

State 2: The SPC has initiated the activation process. No incoming call is waiting for setup.

State 3: The SIP UA is active.

The incoming call waiting for setup at State 1 is referred to as the outstanding call. There is at most one outstanding call during the SIP UA activation process. The state transition diagram for the FSM of a status record is illustrated in Figure 8 and the details are given below:

Transition 1: An incoming call request arrives at State 0. The SPC sends a message to activate the SIP UA. The SPC sets a timer $T1$ and changes the state to ‘1’.

Transition 2: The timer $T1$ expires at State 1. The SPC drops the current outstanding call request by sending a timeout message to the caller. The state changes to ‘2’.

Transition 3: An incoming call arrives at State 1. The SPC drops this call request (because the called MS is already engaged in an outgoing call setup). The state remains in ‘1’.

Transition 4: An incoming call request arrives at State 2. This call becomes the outstanding call. The SPC sets the timer $T1$ and changes the state to ‘1’.

Transition 5: When the SPC receives the activation complete message from the called MS at State 1, the SPC forwards the outstanding call request to the SIP UA of the called MS following the standard SIP protocol. The state is changed to ‘3’.

Transition 6: When the SPC receives the activation complete message from the called MS at State 2, the SPC changes the state to ‘3’.

Transition 7: When the SPC receives a call request at State 3, it directly forwards the call request to the SIP UA of the called MS following the standard SIP protocol.

It is clear that for every SIP UA, the FSM eventually moves to State 3. There is exactly one outstanding call at State 1, and there is no outstanding call at State 2. During the state transition, an incoming call is ‘lost’ if either Transition 2 or 3 occurs. Consider the timing diagram in Figure 9. Suppose that the first outstanding call arrives at the SPC at time $\tau_{0,1}$ when the FSM is at State 0 (Figure 9, label 1). At time τ , the SPC received the activation complete message from the called MS (which indicates that the SIP UA has been activated; see Figure 9, label 7). The i th outstanding call arrives at the SPC at time $\tau_{0,i}$ (see Figure 9, label 4), which means that the previous $i - 1$ outstanding calls were timed out and lost). Several periods are defined:

- (i) The $T1$ timer for the i th outstanding call expires at $\tau_{1,i}$ (Figure 9, labels 2, 3 and 5). The timeout period is $t_{1,i} = \tau_{1,i} - \tau_{0,1}$, which has the density function $f_{t_{1,i}}(t) = \mu e^{-\mu t}$.
- (ii) The incoming call arrivals are a Poisson process with rate λ . Therefore the inter call arrival times are exponentially distributed with mean $1/\lambda$. The i th outstanding call is timed out at time $\tau_{1,i}$, and the $i + 1$ st outstanding call arrives at time $\tau_{0,i+1}$ (Figure 9, label 6). From the residual life theorem [27] and the memoryless property of the exponential distribution, the period $t_{2,i} = \tau_{0,i+1} - \tau_{1,i}$ has the exponential distribution with the density function $f_{t_{2,i}}(t) = \lambda e^{-\lambda t}$.
- (iii) The SIP UA activation time is $t_{3,1} = \tau - \tau_{0,1}$, which has the density function $f_{t_{3,1}}(t) = \gamma e^{-\gamma t}$. The activation time ‘seen’ by the i th outstanding call is $t_{3,i} = \tau - \tau_{0,i}$. The density function of $t_{3,i}$ is derived as follows. We first observe that $t_{3,1} = t_{1,1} + t_{2,1} + t_{3,2}$.

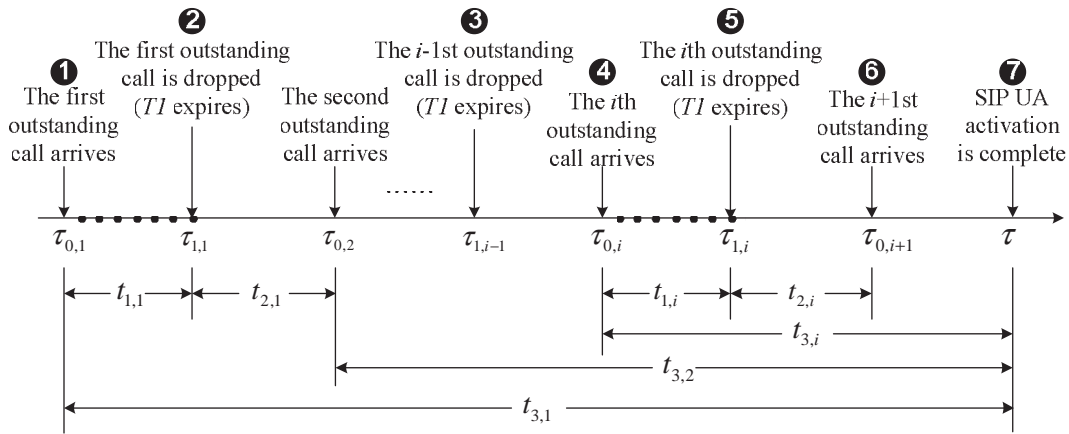


FIGURE 9. The timing diagram I (a dot ‘·’ represents dropping of an incoming call immediately after it arrives at the SPC).

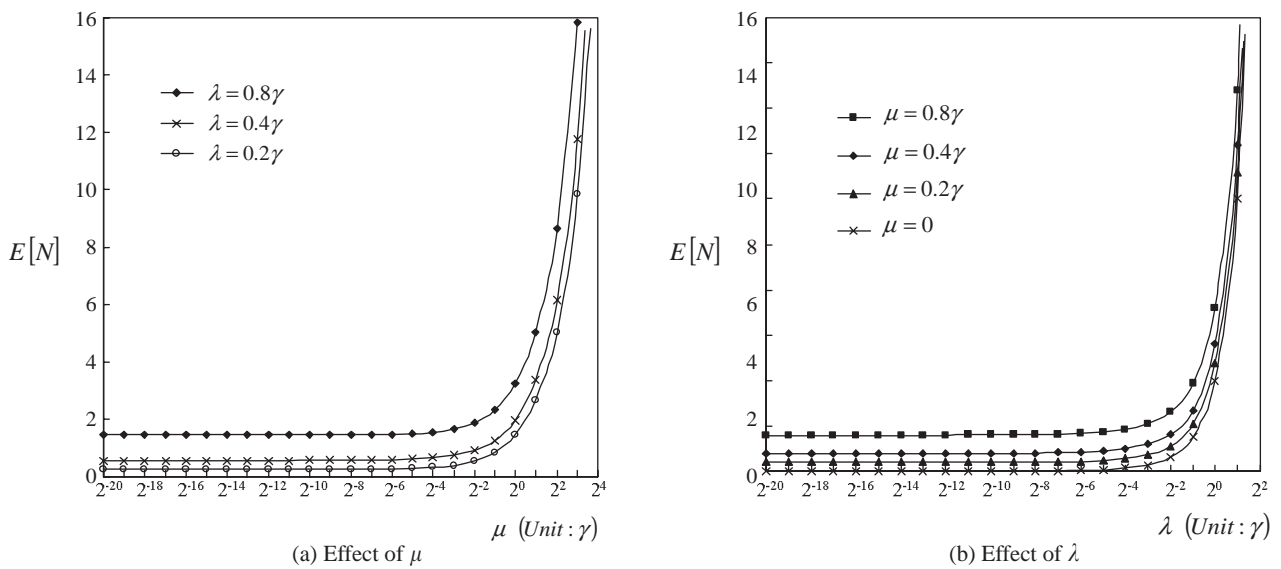


FIGURE 10. Effects of (a) μ and (b) λ .

Therefore,

$$\begin{aligned}
 f_{t_{3,2}}(t) &= \int_{t_{1,1}=0}^{\infty} \int_{t_{2,1}=0}^{\infty} f_{t_{1,1}}(t_{1,1}) f_{t_{2,1}}(t_{2,1}) \\
 &\quad \times f_{t_{3,1}}(t_{1,1} + t_{2,1} + t) dt_{2,1} dt_{1,1} \\
 &= \int_{t_{1,1}=0}^{\infty} \int_{t_{2,1}=0}^{\infty} (\mu e^{-\mu t_{1,1}})(\lambda e^{-\lambda t_{2,1}}) \\
 &\quad \times [\gamma e^{-\gamma(t_{1,1}+t_{2,1}+t)}] dt_{2,1} dt_{1,1} \\
 &= \left[\frac{\mu\lambda}{(\lambda + \gamma)(\mu + \gamma)} \right] \gamma e^{-\gamma t} \quad (1)
 \end{aligned}$$

Since $t_{3,i-1} = t_{1,i-1} + t_{2,i-1} + t_{3,i}$, the density function $f_{t_{3,i}}(t)$ can be iteratively derived from (1), and the resulting expression is

$$f_{t_{3,i}}(t) = \left[\frac{\mu\lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{i-1} \cdot \gamma e^{-\gamma t} \quad (2)$$

Note that $t_{1,i}$, $t_{2,i}$ and $t_{3,1}$ are assumed to be exponentially distributed, which provide mean value

analysis [28] for quick and primary investigation on the SPC performance. The SPC may exercise fixed timeout period for $T1$. From our previous study of mobility management [17], the performance of fixed timeout period is similar to the exponential periods. Furthermore, exponential timeout periods provide randomness (just like the exponential backoffs of re-transmission protocols), which avoids traffic congestion at the SPC.

In Figure 9, the bullets in the periods $t_{1,i}$ represent the incoming call losses due to Transition 3. The bullets at $\tau_{1,i}$ represent the outstanding call drops due to Transition 2.

Based on the above description, Appendix A derives the expected number $E[N]$ of lost calls during a SIP UA activation process, which is expressed as

$$E[N] = \frac{(\lambda + \gamma)(\lambda + \mu)}{\gamma} \quad (3)$$

Based on (3), Figure 10 plots $E[N]$ against μ and λ . Figure 10a indicates that when $\mu < \gamma/8$, increasing the timeout period for $T1$ only insignificantly reduces the $E[N]$ value. Therefore, if the expected SIP UA activation delay is 1 s, then it is appropriate to set the $T1$ timeout period as 8 or 16 s. Figure 10b indicates that $E[N]$ is insignificantly affected by the incoming call arrival rate λ when $\lambda < \gamma/32$. In other words, it is appropriate to select any $E[t_{3,i}]$ value less than $E[t_{2,i}]/128$. For example, if a WGSN user receives an incoming call for every 20 min, then good $E[N]$ performance is expected if the elapsed time for SIP UA activation is less than 19 s.

6. CONCLUSION

This paper proposed WGSN as a solution for integrating 3G and WLAN services. We described how the 3G mechanisms are re-used for WLAN user authentication and network access without introducing new procedures and without modifying the existing 3G network components. We described the WGSN features and showed how they are designed and implemented. Then we focused on the WGSN push mechanism. We proposed an analytic model to investigate the restrictions on WGSN transmission delay so that the system can accommodate most SIP-based terminated calls (i.e. the incoming calls) to a WGSN user during the SIP UA activation process. A WGSN prototype has been implemented in the Industrial Technology Research Institute and National Chiao Tung University Joint Research Center.

ACKNOWLEDGEMENTS

This work was sponsored in part by the MOE Program for Promoting Academic Excellence of Universities under grant number 89-E-FA04-1-4, Chair Professorship of Providence University, IIS/Academia Sinica, CCL/ITRI, National Telecommunication Development Program, the Lee and MTI Center for Networking Research/NCTU.

REFERENCES

- [1] 3GPP TR 22.934, v6.0.0 (2002) *Services and System Aspects; Feasibility Study on 3GPP System to Wireless Local Area Network (WLAN) Interworking*. 3rd Generation Partnership Project.
- [2] 3GPP TS 23.040, v5.5.1 (2002) *Technical Specification Group Terminals; Technical Realization of Short Message Service (SMS)*. 3rd Generation Partnership Project.
- [3] 3GPP TS 22.140, v5.4.0 (2002) *Technical Specification Group Services and System Aspects; Multimedia Messaging Service (MMS); Stage 1*. 3rd Generation Partnership Project.
- [4] 3GPP TS 22.228, v5.6.0 (2002) *Technical Specification Group Services and System Aspects; Service Requirements for the Internet Protocol (IP) Multimedia Core Network Subsystem; Stage 1*. 3rd Generation Partnership Project.
- [5] Lin, Y.-B., Haung, Y.-R., Pang, A.-C. and Chlamtac, I. (2002) All-IP approach for UMTS third generation mobile networks. *IEEE Network*, **16**(5), 8–19.
- [6] Haverinen, H., Mikkonen, J., and Takamaki, T. (2002) Cellular access control and charging for mobile operator wireless local area networks. *IEEE Wireless Commun.*, **9**(6), 52–60.
- [7] Salkintzis, A. K., Fors, C., and Pazhyannur, R. (2002) WLAN–GPRS integration for next-generation mobile data networks. *IEEE Wireless Commun.*, **9**(5), 112–124.
- [8] Holma, H. and Toskala, A. (eds) (2000) *WCDMA for UMTS*. John Wiley & Sons.
- [9] GSM 09.02, v7.3.0 (2000) *Mobile Application Part (MAP) Specification*. European Telecommunications Standards Institute/Technical Committees.
- [10] IETF RFC 2131 (1997) *Dynamic Host Configuration Protocol*. Internet Engineering Task Force.
- [11] 3GPP TS 23.060, v4.1.0 (2001) *Technical Specification Group Services and Systems Aspects; General Packet Radio Service (GPRS); Service Description; Stage 2*. 3rd Generation Partnership Project.
- [12] Technical Report (2003) *System Requirement Specification of WLAN-based GPRS Support Node (WGSN)*. ITRI and NCTU Joint Research Center.
- [13] IETF RFC 3261 (2002) *SIP: Session Initiation Protocol*. Internet Engineering Task Force.
- [14] IETF RFC 3550 (2003) *RTP: A Transport Protocol for Real-Time Applications*. Internet Engineering Task Force.
- [15] IETF draft-biggs-sip-nat-00 (2000) *A SIP Application Level Gateway for Network Address Translation*. 3COM Inc.
- [16] Rao, C. H., Chang, D.-F., and Lin, Y.-B. (2001) iSMS: an integration platform for short message service and IP networks. *IEEE Network*, **15**(2), 48–55.
- [17] Lin, Y.-B. and Chen, Y.-K. (2003) Reducing authentication signaling traffic in third generation mobile network. *IEEE Trans. Wireless Commun.*, **2**(3), 491–501.
- [18] Lin, Y.-B. and Chlamtac, I. (2001) *Wireless and Mobile Network Architectures*. Wiley.
- [19] IETF RFC 2486 (1999) *The Network Access Identifier*. Internet Engineering Task Force.
- [20] IETF RFC 2284 (2003) *PPP Extensible Authentication Protocol (EAP)*. Internet Engineering Task Force.
- [21] IEEE Std 802.1X-2001 (2001) *IEEE Standard for Local and Metropolitan Area Networks-Port-Based Network Access Control*. Institute of Electrical and Electronics Engineers.
- [22] IETF RFC 2960 (2000) *Stream Control Transmission Protocol*. Internet Engineering Task Force.
- [23] 3GPP TS 33.102, v3.7.0 (2000) *Technical Specification Group Services and Systems Aspects; 3G Security; Security Architecture*. 3rd Generation Partnership Project.
- [24] MRTG: Multi Router Traffic Grapher. <http://people.ee.ethz.ch/~oetiker/webtools/mrtg/>.
- [25] Lin, Y.-B., Lo, Y.-C., and Rao, C.-H. (2003) A push mechanism for GPRS supporting private IP addresses. *IEEE Commun. Lett.*, **7**(1), 24–26.
- [26] Feng, V., Lin, Y.-B., and Chou, S.-L. (2004) Design and implementation of a softswitch for third generation mobile all-IP network. *Wireless Commun. Mobile Comput. J.*, in press.
- [27] Ross, S. M. (1996) *Stochastic Processes*. John Wiley & Sons.
- [28] Lazowska, E. D., Zahorjan, J., Graham, G. S., and Sevcik, K. C. (1984) *Quantitative System Performance*. Prentice-Hall.

APPENDIX A

Suppose that we observe j outstanding calls (where $j > 0$) during the SIP UA activation process (i.e. the transition period from State 0 to State 3). The first $j - 1$ outstanding calls are

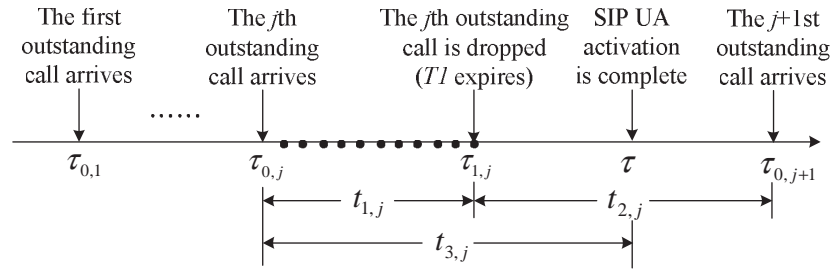


FIGURE A1. The timing diagram II (a dot ‘.’ represents dropping of an incoming call immediately after it arrives at the SPC).

timed out and are lost. These outstanding calls are referred to as Type A calls. The j th (i.e. the last) outstanding call is either timed out (which is referred to as the Type B call) or successfully set up (Type C call).

In Figure 9, $t_{1,i} + t_{2,i} < t_{3,i}$ for the i th Type A call. Let N_{A_i} be the number of lost calls during the waiting time $t_{1,i}$ of this outstanding call (including itself). We note that N_{A_i} has a Poisson distribution [27]. Let $P_{A_i}(n)$ be the probability that $N_{A_i} = n$. From (2) and the Poisson probability density function, we have

$$\begin{aligned}
 P_{A_i}(n) &= \Pr [N_{A_i} = n | t_{1,i} + t_{2,i} < t_{3,i}] \\
 &\quad \cdot \Pr [t_{1,i} + t_{2,i} < t_{3,i}] \\
 &= \int_{t_{1,i}=0}^{\infty} \int_{t_{2,i}=0}^{\infty} \int_{t_{3,i}=t_{1,i}+t_{2,i}}^{\infty} \left[\frac{e^{-\lambda t_{1,i}} (\lambda t_{1,i})^{n-1}}{(n-1)!} \right] \\
 &\quad \times f_{t_{1,i}}(t_{1,i}) f_{t_{2,i}}(t_{2,i}) f_{t_{3,i}}(t_{3,i}) dt_{3,i} dt_{2,i} dt_{1,i} \\
 &= \int_{t_{1,i}=0}^{\infty} \int_{t_{2,i}=0}^{\infty} \int_{t_{3,i}=t_{1,i}+t_{2,i}}^{\infty} \left[\frac{e^{-\lambda t_{1,i}} (\lambda t_{1,i})^{n-1}}{(n-1)!} \right] \\
 &\quad \times (\mu e^{-\mu t_{1,i}}) (\lambda e^{-\lambda t_{2,i}}) \left\{ \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{i-1} \right. \\
 &\quad \left. \times \gamma e^{-\gamma t_{3,i}} \right\} dt_{3,i} dt_{2,i} dt_{1,i} \\
 &= \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{i-1} \left(\frac{\mu \lambda}{\gamma + \lambda} \right) \left(\frac{\lambda}{\mu + \gamma + \lambda} \right)^{n-1} \quad (\text{A1})
 \end{aligned}$$

From (A1) the expected number $E [N_{A_i} | t_{1,i} + t_{2,i} < t_{3,i}] \Pr [t_{1,i} + t_{2,i} < t_{3,i}]$ is expressed as

$$\begin{aligned}
 &E [N_{A_i} | t_{1,i} + t_{2,i} < t_{3,i}] \Pr [t_{1,i} + t_{2,i} < t_{3,i}] \\
 &= \sum_{n=1}^{\infty} n \cdot P_{A_i}(n) \\
 &= \sum_{n=1}^{\infty} n \left\{ \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{i-1} \left(\frac{\mu \lambda}{\gamma + \lambda} \right) \right. \\
 &\quad \left. \times \left(\frac{\lambda}{\mu + \gamma + \lambda} \right)^{n-1} \right\} \\
 &= \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{i-1} \left(\frac{\mu \lambda}{\lambda + \gamma} \right) \left(\frac{\gamma + \lambda + \mu}{\mu + \gamma} \right)^2 \quad (\text{A2})
 \end{aligned}$$

The expected number of lost calls during the waiting time of the last outstanding call is derived in two cases. With probability $\Pr [t_{1,j} < t_{3,j} < t_{1,j} + t_{2,j}]$, the last outstanding call is a Type B call (see Figure A1). Let N_{B_j} be the number of lost calls during the waiting time $t_{1,j}$ of this outstanding call (including itself). Let $P_{B_j}(n)$ be the probability that $N_{B_j} = n$. Then

$$\begin{aligned}
 P_{B_j}(n) &= \Pr [N_{B_j} = n | t_{1,j} < t_{3,j} < t_{1,j} + t_{2,j}] \\
 &\quad \cdot \Pr [t_{1,j} < t_{3,j} < t_{1,j} + t_{2,j}] \\
 &= \int_{t_{1,j}=0}^{\infty} \int_{t_{3,j}=t_{1,j}}^{\infty} \int_{t_{2,j}=t_{3,j}-t_{1,j}}^{\infty} \left[\frac{e^{-\lambda t_{1,j}} (\lambda t_{1,j})^{n-1}}{(n-1)!} \right] \\
 &\quad \times f_{t_{1,j}}(t_{1,j}) f_{t_{2,j}}(t_{2,j}) f_{t_{3,j}}(t_{3,j}) dt_{2,j} dt_{3,j} dt_{1,j} \\
 &= \int_{t_{1,j}=0}^{\infty} \int_{t_{3,j}=t_{1,j}}^{\infty} \int_{t_{2,j}=t_{3,j}-t_{1,j}}^{\infty} \left[\frac{e^{-\lambda t_{1,j}} (\lambda t_{1,j})^{n-1}}{(n-1)!} \right] \\
 &\quad \times (\mu e^{-\mu t_{1,j}}) (\lambda e^{-\lambda t_{2,j}}) \\
 &\quad \times \left\{ \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{j-1} \gamma e^{-\gamma t_{3,j}} \right\} dt_{2,j} dt_{3,j} dt_{1,j} \\
 &= \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{j-1} \left(\frac{\mu \gamma}{\gamma + \lambda} \right) \left(\frac{\lambda}{\mu + \gamma + \lambda} \right)^{n-1} \quad (\text{A3})
 \end{aligned}$$

From (A3), the expected number $E [N_{B_j} | t_{1,j} < t_{3,j} < t_{1,i} + t_{2,i}] \Pr [t_{1,j} < t_{3,j} < t_{1,i} + t_{2,i}]$ is expressed as

$$\begin{aligned}
 &E [N_{B_j} | t_{1,j} < t_{3,j} < t_{1,i} + t_{2,i}] \Pr [t_{1,j} < t_{3,j} < t_{1,i} + t_{2,i}] \\
 &= \sum_{n=1}^{\infty} n \cdot P_{B_j}(n) \\
 &= \sum_{n=1}^{\infty} n \left\{ \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{j-1} \left(\frac{\mu \gamma}{\gamma + \lambda} \right) \right. \\
 &\quad \left. \times \left(\frac{\lambda}{\mu + \gamma + \lambda} \right)^{n-1} \right\} \\
 &= \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{j-1} \left(\frac{\mu \gamma}{\lambda + \gamma} \right) \left(\frac{\gamma + \lambda + \mu}{\mu + \gamma} \right)^2 \quad (\text{A4})
 \end{aligned}$$

With probability $\Pr [0 < t_{3,j} < t_{1,j}]$, the last outstanding call is a Type C call (see Figure A2). Let N_{C_j} be the number of lost calls during the waiting time $t_{3,j}$ of this outstanding call.

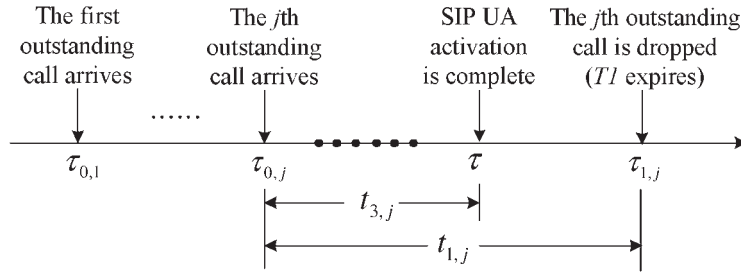


FIGURE A2. The timing diagram III (a dot ‘.’ represents dropping of an incoming call immediately after it arrives at the SPC).

Let $P_{C_j}(n)$ be the probability that $N_{C_j} = n$. Then

$$\begin{aligned}
 P_{C_j}(n) &= \Pr [N_{C_i} = n | 0 < t_{3,j} < t_{1,j}] \\
 &\cdot \Pr [0 < t_{3,j} < t_{1,j}] \\
 &= \int_{t_{3,j}=0}^{\infty} \int_{t_{1,j}=t_{3,j}}^{\infty} \left[\frac{e^{-\lambda t_{3,j}} (\lambda t_{3,j})^n}{n!} \right] \\
 &\times f_{t_{1,j}}(t_{1,j}) f_{t_{3,j}}(t_{3,j}) dt_{1,j} dt_{3,j} \\
 &= \int_{t_{3,j}=0}^{\infty} \int_{t_{1,j}=t_{3,j}}^{\infty} \left[\frac{e^{-\lambda t_{3,j}} (\lambda t_{3,j})^n}{n!} \right] (\mu e^{-\mu t_{1,j}}) \\
 &\times \left\{ \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{j-1} \cdot \gamma e^{-\gamma t_{3,j}} \right\} dt_{1,j} dt_{3,j} \\
 &= \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{j-1} \gamma \left(\frac{\lambda}{\gamma + \lambda + \mu} \right)^n \quad (A5)
 \end{aligned}$$

From (A5), the expected number $E[N_{C_j} | t_{3,j} < t_{1,j}]$ $\Pr [t_{3,j} < t_{1,j}]$ is expressed as

$$\begin{aligned}
 &E[N_{C_j} | t_{3,j} < t_{1,j}] \Pr [t_{3,j} < t_{1,j}] \\
 &= \sum_{n=1}^{\infty} n \cdot P_{C_j}(n) \\
 &= \sum_{n=1}^{\infty} n \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{j-1} \gamma \left(\frac{\lambda}{\gamma + \lambda + \mu} \right)^n \\
 &= \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{j-1} \left[\frac{\gamma \lambda (\gamma + \lambda + \mu)}{(\gamma + \mu)^2} \right] \quad (A6)
 \end{aligned}$$

From (A2), (A4) and (A6), the expected number $E[N]$ of lost calls during a SIP UA activation process is

$$\begin{aligned}
 E[N] &= \sum_{i=0}^{\infty} (E[N_{A_i} | t_{1,i} + t_{2,i} < t_{3,i}] \Pr [t_{1,i} + t_{2,i} < t_{3,i}] \\
 &+ E[N_{B_i} | t_{1,i} < t_{3,i} < t_{1,i} + t_{2,i}] \\
 &\times \Pr [t_{1,i} < t_{3,i} < t_{1,i} + t_{2,i}] \\
 &+ E[N_{C_i} | t_{3,i} < t_{1,i}] \Pr [t_{3,i} < t_{1,i}]) \quad (A7) \\
 &= \sum_{i=0}^{\infty} \left\{ \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{i-1} \left(\frac{\mu \lambda}{\lambda + \gamma} \right) \right. \\
 &\times \left(\frac{\gamma + \lambda + \mu}{\mu + \gamma} \right)^2 + \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{i-1} \\
 &\times \left(\frac{\mu \gamma}{\lambda + \gamma} \right) \left(\frac{\gamma + \lambda + \mu}{\mu + \gamma} \right)^2 \\
 &\left. + \left[\frac{\mu \lambda}{(\lambda + \gamma)(\mu + \gamma)} \right]^{i-1} \left[\frac{\gamma \lambda (\gamma + \lambda + \mu)}{(\gamma + \mu)^2} \right] \right\} \\
 &= \frac{(\lambda + \gamma)(\lambda + \mu)}{\gamma} \quad (A8)
 \end{aligned}$$

In the right-hand side of (A7), the i th term in the summation computes the number of lost calls during the waiting period of the i th outstanding call. In this term, the i th outstanding call exists and is a Type A call with the probability $\Pr [t_{1,i} + t_{2,i} < t_{3,i}]$. Similarly, the probabilities for Type B and Type C calls are $\Pr [t_{1,i} < t_{3,i} < t_{1,i} + t_{2,i}]$ and $\Pr [t_{3,i} < t_{1,i}]$ respectively.