Wireless Netw (2008) 14:683–698
DOI 10.1007/s11276-006-0011-8

PIANO: A power saving strategy for cellular/VoWLAN dual-mode mobiles

Shiao-Li Tsao · E-Cheng Cheng

Abstract The integration of cellular and VoIP over WLAN (VoWLAN) systems recently has attracted considerable interest from both academia and industry. A cellular/VoWLAN dual-mode system enables users to access a low-cost VoIP service in a WLAN hotspot and switch to a wide-area cellular system without WLANs. Unfortunately, cellular/VoWLAN dual-mode mobiles suffer the power consumption problem that becomes one of the major concerns for commercial deployment of the dual-mode service. In this study, we present a novel power saving mechanism, called PIANO (paging via another radio), for the integration of heterogeneous wireless networks, and further apply the proposed methods to implement a cellular/VoWLAN dual-mode system. Based on the proposed mechanisms, a dual-mode mobile can completely switch off its WLAN interface, only leaving the cellular interface awake to listen to paging messages. When a mobile receives a paging message from its cellular interface, it wakes up the WLAN interface and responds to connection requests via WLAN networks. Therefore, a dual-mode mobile reduces the power consumption by turning off the WLAN interface during idle, and can also receive VoWLAN services. Measurement results based on the prototype system demonstrate that the proposed methods significantly extend the standby hours of a dual-mode mobile.

Keyword Cellular-WLAN interworking · Dual-mode mobile · Voice over IP (VoIP) · VoIP over WLAN · Power saving technology

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1 Introduction

VoIP over WLAN (VoWLAN) is considered a low-cost technology for providing mobile telecommunication services owing to free the Industrial, Scientific and Medical (ISM) spectrum and the reuse of the existing public and private WLAN infrastructures. The integration of a cellular and a VoWLAN system that further offers users convenient accesses to both cellular and VoWLAN services recently has attracted considerable interest from both academia and industry [1–3]. For example, a cellular/VoWLAN system involves a user with a dual-mode mobile being able to access VoWLAN services in enterprise or hotspot WLANs, and switch to a cellular system without WLAN coverage. Therefore, a cellular/VoWLAN dual-mode system can provide a cheaper mobile telecommunication service than a single-mode cellular system, while also achieving high mobility and wide coverage [3].

The power consumption of a WLAN interface presents a serious problem for a battery-operated device [2]. One possible solution to reduce power consumption of a WLAN interface is leaving the WLAN interface in sleep mode or power saving mode (PSM) whenever possible [14]. However, experiments indicate that even the WLAN PSM is activated, the standby hour of a WLAN device is still much less than that of a cellular phone [2]. The extra energy consumed by the WLAN interface of a dual-mode mobile might not be acceptable by users since a handset holder might see VoWLAN as a supplementary service and expect a dual-model handset to have the same standby hour as a cellular phone. Previous research suggests using secondary low-power wakeup radios to reduce the power consumption of sensor nodes, ad hoc networks and a wireless interface [11–13]. Shih et al. further designed and implemented a secondary low-power wakeup radio for a battery-operated WLAN device [2]. According to their design, a mobile device can turn off its WLAN interface, and only listens to the low-power radio. If a packet on a WLAN access point (AP) needs to be sent to the WLAN device, the AP first uses the low-power radio to activate the WLAN interface of the device, and then sends the packet to the WLAN device. Although this approach can reduce the power consumption of a WLAN device, it requires installing new components on WLAN APs and mobile devices. Feng et al. considered a Universal Mobile Telecommunications System (UMTS)/WLAN dual-mode mobile and the standard APs without the installation of extra components, and they proposed a new gateway, called WGSN, to interconnect UMTS and WLAN networks. In their proposed architecture, a WGSN serves as a session initiation protocol (SIP) server to handle VoIP services for WLAN mobiles that might disable the WLAN interface to save power during idle. If an SIP VoIP caller in the Internet issues a call request to a WLAN mobile, the SIP message is received by the WGSN and then the WGSN sends a short message containing the *SIP INVITE* message to the mobile in order to activate the SIP user agent (UA) and WLAN interface [6]. However, they did not consider the integration of cellular/VoWLAN dual-mode services and seamless service issues. Moreover, using short message services (SMS) to send SIP messages to a mobile may introduce significant delays for the call setup. Previous study showed that the latency to deliver a short message to a mobile ranges from five seconds to more than 40 s [15], and the call setup delay based on the WGSN approach might be too long and cannot be guaranteed.

This study presents a novel power saving mechanism, called PIANO (paging via another radio), for a 3G all-IP architecture, and can be extended to the integration of other heterogeneous wireless networks such as WiMAX and 4G networks. The basic concept behind the proposed mechanism is that the WLAN interface of a dual-mode mobile is completely turned off, while leaving the cellular interface awake for listening to paging messages. While an SIP server receives a call to the dual-mode mobile, it tries to page the mobile via a cellular network, and sends *SIP INVITE* messages to the mobile via WLANs in parallel. Once the mobile receives a paging message from its cellular interface, it turns on its WLAN interface to respond to the incoming SIP messages via a WLAN link. Therefore, the power consumption of a mobile can be reduced significantly by switching off the WLAN interface during idle, and users can still receive low-cost VoWLAN services while a WLAN is available.

The remainder of the paper is organized as follows. This study first describes a generic network architecture to which the proposed mechanisms are applied in Section 2. Section 3 then details the design, procedures, and performance models of the proposed mechanisms for a cellular/VoWLAN dual-mode system. Subsequently, Section 4 presents and discusses simulations, prototyping experiences, and the experimental results. Finally, conclusions are presented in Section 5.

2 System architecture

The proposed power saving mechanisms can be applied to a 3G all-IP or an enterprise network. Figure 1 depicts a generic system architecture to provide cellular/VoWLAN dual-mode services. The proposed mechanisms applied to a 3G all-IP network are first discussed. In a 3G all-IP network, an IP multimedia subsystem (IMS) that is an IP-based service infrastructure is established on top of a 3G packet-domain network. An IMS composes of a call session control function (CSCF) based on SIP, a home subscriber server (HSS) which maintains a mobile subscriber database, and signaling and media gateways (SGW/MGW) that convert circuit-switch voice calls between public switched telephone network (PSTN)/public land mobile network (PLMN) and a 3G network. To access all-IP services, a mobile must attach to a 3G packet-domain network first, acquire an IP address from the gateway GPRS support node (GGSN), and further register to the CSCF. After attaching to 3G and IMS networks, a mobile can be reached by a mobile subscriber ISDN (MSISDN) number, IP addresses, or an SIP uniform resource identifier (URI). To inter-work with WLANs and provide dual-mode services, 3GPP defines a 3G-WLAN inter-working architecture and develops new components such as wireless access gateway (WAG) and packet data gateway (PDG) to bridge WLANs and a 3G core network [18]. Then, a dual-mode mobile further uses its WLAN interface to attach to a WLAN network, acquires another IP address from a PDG for its WLAN interface, and accesses 3G packet-domain services. Based on this 3G-WLAN interworking architecture, a dual-mode mobile can access both packet-domain and voice services. Considering voice services, external circuit-switch calls from PSTNs/PLMNs and packet-switched VoIP calls from an IP network to a dual-mode mobile are eventually routed to the CSCF. The CSCF can either direct the call to the dual-mode mobile via a cellular network or via WLANs. In this situation, the proposed mechanisms and the dual-mode service can be implemented on the CSCF. According to the proposed mechanisms, the cellular interface of a dual-mode mobile is always turned on, but the WLAN interface of the mobile is switched off during idle. If the CSCF receives a call to the mobile, it first pages the mobile via a cellular network to wake up the WLAN interface of the mobile. The paging message can be either embedded into a GSM/3G paging channel sending to the mobile's cellular interface or can be carried by a packet sending to the IP address associated with the cellular interface of the mobile. The first approach needs to modify GSM/3G protocols,

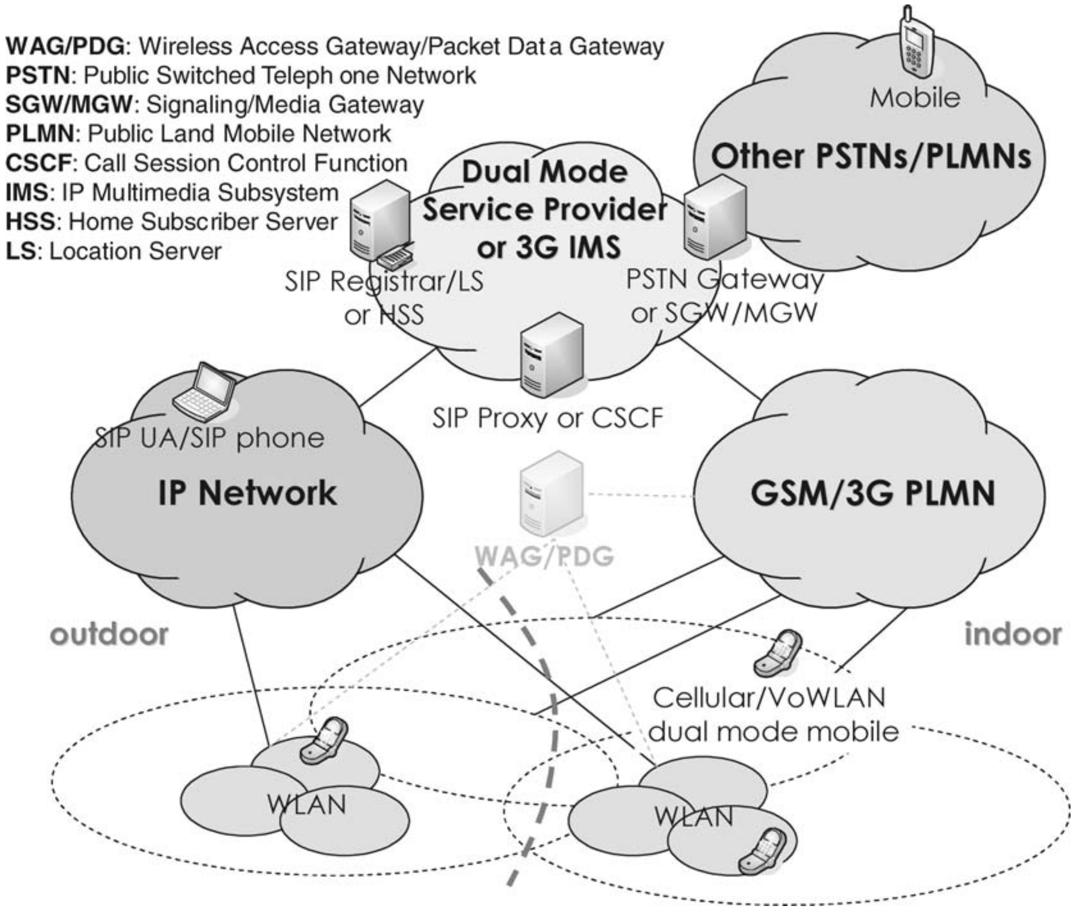

Fig. 1 System architecture for cellular/VoWLAN dual-mode services

and the second approach can be implemented on the application layer. The proposed mechanisms can also support packet-domain services, and be implemented on a PDG. If the PDG receives a packet from the Internet to the IP address associated with the WLAN interface of the mobile, it sends a paging message to the mobile via a cellular network to wake up the WLAN interface. The paging message can be sent to the IP address associated with the cellular interface through the GGSN. If the dual-mode mobile receive a paging message from its cellular interface, it wakes up the WLAN interface to receive the incoming packets.

In this paper, an enterprise dual-mode system which can be realized without the involvement of cellular operators is used as an example to describe the proposed ideas. Also, only voice service is considered in this work. To implement dual-mode services, an enterprise can reserve a range of PSTN numbers or enterprise extension numbers, and install a PSTN/VoIP gateway between PSTN/cellular networks and an enterprise IP network. These PSTN numbers or extension numbers are assigned to dual-mode mobiles as their new dual-mode service numbers. For implementation using enterprise extension numbers, the dual-mode service requires two-step dialing, which means callers must dial an enterprise number first followed by extension numbers. New dual-mode SIP URIs generated based on these numbers are further allocated to these dual-mode mobiles. Consequently, dual-mode mobiles have new dual-mode numbers and new dual-mode SIP URIs that are used for dial-in. Incoming calls to the dual-mode numbers or SIP URIs are processed by using the proposed procedures.

3 Proposed power saving strategy: Paging via another radio

3.1 Outgoing calls

To handle outgoing calls for a dual-mode mobile is straightforward. The interface of a dual-mode mobile used to make outgoing calls can be selected by a user manually or by a management software automatically. The criteria for the interface selection could be based on network connectivity, user preference, cost and etc. If a user selects the cellular interface, a call goes through a cellular network. Otherwise, a user turns on the WLAN interface, and performs SIP call setup procedures via WLANs.

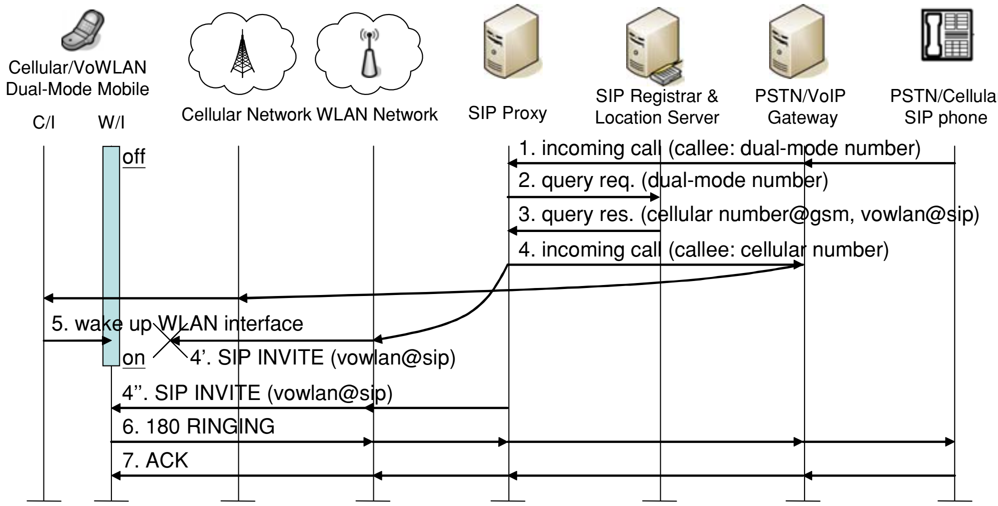

Fig. 2 Procedures to handle an incoming call to a dual-mode mobile based on the parallel fork approach

3.2 Incoming calls to a dual-mode mobile - parallel fork approach

Two solutions, “parallel fork” and “wakeup and register,” are proposed for handling incoming calls to a dual-mode mobile. First, the parallel fork approach is described. Figure 2 illustrates the procedures for processing incoming calls from a PSTN or a cellular network to a mobile. Since the number range for dual-mode mobiles is held by an enterprise, incoming calls to a dual-mode mobile are routed to the PSTN/VoIP gateway and then the SIP server through a standard call routing procedure. After an incoming call to a dual-mode mobile is received by the SIP server, the SIP server uses the dual-mode number as the key to query the subscriber database. If the database replies a cellular number and a dual-mode SIP URI to the SIP server, the SIP server pages the dual-mode mobile via a cellular network, and also sends an *SIP INVITE* message to the mobile via WLANs in parallel. The cellular paging message is implemented by dialing the cellular number of the dual-mode mobile via the PSTN/VoIP gateway. The dual-mode mobile receives a paging message, i.e. an incoming call, from its cellular interface, but the mobile should not ring immediately. The mobile activates its WLAN interface, obtains WLAN and IP connectivity and tries to receive the *SIP INVITE* message from its WLAN interface. If the mobile can receive the SIP message, it responds to the SIP server through its WLAN interface. By that time, the mobile rings the user to answer the incoming call via WLANs. If a dual-mode mobile cannot receive the *SIP INVITE* message within a pre-configured time-out period, it rings the user to answer the call via the cellular interface. Notably, the WLAN interface of a dual-mode mobile is completely off during idle, and this design significantly reduces the power consumption. One problem with this approach is that an SIP server sends an *SIP INVITE* message to an SIP UA without getting a response, and the SIP server activates exponential backoffs for SIP message retransmissions [4]. The exponential backoff retransmission mechanism of SIP messages is originally designed for fixed networks to avoid network congestion, but it introduces extra call setup delays for the parallel fork method since the mobile has to wait for resent *SIP INVITE* messages after the WLAN interface is turned on. To ease this effect, we can disable the SIP exponential backoff retransmission, shorten the SIP retransmission timer, or apply the next proposed wakeup and register method.

3.3 Incoming calls to a dual-mode mobile - wakeup and register approach

The wakeup and register method is proposed to avoid delays associated with the exponential backoff retransmission of SIP messages. The major difference between the wakeup and register and parallel fork approach is that the wakeup and register approach requires a dual-mode mobile to check the SIP server actively instead of waiting for incoming *SIP INVITE* messages. That is, following a cellular paging message is received by a mobile and the WLAN interface is activated, the dual-mode mobile sends *SIP REGISTER* to the SIP server. Then, the SIP server can send *SIP INVITE* messages to the current location of the mobile. Figure 3 illustrates the procedures to handle an incoming call from an SIP phone to a dual-mode mobile. Unlike the parallel fork approach, the wakeup and register approach avoids the delay to wait resent SIP messages, but it requires additional effort for registering with the SIP server. One possible problem with the wakeup and register approach is that an SIP server may handle a large number of accounts, and to search the registrant may introduce considerable processing delay during a registration phase. To speed up the registrant lookup, the SIP

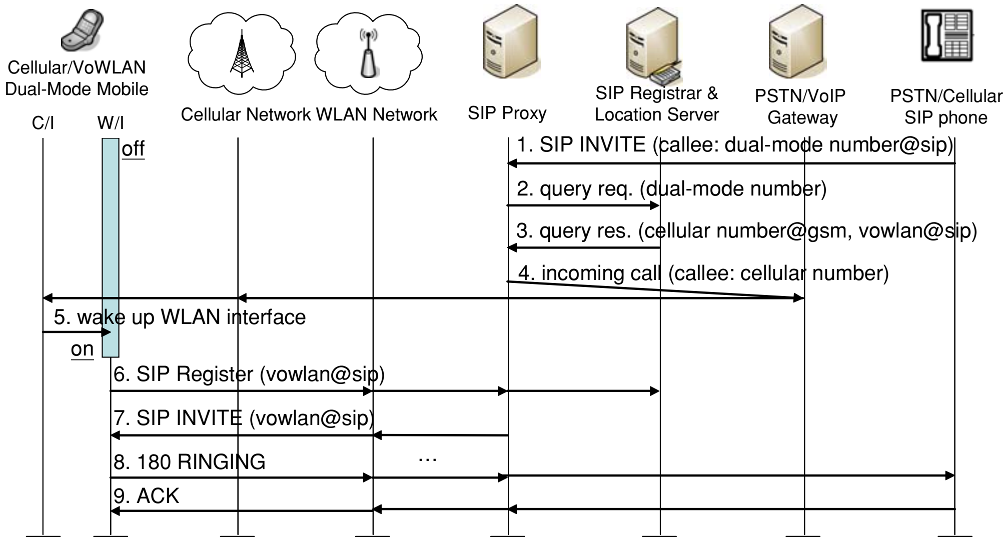

Fig. 3 Procedures to handle an incoming call to a dual-mode mobile based on the wakeup and register approach

server can pre-fetch the mobile subscriber information into cache buffer while the SIP server tries to page the dual-mode mobile. Once the mobile receives the paging message, wakes up the WLAN interface, the registrant information is ready on the SIP server. Then, the mobile can get a fast registration response from the server.

3.4 Modeling power consumption and call setup delay for the conventional dual-mode system

The idle-mode power consumption of a dual-mode mobile comprises the power consumption of a handset itself, a cellular interface, and a WLAN interface. Assume that the total power consumption of a handset and the cellular interface both in the idle mode is a constant, say $P_{mobile\text{-}idle}$, and the power consumption of a WLAN interface is modeled. A WLAN interface in PSM wakes up every listening interval, say $T_{listen\text{-}int}$, to receive a beacon frame. The WLAN interface spends P_{doze} power at doze mode, T_{beacon} time and $P_{wlan\text{-}listen}$ power to process a beacon frame. Consequently, the idle-mode power consumption of a WLAN interface in PSM can be presented as:

$$P_{wlan} = \frac{P_{wlan\text{-}doze} \times T_{listen\text{-}int} + (P_{wlan\text{-}listen} - P_{wlan\text{-}doze}) \times T_{beacon}}{T_{listen\text{-}int}}.$$

To model the call setup delay, we consider the latency from a caller making a call to a mobile detecting an incoming call. Also, the model ignores the processing latencies on a WLAN AP and a dual-mode mobile since these delays contribute a relatively small proportion of the total call setup delay. To setup a cellular call, the delay is $D_{cellular}$. For a VoWLAN call setup, the delay can be modeled as: $D_{wlan} = t_{caller\text{-}sip} + t_{sip\text{-}sta} + t_{wlan\text{-}queue}$, where $t_{caller\text{-}sip}$ and $t_{sip\text{-}sta}$ represent the network transmission delays between a caller node and an SIP server, and between an SIP server and a mobile, respectively. $t_{wlan\text{-}queue}$ denotes the queuing delay at WLAN APs, since the mobile in PSM might not be able to receive the packet immediately. A mobile wakes up every listening interval, checks the beacon, and then receives packets. On average, a mobile requires $E[t_{wlan\text{-}queue}] = \frac{1}{2} \times T_{listen\text{-}int}$ to detect a call setup message in PSM.

3.5 Modeling power consumption and call setup delay for the proposed approaches

The power consumption of a WLAN interface is zero for the parallel fork and wakeup and register approaches during idle. This phenomenon occurs because the WLAN interface is completely switched off if there is no active session. To model the call setup delay of the proposed methods, Fig. 4 presents timing diagrams for all possible conditions. The figure illustrates a dual-mode mobile that moves between three different APs. The first two APs belong to the same sub-network, but the third one belongs to another sub-network domain. The upper part of the figure shows all possible delays introduced by the parallel fork approach, while the lower part shows the delays associated with the wakeup and register case. Three different situations may occur for an incoming call to the mobile. The first one is that the WLAN interface of the mobile is activated and finds it can still access the original AP that the mobile associated. This situation is called a layer one location update case. After the mobile receives a cellular paging message from a cellular network, it takes D_{L1} time to activate the WLAN interface and sense the original AP using the WLAN *Probe Request* and *Probe Response* messages. The WLAN interface then associates

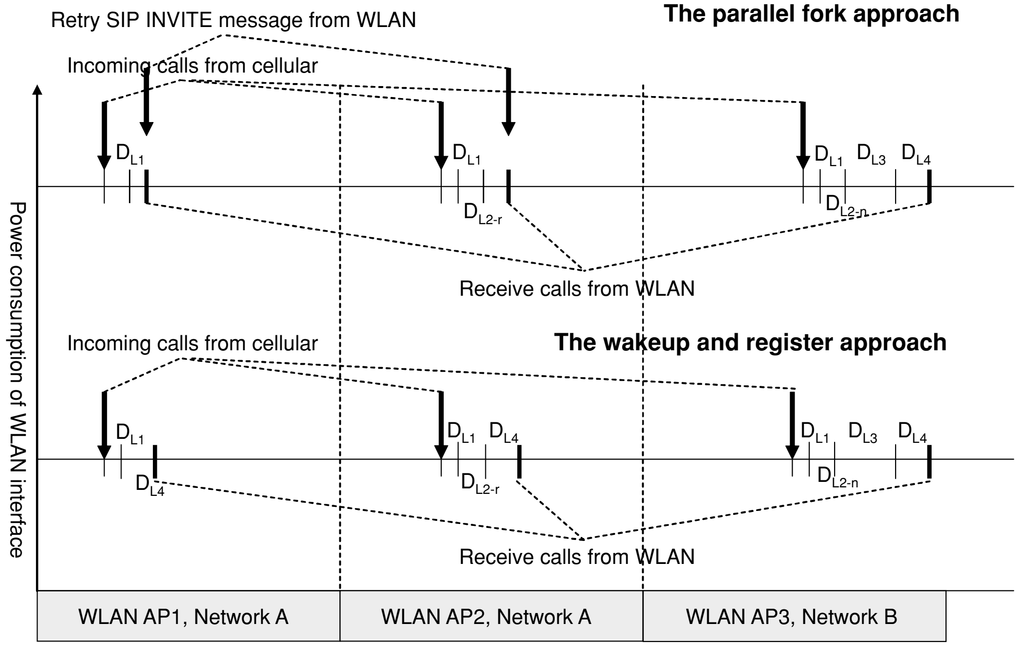

Fig. 4 Call setup delays for the parallel fork and wakeup and register approaches

with the AP and can receive incoming packets from WLANs. As noted above, for the parallel fork approach, since an SIP server sends an *SIP INVITE* message and pages the mobile via a cellular network in parallel, the first one or several *SIP INVITE* messages are not received by the mobile before the WLAN interface is turned on. The SIP server triggers the exponential backoff retransmission mechanism to resend *SIP INVITE* messages. Assume that the dual-mode mobile finally receives the *i*th *SIP INVITE* message from an SIP server. The delay time for the VoWLAN path can be modeled as:

$$D^{i}_{sip\text{-}invite} = \begin{cases} t_{caller\text{-}sip} + (2^{i-1}-1)\times t_{sip\text{-}T1} + t_{sip\text{-}sta}, & 2\le i\le 7 \\ t_{caller\text{-}sip} + t_{sip\text{-}sta}, & i=1 \end{cases}. \qquad \text{(A)}$$

In the above equation, $t_{sip\text{-}T1}$ denotes the default *SIP INVITE* retransmission interval defined in SIP [4]. The interval is normally set to 500 ms. If the SIP server cannot receive the response of the first *SIP INVITE* message, it waits for $t_{sip\text{-}T1}$, and resends an *SIP INVITE* message. The time-out value doubles after each retransmission. Therefore, the SIP server contributes a total of $(2^{i-1}-1)\times t_{sip\text{-}T1}$ time for the *i*th *SIP INVITE* owing to the retransmission mechanism. Importantly, according to the SIP, the maximal retransmission time of a message is $64 \times t_{sip\text{-}T1}$; restated, i must be 7 or lower. Consequently, the delay introduced by the parallel fork approach in a layer one location update case is$D^{piano\text{-}p}_{L1} = D^{i}_{sip\text{-}invite}$, and i must satisfy$D^{i-1}_{sip\text{-}invite} < D_{cellular} + D_{L1} \le D^{i}_{sip\text{-}invite}$, where $D_{cellular}$ represents the delay required to page the mobile via a cellular network. The above equation reveals that the mobile needs to wait for the next *SIP INVITE* message after the WLAN interface of a mobile is activated. The wakeup and register approach that is different from the parallel fork approach requires performing the SIP registration and listening incoming *SIP INVITE* messages after WLAN turn-on and channel sensing procedures. Accordingly, the delay time for this approach is$D^{piano\text{-}w}_{L1} = D_{cellular} + D_{L1} + D_{L4}$ time, where D_{L4} is the time required to perform the SIP registration including the processing delay on the SIP server and an *SIP INVITE* message delay.

The second situation is that the WLAN interface wakes up but cannot sense the original AP. This situation is called a layer two location update case. This situation needs a mobile to perform a WLAN channel scan and associate with a new AP. After a mobile identifies an AP, it attempts to re-authenticate and re-associate with the AP. If the AP belongs to the same sub-network as the original AP that the mobile attached, the new AP accepts the re-association, and the mobile can receive the resent *SIP INVITE* messages. The delay for a layer two location update case is $D^{piano\text{-}p}_{L2} = D^{i}_{sip\text{-}invite}$ where $D^{i}_{sip\text{-}invite}$is shown in Eq. (A) and i must satisfy:

$$D^{i-1}_{sip\text{-}invite} \le D_{cellular} + D_{L1} + D_{L2\text{-}r} + D_{L4} \le D^{i}_{sip\text{-}invite},$$

where $D_{L2\text{-}r}$ denotes a layer two re-association delay that comprises the time required to perform WLAN active scan, re-authentication and re-association. The wakeup and register approach requires an additional delay for the SIP registration and an *SIP INVITE* message, that is:$D_{L2}^{piano\text{-}w} = D_{cellular} + D_{L1} + D_{L2\text{-}r} + D_{L4}$.

The worse case is that the WLAN interface wakes up, finds a new AP, but this new AP is in a different network domain as the AP that the mobile originally associated. In this situation, the WLAN must associate with the new AP, acquire a new IP, perform SIP registration and then receive *SIP INVITE* messages. Since in this case, the mobile also needs to register with the SIP sever and then receives *SIP INVITE* messages for the parallel fork approach, the delay becomes: $D_{cellular} + D_{L1} + D_{L2\text{-}n} + D_{L3} + D_{L4}$. In the above equation, $D_{L2\text{-}n}$ comprises the time required to perform WLAN active scan, full-authentication and full-association, and D_{L3} comprises dynamic host configuration protocol (DHCP) delay to acquire an IP address. As suggested by the previous research [8], duplicate address detection (DAD) after DHCP is disabled in this study to avoid extra DAD delays. The delay involved in the wakeup and register approach is the same as that for the parallel fork approach since both two methods need to register with the SIP server for a layer three location update case. The above equations are derived based on the assumption that SIP mobility is employed instead of mobile IP. Moreover, to avoid any call loss, the parallel fork and wakeup and register approaches both set a maximum waiting time. If a dual-mode mobile cannot receive an *SIP INVITE* message from the WLAN interface within the maximum waiting time, the mobile rings the user to answer the call via the cellular interface. The maximal waiting time is a manageable parameter.

3.6 Periodical location update

Although the proposed approaches reduce the power consumption of a mobile, they introduce extra call setup delays, particularly while the WLAN interface of a mobile is activated and cannot find the original WLAN AP. For example, in the parallel fork approach, the SIP server may send SIP messages to a wrong location of a mobile if the mobile moves to a new network domain without updating its new location to the SIP server. The mobile in the new location is paged; it wakes up the WLAN interface, but cannot receive SIP messages. Finally, after a maximal waiting period, the mobile rings the user to answer the call through the cellular interface. Therefore, the call setup delay for the parallel fork approach increases. Similarly, the call setup delay for the wakeup and register approach may increase if the mobile frequently changes its location and has to perform a layer two or a layer three updates before it can register with the SIP server. To reduce the average call setup delay, periodic location update procedures are further proposed. The idea is that the WLAN interface wakes up every $T_{wake\text{-}up}$ seconds to check whether it can still sense the original AP. $T_{wake\text{-}up}$ is a design parameter and it depends on a network environment and user mobility. If a mobile moves to a new AP, the mobile performs either a layer two or layer three location update. The location updates reduce the average call setup delay, but consume extra energy. The expected extra energy for the periodical location update for the parallel fork and wakeup and register approaches can be obtained as follows:

$$E\left[P_{wlan}^{piano\text{-}U}\right] = \gamma_{L1}^{piano\text{-}U} \times \frac{E_{L1}}{T_{update\text{-}int}} + \gamma_{L2}^{piano\text{-}U} \times \frac{E_{L1}+E_{L2\text{-}r}}{T_{update\text{-}int}} + \gamma_{L3}^{piano\text{-}U} \times \frac{E_{L1}+E_{L2\text{-}n}+E_{L3}+E_{L4}}{T_{update\text{-}int}},$$

where $\gamma_{L1}^{piano\text{-}U}$, $\gamma_{L2}^{piano\text{-}U}$ and $\gamma_{L3}^{piano\text{-}U}$ are the probabilities of a layer one, layer two and layer three location update. In the above equation, $E_{L1}, E_{L1} + E_{L2\text{-}r}, E_{L1} + E_{L2\text{-}n} + E_{L3} + E_{L4}$ denote the energy consumed for layer one, layer two and layer three location update procedures respectively. For a layer one and a layer two location update, the energy consumptions are assumed constants. E_{L1}, $E_{L2\text{-}r}$, and $E_{L2\text{-}n}$ are collected from the measurement results. However, the energy consumption of a layer three location update depends on how long the WLAN interface can obtain network connectivity and start to receive packets from networks. The network latencies for DHCP or SIP message exchanges influence the energy consumption for a layer three location update significantly. Instead of calculating the energy consumption by every message exchange of a layer three location update, a simple energy consumption model for a layer three location update is applied. Since a WLAN interface mostly stays in receiving mode and only spends a small portion of time in transmitting messages, the power consumption of a layer three location update is assumed to be dominated by the receiving-mode power consumption of a WLAN interface. Therefore, the product of the receiving-mode power consumption of a WLAN interface and the duration of a layer three location update approximates the energy consumption. In other words, $E_{L1} + E_{L2\text{-}n} + E_{L3} + E_{L4} = E_{L1} + E_{L2\text{-}n} + (D_{L3} + D_{L4}) \times P_{RX}$ is assumed, where P_{RX} denotes the receiving-mode power consumption of a WLAN interface. Experiment results indicate that the approximation and the real measurements are very close.

3.7 Session continuity for cellular and VoWLAN handoffs

To support session continuity during cellular and VoWLAN handoffs, the call transferring feature that is designed in SIP protocol can be utilized. Once a dual-mode mobile with an active VoWLAN session detects the WLAN signal strength going down to a specific threshold, it sends an *SIP REFER* message to the SIP server. The message informs the SIP server that the mobile wants to switch its current session from WLAN to cellular. The SIP server tries to establish a session by dialing the mobile via the PSTN/VoIP gateway and invites the cellular interface of the mobile into the conference call. After the three-way conference call is established, the mobile disconnects the original VoWLAN session. The SIP server is a stateful proxy, and also manages the newly established cellular session that joins the original VoWLAN session as a conference session during a handoff. In other words, two parallel sessions are active during a handoff period so that the service disruption time can be minimized. Therefore, users can have a continuous service while they move from a WLAN to a cellular network. The idea can be applied to cellular to VoWLAN handoffs. While a dual-mode mobile detects WLANs, it attaches to the WLAN, registers with the SIP server and sends an *SIP REFER* message to the dual-mode mobile SIP URI. The SIP server receives the special *SIP REFER* message from the mobile, understands that the mobile wants to switch its session from cellular to WLAN, and it invites the VoWLAN SIP URI into the conference call. After a VoWLAN session is established, the cellular call is hung up.

4 Performance evaluation and prototyping

Simulations are conducted to evaluate the performance of the proposed parallel fork and wakeup and register methods. Table 1 presents the simulation parameters. Two mobile hardware platforms and WLAN cards that use two different WLAN ICs [16, 17] are considered in the simulation. The average cellular call setup delay is from the report [10], and the other parameters are collected from the experimental measurements made in this study. A Tektronix TD5104B, a digital oscilloscope, is used to measure the electronic current and voltage that consumed by devices and WLAN interfaces. Hence, the power consumption of WLAN interfaces and mobile devices, as well as the energy required to perform particular location update procedures can be derived. For layer one and layer two location update delays, Ethereal, a network monitor tool, is used to observe the latencies. A layer two location update involves a WLAN active scan, which is performed using the same WLAN parameter settings - minimal channel time and maximal channel time, as indicated in [9]. In this paper, the security related functions of WLANs such as 802.1x and 802.11i are disabled. Therefore, the delay for WLAN re-association is the same as that for the WLAN association. That is, $D_{L2\text{-}r} = D_{L2\text{-}n}$ and $E_{L2\text{-}r} = E_{L2\text{-}n}$. In evaluating the network latencies, a one-way SIP message delay between a caller node and an SIP server is assumed to be equal to a one-way SIP message delay between an SIP server and a dual-mode mobile, i.e. $t_{caller\text{-}sip} = t_{sip\text{-}sta}$. The latencies of a layer three and layer four location update reuse the delay models defined in [8]. That is, a layer three location update delay, $D_{L3} = 4 \times t_{sip\text{-}sta}$, which comprises the time to exchange two round-trip DHCP message interactions without DAD is assumed. A layer four location update delay, $D_{L4} = 3 \times t_{sip\text{-}sta}$, comprises the time to exchange a round-trip *SIP REGISTER* message and a one-way delay for an *SIP INVITE* message. In the simulations, while an SIP server pages a mobile via a cellular network, it searches and pre-fetches the mobile subscriber information into cache buffer before the mobile registers with the SIP server. The experimental results show that the average processing delays per *SIP REGISTER* request are 17 ms, 18 ms, and 21 ms while an SIP server has 1,000, 10,000, and 100,000 accounts, respectively. The results indicate that the pre-fetching delays are much less than the paging delays. Therefore, the registrant searching delay on the SIP server during the SIP registration phase can be ignored after the pre-fetch scheme is employed. In following simulations, four network speeds that affect the message exchanging latencies between two network nodes are simulated. They are $t_{caller\text{-}sip} = t_{sip\text{-}sta} = 10$ ms for a high-speed network such as an intranet, $t_{caller\text{-}sip} = t_{sip\text{-}sta} = 50$ ms for a normal speed network, and $t_{caller\text{-}sip} = t_{sip\text{-}sta} = 100$ ms, and $t_{caller\text{-}sip} = t_{sip\text{-}sta} = 200$ ms for slow networks, such as the Internet. Also, the exponential backoff mechanism is turned off and an *SIP INVITE* message is sent in a constant 500 ms retransmission interval in the following simulations.

Table 1 Simulation parameters

Parameters	Value	
$P_{mobile\text{-}idle}$	48 mW (Mio 8380/Intel PXA 250@200 Mhz with a GSM interface in idle mode) 170 mW (O2 XDA II/Intel PXA 255@400 Mhz with a GSM interface in idle mode)	
P_{wlan} ($T_{listen\text{-}int}$:100 ms)	Low-Power WLAN IC 37.2 mW(Sychip SDIO chip) [16]	Standard WLAN IC 93 mW(Prism 2.5 chip) [17]
P_{RX}	685 mW	950 mW
E_{L1}	8 mJ	10 mJ
$E_{L2\text{-}r}/E_{L2\text{-}n}$	172 mJ	307 mJ
D_{L1}	8.5 ms	8.5 ms
$D_{L2\text{-}r}/D_{L2\text{-}n}$	251 ms	261 ms
D_{cellular}	3.6 seconds [10]	

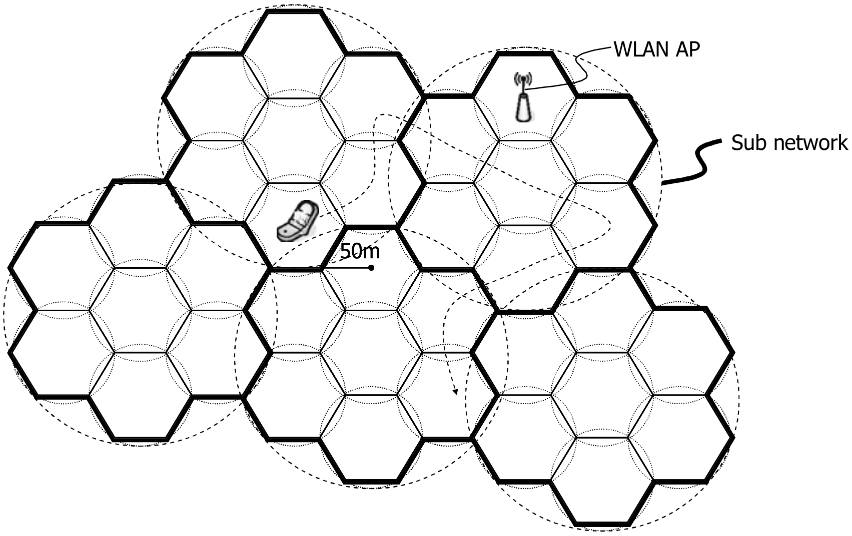

Fig. 5 Simulation network environment

Figure 5 presents the simulation network environment. Sub-networks are wraparound and each sub-network has seven APs. Also, each AP covers an area with a radius of 50 meters. Two typical user mobility behaviors, based on the random walk model, are simulated [5]. The first case simulates infrequently and slow moving users such as office workers. The mobility model A involves a person's moving in a randomly selected direction at a speed from 0 to 3 Km/hour, where each move lasts 30 min. Another mobility behavior is that of frequently and fast moving users, such as salespeople. Mobility model B involves a person's moving at a random selected direction and speed from 0 to 100 Km/hour, where each move lasts also for 30 min.

Table 2 presents the power consumption and mean call setup delays of a dual-mode mobile for the traditional approach without any improvement and the proposed approaches. In this simulation, *SIP INVITE* retransmission interval is set to 500 ms and the network speed between an SIP proxy server and SIP UAs is set to normal speed, i.e. $t_{caller\text{-}sip} = t_{sip\text{-}sta} = 50\,\text{ms}$. The cellular call setup delay is 3.6 seconds. Four implementation combinations of a dual-mode mobile using two hardware platforms and two WLAN chips are investigated. Measurement results reveal that a dual-mode mobile consumes 263 mW, 207 mW, 141 mW and 85 mW for a PDA with a standard WLAN IC, a PDA with a low-power WLAN IC, a smartphone with a standard WLAN IC and a smartphone with a low-power WLAN IC, respectively. When the proposed parallel fork and wakeup and register approaches are applied, only 170 mW and 48 mW are required to power a PDA-based and smartphone-based dual-mode mobile. The power consumed by a dual-mode mobile with the two proposed methods approximates to the power consumption of a single-mode GSM mobile. The power consumption of a dual-mode mobile by employing our methods is also independent of the power consumed by a WLAN interface, because the proposed approaches completely turn off the WLAN interface. The power consumed by a dual-mode mobile based on a PDA with a standard and a low-power WLAN IC is 35% and 18% reduced, respectively. The proposed methods perform better for a dual-mode mobile that uses low-power hardware platforms, because the power consumed by a WLAN interface, which is a significant fraction of the total power consumption, can be reduced. The power consumptions of a smartphone-based mobile using a

Table 2 Performance comparisons of parallel fork/wakeup & register approaches

	Power consumption (mW)				
	PDA		Smartphone		
	Low-power	Standard	Low-power	Standard	Avg. Call setup delay (ms)
Mobility model A					
Dual mode w/o improvement	207.2	263	85.2	141	Cellular:3600 VoWLAN:100
Parallel Fork	170.5	170.7	48.5	48.7	4500
Wakeup & Register	170.6	170.8	48.6	48.8	4123.3
Mobility model B					
Dual mode w/o improvement	207.2	263	85.2	141	Cellular: 3600 VoWLAN:100
Parallel Fork	170.6	170.9	48.7	48.9	4500
Wakeup & Register	170.7	170.9	48.7	48.9	4194.1

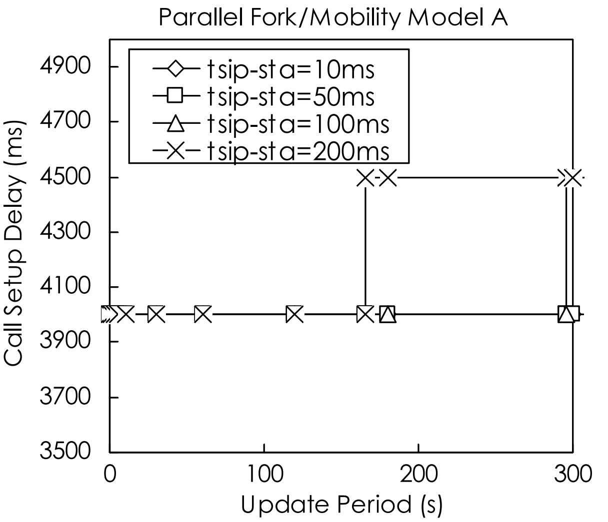

Fig. 6 Location update period vs. call setup delay for the parallel fork apporach given mobility model A

standard and low-power WLAN IC can be reduced by 65% and 43%, respectively. The power consumed by the wakeup and register approach typically exceeds slightly than that consumed by the parallel fork approach, because the wakeup and register approach always needs to perform an SIP registration and then can receive an *SIP INVITE* message, and this procedure consumes energy. This fact can be used to explain why the power consumed by slow-moving mobiles (mobility model A) is a little lower than that consumed by fast-moving mobiles (mobility model B). If the location of a mobile frequently changes, then the awoken mobile requires more time and energy to update its location.

A dual-mode mobile without any improvement that keeps both cellular and WLAN interfaces awake exhibits the shortest call setup delays. It takes 3.6 seconds to receive a call from a cellular network or 0.1 second to receive a call from WLANs. In the proposed approaches, the mobile must be first paged via a cellular network, the WLAN interface of the mobile awoken and the call taken via WLANs. The simulation results demonstrate that another 500 ms to 900 ms is required to receive a call from a WLAN interface for a normal speed network. Restated, a total call setup delay of 4.1 seconds to 4.5 seconds is required for the proposed approaches. Table 2 also shows that the parallel fork approach spends more time to receive a call than the wakeup and register approach, because the dual-mode wakes up; cannot immediately receive the *SIP INVITE* message, and must wait for the next *SIP INVITE* message in the parallel fork approach. In the simulation, the exponential backoff mechanism is turned off and an *SIP INVITE* is sent every 0.5 second. Therefore, the call setup delay for the parallel fork approach is always multiple SIP retransmission intervals. In the following simulations, only the performance of a smartphone using a low-power WLAN IC implementation is investigated.

In the following simulations, the periodical location update function is turned on to reduce the call setup delay for both the parallel fork and wakeup and the register approaches. Firstly, the performance of the parallel fork approach for a slow-moving mobile is studied. Figure 6 presents the call setup delay of a mobile given various location update frequencies. In this simulation, the time required to perform a layer three location update is assumed $D_{L3} = 4 \times t_{sip\text{-}sta} = 40$ ms, 200 ms, 400 ms and 800 ms for high-speed, normal speed, slow and very slow networks respectively. Also, the delays of a layer four location update are $D_{L4} = 3 \times t_{sip\text{-}sta} = 30$ ms, 150 ms, 300 ms and

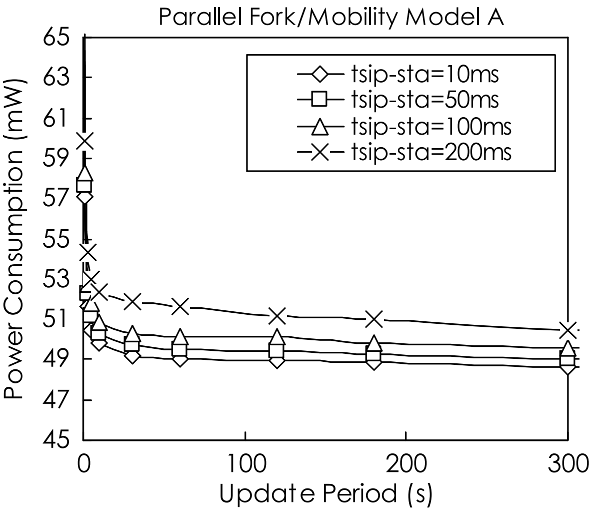

Fig. 7 Location update period vs. power consumption for the parallel fork apporach given mobility model A

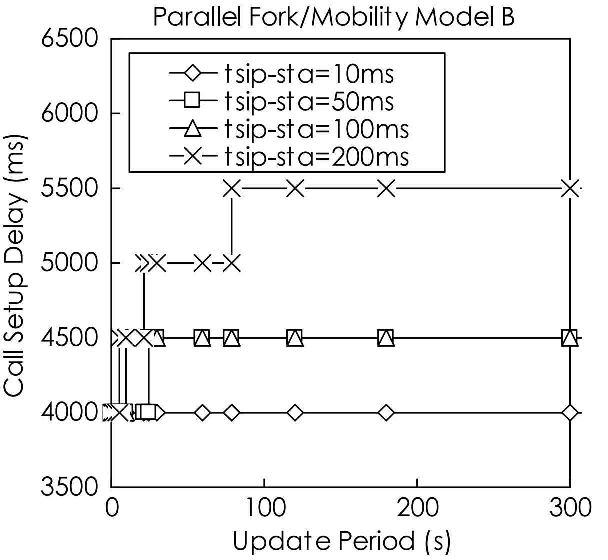

Fig. 8 Location update period vs. call setup delay for the parallel fork apporach given mobility model B

600 ms under four different network speeds. Figure 6 reveals that frequently updating the location can reduce the call setup delays. For a location update period under 160 seconds, 4000 ms call setup delay is required. Given a location update period over 160 seconds, 4000 ms call setup delay can be still achieved while the network speeds are fast, normal or slow, but 4500 ms call setup delay is required for a very slow network. The figure shows that the call setup delays for the parallel fork approach are multiple SIP retransmission intervals, and each interval is 500 ms. This is because that a dual-mode mobile must wait for the next *SIP INVITE* message while the mobile wakes up and cannot immediately receive the SIP message. Figure 7 presents the power consumed by the parallel fork approach given various location update frequencies. Frequent location updates spend more energy to perform periodical location update procedures. For example, while $t_{sip\text{-}sta} = 50$ ms and a location update period around 160 seconds, the parallel fork approach yields an idle-mode power consumption of 49 mW to 50 mW. A comparison with Table 2, which relates to the parallel fork approach without location updates, reveals that the parallel fork with periodical location updates consumes an extra 1 mW to 2 mW, but can reduce call setup delays by 500 ms. The parallel fork approach with periodical location updates still can reduce the power consumption by 43% below that of a dual-mode mobile without improvements. Figure 7 also reveals that the network speed affects the power consumed by a dual-mode mobile, because a dual-mode mobile takes less time, and thus consumes less energy, to complete location update procedures and message exchanges over a high-speed network.

Secondly, the performance of the parallel fork approach for a fast-moving mobile is evaluated. Figures 8 and 9 present the call setup delay and power consumption of a mobile under various location update frequencies, respectively. For a fast-moving mobile, call setup delay increases if the mobile does not often update its location. If the location is not updated frequently, a mobile typically must perform location updates before a call can be established in the WLAN. Depending on the network speeds and location update frequencies, the parallel fork method takes an extra 600 ms to 2 seconds delay to setup a call. Figure 9 shows the power consumed by a mobile when the parallel fork approach with the periodical location update is applied. To compare Figs. 9 and 7, we can learn that a fast-moving mobile consumes more energy than a slow-moving mobile because the percentage of layer two and layer three location updates for fast-moving mobiles exceeds these for slow-moving mobiles.

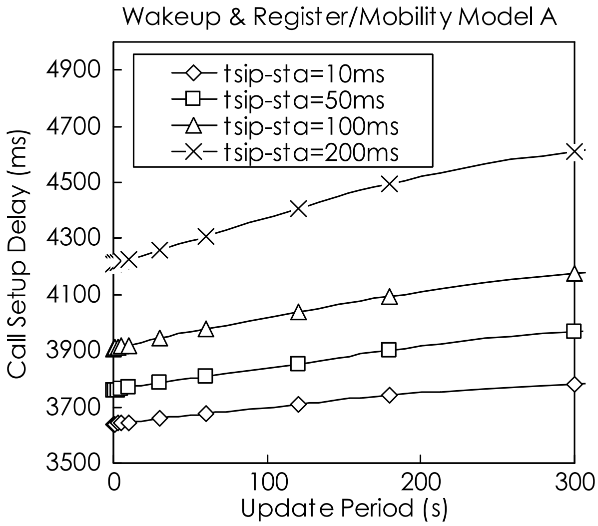

Fig. 10 Location update period vs. call setup delay for the wakeup and register apporach given mobility model A

Figures 10 and 11 display the call setup delay and power consumption under various location update frequencies

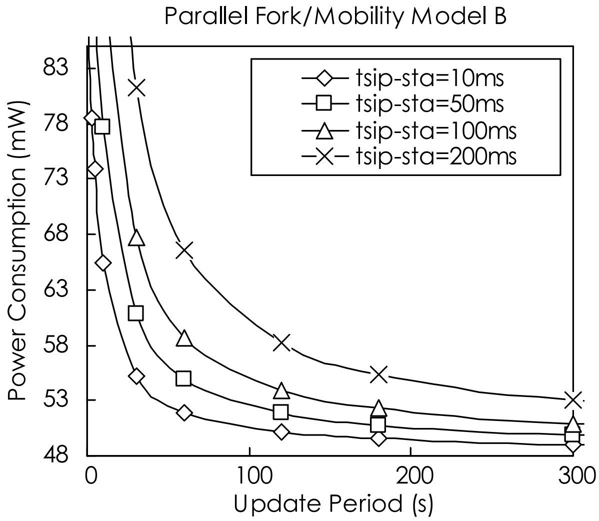

Fig. 9 Location update period vs. power consumption for the parallel fork apporach given mobility model B

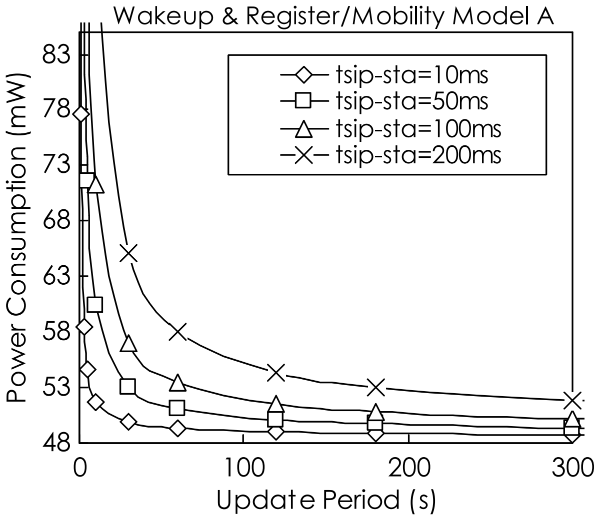

Fig. 11 Location update period vs. power consumption for the wakeup and register apporach given mobility model A

while the wakeup and register method and mobility model A are applied. As in the parallel fork approach, less frequent location update reduces the energy consumption but increases the delay to establish a call. Also, a slow network corresponds to longer call setup delays and greater power consumption. We use a location update period of 120 seconds as an example. Depending on the network speeds, the wakeup and register method reduces 38% to 42% of the power consumed by a mobile without the improvement. The power consumed is about 2 mW greater than that consumed by the wakeup and register approach without periodical location update but the call setup delay is reduced by 300 ms at a normal network speed. The simulation results also indicate that very frequent location update causes serious power consumption problems and must be avoided. For instance, in Fig. 11, a mobile that uses the wakeup and register approach with a periodical location update of under 10 sec. consumes more energy than a mobile without any enhancement. Figures 7 and 11 demonstrate that the parallel fork method consumes less energy than the wakeup and register approach, because the former does not always needs an SIP registration after wakeup. On the other hand, the wakeup and register approach outperforms the parallel fork in terms of call setup delays, because the latter might have to wait for an SIP retransmission message.

Figures 12 and 13 plot the performance of the wakeup and register approach using the same parameters as used in Figs. 10 and 11, but the mobility model B is assumed. A comparison with the results presented in Table 2, for an example, with a 300 second location update period and a normal network speed reveals that the power consumption increases 3 mW but the call setup delay reduces 20 ms. The figures also demonstrate that the power consumptions and call setup delays for mobility model B exceed those for mobility model A since fast-moving mobiles change and have to update their locations frequently.

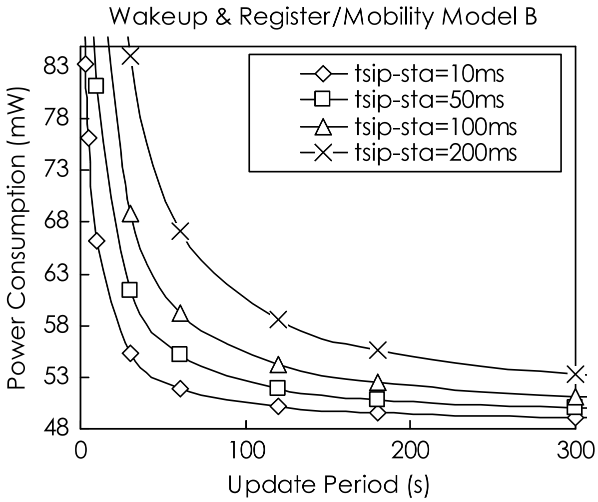

Fig. 13 Location update period vs. power consumption for the wakeup and register apporach given mobility model B

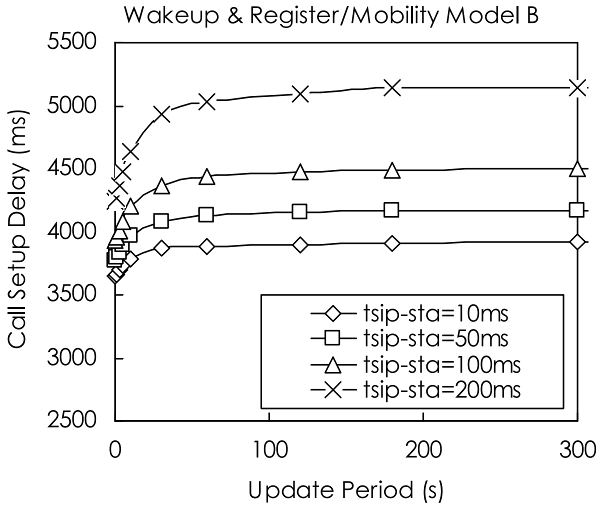

Fig. 12 Location update period vs. call setup delay for the wakeup and register apporach given mobility model B

The call setup delays are then evaluated under different cellular call setup latencies and SIP retransmission intervals. In this simulation, only normal network speed is considered. Figures 14 and 15 plot the simulation results for slow-moving and fast-moving mobiles, respectively. Two SIP retransmission intervals, i.e. 300 ms and 500 ms, and two cellular call setup delays, i.e. 3600 ms and 3000 ms, are simulated. The simulation results show that the call setup delays associated with the parallel fork approach do not always exceeds those associated with the wakeup and register approach. The delay time associated with the parallel fork approach depends on the SIP retransmission interval, the cellular call setup delays,

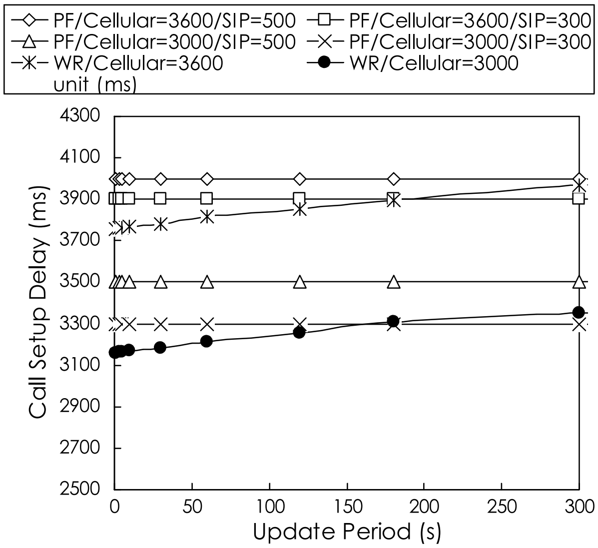

Fig. 14 Location update period vs. call setup delay under different cellular call setup delays and SIP retransmission time intervals given mobility model A

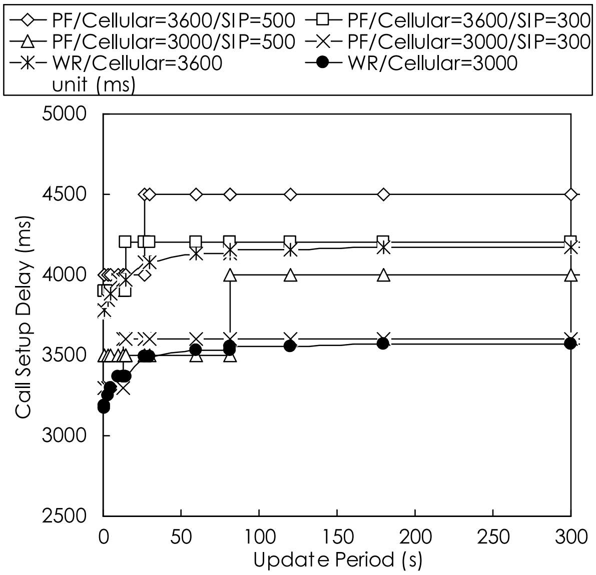

Fig. 15 Location update period vs. call setup delay under different cellular call setup delays and SIP retransmission intervals given mobility model B

and the extra delay introduced by location update procedures. If the mobile that applies the parallel fork method wakes up; completes the location update procedures, and just receives the retransmission of *SIP INVITE* message, then the parallel fork can achieve lower call setup delays than the wakeup and register approach. If the mobile wakes up but does not receive the most recent *SIP INVITE* message, then the mobile must wait for the next SIP retransmission and the delay increases. For example, while a location update period of is over 180 seconds, the parallel fork requires only 3900 ms to establish a VoWLAN call. In such a case, the wakeup and register approach spends more than 3900 ms to setup a VoWLAN session.

Finally, the service disruption time due to a WLAN to cellular handoff is simulated. A cellular to WLAN handoff is not simulated since a cellular coverage is normally larger than a WLAN coverage. While a mobile with an active cellular session moves to an area with WLANs, it tries to attach WLANs, acquires an IP address, and then performs the SIP registration. The cellular session can be disconnected after a new VoWLAN session is established. Therefore, the service disruption time due to a cellular to WLAN handoff could be zero. However, while a mobile with an active VoWLAN session moves out of a WLAN coverage but the new cellular session is not yet established, the service is disrupted. In this simulation, an in-door WLAN propagation model is assumed, and the handoff threshold is set to −50 dB to −85 dB. The mobile triggers WLAN to cellular handoff procedures if it detects the WLAN signal strength lower than the pre-defined threshold. In Fig. 16, we can learn that if the threshold is set to −80 dB or higher, the voice service is not disrupted for slow-moving mobiles, i.e. mobility model A. However, 0.5 second to 3.6 seconds service disruption time occurs for fast-moving mobiles, i.e. mobility model B. This is because the mobile moves too fast; a cellular session is not yet established, but the mobile moves out of the WLAN coverage.

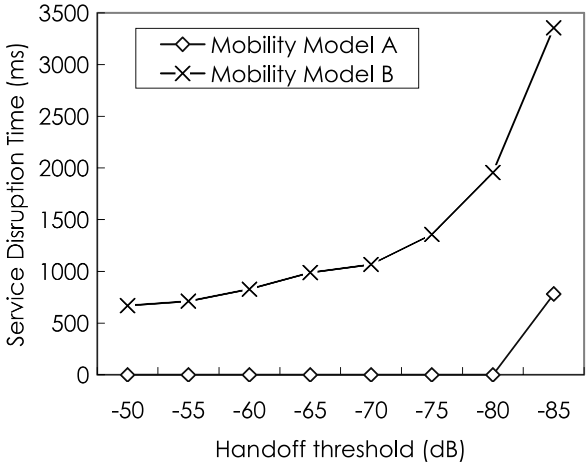

Fig. 16 Service disruption time for a VoWLAN to cellular handoff under different handoff thresholds

Open source projects and commercial products are integrated to implement an enterprise dual-mode system and the proposed power saving strategies. SIP Express Router (SER), an open source SIP server developed by IPTel [7], is used as an SIP proxy server, and a Cisco 1760 is used as a PSTN/VoIP gateway. The proposed parallel fork and wakeup and register methods are both implemented in the SIP Express Router. For dual-mode mobiles, the implementation is based on WinCE/Smartphone 2003, so that it can be applied to a mobile running WinCE. Currently, O2 XDAII and Mio8380, both with GSM built-in and a WLAN SDIO add-on card, are used for the PDA and smartphone platforms. The dual-mode client program fully integrates cellular functions and VoWLAN functions, and supports the parallel fork and wakeup and register methods.

Figure 17 presents the software architecture of the integrated dual-mode client program on WinCE. The cellular/VoWLAN integrated client is developed using embedded VC++. Telephony API 2.0 (TAPI) is utilized to control the GSM interface. The TAPI allows incoming call events to be detected, and calls to be answered and dialed. The object identifier (OID) services provided by an 802.11 network driver interface specification (NDIS) driver are accessed directly to control the low level behaviors of a WLAN interface. The API allows us to turn on or off the WLAN radio, perform a WLAN active scan, to associate and de-associate with APs, and measure the WLAN signal strengths. The integrated cellular/VoWLAN client implements a threshold-based mobility management for WLAN to cellular and

Table 3 Delay measurements based on the prototype system

	Parallel Fork Approach		Wakeup and Register Approach	
	Avg. call setup delay (ms)	Standard deviation	Avg. call setup delay (ms)	Standard deviation
Mobile wakes up and situates in the same AP				
Cellular call setup delay (Operator 1)	3592	388	3540	181
Cellular call setup delay (Operator 2)	4609	178	4591	197
WLAN switch-on and association	22	10	22	8
Resent *SIP INVITE* message received	243	152	–	–
SIP registration and *SIP INVITE* message received	–	–	7	1
Total call setup delay (Operator 1)	3849	399	3570	178
Mobile wakes up and situates in a different AP but in the same sub-network				
Cellular call setup delay (Operator 1)	3474	283	3661	429
WLAN switch-on, active scan, and association	354	14	356	15
Resent *SIP INVITE* message received	259	146	–	–
SIP registration and *SIP INVITE* message received	–	–	7	1
Total call setup delay (Operator 1)	4088	340	4025	430
Mobile wakes up and situates in a different AP and sub-network				
Cellular call setup delay (Operator 1)	3765	467	3473	145
WLAN switch-on, active scan, and association	357	9	358	2
IP acquisition and setup	1055	13	1056	15
Duplicated address detection (DAD)	1910	86	1903	108
Resent *SIP INVITE* message received	238	157	–	–
SIP registration and *SIP INVITE* message received	–	–	7	1
Total call setup delay (Operator 1/without DAD)	6267	434	5694	305

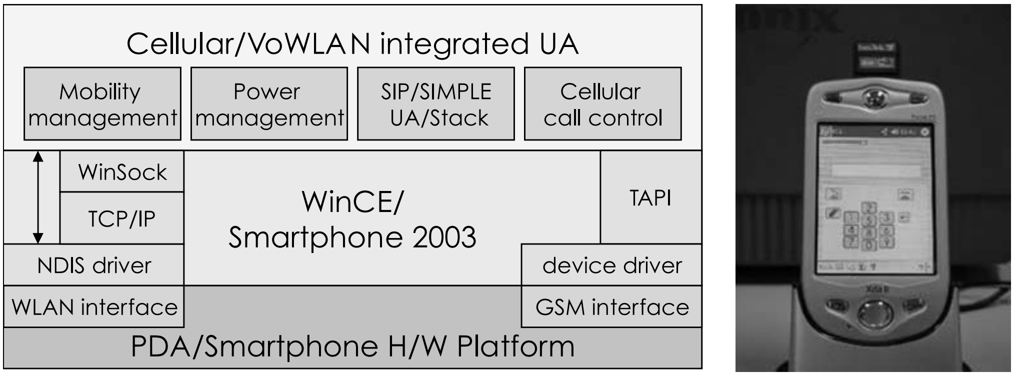

Fig. 17 Software architecture and snapshot of the prototype cellular/VoWLAN dual-mode mobile

cellular to WLAN handoffs. Table 3 summarizes the measurement results based on the prototype system. An SIP server, a PSTN/VoIP gateway, and WLAN APs are all connected to a campus intranet, and the timers on the nodes related to the delay measurements are synchronized using the network time protocol (NTP). The SIP UA running on a caller node automatically generates calls to the dual-mode mobile, and the delays are measured by an application program on the mobile. Therefore, the measurement results include the software/operating system delays and the network delays. Each measurement runs 30 times and the average delays and the standard deviation are both listed in Table 3. The measurement results show that the delay to page a mobile via a cellular network, i.e. to dial the cellular number of the mobile, quite depends on the operators. The average call setup delays are 3.6 seconds and 4.5 seconds while the mobile installs two different subscriber identity module (SIM) cards that belong to Operator 1 and Operator 2, respectively. We believe the reason why the call setup delays for the Operator 1 number are always less than these for the Operation 2 number is because our PSTN/VoIP gateway connects to the PSTN also operated by Operator 1. For the situation that the dual-mode mobile wakes up and situates in the same AP, 3.8 seconds and 3.6 seconds are required from a caller making a call to the mobile detecting the VoWLAN call for the parallel fork and wakeup and register approaches, respectively. The experimental results are higher than the simulation results since the simulations only consider pure network latencies without taking software overheads into considerations. For the situation that the dual-mode mobile wakes up and situates in a different AP but in the same sub-network, about extra 600 ms, and 350 ms call setup delays are introduced by the parallel fork and wakeup and register approaches, respectively. Finally, the case that a dual-mode mobile wakes up and situates in a different AP and a different sub-network is measured. The results show that the call setup delays significantly increase to about 8 seconds and 7 seconds for the parallel fork and wakeup and register approaches. To examine the differences between the simulation and measurement results, we compare the packet logs recorded by the measurement program on the mobile and the logs recorded by the Ethereal running on the traffic monitoring node. The measurement records illustrate that a layer three location update spends a 1.9-second extra delay for the duplicated address detection, and 1-second extra delay to renew the IP address in the operating system after DHCP procedures. These delays are not taken into account in the simulations.

5 Conclusions

This study presented two power saving mechanisms for a cellular/VoWLAN dual-mode system. Based on the proposed mechanisms, the WLAN interface of a dual-mode mobile is completely switched off during idle, and the cellular interface is awake and it is used as a paging medium to activate the WLAN interface. Therefore, a dual-mode mobile can reduce the idle-mode power consumption, and still receive VoWLAN calls. Measurement results based on the prototype system demonstrate that the proposed methods reduce 43% to 65% idle-mode power consumption of a smartphone-based dual-mode mobile while extra 30 ms to 2500 ms call setup delays than the cellular calls are introduced.

Acknowledgment The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 95-2221-E-009-025.

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