

# Idle Mode for Deep Power Save in IEEE 802.11 WLANs

Sunggeun Jin, Kwanghun Han, and Sunghyun Choi

**Abstract:** Along with the wide acceptance of IEEE 802.11 wireless local area network (WLAN), new applications such as Internet protocol (IP) telephony over WLAN are fast emerging today. For battery-powered IP phone devices, the life time extension is a key concern for the market acceptance while today's 802.11 is not optimized for such an operation. In this paper, we propose a novel idle mode operation, which comprises *paging*, *idle handoff*, and *delayed handoff*. Under the idle mode operation, a mobile host (MH) without any active session does not need to perform handoff within a predefined paging area (PA). Only when it enters a new PA, an *idle handoff* is performed. The proposed idle mode allows an MH without traffic to extend its life time. We develop a new analytical model in order to comparatively evaluate our proposed scheme. The numerical results demonstrate that the proposed scheme outperforms the existing schemes with respect to power consumption.

**Index Terms:** Idle mode, IEEE 802.11 wireless local area networks (WLANs), power saving.

## I. INTRODUCTION

Recently, IEEE 802.11 wireless local area network (WLAN) became a prevailing technology for the broadband wireless Internet access. Along with that, new types of applications such as Internet protocol (IP) telephony over WLAN are fast emerging today. For the wide market acceptance of battery-powered IP phones in the growing 802.11 WLANs, IP phone's power consumption efficiency appears a key concern for the mobility management in the 802.11 WLAN while today's 802.11 is not optimized for this. The reason why the 802.11 WLAN provides poor efficiency in power consumption for the IP phones is rooted in the fact that the 802.11 WLAN medium access control (MAC) protocol [1] defines only two operational modes, which an mobile host (MH) can operate in, namely, *active mode* (AM) and *power save mode* (PSM).

In both modes, an MH has to always remain associated with an access point (AP) even when there is no traffic to/from it. This issues a critical problem that it has to perform handoffs at every AP cell boundary in order to maintain the association with an AP. The inevitable handoffs, at every AP cell boundary, cause MH without active traffic<sup>1</sup> to waste precious battery power in vain. As the handoff frequency, approximately proportional to

the MH's speed, increases, the MH consumes more power.

Even worse, when IEEE 802.11i [2] is employed for security enhancement, a larger amount of message exchanges during the handoff operation are expected, and these incur more power consumption. Currently, IEEE 802.11r [3] is being developed in order to overcome the overhead for performing the 802.11i-related security operations during the handoff. Despite of the efforts, 802.11r does not remove the handoff of idle MH itself so that it still incurs the waste of power.

That is, IEEE 802.11 WLAN is naturally lack of an efficient support of the mobility with respect to power consumption when there is no traffic to be served for the MHs. Therefore, it is desired to have a new mode of operation, called idle mode (IM), on top of the currently-available AM and PSM. Due to the absence of such an IM operation, the combination of the IP paging and the PSM, called the PSM with IP paging in this paper, have been proposed as an alternative to the IM operation [4] though the original aim of the IP paging is to facilitate the integration of different wireless technologies and the IP paging is independent of layer-2 (L2) technologies [5].

However, as discussed further later, IP paging is found to be harmful to the power consumption efficiency since the power consumption under the IP paging increases as the amount of broadcast/multicast traffic in the network increases while there are frequent broadcast/multicast frame transmissions in typical WLANs. This fact implies that an MH should wake up frequently than common expectations in order to manage broadcast/multicast frames, and hence, it wastes more power in vain.

In order to overcome the discussed problems, we propose an IM operation, comprising *paging*, *idle handoff*, and *delayed handoff*, which can be used when an IEEE 802.11 WLAN standard-based MH does not have traffic or on-going sessions. Using the proposed IM operation, the MH can stay in the doze state requiring very little power. In our scheme, an MH does not perform any handoff within a predefined paging area (PA). The handoff with the minimum operation, called idle handoff, is performed only when an MH leaves a PA. The paging provides a way to inform an MH in the IM of a new frame arrival. The IP-level handoff should be deferred until a paging success in order to reduce redundant operations, and hence, it is referred to as *delayed handoff*.

In [6], the authors also discuss a paging scheme similar to our IM operation for 802.11 WLAN. In their scheme, tracking agent keeps a cache containing MAC addresses and IP addresses for both MH and its associated AP. However, the cache is updated at every reassociation, i.e., L2 handoff, and hence, it incurs redundant signaling cost and power consumption.

The rest of this paper is organized as follows. In Section II, we discuss the limitations of the PSM with IP paging. In Section III,

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<sup>1</sup>We refer to an MH without active traffic as an idle MH.

Table 1. Summary of acronyms.

AM	Active mode
AP	Access point
BSS	Basic service set
FA	Foreign agent
HA	Home agent
HD	Handheld device
IM	Idle mode
IP	Internet protocol
L2	Layer-2
L3	Layer-3
MAC	Media access control
MH	Mobile host
MRA-AP	Most recently associated AP
PA	Paging area
PAID	Paging area identification number
PSM	Power saving mode
PTK	Pairwise transient key
RRB	Remote request broker
VoIP	Voice over IP
VoWLAN	Voice over WLAN
WNIC	Wireless network interface card
WLAN	Wireless local area network

we introduce the IM for the IEEE 802.11 WLAN. Additionally, we propose new protocols constituting the IM. In Section IV, we develop an analytical model to evaluate the proposal in terms of power consumption. In Section V, through our mathematical model, we evaluate our proposal and demonstrate the superiority of our proposal compared with the current PSM with IP paging. Finally, in Section VI, we conclude this paper with the summary of our efforts and results. The acronyms used in this paper are summarized in Table 1.

## II. CURRENT LIMITATIONS

Paging is developed to locate an idle MH when there arrives an incoming call destined to the idle MH. If an access network capable of supporting IP, however, does not offer paging scheme, IP paging can be used as an alternative for the wireless network level paging. For this reason, researchers have considered that the PSM together with IP paging could be the alternative scheme for the 802.11 WLANs [4]. However, since the PSM was developed without consideration of IP paging, the use of IP paging along with the PSM could be an inefficient approach. In this section, we discuss the reason why the combination of the PSM and IP paging is not suitable as an alternative to the IM for IEEE 802.11 WLAN.

### A. Limitations of the PSM with IP Paging

The 802.11 standard specifies that MH's wireless network interface card (WNIC) can be in either of *awake* and *doze* states [1]. In *awake* state, it can transmit, receive or sense the physical channel while it actually continues to sense the channel unless it either transmits or receives a frame. On the other hand, in *doze* state, it is not able to transmit nor receive, and hence, consumes very little power. How WNIC switches between these two states is determined by its power management mode, i.e., the AM and the PSM. A WNIC in the AM always keeps operating in the *awake* state while the WNIC in the PSM can change its state between the *awake* and *doze* states depending on the

Table 2. Broadcast/multicast frame inter-arrival time statistics.

0~10 ms	10~100 ms	100 ms~1 s	≥ 1 s
59.73 %	10.50 %	29.41 %	0.36 %

Table 3. Various types of multicast and broadcast frames.

Protocol	%	Protocol	%
ARP request	67.27	UDP (SSDP)	9.56
UDP (LLMNR)	5.33	IGMP	4.92
UDP (WSD)	4.60	UDP (unknown)	3.58
UDP (802.11 IAPP)	2.74	DNS	1.15

traffic pattern. Based on these features, we summarize the limitation of the PSM with IP paging for an alternative to the IM as follows.

Since an MH running in the PSM stays associated with an AP, handoff is performed at every AP cell boundary in order to maintain its association, thus resulting in redundant power consumption. During a handoff procedure, the MH has to stay in the AM since the handoff can be severely delayed otherwise.

In order to employ the PSM with IP paging, several foreign agents (FAs) are grouped to cover an IP paging area. Whenever an MH crosses an IP paging area, it should perform a location update procedure including an layer-3 (L3) handoff. As proved in [7], it takes several seconds to perform an L3 handoff due to the L3 operation features. For this reason, higher mobility drives power saving schemes to require more power. When a new call arrives, a selected agent broadcasts IP paging message(s) through the entire IP paging area [5]. An MH in the PSM is informed that it is paged by receiving the broadcast IP paging message, which all APs in the IP paging area forward after delivery traffic indication message (DTIM) transmission.<sup>2</sup>

However, this policy requires unnecessary manipulations of broadcast/multicast frames. The PSM with IP paging scheme is employed when there is no active traffic for an MH. As explained early, IP paging depends on broadcast IP frames to inform idle MHs that new calls destined to the MHs are about to be established. Therefore, an idle MH in the PSM should receive basically all the broadcast/multicast frames in order to detect the existence of newly-arriving calls although most frames are actually useless, and then, the received broadcast/multicast frames are forwarded from MAC to IP layer.

As to practical devices, an MH consists of WNIC and handheld device (HD) where WNIC is attached. HDs are portable equipments such as personal digital assistance (PDA) or smart phone. IEEE 802.11 WLAN standard-based MAC layer resides in a WNIC while IP layer, as a part of operating system (OS), is embedded in HDs. It implies that HD needs to process these forwarded IP frames by consuming considerable energy. In order to verify the reasoning, we measure the inter-arrival times of broadcast/multicast frames, i.e., the times between two consecutive broadcast or multicast frames, for an hour in NESPOT, which is a large-scale commercial WLAN operated by Korea telecom (KT). Additionally, we obtain another statistics in order to take a closer look at what kinds of broadcast/multicast frames are being transmitted in the network. For the measurement, we

<sup>2</sup>DTIM transmission interval is a count of the number of beacon frames, of which transmission period is typically 100 ms.

have used three MHs associated with an AP in the NESPOT.

Tables 2 and 3 show the inter-arrival times and the types of the measured broadcast/multicast traffic. From the tables, surprisingly the inter-arrival times under 10 ms represent the major portion. The average frame inter-arrival time is 116.7845 ms. This fact shows that there will be a broadcast/multicast frame every beacon interval (assuming 100 ms beacon interval) in average, and hence, the MH has to wake up often, e.g., every beacon interval, to receive these frames. For this reason, any MHs adopting an IP paging are compelled to consume their energy in vain in order to receive useless frames.

We classify the collected packets by referring to the destination port since the destination port typically indicates the usage of the frame [8]. However, we cannot recognize the usage when a multicast frame contains a particular port number, of which usage is unknown. Table 3 shows what kind of multicast and broadcast frames are in the wireless network. The ratio is obtained by dividing the number of the corresponding type frames by the total collected broadcast/multicast frames.

In this table, we observe that ARP request frames occupy 67.27 % of the broadcast/multicast frames. The ARP request frames are necessary to IP address management for the dynamic host configuration protocol (DHCP). When there is no response corresponding to an ARP request, DHCP server determines that it should withdraw the corresponding IP address allocated to an MH. UDP (SSDP) accounting for 9.56 % represents UDP multicast packets for simple service discovery protocol (SSDP), which is designed for universal plug-and-play by Microsoft and Hewlett-Packard. Internet group management protocol (IGMP) and UDP (LLMNR) are utilized for the membership management of Internet protocol multicast groups and link local multicast name resolution (LLMNR) protocol, respectively. UDP (WSD) is used for web service discovery (WSD) protocol. UDP (unknown) indicates the broadcast/multicast frames of which usage is not known. We do not present the rest frames, of which portion is less than 1 %.

Moreover, IPTV services relying on IP broadcast/multicast transmissions are launched for wired network in Korea. Naturally, the IPTV services are expected to be served in wireless networks soon. It implies that we will face more congested IP broadcast/multicast traffic in wireless network in the near future. Lastly, the original IP paging is targeted at the integration of heterogeneous wireless networks by providing paging scheme in IP layer. However, under wireless network exploiting its own MAC-specific paging scheme, IP paging actually would provoke redundant operations since both MAC and IP provide the same functionality, i.e., *paging*. Nevertheless, due to the absence of a paging in IEEE 802.11 WLANs, IP paging would have been regarded as a useful candidate for the MAC-level paging [4].

### III. PROPOSED IM OPERATION

#### A. Definition of IM

In order to overcome the problems discussed in Section II, we define a new mode, i.e., IM, for IEEE 802.11 WLAN. By utilizing the IM, we allow idle MHs to minimize required operations, thus leading to high power saving efficiency. When an MH is in

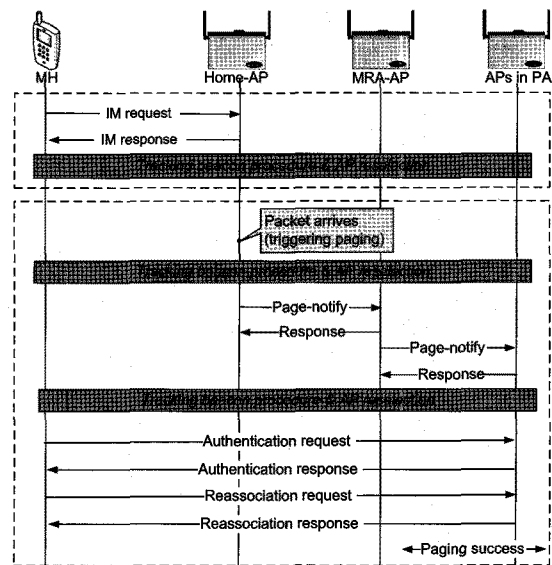


Fig. 1. Procedure for the IM operation.

the IM, it performs only essential operations to wake up to catch a newly-arriving call in time. The necessary operations for the IM are defined as follows:

1. A handoff does not occur at every cell boundary unlike an MH in the PSM. A handoff, called *idle handoff*, is performed only when an MH leaves a PA to enter another PA.
2. When an MH is in the IM, the MH is not associated with any AP. The only thing that the MH in the IM has to do is to listen to the beacons periodically at every predefined interval in order to switch itself to the *active mode* when a frame destined to itself arrives. The typical beacon listening interval for receiving beacons to wake up is set to 1 s, while beacons are transmitted by APs every 100 ms typically. It should be noted that the call setup latency increases proportional to the beacon listening interval.
3. Only a successful paging makes an MH in the IM enter the *active mode*.

Security is indispensable for proper VoWLAN services. The emerging 802.11r standard is expected to provide efficient security schemes for fast roaming when a MH moves across APs [3]. We integrate the IM operation with those schemes defined in the 802.11r.

#### B. Protocols for IM

A number of neighboring AP cells are grouped into a PA. The APs belonging to different routers can also be grouped into a single PA. The APs in the same PA have the same identifier, which is broadcast through the beacons with a newly-defined paging area identifier (PAID) field. Each MH in the IM can differentiate a PA via its PAID.

We define a new procedure in order to support the IM. Fig. 1 shows the procedure when an MH enters and leaves the IM. After a session (e.g., a VoIP session) completion, the MH transmits an *IM request* frame, a management frame, to enter the IM. After receiving the corresponding *IM response* from the AP, the MH in the IM can move around within the same PA while the AP, which transmitted the *IM response*, maintains the information

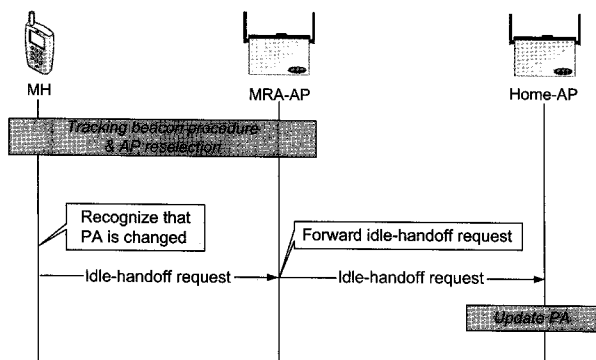


Fig. 2. Idle handoff.

regarding the MH in the IM. The information is used to support the movements to other PAs, security, and call setup process in the future.

This AP is referred to as home-AP. After entering the IM, the MH starts listening to beacons periodically (e.g., every one second). Even when an MH recognizes the change of AP cell through the beacon information, the MH only keeps listening to the beacons as long as the MH stays in the same PA. This continuous beacon listening operation is called AP-reselection. For an efficient AP-reselection, there could be many optimization issues as addressed in [9]–[11]. However, we do not consider the AP-reselection issues since they are beyond the scope of this paper.<sup>3</sup>

When a frame destined to a particular MH in the IM arrives at the home-AP, the home-AP broadcasts a *page-notify* message to all the APs, belonging to the same PA, which in turn start paging the destination MH. That is, the APs convey the paging information via their beacon frames. If an MH recognizes that it is paged by receiving such beacon(s) from an AP, it attempts to associate with the AP by transmitting a *reassociation request* frame. After finishing all the preparations for serving the MH, the new AP replies to the MH with a *reassociation response* frame and broadcasts *paging-success* to the APs in the same PA to stop paging operations of these APs. Along with that, after a successful paging, the MH begins a delayed handoff operation as presented below. Ultimately, the proposed IM enables the 802.11 WLAN to page the deeply sleeping MHs only in L2 without depending on the IP paging since the PSM with IP paging has redundancies in paging as explained earlier.

The paging may fail when a new call arrives in case that an MH in the IM does not update its movement to a newly-entered PA. However, the paging failure probability is ignorable as proved in Appendix I. In spite of the ignorable paging failure probability, it is required to cope with the paging failure for reliable service. In case of the paging failure, the paging retry should be conducted  $\bar{T}_{bli}$  later since an MH in the IM requires  $\bar{T}_{bli}$  to recognize its movement to a new PA.

C. Idle and Delayed Handoff

Idle handoff is a handoff that is performed whenever an MH in the IM moves across a PA boundary. Fig. 2 shows the proce-

<sup>3</sup>For example, the *Neighbor Report* information from the emerging 802.11k [10] will make this possible.

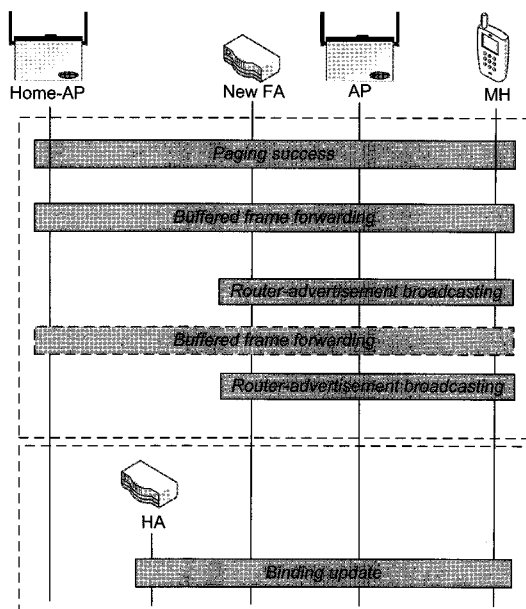


Fig. 3. Delayed handoff.

cedure for idle handoff. After an MH enters a new PA, which can be identified by a newly-received beacon, it transmits an *idle-handoff request* frame including the basic service set identifier (BSSID) of its home-AP. If it fails, it can retry the transmission. Upon receiving the *idle-handoff request* frame, the new AP receiving the frame forwards it to the home-AP.<sup>4</sup> In case that a home-AP receives an *idle-handoff request* frame, it updates the PAID for an idle MH with the value conveyed through *idle-handoff request*. After transmitting *idle-handoff request*, the MH resumes listening to the beacons periodically in order to receive the paging information. The AP, which is involved with the 2-way frame exchange, is referred to as *most recently associated AP (MRA-AP)*.

When there is at least one idle handoff, a home-AP transmits a *page-notify* to an MRA-AP, which in turn forwards it to all the APs in the same PA. Since our proposed scheme enables 802.11 WLAN to keep track of the locations of the MHs in the IM, IP-layer related operations including IP paging becomes redundant. That is, our proposed protocol replaces IP paging. Therefore, in our approach, handoff operations related to an IP layer are postponed until a successful completion of the paging even when an MH needs to conduct IP-layer handoff by departing the coverage of an FA, where a home-AP is attached. For this reason, we refer to this handoff operation, which delays the activation of IP layer, as delayed handoff.

We define a protocol for delayed handoff as shown in Fig. 3. During the paging operation, frames destined to an idle MH are buffered at the home-AP. After a successful paging, the home-AP forwards the buffered frames to a new AP, which the paged MH is newly associated with. While the home-AP forwards those frames, the MH begins listening to *router-advertisement-messages*, which an FA broadcasts to provide the

<sup>4</sup>The mapping between an AP’s MAC address and its IP address can be obtained from a server as defined in IEEE 802.11F [12]. Note that the 802.11F is not a standard. The mapping information can be utilized when a new AP forwards the *idle-handoff request* frame to the home-AP.

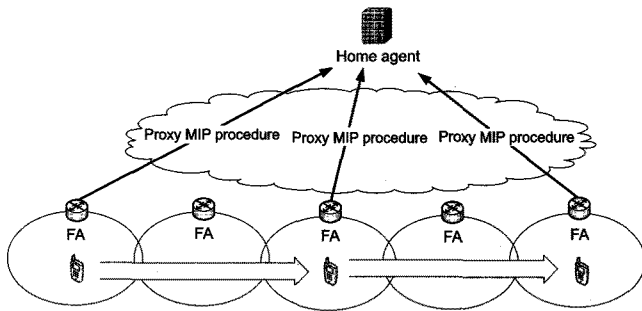


Fig. 4. Proxy MIP procedure.

IP-layer handoff. By receiving *router-advertisement-messages*, the MH can initiate an IP handoff deferred until the paging.

However, it incurs a corresponding call setup latency. Therefore, we provide a remedy reducing the latency by utilizing proxy MIP [13]. Additionally, we prove that there exists a trade-off relationship between the power consumption, which is represented by a signaling cost, and the call setup latency. The previous study only deals with IP layer procedure, and hence, we provide an integrated scheme combining the proposed IM and the IP layer procedure as follows.

We design FAs to perform an MIP handoff on behalf of an idle MH, which is referred to as PMIP procedure, whenever an idle MH enters an FA's coverage. An idle MH neither performs an MIP handoff nor receives broadcast/multicast IP packets, thus reducing power consumption as well as signaling cost as well. In fact, FAs, however, do not need to conduct a PMIP procedure whenever an idle MH enters their coverage since an idle MH does not have a session. We assume FAs perform a PMIP procedure only if an idle MH reaches the coverage of a new FA located at a predefined distance from the old FA (oFA), which has performed the latest PMIP procedure as shown in Fig. 4.

Keeping these features in mind, we develop a protocol for the 802.11 WLANs as follows: (1) An MH enters the IM by completing an IM entrance procedure involved with a home-AP. The home-AP begins managing the location of the MH after activating PMIP in the FA connected with the home-AP. (2) When the idle MH performing the idle handoff moves to the coverage of a new PA, the corresponding MRA-AP determines whether the idle MH enters a coverage of a new FA by querying the home-AP about the previous FA, where the MH stayed.

In this case, the MRA-AP<sup>5</sup> obtains the distance between the new FA and the oFA. If the distance is equal to a predefined value, it requests the new FA (nFA)<sup>6</sup> to conduct the PMIP procedure. Additionally, it requests oFA to remove obsolete context about the idle MH and takes over the role of home-AP. Otherwise, it informs the home-AP that the MH is in its PA. (3) Since FAs do not perform the PMIP procedure whenever an idle MH enters a new FA-coverage, IP packets destined for the idle MH arrive at oFA. For this reason, the oFA triggers the home-AP to page the idle MH. Consequently, the paged idle MH can conduct an MIP handoff by itself after the completion of a network entry procedure for the wireless network while oFA forwards

<sup>5</sup>MRA-AP can be designed to have a mapping table containing distances among FAs based on pre-configured location information for each FA.

<sup>6</sup>nFA represents the new FA performing PMIP procedure.

the arrived IP packets by querying the information about under which FA the paged MH is from the home-AP. As a result, this proposal enables an idle MH to fully exploit the power saving efficiency, which the IM can provide by removing the necessity to receive broadcast/multicast IP packets.

#### D. Security for IM Operation

The IM is designed to work with the existing and emerging 802.11 security schemes including the 802.11i [2] and the 802.11r [3]. In the 802.11i, an MH that handoffs to a new AP performs the 802.1x authentication procedure prior to the 4-way handshake. However, an MH in the IM keeps disassociated from a WLAN. It implies the WLAN does not need to provide it with a secure service. For this reason, an MH employing the IM can defer the authentication procedure up to the end of a successful paging, thus incurring less power consumption. Since the 802.11i-based commercial networks are already deployed in many places, we consider the 802.11i WLAN for our evaluations.

In an 802.11r WLAN, fast transition (FT) key hierarchy is designed to accelerate handoff by providing hierarchical key management strategy to establish pairwise transient key (PTK) fast. However, since an idle MH does not have any data to be served, it does not need to derive the PTK whenever it moves to another AP but computes fresh PTK for secure data transmission with a successful paging. Excepting the secure data transmission, when an idle MH conducts idle handoff, secure *idle-handoff request* should be forwarded to home-AP. In the 802.11r, remote request broker (RRB) assumes the role of frame forwarding, and hence, we adopts the functions of RRB in order to support idle handoff. When an MH enters the IM, the idle MH and home-AP do not release the PTK for future use. An idle MH trying to transmit *idle-handoff request* frame encrypts the frame with the PTK, which is used for secure transmission with home-AP, and then, transmits it to an MRA-AP. Upon receiving the encrypted *idle-handoff request* frame, an RRB in the MRA-AP forwards the frame encrypted with the PTK to home-AP guaranteeing secure validity.

## IV. POWER CONSUMPTION ANALYSIS

The IM is developed to improve power consumption efficiency, and hence, we analyze the performances of both the IM and the the PSM with IP paging in terms of power consumption. For the numerical analysis, we separate MH into WNIC and HD, which take roles of MAC and IP, respectively since their power consumption is different from each other.

#### A. Assumptions

We consider VoIP telephony as a target application for our analysis. When VoIP phone is used, a session is initiated by an incoming or outgoing call. In order to indicate the operational status of VoIP phone, we define two states for the service as follows:

*State 1:* An MH holds an active session. In other words, WNIC is in the *awake* state and the HD is powered on. The MH has an session for traffic. It performs handoff whenever it moves across AP cells.

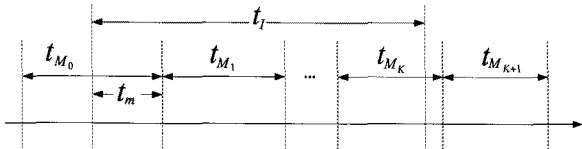


Fig. 5. Timing for area crossings: The term “area” is used to imply an IP paging area as well as a paging area.

*State 2*: An MH stays idle without holding active session. It implies that WNIC switches between the *awake* and the *doze* states at every predefined time interval periodically in order to receive beacons including the paging information. If the IM is utilized, WNIC performs idle handoff whenever it leaves a PA. A successful paging or outgoing call makes the MH enter *state 1*.

For general assumption, we do not consider microsleeping<sup>7</sup> for on-going VoIP session in *state 1*, i.e., the state transition from the *awake* state to the *doze* state does not occur during the whole on-going session time. In order to determine the steady state probability, we make the following assumptions:

1. Incoming and outgoing calls at an MH occurs according to a Poisson process with rates  $\lambda_{in}$  and  $\lambda_{out}$ , respectively.
2. Session holding time  $t_h$  is generally distributed with a probability density function  $f_h(t)$  and its expectation is  $1/\lambda_h$ .
3. Idle time  $t_I$  is exponentially distributed with the expectation  $1/\lambda_I$ . Note that  $\lambda_I = \lambda_{in} + \lambda_{out}$ .

**B. Area Crossing Probability**

IP paging area encompasses multiple routers, each of which may include several APs, and hence, it is reasonable that an IP paging area comprises several PAs, which in turn consists of several AP cells. For this reason, IP paging area and PA are structured in hierarchal network topology, where MH would move around by crossing AP cells while possibly crossing them as well. Power consumption depends on how many areas including IP paging areas, PAs, or AP cells an MH passes through.

In Fig. 5, let random variable  $t_I$  represent an idle time.  $f_I(t)$  is the probability density function (pdf) of  $t_I$ . Generally,  $f_I(t)$  can be an arbitrary pdf, but we assume an exponential distribution. Random variable  $t_{M_i}$  represents area sojourn time at the  $i$ th area.  $f_{M_i}(t)$  and  $E[t_{M_i}] (= 1/\lambda_{M_i})$  are the pdf and the expectation of area sojourn time, respectively. We assume that area sojourn times,  $t_{M_i}$ 's, are i.i.d., and follow the same distribution. Therefore, we simply denote  $t_{M_i}$  and  $f_{M_i}(t)$  as  $t_M$  and  $f_M(t)$ , respectively. Let  $t_m$  be the interval between the beginning of the IM and the instance when the MH leaves the first area while  $f_m(t)$  indicates its pdf.  $f_M(t)$  and  $E[t_M] (= 1/\lambda_M)$  are the pdf and the expectation of  $t_M$ , respectively.  $F_m^*(s)$  and  $F_M^*(s)$  represent the Laplace transform functions of  $f_m(t)$  and  $f_M(t)$ , respectively.

We derive the probability  $\Pr(t_M < t_I)$  that an MH crosses an area during idle time by:

<sup>7</sup>Microsleeping is a sleeping for silent voice period while MH holds active session.

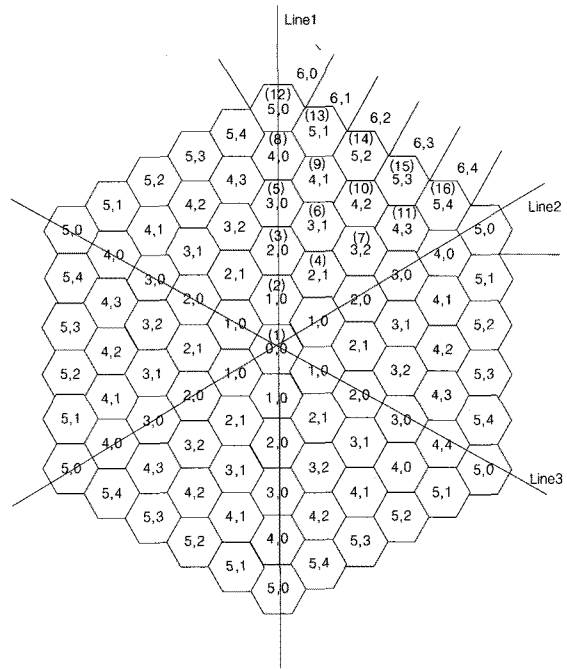


Fig. 6. Types of cells within an area and outside-regions.

$$\begin{aligned} \Pr(t_M < t_I) &= \int_0^\infty \int_0^{t_i} f_I(t_i) f_M(t) dt dt_i \\ &= \lambda_I \int_0^\infty e^{-\lambda_I t_i} \int_0^{t_i} f_M(t) dt dt_i \\ &= \lambda_I \frac{F_M^*(\lambda_I)}{\lambda_I} = F_M^*(\lambda_I). \end{aligned}$$

Similarly, we have the probability that an MH crosses the first area by  $F_m^*(\lambda_I)$ . Now, we easily derive the probability  $\Pr(K = k)$  that an MH crosses areas  $k$  times during idle time from the reasoning: (1) The MH crosses the first area with the probability  $F_m^*(\lambda_I)$ , and thereafter, (2) it crosses  $(k - 1)$  PAs with the probability  $(F_M^*(\lambda_I))^{k-1}$ ; finally, it stops crossing the PA with the probability  $(1 - F_M^*(\lambda_I))$ . The equation is obtained by multiplying those probabilities summarized by:

$$\Pr(K=k) = \begin{cases} 1 - F_m^*(\lambda_I), & k=0, \\ F_m^*(\lambda_I)(F_M^*(\lambda_I))^{k-1}(1 - F_M^*(\lambda_I)), & k \geq 1 \end{cases} \quad (1)$$

where  $k = 0$  implies that MH stays within the first area. We introduce another derivation in Appendix II.

**C. Area Sojourn Time Probability**

Since an area, i.e., either an IP paging area or a PA, is composed of a number of cells, we can derive  $f_m(t)$  and  $f_M(t)$  as follows. Fig. 6 shows the cell types in an area and the outside-region types at the outside of an area. In this figure, cells are classified into different types according to the absolute position in a sector. A sector is defined by a region between adjacent intersecting lines.

The outside-region type is labeled after the type of its adjacent cell in an area. A layer is defined as a group of cells with the

same depth from the area center. The probability matrix  $P^{(k)}$ , where element  $p_{(x,y),(x',y')}^{(k)}$  of  $P^{(k)}$  represents the probability that MH moves from either a type  $\langle x, y \rangle$  cell or a type  $\langle x, y \rangle$  outside-region to a type  $\langle x', y' \rangle$  cell or outside-region exactly at the  $k$ th random crossing, can be derived by:

$$P^{(k)} = P \cdot P^{(k-1)}, \quad k \geq 1,$$

where  $P = (p_{(x,y),(x',y')})$  is the transition matrix, and  $p_{(x,y),(x',y')}$  is the probability that MH departs either a type  $\langle x, y \rangle$  cell or a type  $\langle x, y \rangle$  outside-region to enter a type  $\langle x', y' \rangle$  cell or outside-region.

Let the maximum number of the layers in an area be  $N$ . If there exists only a single cell in an area, namely, type  $\langle 0, 0 \rangle$  cell,  $N = 1$ . The transition matrix  $P$  becomes  $(\frac{N(N+1)}{2} \times \frac{N(N+1)}{2})$  matrix. MH can reach type  $\langle N, j' \rangle$  outside-region by departing an area only via type  $\langle N-1, j' \rangle$  cell. Using the transition matrix, the probability  $p_{k,(x,y),(N,j)}$  that an MH initially resides at a type  $\langle x, y \rangle$  cell, and moves into a type  $\langle N-1, j \rangle$  cell at the  $(k-1)$ st crossing, and then, departs an area at the  $k$ th crossing is derived by [14]:

$$p_{k,(x,y),(N,j)} = \begin{cases} p_{(x,y),(N,j)}, & k = 1, \\ p_{(x,y),(N,j)}^{(k)} - p_{(x,y),(N,j)}^{(k-1)}, & k > 1 \end{cases} \quad (2)$$

where  $0 \leq j < N-1$ .

Random variable  $t_{(k)}$  represents the time that an MH spends until leaving an area while it visits  $k$  cells. If an MH begins the IM in the area, it is denoted by:

$$t_{(k)} = \left( t_r + \sum_{i=2}^k t_c \right)$$

where  $t_r$  is the random variable for the residual service time [15] defined by that required to leave a cell when an MH begins the IM in the area. Let  $t_c$  denote a random variable for cell sojourn time.  $E[t_c] (= 1/\lambda_c)$  is its expectation. If an MH passes through an area while visiting  $k$  cells,  $t_{(k)}$  is derived by:

$$t_{(k)} = \sum_{i=1}^k t_c.$$

We derive  $F_m^*(s)$  and  $F_M^*(s)$  by considering how many cells an MH visits until leaving an area. Let  $f_{(k)}(t)$  represent the pdf of  $t_{(k)}$ . Accordingly,  $f_m(t)$  is derived by [16]:

$$f_m(t) = \sum_{k=1}^{\infty} \sum_{n=0}^{N-1} \sum_{y=0}^{n-1} \sum_{j=0}^{N-2} \psi(n, y) p_{k,(n,y),(N,j)} f_{(k)}(t) \quad (3)$$

where  $\psi(n, y)$  is the probability that MH starts its IM when staying in a type  $\langle n, y \rangle$  cell. In a hexagonal area, there are six cells of the same type except for type  $\langle 0, 0 \rangle$  cell. Assuming that the total number of cells in an area is  $S(N)$ ,  $\psi(n, y)$  is derived by:

$$\psi(n, y) = \begin{cases} \frac{1}{S(N)}, & n = 0 \text{ and } y = 0, \\ \frac{1}{6S(N)}, & \text{otherwise.} \end{cases}$$

In this equation,  $S(N)$  is given by  $6\frac{N(N-1)}{2} + 1$ . Since the pdf of  $t_r$  is defined by  $f_r(t) = \lambda_c \int_t^{\infty} f_c(\tau) d\tau$  [15], the Laplace transform function of  $f_r(t)$  is derived by:

$$F_r^*(s) = \frac{\lambda_c}{s} (1 - F_c^*(s)).$$

From (3), the Laplace transform  $F_m^*(s)$  is derived by:

$$F_m^*(s) = \sum_{k=1}^{\infty} \sum_{n=0}^{N-1} \sum_{y=0}^{n-1} \sum_{j=0}^{N-2} \psi(n, y) p_{k,(n,y),(N,j)} \cdot \frac{\lambda_c}{s} (1 - F_c^*(s)) (F_c^*(s))^{k-1} \quad (4)$$

When an MH enters an area, it begins its movement at type  $\langle N-1, y \rangle$  cell. It implies that the probability that the MH leaves the area at the  $k$ th cell crossing becomes  $p_{k,(N-1,y),(N,j)}$ . Therefore, the pdf of area sojourn time required to cross an area is derived by [16]:

$$f_M(t) = \sum_{k=1}^{\infty} \sum_{y=0}^{N-2} \sum_{j=0}^{N-2} \varphi_{(N-1,y)} p_{k,(N-1,y),(N,j)} f_{(k)}(t) \quad (5)$$

where  $\varphi_{(N-1,y)}$  is the probability that MH enters an area through a type  $\langle N-1, j \rangle$  cell at the first crossing. The values of  $\varphi_{(N,y)}$  are obtained as follows:

$$\varphi_{(N,y)} = \begin{cases} \frac{3}{2N+1}, & y = 0, \\ \frac{1}{2N+1}, & \text{otherwise.} \end{cases}$$

Using (5), the Laplace transform function  $F_M^*(s)$  of  $f_M(t)$  is derived by:

$$F_M^*(s) = \sum_{k=1}^{\infty} \sum_{y=0}^{N-2} \sum_{j=0}^{N-2} \varphi_{(N-1,y)} p_{k,(N-1,y),(N,j)} (F_c^*(s))^k. \quad (6)$$

We apply (4) and (6) to the derivations of  $\Pr(K_{IP} = k)$  and  $\Pr(K_{PA} = k)$ , each of which represents the probability that an MH crosses IP paging area and PA  $k$  times during an idle time  $t_I$ , respectively. For the purpose, we use new notations  $F_{IP}^*(s)$  and  $F_{ip}^*(s)$  instead of  $F_M^*(s)$  and  $F_m^*(s)$  for  $\Pr(K_{IP} = k)$ . Similarly,  $F_{PA}^*(s)$  and  $F_{pa}^*(s)$  correspond to  $F_M^*(s)$  and  $F_m^*(s)$  for the derivation of  $\Pr(K_{PA} = k)$ , respectively. Consequently, we summarize the corresponding Laplace transform functions as follows:

$$F_{IP}^*(s) = \sum_{k=1}^{\infty} \sum_{y=0}^{L-2} \sum_{j=0}^{L-2} \varphi_{(L-1,y)} p_{k,(L-1,y),(L,j)} (F_c^*(s))^k \Big|_{s=\lambda_I}, \quad (7)$$

$$F_{ip}^*(s) = \sum_{k=1}^{\infty} \sum_{n=0}^{L-1} \sum_{y=0}^{n-1} \sum_{j=0}^{L-2} \psi(n, y) p_{k,(n,y),(L,j)} \cdot \frac{\lambda_c}{s} (1 - F_c^*(s)) (F_c^*(s))^{k-1} \Big|_{s=\lambda_I}, \quad (8)$$

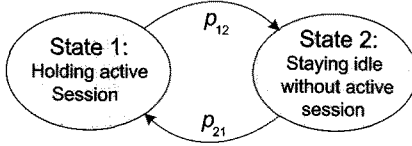


Fig. 7. State transition diagram for Markov chain modeling.

$$F_{PA}^*(s) = \sum_{k=1}^{\infty} \sum_{y=0}^{l-2} \sum_{j=0}^{l-2} \varphi_{(l-1,y)p_{k,(l-1,y),(l,j)}} (F_c^*(s))^k \Big|_{s=\lambda_I}, \quad (9)$$

$$F_{pa}^*(s) = \sum_{k=1}^{\infty} \sum_{n=0}^{l-1} \sum_{y=0}^{n-1} \sum_{j=0}^{l-2} \psi_{(l,y)p_{k,(n,y),(l,j)}} \cdot \frac{\lambda_c}{s} (1 - F_c^*(s)) (F_c^*(s))^{k-1} \Big|_{s=\lambda_I} \quad (10)$$

where  $L$  and  $l$  are the maximum number of the layers for IP paging area and PA, respectively. Typically, IP paging area is larger than PA, and hence, it satisfies that  $L \geq l$ . We derive the AP-cell crossing probability  $\Pr(K_c = k)$  simply by replacing  $F_m^*(s)$  and  $F_M^*(s)$  with  $\frac{\lambda_c}{s}(1 - F_c^*(s))$  and  $F_c^*(s)$ , respectively.

#### D. Power Consumption

We derive MH's power consumption including WNIC's when it adopts the IM or the PSM with IP paging. In [17] and [18], the authors present the analysis regarding power consumption. We, however, derive a new power consumption model since the previously presented analysis did not deal with hierarchical network topology. Fig. 7 shows two operational states of an MH for a Markov chain modeling by considering our assumptions. The steady state analysis is based on the embedded-Markov process because state changes occur with a Markov chain, but take a random amount of time between the changes. In this figure,  $p_{12}$  and  $p_{21}$  are the state transition probabilities, representing a session completion in *state 1* and a session arrival in *state 2*, respectively. Both  $p_{12}$  and  $p_{21}$  are simply 1, and hence, we easily obtain the stationary probabilities of this *embedded Markov Chain* as  $\pi_1 = 1/2$  and  $\pi_2 = 1/2$ , respectively. In addition, we can analyze the average time, which the MH stays in each state, as  $\bar{T}_1 = 1/\lambda_h$  and  $\bar{T}_2 = 1/\lambda_I = 1/(\lambda_{in} + \lambda_{out})$ . Then, we obtain the steady state probabilities of the *embedded-Markov process* as follows:

$$p_i = \frac{\pi_i \bar{T}_i}{\sum_{j=1}^2 \pi_j \bar{T}_j}, \quad i = 1, 2. \quad (11)$$

In the steady state, MH's average power consumption is derived by:

$$\bar{P} = p_1 \bar{P}_1 + p_2 \bar{P}_2,$$

where  $p_1$  and  $p_2$  are the probabilities derived in (11) for *state 1* and *state 2*, respectively.  $\bar{P}_1$  and  $\bar{P}_2$  are the corresponding power consumption in each state.

Since an MH in the IM does not need to perform IP-layer

Table 4. Parameters for power consumption analysis.

Parameter	Definition
$\lambda_{br}$	Ave. delay for paging message delivery
$\lambda_{in}$	Incoming call rate
$\lambda_{out}$	Outgoing call rate
$t_c$	A random variable for cell sojourn time
$t_h$	A random variable for session holding time
$t_{(k)}$	A random variable for area sojourn time
$t_r$	A random variable for residual service time
$t_I$	A random variable for idle time
$\bar{D}_p$	Ave. delay for paging message delivery
$\bar{E}_{1x}$	Energy required to perform 802.1x procedure
$\bar{E}_{AP\_res}$	Energy required to perform AP reselection
$\bar{E}_b$	Energy required to receive beacon
$\bar{E}_{br}$	Energy required to receive broadcasts
$\bar{E}_{DHO}$	Energy required for delayed handoff
$\bar{E}_{iho}$	Energy required for idle handoff
$\bar{E}_{L2HO}$	Energy required for L2 handoff
$\bar{E}_{L3HO}$	Energy required for L3 handoff
$\bar{E}_p$	Energy required for paging
$\bar{E}_{WN\_slp}$	Energy consumed while a WNIC is sleeping when it is in the IM
$\bar{N}_{bi}$	Ave. number of beacon listening in IM
$\bar{N}_{br}$	Ave. number of broadcast frames within a Target Beacon Transmission Time (TBTT)
$\bar{N}_{PA\_cng}$	Ave. number that an MH leaves PAs
$\bar{P}_{HD\_act}$	Ave. power consumption of HD being in active state
$\bar{P}_{HD\_slp}$	Ave. power consumption of HD being in sleep state
$\bar{P}_{WN\_awak}$	Ave. power consumption of WNIC in <i>awake</i> state
$\bar{P}_{WN\_slp}$	Min. power consumption of WNIC in <i>doze</i> state
$\bar{T}_{1x}$	Ave. time for 802.1x procedure
$\bar{T}_{auth}$	Ave. time for authentication procedure
$\bar{T}_{bli}$	Beacon listening interval
$\bar{T}_b$	Ave. time for beacon frame transmissions
$\bar{T}_{b\_sg}$	Ave. time for a single beacon frame transmission
$\bar{T}_{br}$	Ave. time for broadcast frame transmissions
$\bar{T}_{br\_sg}$	Ave. time for a single broadcast frame transmission
$\bar{T}_{brp}$	Ave. time for inter-arrival of broadcast frames
$\bar{T}_{DHO}$	Ave. time for delayed handoff procedure
$\bar{T}_{ih}$	Ave. time for idle handoff procedure
$\bar{T}_{L2HO}$	Ave. time for L2-level handoffs
$\bar{T}_{L2HO\_sg}$	Ave. time for a single L2-level handoff
$\bar{T}_{L3HO}$	Ave. time for L3-level handoffs
$\bar{T}_{L3HO\_sg}$	Ave. time for a single L3-level handoff
$\bar{T}_p$	Ave. time for paging procedure
$\bar{T}_{ras}$	Ave. time for reassociation procedure
$\bar{T}_{scan}$	Ave. time for scanning procedure

operations as discussed in Section III, an HD transits its power mode to standby mode. In contrast, when the PSM with IP paging, is employed, it has to perform inter-AP handoff along with probable IP-layer handoff. For this reason, it is reasonable to assume HD is always powered on.

We first determine the power  $\bar{P}_1$  consumed in *state 1* as follows:

$$\bar{P}_1 = \bar{P}_{WN\_act} + \bar{P}_{HD\_act}$$

where  $\bar{P}_{WN\_act}$  and  $\bar{P}_{HD\_act}$  are the power consumptions by active WNIC and active HD during a session holding time, respectively. Prior to further discussion, we summarize all the parameters employed for power consumption analysis in Table 4.

#### E. Power Consumption for IM

When the IM is employed,  $\bar{P}_2$  is determined by:

$$\bar{P}_2 = \bar{P}_{IM} + \bar{P}_{HD\_slp} = \lambda_I \bar{E}_{IM} + \bar{P}_{HD\_slp}$$



where  $\bar{E}_{IM}$  is the energy consumed for the idle time  $1/\lambda_I$ , and is represented by:

$$\bar{E}_{IM} = \bar{E}_{WN\_slp} + \bar{E}_{1x} + \bar{E}_p + \bar{E}_{AP\_res} + \bar{E}_b + \bar{E}_{iho} + \bar{E}_{DHO}.$$

Since the 802.1x authentication and delayed handoff procedures are performed once at maximum, we approximate  $\bar{E}_{IM}$  to:

$$\begin{aligned} \bar{E}_{IM} &\simeq \bar{E}_{WN\_slp} + \bar{E}_p + \bar{E}_{AP\_res} + \bar{E}_b + \bar{E}_{iho} \\ &= \bar{P}_{WN\_slp} \bar{T}_{WN\_slp} + \\ &\quad \bar{P}_{WN\_awk} \left( \bar{T}_p \frac{\lambda_{in}}{\lambda_{in} + \lambda_{out}} + \bar{T}_{AP\_res} + \bar{T}_b + \bar{T}_{iho} \right). \end{aligned}$$

The sleep time  $\bar{T}_{WN\_slp}$  becomes the remaining time excluding all the times required for the IM operations. Therefore, we derive  $\bar{T}_{WN\_slp}$  by:

$$\begin{aligned} \bar{T}_{WN\_slp} &= \int_0^\infty \left( t - \left( \bar{T}_p \frac{\lambda_{in}}{\lambda_{in} + \lambda_{out}} + \bar{T}_{1x} + \bar{T}_{L2HO\_sg} + \bar{T}_{AP\_res} \right. \right. \\ &\quad \left. \left. + \bar{T}_b + \bar{T}_{iho} + \bar{T}_{DHO} \right) \right) f_I(t) dt \\ &= \frac{1}{\lambda_I} - \left( \bar{T}_p \frac{\lambda_{in}}{\lambda_{in} + \lambda_{out}} + \bar{T}_{1x} + \bar{T}_{L2HO\_sg} + \bar{T}_{AP\_res} \right. \\ &\quad \left. + \bar{T}_b + \bar{T}_{iho} + \bar{T}_{DHO} \right) \end{aligned}$$

where  $\bar{T}_p \frac{\lambda_{in}}{\lambda_{in} + \lambda_{out}}$  and  $\bar{T}_{1x}$  are the times required for paging and the 802.1x authentication procedures, respectively. L2 handoff, composed of scanning, reassociation and authentication, is needed after a successful paging procedure. Accordingly, the time  $\bar{T}_{L2HO\_sg}$  for a L2 handoff can be obtained by summing the required times as follows:

$$\bar{T}_{L2HO\_sg} = \bar{T}_{ras} + \bar{T}_{auth} + \bar{T}_{scan}$$

where  $\bar{T}_{ras}$ ,  $\bar{T}_{auth}$ , and  $\bar{T}_{scan}$  are the times for reassociation, authentication, and scanning, respectively.  $\bar{T}_{AP\_res}$  is the total required time to perform AP reselection during  $t_I$ .  $\bar{T}_b$ ,  $\bar{T}_{iho}$ , and  $\bar{T}_{DHO}$  are the times for beacon listening, idle handoff, and delayed handoff, respectively.

AP reselection is performed at every cell boundary so that we derive  $\bar{T}_{AP\_res}$  by obtaining the entire number of cells which an MH travels during idle time as follows:

$$\bar{T}_{AP\_res} = \bar{T}_{scan} \sum_{k=0}^{\infty} k \Pr(K_c = k) = \frac{\bar{T}_{scan} F_r^*(\lambda_I)}{1 - F_c^*(\lambda_I)}. \quad (12)$$

The sum  $\bar{T}_b$  of the periodic beacon listening times is determined by:

$$\bar{T}_b = \bar{N}_{bi} \bar{T}_{b\_sg}$$

where  $\bar{N}_{bi}$  is the expected number of beacons which an MH receives during idle time. Since beacons are received every  $T_{bli}$ ,

we obtain  $\bar{N}_{bi}$  by dividing idle time by  $T_{bli}$  as follows:

$$\bar{N}_{bi} = \int_0^\infty \frac{t}{T_{bli}} f_I(t) dt = \frac{1}{\lambda_I T_{bli}}.$$

An MH conducts an idle handoff whenever it crosses a PA so that the time required for the idle handoffs is derived by:

$$\bar{T}_{iho} = \frac{\bar{T}_{ih} F_{pa}^*(\lambda_I)}{1 - F_{PA}^*(\lambda_I)}.$$

Finally,  $\bar{T}_{WN\_slp}$  can be approximated as follows:

$$\begin{aligned} \bar{T}_{WN\_slp} &\simeq \frac{1}{\lambda_I} - \bar{T}_p \frac{\lambda_{in}}{\lambda_{in} + \lambda_{out}} \\ &\quad - \bar{T}_{L2HO} - \bar{T}_{AP\_res} - \bar{T}_b - \bar{T}_{iho}. \end{aligned}$$

#### F. Power Consumption for PSM

On the other hand, if the IM is not employed, i.e., PSM with IP paging is used, the power  $P_2$  in state 2 is determined by:

$$P_2 = \lambda_I \bar{E}_{PSM} + \bar{P}_{HD\_act}.$$

We have the energy required for the PSM by:

$$\begin{aligned} \bar{E}_{PSM} &= \bar{E}_{WN\_slp} + \bar{E}_b + \bar{E}_{br} + \bar{E}_{L2HO} + \bar{E}_{L3HO} \\ &= \bar{P}_{WN\_slp} \bar{T}_{WN\_slp} \\ &\quad + \bar{P}_{WN\_awk} (\bar{T}_b + \bar{T}_{br} + \bar{T}_{L2HO} + \bar{T}_{L3HO}) \end{aligned} \quad (13)$$

where  $E_{br}$  is the energy required to receive broadcast frames. In order to support IP paging, MH has to receive as many broadcast frames as possible since IP paging schemes are designed on the basis of broadcast frames for the notification of a new call arrival.  $E_{L2HO}$  and  $E_{L3HO}$  are energies consumed for an L2 handoff and an L3 handoff, respectively.

For each term in (13), we first derive the sleep time  $\bar{T}_{WN\_slp}$  as follows:

$$\bar{T}_{WN\_slp} = \frac{1}{\lambda_I} - (\bar{T}_b + \bar{T}_{br} + \bar{T}_{L2HO} + \bar{T}_{L3HO}).$$

If there exists at least one MH running in the PSM, the serving AP should buffer every broadcast frame and forward it by using normal transmission rule after DTIM transmission. For this reason, under the assumption that broadcast frame arrives with exponential distribution, we derive the time required to receive the buffered broadcast frames by:

$$\bar{T}_{br} = \bar{T}_{br\_sg} \int_0^\infty \frac{t}{T_{brp}} f_I(t) dt = \frac{\bar{T}_{br\_sg}}{\lambda_I T_{brp}}$$

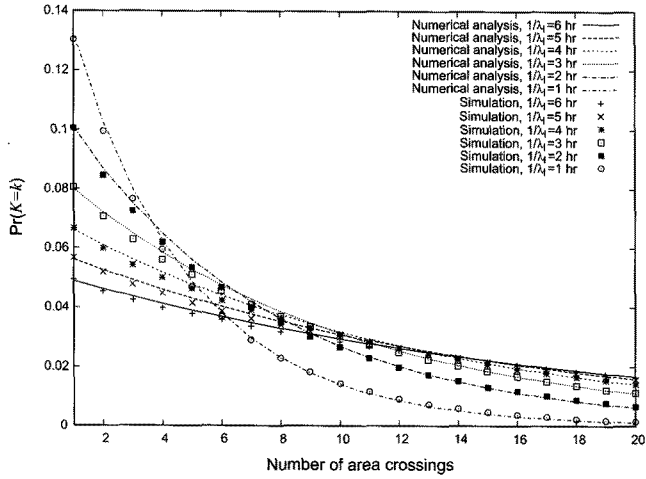
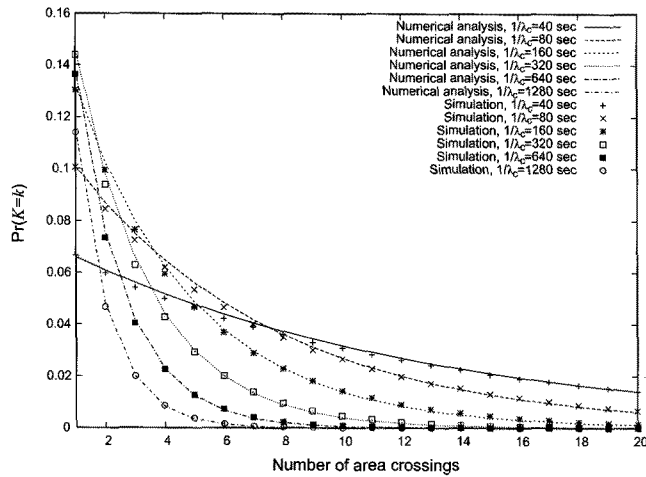
where  $T_{brp}$  is expected inter-arrival time of broadcast frames.  $\bar{T}_{L2HO}$  is the total required time for L2 handoffs while an MH crosses cells. In a similar manner to (12), we have  $\bar{T}_{L2HO}$  by:

$$\bar{T}_{L2HO} = \frac{\bar{T}_{L2HO\_sg} F_r^*(\lambda_I)}{1 - F_c^*(\lambda_I)}.$$

The time for L3 handoffs  $\bar{T}_{L3HO}$  is derived by:

$$\bar{T}_{L3HO} = \frac{\bar{T}_{L3HO\_sg} F_{ip}^*(\lambda_I)}{1 - F_{IP}^*(\lambda_I)}$$

where  $\bar{T}_{L3HO\_sg}$  is a time for a single L3 handoff.

Fig. 8.  $\Pr(K = k)$  when  $1/\lambda_c$  is 160 seconds.Fig. 9.  $\Pr(K = k)$  when  $1/\lambda_I$  is 1 hour.

## V. ANALYTICAL RESULTS

### A. Model Validation

Figs. 8 and 9 show the area crossing probability  $\Pr(K = k)$ , where  $k \geq 1$ , when an MH crosses areas of which the maximum number of layers is 6. Table 5 presents the probability that an MH stays at the first area, i.e.,  $k = 0$ . In order to validate the derived equations, we conduct simulation by using the simulator, which we have developed for the exclusive purpose.

Both analysis and simulation results are presented for the comparison. From both figures and the table, we observe that analysis and simulation results match very well, thus verifying the validity of our analysis.

Fig. 8 shows  $\Pr(K = k)$  as the number of area crossings  $k$  increases when  $1/\lambda_c$  is fixed at 160 s under the condition that  $E[t_I] (= 1/\lambda_I)$  varies from 1 hr to 6 hr. For  $0 \leq k < 4$ ,  $\Pr(K = k)$  is high when the value of  $1/\lambda_I$  is small. In the contrast, for  $k > 12$ ,  $\Pr(K = k)$  is high when  $1/\lambda_I$  is long. It implies that long  $1/\lambda_I$  provides more chances for MH to cross areas as the expectation of idle time  $1/\lambda_I$  increases. Fig. 9 shows  $\Pr(K = k)$  under given  $1/\lambda_I$ . In this case, the expected cell sojourn time  $E[t_c] (= 1/\lambda_c)$  varies from 40 s to 1280 s. This figure shows how mobility influences the area crossing proba-

Table 5.  $\Pr(K = 0)$  values.

	$1/\lambda_c$ is 160 seconds					
$1/\lambda_I$ (hour)	1	2	3	4	5	6
$\Pr(K = 0)$ (numerical)	0.413	0.269	0.200	0.160	0.133	0.114
$\Pr(K = 0)$ (simulation)	0.414	0.269	0.200	0.161	0.134	0.114
	$1/\lambda_I$ is 1 hour					
Cell sojourn time (sec)	40	80	160	320	640	1280
$\Pr(K = 0)$ (numerical)	0.160	0.269	0.413	0.568	0.700	0.811
$\Pr(K = 0)$ (simulation)	0.161	0.269	0.414	0.566	0.702	0.809

Table 6. Parameter values for power consumption evaluation.

Parameter	Value	Parameter	Value
From the data sheet			
$P_{WN\_awk}$	$(925+2565)/2$ mW	$P_{WN\_slp}$	45 mW
$P_{HD\_act}$	625 mW	$P_{HD\_slp}$	86 mW
Battery cap.	1250 mAh	-	-
From practical measurement			
$\bar{T}_{L3HO}$	3 s	$\bar{T}_{1x}$	525 ms
Assumed values			
$\bar{T}_b$	500 $\mu$ s	$\bar{T}_p$	5 ms
$\bar{T}_{auth}$	2 ms	$\bar{T}_{bli}$	1 s / 100 ms
$\bar{T}_{ras}$	1.3 ms	$\bar{T}_{ih}$	500 $\mu$ s
$\bar{T}_{scan}$	300 ms	$1/\lambda_h$	5 min

bility. Small  $1/\lambda_c$  represents high mobility of an MH. For this reason, the smaller  $1/\lambda_c$  incurs the higher value of  $\Pr(K = k)$  for  $k > 10$ . It implies that smaller  $1/\lambda_c$  encourages an MH to cross areas more frequently.

### B. Power Consumption Results

Table 6 lists the values of all the parameters used for the numerical evaluation including (1) the values from the data sheets (related to the power consumption) [19], [20],<sup>8</sup> (2) practically measured values [7], [21],<sup>9</sup> and (3) some assumed values. For simplicity, we ignore the state transition overhead of WNIC.

Fig. 10 shows the evaluation results about power consumption and life time according to average cell sojourn time (ACST). Fig. 10(a) shows the overall power consumption of WNIC.  $L$  and  $l$  represent the maximum number of layers of IP paging area and PA, respectively. For a fair comparison, we use 1 s as well as 100 ms for beacon listening interval  $T_{bli}$ . As expected, smaller  $T_{bli}$  results in more power consumption.

In this figure, we observe both the IM and PSM with IP paging (PIP) require more power for smaller ACST. As discussed earlier, small ACST implies high mobility. Accordingly, the higher mobility incurs the more handoffs, thus resulting in the more power consumption. The power consumptions depending on the mobility are attributed to L2 handoff and AP reselection in case of PIP and the IM, respectively.

Meanwhile, PIP needs more power in case that  $L = 4$  rather than  $L = 6$  under the same ACST. However, the power for the IM remains virtually unchanged irrespective of  $l$ . It implies the power for idle handoff is ignorable so that the size of PA hardly influences the amount of the power consumption.

Fig. 10(b) shows MH's life time including session holding time as well as idle time according to the incoming call arrival

<sup>8</sup> $\bar{P}_{WN\_awk}$  is the average of the reception and transmission powers.

<sup>9</sup>In [21], the authors measured the authentication delay when the 802.11i is employed.

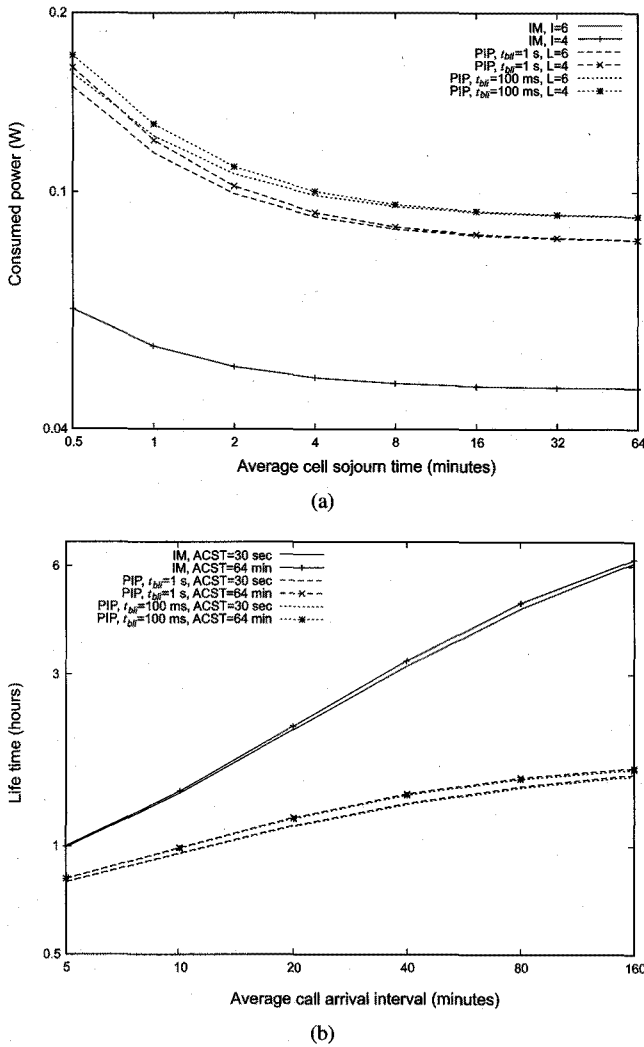


Fig. 10. Power consumption and life time: (a) Power consumption of WNIC and (b) life time of MH.

interval for each ACST bound when  $l = 4$  and  $L = 6$ . The upper and the lower bounds of each scheme are obtained for 64 min and 30 sec of ACST, respectively. As expected, higher mobility results in shorter life time. However, we observe that the line for each bound is not well spaced since the power consumption required for an HD as a part of an MH is very large compared with that of WNIC.

As a result, we find that the life time become longer as incoming or outgoing call arrival interval increases. From all the above observations, we conclude that our scheme provides an MH with longer life time since it needs less power consumption compared with the PIP.

## VI. CONCLUSION

In this paper, we propose a new protocol to support the IM operation in the 802.11 WLAN. The proposed protocol can be easily applied to already-deployed products by just updating their firmwares or device drivers [22]. It can be employed to work with the existing security schemes including the 802.11r and the 802.11i with minor additional protocol in order to support idle

handoff. Therefore, the proposed IM is expected to contribute to commercial VoIP system deployment by extending the VoIP service life time.

In order to evaluate our proposal, we develop new analytical models, which are useful to analyze the power consumption in hierarchically structured networks. These network structure will be typical in near future since wireless access networks are evolving to support IP layer. The numerical results demonstrate that our proposed IM operation outperforms the PSM with IP paging with respect to the power consumption. As a result, it enables a longer life time of the 802.11-equipped MHs. Additionally, we deal with L3 handoff scheme to reduce the call set up latency incurred by the *delayed handoff*, and then, integrate them with the proposed protocol for the IM in L2.

## APPENDICES

### I. PAGING FAILURE PROBABILITY

Let  $P_f$  be the paging failure probability. A paging failure occurs only when a new call arrives before an MH in the IM updates its location at a new PA. Otherwise, the paging is conducted successfully. Therefore,  $P_f$  is derived by:

$$P_f = \sum_{K=1}^{\infty} \Pr(K = k) \int_0^{\bar{T}_{bli}} \frac{1}{\bar{T}_{bli}} \int_{t_{bli}}^{\bar{T}_{bli}} \frac{1}{\bar{T}_{bli}} d\tau dt_{bli} \int_0^{\bar{T}_{bli}} f_c(t) dt$$

$$= \frac{1}{2} \sum_{K=1}^{\infty} \Pr(K = k) (1 - e^{-\lambda \bar{T}_{bli}}).$$

Typically, the average call arrival interval is much longer than  $\bar{T}_{bli}$ . Therefore, we can justify  $P_f$  converges to zero. For example, when the average call arrival interval is 5 minutes, i.e.,  $\lambda = 1/300$ , and  $\bar{T}_{bli} = 1$  second, the value of  $P_f$  is equal to 0.0002.

### II. MH'S $K$ TH AREA CROSSING PROBABILITY

Let  $\tau_{(k)} = t_m + \sum_{i=1}^k t_{M_i}$ .  $f_{\tau_{(k)}}(t)$  is the pdf for random variable  $\tau_{(k)}$  and  $F_{\tau_{(k)}}^*(s)$  is its Laplace transform function. We derive the probability that an MH crosses areas  $k$  times during idle time by:

$$\Pr(K = k) = \Pr(\tau_{(k)} < t_I) - \Pr(\tau_{(k+1)} < t_I)$$

$$= \int_0^{\infty} \int_0^{t_i} f_I(t_i) (f_{\tau_{(k)}}(t) - f_{\tau_{(k+1)}}(t)) dt dt_i$$

$$= \lambda_I \int_0^{\infty} e^{-\lambda_I t_i} \int_0^{t_i} (f_{\tau_{(k)}}(t) - f_{\tau_{(k+1)}}(t)) dt dt_i$$

$$= F_{\tau_{(k)}}^*(\lambda_I) - F_{\tau_{(k+1)}}^*(\lambda_I)$$

$$= F_m^*(\lambda_I) (F_M^*(\lambda_I))^{k-1} (1 - F^*(\lambda_I))$$

where  $k \geq 1$ .

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