IIPP: Integrated IP paging protocol with a power save mechanism

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SUMMARY

The advent of advanced mobile/wireless systems has been facilitating the battery-powered mobile computing devices (nodes) to remain always-connected to the Internet. However, until now, the power-drain rate of mobile nodes is very high in comparison with the available power of portable batteries. To reduce the energy consumption of mobile nodes, we present an integrated IP paging protocol (IIPP) by integrating the IP-layer paging protocol based on Mobile IPv4 regional registration (MIPRR) with a power save mechanism. IIPP reduces the frequency of signaling messages between mobile nodes and networks. When not sending or receiving data for a certain time, mobile nodes enter power save mode and consume very low power. We formulate analytical models and carry out simulations to evaluate the proposed IIPP. The results show that, compared to MIPRR, IIPP significantly reduces the average power consumption of the mobile node and signaling overheads in the network.

KEY WORDS

Mobile IPv4 regional registration; integrated IP paging; IIPP; power save mechanism; performance analysis

1 Introduction

The number of mobile computing devices is increasing rapidly owing to the introduction of advanced mobile communication systems (3G and beyond) with a wide variety of application services in many countries around the world. These mobile devices (nodes) are expected to have ubiquitous access to the Internet, regardless of their location, time or mobility. To provide ubiquitous access to the Internet, we need efficient mobility management protocols. The Internet Engineering Task Force (IETF) has developed a number of protocols for mobility management, such as Mobile IP protocols for IP version 4 (MIPv4) [1] and IP version 6 (MIPv6) [2], Mobile IPv4 regional registration (MIPRR) [3], Hierarchical Mobile IPv6 (HMIPv6) [4], Fast Handover for Mobile IPv6 (FMIPv6) [5]. The MIPv4 and MIPv6 protocols deal with the movement of mobile nodes across networks, and allow the transparent routing of IP datagrams to mobile nodes in the Internet. The MIPRR and HMIPv6 protocols deal with the movement of mobile nodes from a foreign agent (FA) or an access router (AR) to another within the same *visited domain*. These two protocols reduce the number of signaling messages to the home agent of a mobile node and, hence, reduce signaling delay when the mobile node moves within the visited network. Although the above-mentioned mobility management protocols allow transparent routing of IP datagrams and reduce the number of signaling messages between the mobile node and its home agent, they do not address the following two problems: unnecessary energy consumption of mobile nodes and excessive signaling overhead in the visited domain.

Future IP mobile nodes are expected to support a large bandwidth for multimedia applications. To provide larger bandwidth access by a wireless network, the geographical coverage area or cell size of a radio access point or access router should be very small compared with that of the existing cellular networks. If the coverage area is small, a mobile node is likely to change its point of attachment to the network more frequently.

Although the mobile nodes seem “electrically” very mobile to the network, most of them do not transmit or receive data all the time. If a mobile node is currently sending or receiving datagrams, it is said to be in active mode or active state, otherwise it is in idle mode. Like current cellular mobile terminals, most of the IP mobile nodes are expected to remain in idle mode for the considerable portion of time [6]. Registering the location of an idle mobile node every time it moves to the coverage of a new foreign agent has no significant advantage to the network and mobile node. To the network, it is just a waste of network resources, and to the mobile node, it is just a waste of battery power.

To eliminate these problems, we therefore developed an integrated IP paging protocol (IIPP) by integrating the IP paging protocol based on Mobile IPv4 regional registration with a power save mechanism. We select the Mobile IPv4 protocol as the base of our study because it is currently being deployed on a wide basis, such as in cdma2000 networks [7]. Our proposed IIPP reduces the number of signaling messages in the visited domain, and saves the energy consumption by mobile nodes. To reduce signaling, the idle mobile nodes do not register their locations with the *gateway foreign agent* (GFA) every time they move from the coverage or cell of one foreign agent to that of another. Instead, they register only when they cross the boundary of a *paging area* (PA), which includes a number of cells of the network. To reduce the energy consumption, IIPP additionally employs a power save mechanism to allow the idle mobile nodes enter power save mode

(PSM) or dormant mode[1][8].

When a data packet destined for a mobile node in dormant mode arrives at the GFA, the GFA buffers the data, and asks the paging agent to send a paging request alert the mobile node. The paging agent polls or pages all cells belonging to the current PA of the mobile node. The mobile node in dormant mode wakes intermittently for a very short time to listen to the broadcast messages from the AR. If there is a paging request for the mobile node, it terminates its power save mode and enters active mode, and registers its location with the GFA. After the registration, the GFA delivers all the buffered and subsequently arriving data packets to the mobile node. The mobile node in active mode behaves in the same way as a mobile node does in MIPRR.

The main advantage of implementing the power save mechanism in the IP layer is that it can control the power consumption of different kinds of network interfaces. In recent years, a wide variety of radio access technologies, such as IEEE 802.11/16/20, HSDPA (high-speed downlink packet access), EDGE (enhanced data rates for global evolution), and UMTS (universal mobile telecommunications system), supporting different bandwidths and coverage are being developed. To access such heterogeneous networks, a mobile node has to be employed with a number of network interfaces. The use of the power save mechanism in the IP layer enables the mobile node to use a single algorithm to control the power consumption of all interfaces.

In this paper, we formulate analytical models to evaluate IIPP in terms of the average power consumption of a mobile node and the average signaling load in the network. We discuss the impact of different parameters, such as size of paging area, speed of a mobile node, and data session rates, on

[1]In this paper, we use power save mode (PSM) or dormant mode interchangeably.

the power consumption and signaling overhead. We show analytically that, as compared to MIPRR, IIPP reduces the energy consumption of a mobile node by about 80%, while simultaneously reducing the signaling overhead in the visited domain. We also carry out simulations to further elaborate the performance of the proposed scheme.

The remaining sections of this paper are organized as follows. In Section 2, we present the related research work. Sections 3 and 4 describe the architecture and power save mechanism of IIPP, respectively. We formulate analytical models in Section 5, and discuss the numerical results in Section 6. Section 7 presents the simulation setup and results. Finally, we present our conclusion in Section 8.

2 Related Work

P-MIP [6] presents a paging extension to Mobile IP to reduce the registration frequency when a mobile node is in idle state. A paging area includes a number of foreign agents, and an idle mobile node is not required to register its location when it moves to new cells belonging to the same paging area. The home agent intercepts data packets arriving from a correspondent node to a mobile node, and forwards the packets to the address of last registered foreign agent of the mobile node. On receiving the packets, the foreign agent checks the state of the mobile node. If the state is active, the foreign agent directly delivers the packets to the mobile node. On the other hand, if the state is idle, the foreign agent buffers the packets and sends a paging request to all foreign agents belonging to the paging area. On receiving the paging request, the mobile node first performs home registration through the foreign agent nearest to the mobile node; it then sends a paging reply to the previous foreign agent in order to ask it to forward the buffered packets.

Although P-MIP has been an inspiration for our work, IIPP differs from P-MIP in the following aspects. Namely, we consider the hierarchical configuration of foreign agents and use Mobile IP and Mobile IPv4 regional registration protocols for dealing with the macro level and micro level mobility, respectively. P-MIP performs home registration on every paging request, whereas IIPP performs regional registration when responding to a paging request. Unlike P-MIP, IIPP includes the power save mechanism to enable an idle mobile node to go to dormant mode and consume extremely low power.

Ramjee et al. described the architecture, protocols, and algorithms for an IP paging service [9]. They discussed three types of paging architectures: home agent paging, foreign agent paging, and domain paging. They used the paging latency and rate of location update as the metrics for comparing the performances of different protocols and algorithms under different paging load and paging area sizes, and showed that the domain paging architecture could support a fairly large load. Our proposed architecture of IIPP resembles that of the domain paging protocol.

Castelluccia proposed an extension to Mobile IP with adaptive individual paging [10]. A mobile node dynamically computes its optimal location area size according to its traffic and mobility parameters. However, the computation of the optimal paging area requires prior knowledge of access network topology. Besides, the adaptive paging protocol may adversely affect the power consumption of mobile nodes as the mobile nodes frequently need to compute their optimal paging areas.

Tao et al. presented an IP paging protocol that could be used independently of a mobility management protocol [11]. They distributed the paging functionality in three logical entities: triggering agent, paging coordination agent, and paging agent, and showed analytically that when the paging coordination agent was located in the access network, their protocol reduced the signaling overhead in the network as compared to Mobile IP and P-MIP.

HAWAII [12] and Cellular IP [13] are other two micro-mobility protocols that support IP paging. These protocols are designed to reduce the effect of home-registration delay and enhance performances during handover. The Cellular IP nodes maintain a separate paging cache to keep information for paging a mobile node. Cellular IP updates the paging or route cache by general data packets, whereas HAWAII uses an explicit signaling for path setup and update. These protocols use mobile specific routings in the visited domain. In contrast, IIPP uses hierarchical tunnelings to deliver data packets in the access network.

3 IIPP Architecture Overview

We take Mobile IPv4 [1] and MIPRR [3], as shown in Figure 1, as the bases of the IIPP architecture. IIPP uses all functions, messages, and algorithms used in MIPRR, with a little or no modification. In addition, we define some new functions, messages, and algorithms in IIPP to integrate the IP paging and a power save mechanism. Even though IIPP is based on MIPRR, the proposed concept, i.e., integration of paging and a power save mechanism in layer 3 (L3), can be utilized for any other mobility support protocols, like HMIPv6 [4], HAWAII [12], Cellular IP [13], and intra-domain mobility management protocol (IDMP) [14].

3.1 Hierarchical Configuration of Foreign Agents

A visited domain has two or more hierarchical levels of foreign agents. It has one gateway foreign agent (GFA), or several GFAs, at the top level and a number of foreign agents at the lower levels. At the bottom level, there are a number of foreign agents, which we call *leaf foreign agents* or *access routers* (ARs), equipped with radio access capability. In between the GFA and ARs, there may be none or several levels of *regional foreign agents* (RFAs). We assume that there exists pre-established security associations [15, 16] among the GFA, RFAs and ARs; thus, we do not discuss any security or authentication issues here. The ARs within a GFA can be grouped into a single paging area (PA), or multiple PAs. A mobile node knows the current AR's paging area identifier by listening to the agent advertisement periodically broadcasted by the AR.

3.2 Modes of a Mobile Node

A mobile node can be in active, idle or dormant mode (or state), as shown in Figure 2. The mobile node is in active mode if it is currently sending or receiving data packets. We assume that the mobile node receives or sends a train of packets that constitute a *data session*. After a data session, the mobile node remains in idle mode for the duration of an active timeout. An idle mobile node, however, is capable of sending or receiving data. The mobile node in active mode consumes the maximum amount of battery power, whereas in idle mode, it consumes a little less than that in active mode [17]. Staying in high-power-consuming idle mode, even when there are no data to send or receive, is not efficient with regard to power management.

To save battery power, after an active timeout in idle mode, the mobile node enters the power-saving dormant mode. The dormant mode itself consists of two modes: sleep mode and awake mode. In sleep mode, the mobile node turns off the power of some of its high-power radio components and consumes very low power. As the mobile node in sleep mode cannot communicate with others, it has to wake (go to awake mode) periodically to check whether there is a paging request broadcasted by the AR for the mobile node. If there is a paging request, the mobile node transits to active mode, and registers its location with the network; otherwise, it remains in dormant mode.

3.3 Regional Registration

A mobile node performs regional registration to inform the network that the former is in active mode, and wants to establish or update a data routing path between the GFA and itself. To do this, the mobile node sends a regional registration request to the AR, which in turn forwards the request to the upstream RFA (i.e., the one toward the GFA). This forwarding process is repeated until the request reaches the GFA. The GFA then updates the mobile node's entry in the visitor list and sends back a registration reply to the mobile node by the same route that the registration request had traversed. On receiving the registration reply, each RFA on the downlink route inserts an entry in its visitor list, which is used to route the packets destined for the mobile node.

After regional registration, the GFA and other RFAs maintain the records of mobile nodes in their visitor lists, and start active timers. The active timer is used to indicate the state/mode of the mobile node, and to check the validity of the route from the GFA to the mobile node. The active timer is reset by every data packet destined for or originated from the mobile node and traversing the GFA/RFA/AR. If the mobile node does not send or receive packets during the active timeout, the GFA sets the mobile node's state as dormant, and the RFAs and AR delete the record of the mobile node from their visitor lists. After the active timeout, the mobile node enters dormant mode.

The mobile node terminates its dormant mode and enters active mode to perform regional registration under the following situations: when it moves to a new paging area, when it gets a paging request message, when it has data to send, or when the lifetime of its previous registration is about to expire. The mobile node also performs regional registration when it handovers its ongoing-session to a new cell.

3.4 Paging Functional Architecture

The paging functional architecture decides where the paging related entities reside in the network. As explained in RFC 3154 [18], a paging functional architecture is composed of three logical entities: *dormant monitoring agent*, *tracking agent*, and *paging agent*. The dormant monitoring agent (DMA) deals with the data packets destined for a dormant mobile node. The tracking agent maintains an up-to-date record of the location of mobile nodes in coarse granularity defined by a paging area. The paging agent pages mobile nodes by sending a paging request to all cells belonging to the current paging area.

While implementing these three logical entities, the DMA, tracking agent, and paging agent, can be merged into a single component or multiple physical components. In regard to our IIPP architecture, we assume that the DMA and tracking agent collocate in the GFA. The paging agent can also be included in the GFA if there is a single paging area within the GFA, or it can exist in separate foreign agents if there are multiple paging areas within the GFA, as shown in Figure 3. A foreign agent that includes a paging agent is called a *paging foreign agent* (PFA). The use of multiple PFAs under the GFA serves for the purpose of load balancing.

To implement the dormant monitoring agent and tracking agent in the GFA, we add three more fields in the visitor list maintained by the GFA: the mode of the mobile node, paging area identifier (PAI), and maximum paging interval (MPI). All of these fields are updated through the regional registration performed by a mobile node. The mode field has either active or dormant value. When a mobile node registers its location with the GFA, its mode is set to active and, as stated earlier, the mode is set to dormant after an active timeout occurs in idle mode. On changing paging area, the mobile node performs registration to inform the tracking agent to update the PAI. When the DMA receives data packets addressed to a dormant mobile node, it buffers the data, and asks the tracking agent to find the PAI and MPI of the mobile node. The tracking agent gets the PAI and MPI from the visitor list, and forwards them to the DMA. The DMA now supplies this information to the paging agent, which starts paging algorithms by sending a paging request to relevant ARs, which in turn broadcast the paging request in their cells.

The limitation of this study is explained as follows. We have assumed that mobile nodes will always have connectivity to the ARs so that the latter can communicate with the former at any time. However, in real networks, the quality of connectivity depends on the channel condition (which may vary unpredictably). This will in fact affect the paging latency and the power consumption of mobile nodes. To assess this effect, we will carry out the performance evaluation using the NS-2 simulator in our future work.

3.5 Impact of Hierarchy on Paging Latency

The paging latency in the proposed IIPP depends on two factors: the levels of hierarchy of FAs and the sleep period of a mobile node. This section describes the first factor, while the second factor is explained in section 4. If there are many levels in the hierarchy, the paging latency may become high, as the paging request has to traverse a longer path from the PFA to mobile nodes. An optimal number of levels of hierarchy that keeps the paging latency within some threshold can be determined by using analysis techniques similar to that used in references [19, 20]. For this purpose, the paging latency is formulated as the sum of the times taken by each FA to process and transmit the paging request in the hierarchy. By estimating these times, we can determine the optimal hierarchy levels that keep the paging latency within the given threshold. Similarly, robustness in the hierarchical architecture can be achieved by using the fault tolerance and survivability techniques explained in references [21, 22].

4 IIPP Power Save Mechanism

IIPP includes a power save mechanism for controlling the power drain of mobile nodes. To implement the power save mechanism, we add a few time-related fields in agent advertisement and regional registration messages. The ARs periodically broadcast agent advertisements having an *advertisement interval* extension. This extension has two fields: *agent advertisement interval* (AAI) and *advertisement slot length* (ASL). The AAI field is used to specify the time interval between two successive agent advertisements, and the ASL is used to specify the duration of time in which an AR may broadcast an agent advertisement in its cell. We assume that all ARs under a GFA are synchronized so that the mobile nodes, once synchronized with the advertisement interval in any cell, can remain synchronized in all cells under the GFA.

A dormant mobile node may wake during every AAI for the duration of ASL, and may go to sleep in the remaining time between two agent advertisements. However, waking during every agent advertisement interval may not be very useful in terms of the amount of power saved. Instead, the dormant mobile node may skip a number of advertisements, and wake up less frequently to reduce the awake time and thus save more power.

To save more power by skipping advertisements, we add a *maximum paging interval* (κ) field in the extension used in the regional registration message. This field indicates the maximum interval, in terms of number of AAIs, of two successive times in which a mobile node activates its receiver to listen to the agent advertisement and paging request[2] from the AR, as shown in Figure 4. The mobile node sets the desired value of κ in a regional registration request, and forwards it to the GFA, which stores the value of κ in the visitor list.

When data destined for a dormant mobile node arrives, the GFA retrieves the maximum paging interval from the visitor list, and includes it in the paging request message. The paging request is forwarded to all ARs in the paging area. The ARs use the maximum paging interval mentioned in the paging request to decide when they need to broadcast the paging request in their cells.

As the paging request or alert for a mobile node may arrive any time at an AR, staying in dormant mode and skipping some advertisements by the mobile node may increase the paging latency [23, 24]. The mobile node therefore needs to estimate an optimal value of κ. For this purpose, focusing on a tradeoff between the paging latency and power consumption, the mobile node can use the same or similar algorithm as explained by Pack et al. in reference [25]. They formulate wakeup cost (C_w) and session blocking

[2]We assume that the ARs broadcast the paging request messages following the agent advertisements.

probability (P_B), where the wakeup cost refers to the power consumption when the mobile node wakes up to check whether there are paging requests, and the session blocking is the probability that an incoming session is rejected because of the late reception of the paging requests. Using a threshold blocking probability (P_{th}), a candidate set of κ that satisfies the condition $P_B \leq P_{th}$ is obtained. From this set, an optimal κ that minimizes the wakeup cost is selected. For the details of the algorithm, we refer the reader to [25].

5 Analytical Modeling

In this section, we develop analytical models to show how IIPP, compared to MIPRR [3], reduces both the energy consumption of a mobile node and the signaling overhead in the network. In an actual scenario, as stated in the previous sections, an active mobile node updates the network on its location information by performing regional registration when it moves to a new cell, when the lifetime of the previous registration expires, or when the foreign agent or mobile node is rebooted. In this modeling, however, we consider only the movement-related registrations, assuming that registrations triggered by other phenomena occur rarely and have little impact on the signaling and power consumption of mobile nodes.

Moreover, we assume that the incoming-data session, outgoing-data session, and movement-related regional registration all are independent of each other and do not occur simultaneously. We also take into consideration that three logical entities of dormant mode management, i. e., a dormant monitoring agent, a tracking agent, and a paging agent, collocate in the GFA.

5.1 Mobility Model

We suppose that the cell of an AR is square-shaped with a perimeter of L_c meters, and that the mobile nodes are uniformly distributed, with a density of ρ (nodes/m^2), in the cell area of $L_c^2/16$ (m^2). The number of mobile nodes in a cell is thus $N_c = \rho L_c^2/16$.

We use the fluid-flow mobility model [6, 26] to find the number of mobile nodes crossing the cell boundaries in unit time. This model assumes that the direction of movement of mobile nodes is uniformly distributed over [0,2π]. If v is the average velocity of mobile nodes, the number of mobile nodes crossing a cell per unit time is $\rho v L_c/\pi$ (nodes/s).

Suppose R_c represents the number of times a mobile node crosses the cell boundaries per second (i.e., the cell boundary crossing rate of a mobile node). R_c will thus equal to the number of mobile nodes crossing cell boundary per unit time divided by the total number of mobile nodes in the cell. That is,

$$R_c = \frac{16v}{\pi L_c} \ \ (\textit{per second}). \tag{1}$$

If we suppose that there are n cells in the square-shaped paging area, the perimeter of paging area, L_p, is $4 \times \sqrt{nL_c^2/16} = L_c\sqrt{n}$, and the number of mobile nodes in the paging area is $N_p = \rho L_p^2/16 = \rho n L_c^2/16$. The number of mobile nodes crossing the paging area boundaries per unit time is therefore $\rho v L_p/\pi = \rho v L_c \sqrt{n}/\pi$ (nodes/s).

Similarly, the number of times a mobile node crosses the paging area boundary per second (i.e., the paging boundary crossing rate of a mobile node) is

$$R_p = \frac{16v}{\pi L_c \sqrt{n}} = \frac{R_c}{\sqrt{n}} \ \ (\textit{per second}). \tag{2}$$

We define an inter-session time (IST) as the time interval between two successive communication sessions. The communication sessions include both incoming (i.e., originated from a correspondent node and destined for the mobile node) and outgoing (i.e. originating from a mobile node) data sessions as well as location registrations. Let λ_{sa} and λ_{sd} be denote the incoming and outgoing data session rates, respectively. IST of the IIPP mobile node is thus

$$T_{IIPP} = \frac{1}{(\lambda_{sa} + \lambda_{sd} + R_p)}\ , \tag{3}$$

under the assumption that incoming session, outgoing session, and movement-related registration are independent of each other.

Similarly, since the MIPRR mobile node performs registration when it crosses a cell area, instead of a paging area, the IST of the MIPRR mobile node is

$$T_{MIPRR} = \frac{1}{(\lambda_{sa} + \lambda_{sd} + R_c)}\ . \tag{4}$$

5.2 Energy Costs

We now evaluate the average power consumption of the IIPP and MIPRR mobile nodes in an inter-session time. As shown in Figure 5, the IIPP mobile node consumes active power (P_a) for active time T_a and idle power (P_i) for active timeout duration T_{out}. In dormant mode, the mobile node goes to sleep mode while consuming power P_s, and periodically wakes to listen to the AR. As shown in Figure 4, the number of wake-ups of the mobile node in the dormant duration of an inter-session time is $\lfloor \frac{T_{IIPP} - T_a}{\kappa . AAI} \rfloor$, and the total awake time in an inter-session time is

$$T_w = \Big\lfloor \frac{T_{IIPP} - T_a}{\kappa \cdot AAI} \Big\rfloor ASL,$$

where AAI is the agent advertisement interval, κ is the maximum paging interval, and ASL is the advertisement slot length, i.e., the duration for which the mobile node remains awake in every wake-up. The average power consumed by the IIPP mobile node is

$$P_{IIPP} = \frac{P_a T_a + P_i (T_w + T_{out}) + P_s T_s}{T_{IIPP}}, \tag{5}$$

where $T_s = T_{IIPP} - (T_a + T_w + T_{out})$ is the total duration of sleep time in an inter-session time. We assume that when the mobile node wakes to listen to the messages from the AR, it consumes the same power as in idle mode.

The MIPRR mobile node enters idle mode after finishing a data session. As MIPRR does not employ a power save mechanism, the mobile node continuously consumes idle power in idle mode. Average power consumed by the MIPRR mobile node is therefore

$$P_{MIPRR} = \frac{P_a T_a + P_i (T_{MIPRR} - T_a)}{T_{MIPRR}}. \tag{6}$$

5.3 Signaling Costs

For an IIPP mobile node in active mode, there is no need for paging when data packets destined for the mobile node arrive in the GFA. However, if the mobile node is in dormant mode, the GFA must locate the mobile node by paging before delivering the packets. Therefore, for an active mobile node, signaling cost comprises only the registration cost; however, for a dormant mobile node, it comprises both registration and paging costs.

Processing or transporting a signaling message has different impact on the burden borne by hops in wired and wireless networks. We therefore define two separate weights, α and β (such that $\alpha + \beta = 1$), for signaling cost incurred by processing or transporting a signaling message in wired and wireless hops, respectively. The signaling cost is measured as the product of weighted distances (in terms of number of FAs) and signaling rate (messages per second) [6, 11].

We also define the following additional parameters:

- C_r - the average[3] registration signaling cost per unit registration message per hop (message/registration/hop);
- C_p - the average paging signaling cost per unit paging message per hop (message/paging/hop);
- D_{GFA} - the average distance between the GFA and ARs (number of hops including the GFA and ARs);
- τ - the active time ratio, i.e., the ratio of the active state time to the inter-session time of a mobile node.

We assume that mobile nodes are located at a wireless distance of one hop from an AR, and that there is no message loss or error for signaling.

5.3.1 MIPRR signaling cost

As the MIPRR mobile node updates its location every time it moves to a new cell, there is no need for paging. Its signaling cost therefore consists of the registration cost only. The signaling cost incurred by the mobile node per unit time is

$$C_{MIPRR} = 2R_c(\alpha D_{GFA} + \beta)C_r \ . \tag{7}$$

We use the factor 2 in Eq. (7) because a registration request is always acknowledged by a registration reply.

5.3.2 IIPP signaling cost

The IIPP signaling cost consists of both registration and paging costs. The paging cost is incurred when the paging agent sends a paging request message in all cells belonging to the current paging area of the dormant mobile

[3] An average of registration request and registration reply signaling costs.

node. The paging cost is expressed as

$$C_{paging} = (\alpha D_{GFA} + \beta) n C_p \ , \tag{8}$$

where we assume that the GFA unicasts the paging request to all the ARs in the paging area of n cells. These ARs then broadcast the request in their cells. On receiving a paging request, as the mobile node responds by sending a regional registration request, there is no need for a paging reply.

The total signaling cost incurred by the mobile node per unit time in the IIPP network is thus

$$\begin{aligned} C_{IIPP} &= 2R_p(\alpha D_{GFA} + \beta) C_r \\ &+ \tau \times \Big[2R_c(\alpha D_{GFA} + \beta) C_r - 2R_p(\alpha D_{GFA} + \beta) C_r \Big] \\ &+ 2(\alpha D_{GFA} + \beta)(\lambda_{sa} + \lambda_{sd})(1 - \tau) C_r \\ &+ C_{paging}(1 - \tau)\lambda_{sa}. \end{aligned} \tag{9}$$

All terms, except the last one, in Eq. (9) represent the registration signaling costs. The first term represents the registration signaling cost when the mobile node crosses a paging area boundary. The second long term represents the registration cost if the active mobile node is crossing a cell boundary. The first part of this term represents the registration signaling cost due to the active mobile node crossing the cell boundary and the second part represents the cost due to the active mobile node crossing the paging area boundary. The second part is subtracted from the first because the registration signaling cost due to the active mobile node crossing a paging area is already included in the first term. The third term represents the registration cost of the dormant mobile node when it receives a paging request or when it wants to send data packets. The last term indicates the paging cost when the mobile node is paged by a paging agent. To get the total signaling cost per unit time in the network, we multiply the above expression by the number of mobile nodes present in the area of consideration.

5.4 Power Consumption and Signaling Costs in P-MIP

To compare our scheme with P-MIP [6], we now derive the expressions of power consumption and signaling overhead in P-MIP. The IST of P-MIP is the same as that of IIPP, as both use the concept of paging; that is, $T_{PMIP} = 1/(\lambda_{sa} + \lambda_{sd} + R_p)$. The average power consumption of a P-MIP mobile node is thus

$$P_{PMIP} = \frac{P_a T_a + P_i(T_{PMIP} - T_a)}{T_{PMIP}}. \tag{10}$$

If we compare this equation with Eq. (5), we find that the average power consumption of a mobile node in P-MIP is the same as that in IIPP without PSM. This means, in terms of power consumption, that the IIPP without PSM resembles P-MIP. Moreover, the use of PSM in IIPP gains an additional benefit by saving more power when the mobile node is in idle state.

Like IIPP, P-MIP has both the paging and registration signaling overheads. The paging cost is given by

$$C_{PMIP_{paging}} = [(n-1)\alpha D_{PFA} + n\beta]C_p + (\alpha D_{PFA} + \beta)C_p, \tag{11}$$

where D_{PFA} is the average distance between a paging foreign agent and other foreign agents of the same paging area. The values of D_{PFA} are 1.33, 1.87, 2.67 and 3.20 when the sizes of squared-shaped paging areas are 4, 9, 16, and 25 cells, respectively. That is, the larger the paging area, the larger the value of D_{PFA}. The first and second terms in the above equation represent the paging request and paging reply signaling costs, respectively.

Comparing the above equation with Eq. (8), we can infer that the difference of paging signaling costs in the case of IIPP and P-MIP largely depends on the values of D_{GFA} and D_{PFA}. The IIPP paging cost is lower than the P-MIP paging cost when D_{GFA} is smaller than (or equal to) D_{PFA}, which is possible for larger paging areas. On the other hand, when D_{GFA} is larger than D_{PFA}, the paging signaling cost of P-MIP may be lower than that of IIPP. However, as P-MIP requires a higher registration signaling cost than IIPP, which will be elaborated in the following paragraph, the overall signaling cost of IIPP is less than that of P-MIP.

Similarly, the overall signaling cost of a mobile node in P-MIP is as given below.

$$\begin{aligned} C_{PMIP} &= 2R_p(\alpha D_{HA}+\beta)C_r \\ &+ \tau \times \left[2R_c(\alpha D_{HA}+\beta)C_r - 2R_p(\alpha D_{HA}+\beta)C_r\right] \\ &+ 2(\alpha D_{HA}+\beta)(\lambda_{sa}+\lambda_{sd})(1-\tau)C_r \\ &+ C_{PMIP_{paging}}(1-\tau)\lambda_{sa}, \end{aligned} \tag{12}$$

where D_{HA} is the average distance between the home agent of the mobile node and the foreign agent with which the mobile node is currently associated. Comparing the above equation with Eq. (9), it is clear that P-MIP has larger signaling overhead than IIPP, as the distance D_{HA} is generally longer than D_{GFA}.

In summary, IIPP performs better than P-MIP in terms of both the power consumption and signaling overheads in many general cases. However, as their values depend on different parameters, we cannot compare the performances of IIPP and P-MIP simply by varying a single parameter. Therefore, in the next section we present the performance results of IIPP by comparing with MIPRR only.

6 Numerical Results

To evaluate the performance of IIPP, we assumed a campus-area access network with the configuration parameters shown in Table 1. Most of the parameters used here are set to the same values as used in [6, 12]. The speed of a mobile node is set to 2 m/s, which represents the maximum speed of a pedestrian. We consider two levels of hierarchy of foreign agents: the GFA at top and the ARs at the bottom level. The weights for signaling cost in wired and wireless links are set to 0.4 and 0.6, respectively. For simplicity, we consider the FAs do an equal amount of computation for processing a registration and a paging message; therefore, we take per registration and per paging signaling cost as one. In some papers, it is assumed that registration cost is higher than paging cost [29]. However, our assumption of equal costs does not alter the minimum value by which the IIPP signaling cost is lower than that of MIPRR because IIPP performs fewer registrations. The power-related parameters are referenced from [17]. These parameters represent the powers consumed by the IEEE 802.11b ORiNOCO PC Gold card under active (average of transmit and receive), idle, and sleep modes. The AAI and ASL are taken as 100 and 2 ms, respectively, which correspond to the *BeaconPeriod* and slot length of the IEEE 802.11 wireless LAN [27].

The incoming and outgoing data session rates are set to equal values of 1, 3, and 5 sessions per hour. Substituting these values in Eqs. (3) and (4), we get the inter-session times of IIPP and MIPRR as shown in Fig. 6. This figure shows that the inter-session time of MIPRR is independent of the size of paging area, whereas that of IIPP increases with increasing paging area size. The larger paging area helps the mobile node remain in dormant mode for longer time because the mobile node is not required to update its location while moving in the paging area. This figure also shows that the inter-session time of MIPRR is least affected by the change in session rate. However, the inter-session time of IIPP decreases with the increasing data session rate, and the effect is more prominent when the paging area is large. Based on this observation, for the following evaluations, we set the session duration (i.e., the active time) of both the IIPP and MIPRR mobile nodes as 10 seconds, and the active timeout of the IIPP mobile node as 2 seconds.

6.1 Power Gain

Figure 7 shows the average power consumption, in terms of fraction of active power, of the MIPRR and IIPP mobile nodes. The average power consumed by the MIPRR mobile node is independent of paging area whereas the power consumed by the IIPP mobile node decreases with increasing paging area. As the IIPP mobile node enters very-low-power-consuming dormant mode for a considerable period of time, it consumes far less power than the MIPRR mobile node.

Figure 7 also shows a curve of the average power consumption of the IIPP mobile node without PSM. In this case, the IIPP mobile node does not enter dormant mode but carries out all other paging-related functions. When the paging area size is about one cell, the IIPP mobile node without PSM consumes the same amount of power as the MIPRR mobile node does because in both cases the inter session times are the same and the mobile nodes remain in active mode and idle mode for the same duration of time. However, when the paging area is greater than (or equal to) two cells, the power consumed by the IIPP mobile node is lower than that by the MIPRR mobile node because the former can remain in idle mode for longer time.

We can see that when the paging area size is greater than 10 cells, IIPP reduces the average power consumption of a mobile node by about 75%, and even by 7% when the PSM is not used. It also indicates that increasing the maximum paging interval, κ, has a very little advantage in terms of power saved.

The powers consumed by both IIPP and MIPRR mobile nodes increase as the speed of mobile nodes increases. The rate of increase for an IIPP mobile node is prominent when the size of paging area is low. Similarly, the increase in incoming or outgoing session rate increases the power consumption of both IIPP and MIPRR mobile nodes.

6.2 Signaling Gain

Figure 8 depicts the signaling cost of IIPP and MIPRR with respect to the paging area size. The signaling cost of MIPRR increases linearly with the paging area. The larger paging area includes more mobile nodes that cross the cell boundaries. More cell boundary crossing invokes more registration. Therefore, the MIPRR signaling cost increases linearly as the paging area increases. On the other hand, the IIPP signaling cost consists of both registration and paging costs. The larger paging area size reduces the IIPP registration cost because mobile nodes register their location only after they cross the paging area. However, larger paging area increases the paging cost because many ARs have to be involved in processing and broadcasting the paging request. In contrast, when the paging area is small, mobile nodes cross paging area boundaries and perform registration more frequently; consequently, the registration cost increases. But, when the size of paging area is small, lower number of ARs are involved in processing the paging request, resulting in lower paging cost. In order to get an optimum signaling cost, as shown in Figure 8, the paging area size should be between 10 and 35 cells. When the paging area size is within this range, compared to MIPRR, IIPP reduces the signaling overhead by 18-42%.

Figure 9 illustrates the impact of data session rate on the signaling cost. We have assumed equal incoming and outgoing session rates. The incoming session has double impacts on signaling cost of an IIPP mobile node because it adds both paging and registration costs. As shown in this figure, when the paging area is of 10 cells, the signaling cost of IIPP is lower than that of MIPRR until the data session rate is lower than about nine sessions per hour. However, when the paging area is increased to 25 cells, the range of data session rate reduces to about six sessions per hour where the IIPP signaling cost is lower than that of MIPRR. This is due to the following reason. An IIPP mobile node has to register its location before it receives or sends data packets. The larger paging area reduces the movement-related registration, but increases paging cost. When the data session rate is high, the advantage due to reduction in movement-related registration is overrun by the increase in paging and session-related registration costs.

Similarly, for low-speed mobile nodes, the IIPP signaling cost is more than that of MIPRR. When the speed is very low, it is likely that a mobile node will be in the same cell when data sessions arrive. However, as a dormant IIPP mobile node always registers its location before it starts having a data session, its signaling cost becomes higher than that of MIPRR. In contrast, when the speed is high, the registration cost of IIPP becomes lower than that of MIPRR because the IIPP mobile node registers its location only after crossing a paging area, whereas the MIPRR mobile node registers after crossing a cell.

7 Simulation

We also carried out simulations to elaborate the performance of the proposed IIPP and to confirm the results obtained from the analytical modeling.

7.1 Simulation Setup

We considered an administrative domain of a network having 64 square-shaped cells. These cells could be grouped into one or many paging areas. The number of cells in a paging area was 4, 8, 16, 32 and 64, that means, the domain was partitioned into 16, 8, 4, 2, and 1 paging area, respectively.

We used the random-way point mobility model [6, 28]. The random-way point mobility model captures the reality of pedestrian movement along a street. In this model, before moving from an initial location the mobile node chooses two parameters: destination location and speed. The destination location can be anywhere within the simulation area, i.e., in the administrative domain, and the speed is uniformly distributed between zero and maximum speed. The mobile node moves from an initial location to the destination location with the selected constant speed. When the mobile node reaches at the destination, it waits for a pause time, and then selects another pair of destination and speed and moves again. In this simulation, we take the pause time as 4 seconds, and the maximum speed as 2 m/s.

The incoming and outgoing sessions are Poisson processes and the inter-session time is exponentially distributed with a parameter λ as three sessions/hour. As before, the mean session duration is taken as 10 seconds.

7.2 Simulation Results

For each size of paging area, the simulation was run for 10 hours and the following items were recorded for each mobile node: (1) the number of MIPRR registrations, (2) the number of IIPP registrations, (3) the number of paging, (4) the average of the MIPRR inter-session times, and (5) the average of the IIPP inter-session times.

The random-way point mobility model used for the simulation does not directly correspond to the fluid-flow mobility model used for the analytical evaluation. In the fluid-flow mobility model, a mobile node can move continuously in any direction with a constant speed, whereas in random-way point model, it moves intermittently, with possible changes in both direction and speed in every interval. Similarly, the mobile node's mobility in the random-way point model is confined to the simulation area, whereas that of the fluid-flow model is not limited by any area. Therefore, the simulation results cannot be expected to be the replica of analytical results. However, the results in both cases show similarity in the nature of their variability when some parameters are changed.

Using the power-related parameters of Table 1, we measured the average power consumption of the IIPP and MIPRR mobile nodes. Figure 10 shows that the average power consumption of the IIPP mobile node is a little less than that of the MIPRR mobile node even when the IIPP mobile node does not use PSM. But when the IIPP mobile node uses PSM, the power consumption is drastically reduced by almost the same ratio as seen in the analytical evaluation.

Figure 11 shows the variation of signaling overhead due to varying paging area size. The signaling overhead of MIPRR is higher than that of IIPP. It is clear that when the paging area is small, both IIPP and MIPRR have almost the same signaling overheads in the network. However, when the paging area increases to above 10 cells, the IIPP signaling overhead is lower due to the reason that when the paging area size is above some level, the registration signaling overhead in IIPP is reduced as the mobile node does not register its location on crossing a cell boundary.

8 Conclusion

We presented the integrated IP paging protocol (IIPP) that integrates IP paging and a power save mechanism to reduce the average power consumption of mobile nodes and the signaling overhead in the network. In IIPP, an idle mobile node does not register its location in the visited domain when it crosses a cell boundary, rather it registers only when it crosses a paging area boundary. In this way, IIPP reduces unnecessary registration messages by idle mobile nodes, and lengthens the idle mode time of the mobile nodes. In idle mode, mobile nodes consume less power than in active mode. Furthermore, IIPP includes a power save mechanism that enables an idle mobile node to transit to dormant mode and thus consume very low power.

We formulated analytical models and carried out simulations to evaluate the average power consumption and average signaling overhead for Mobile IP regional registration protocol and IIPP. We discussed the impact of various factors, such as the size of paging area, speed of mobile node, and data session rate, on the power save and signaling overhead. Our results show that the optimum range of paging area size is between 10 and 35 cells, and with this range of paging area, IIPP significantly reduces the power consumption of mobile nodes and signaling overhead in the network.

Although the performance evaluation of IIPP in this study is mostly dependent on the parameters chosen, nonetheless, the proposed scheme shows better performances over reasonable ranges of parameter values. The reduction in power consumption will enable mobile nodes to operate for longer time without re-charging their battery, and the reduction in signaling overhead in the network will enable the network to support a larger number of mobile nodes, thus increasing the scalability of the network. In future work, we will use the NS-2 simulator to assess the impact of channel condition and hierarchical levels on the performances of the proposed IIPP, especially in terms of the paging latency.

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Table 1: Parameters

Item	**Value**
Mobility related:	
Cell perimeter, L_c (m)	400
Speed of mobile node, v (m/s)	2
No of nodes in a cell, N	20
Access network related:	
Average dist. bet. GFA & AR, D_{GFA}	2
Per reg. signaling cost, C_r	1
Per paging cost, C_p	1
Weight, α	0.4
Weight, β	0.6
Power related:	
Active power, P_a (watt)	1.175
Idle power, P_i (watt)	0.805
Sleep power, P_s (watt)	0.06
Agent adv. interval, AAI (s)	0.1
Adv. slot length, ASL (s)	0.002

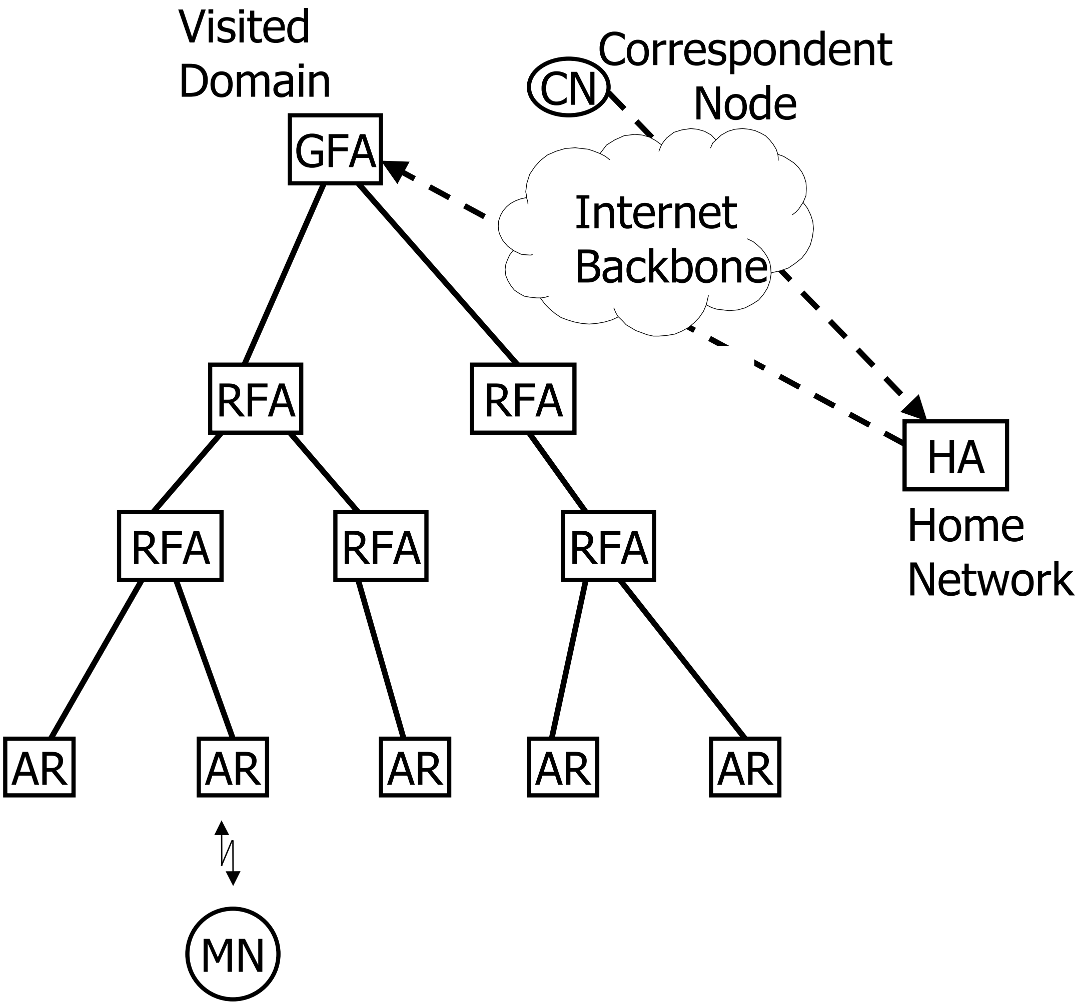

Figure 1: Reference architecture of IIPP.

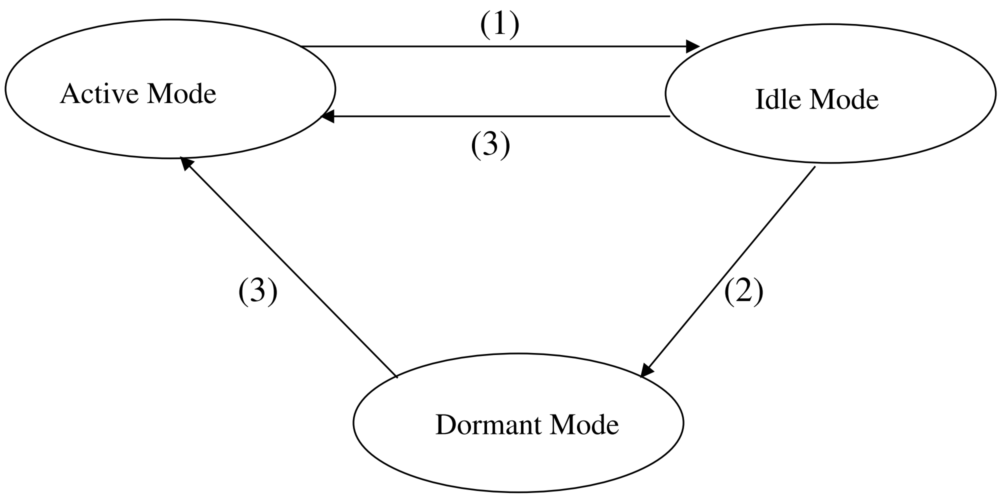

Figure 2: Modes of an IIPP mobile node. The mobile node remains in active mode as long as it is sending or receiving data packets. When it finishes the data session it enters idle mode, as shown by arrow (1). After an active timeout in idle mode, the mobile node enters dormant mode, arrow (2). The mobile node enters active mode from idle mode or dormant mode when it receives a paging request or it has data packets to send or it moves to a new paging area, arrow (3).

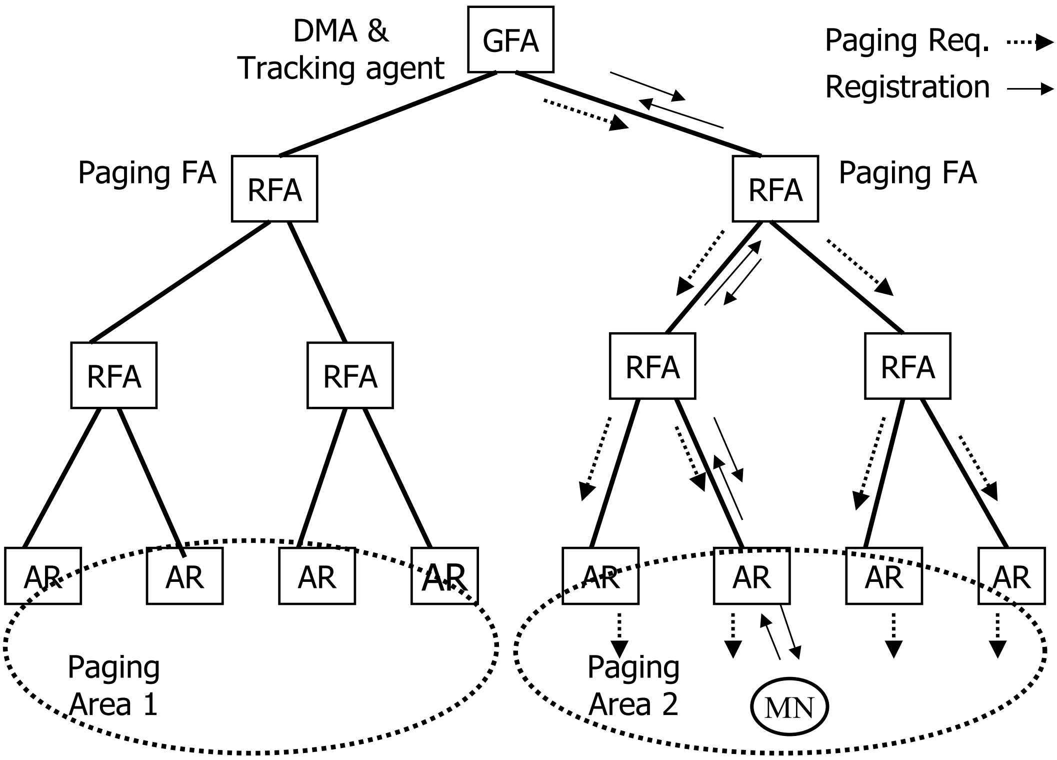

Figure 3: Paging architecture.

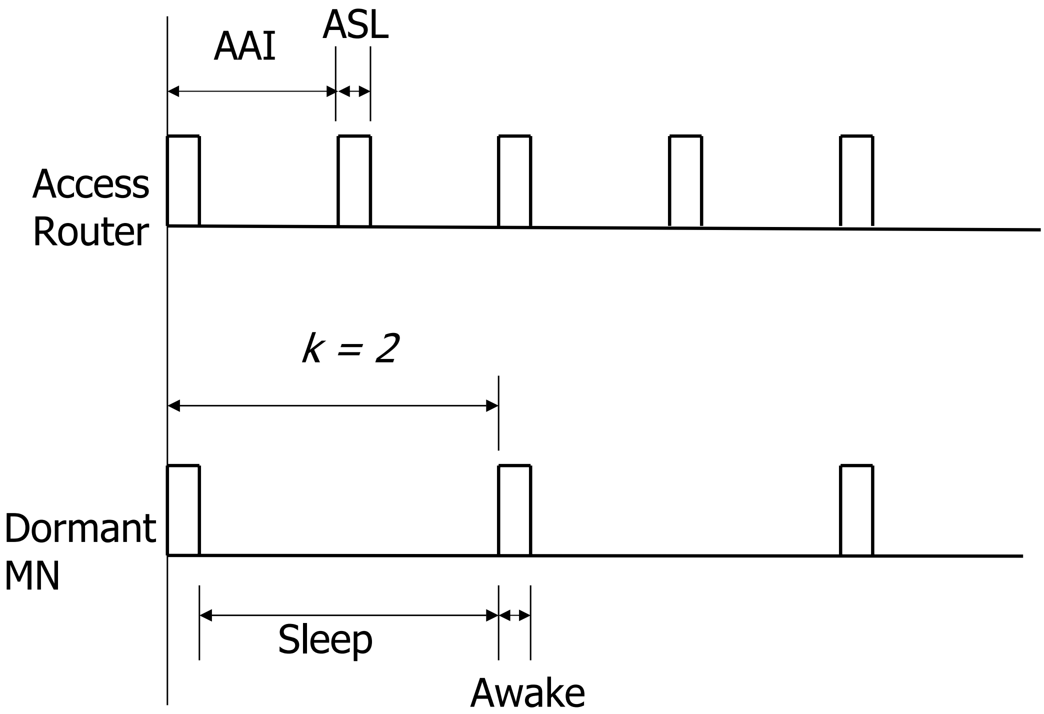

Figure 4: Power save timing diagram. The access router broadcasts agent advertisement (AA) message once per AA interval (AAI). Advertisement slot length (ASL) is the time during which the AR may broadcast an AA. The idle MN wakes once in maximum paging interval, i.e., κ times the AAI, to check if it has a paging alert.

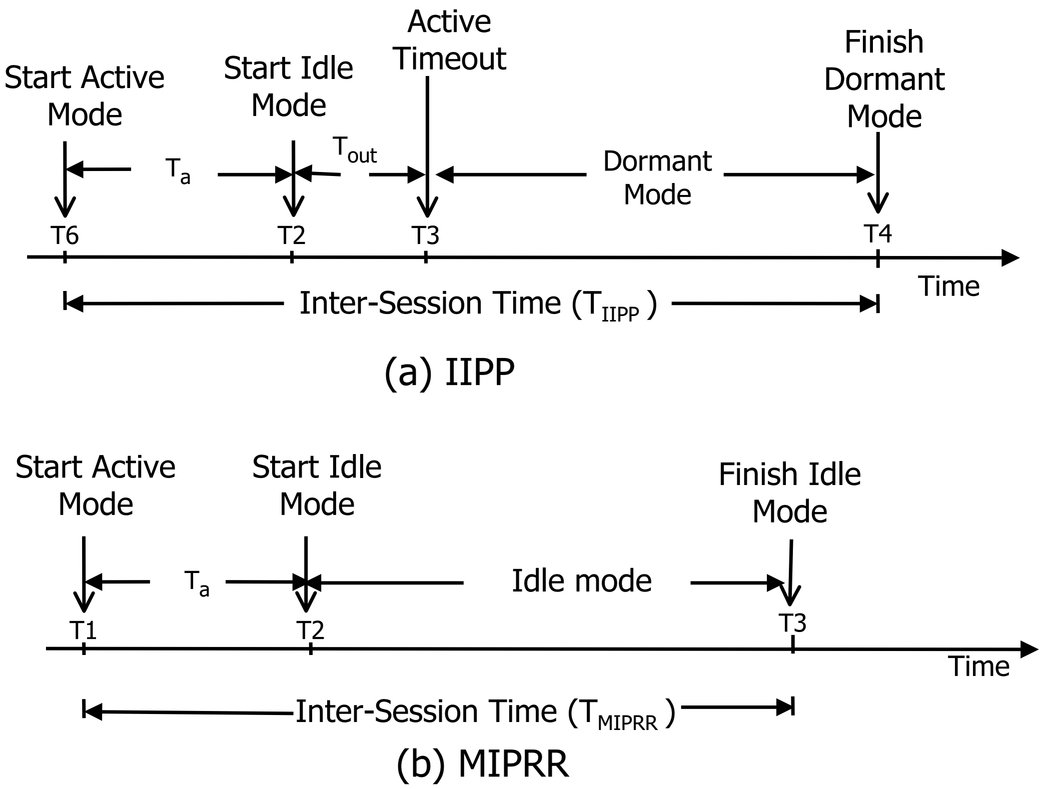

Figure 5: Timing diagram of modes of a mobile node.

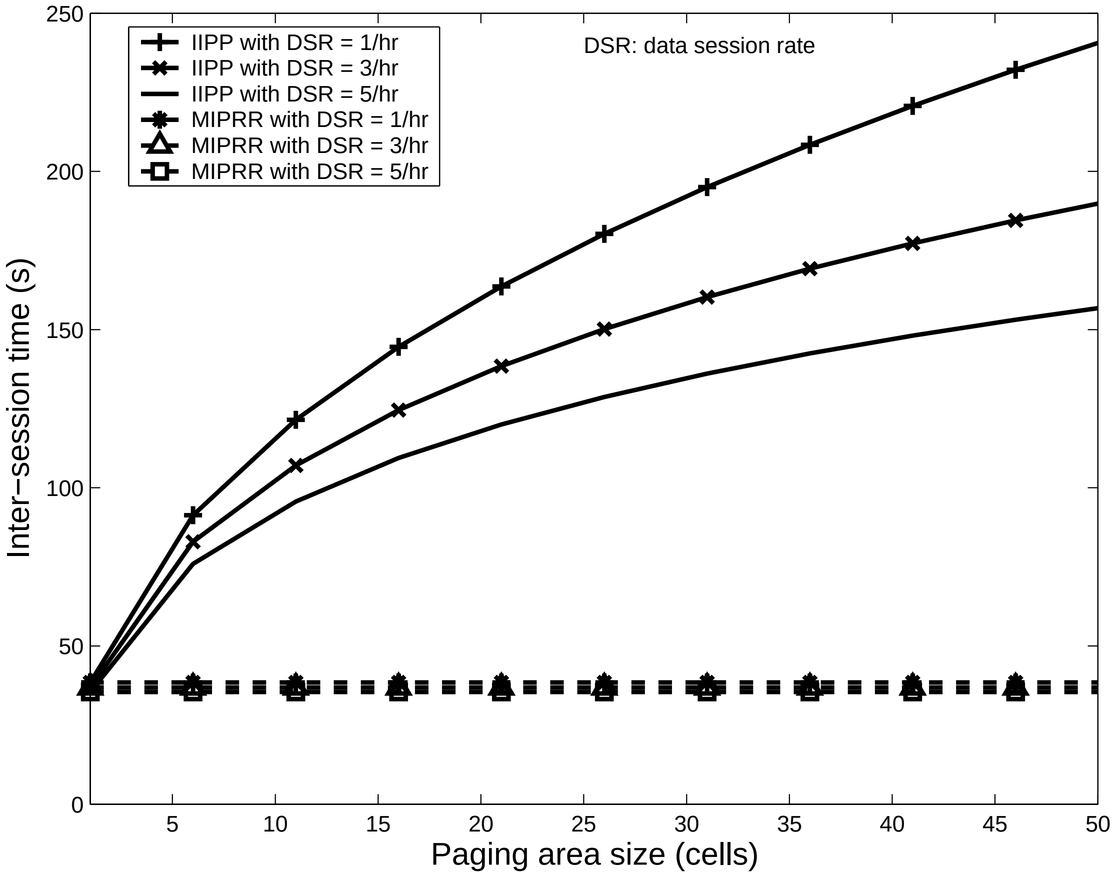

Figure 6: Inter-session time versus paging area size.

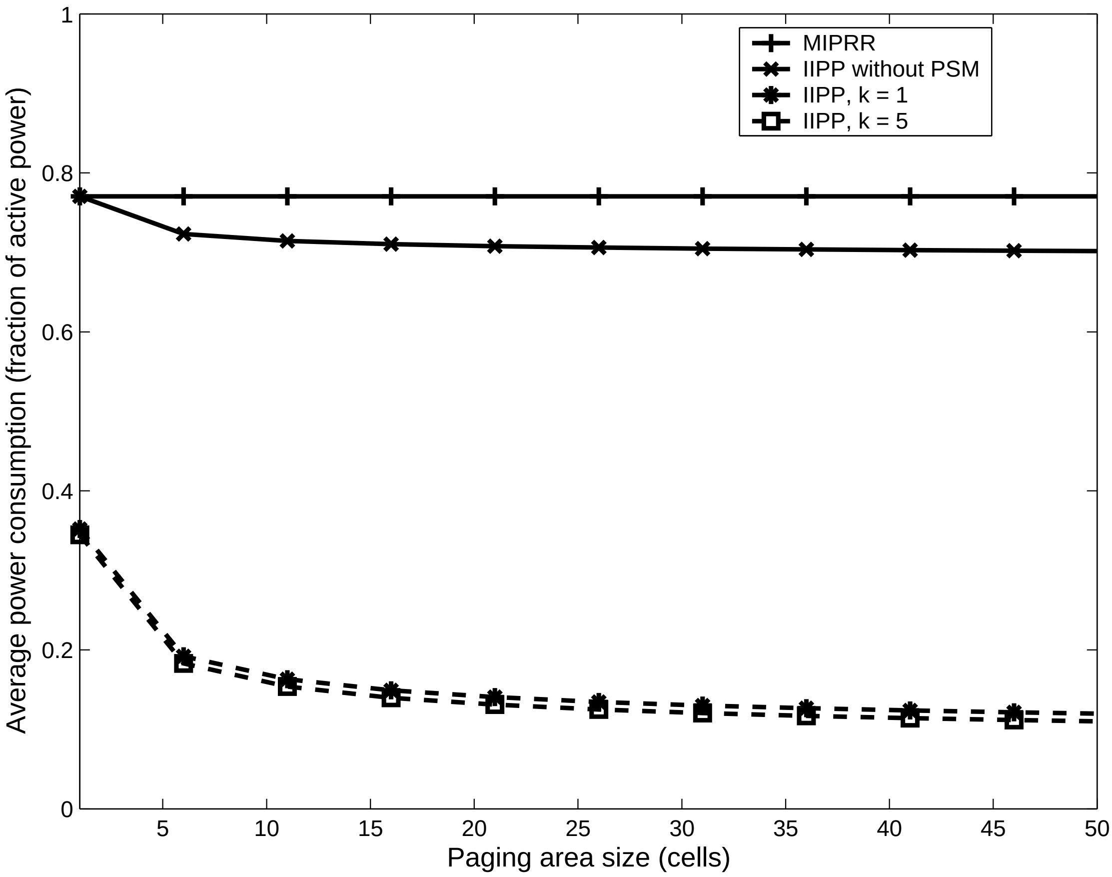

Figure 7: Average power consumption of a mobile node versus paging area size.

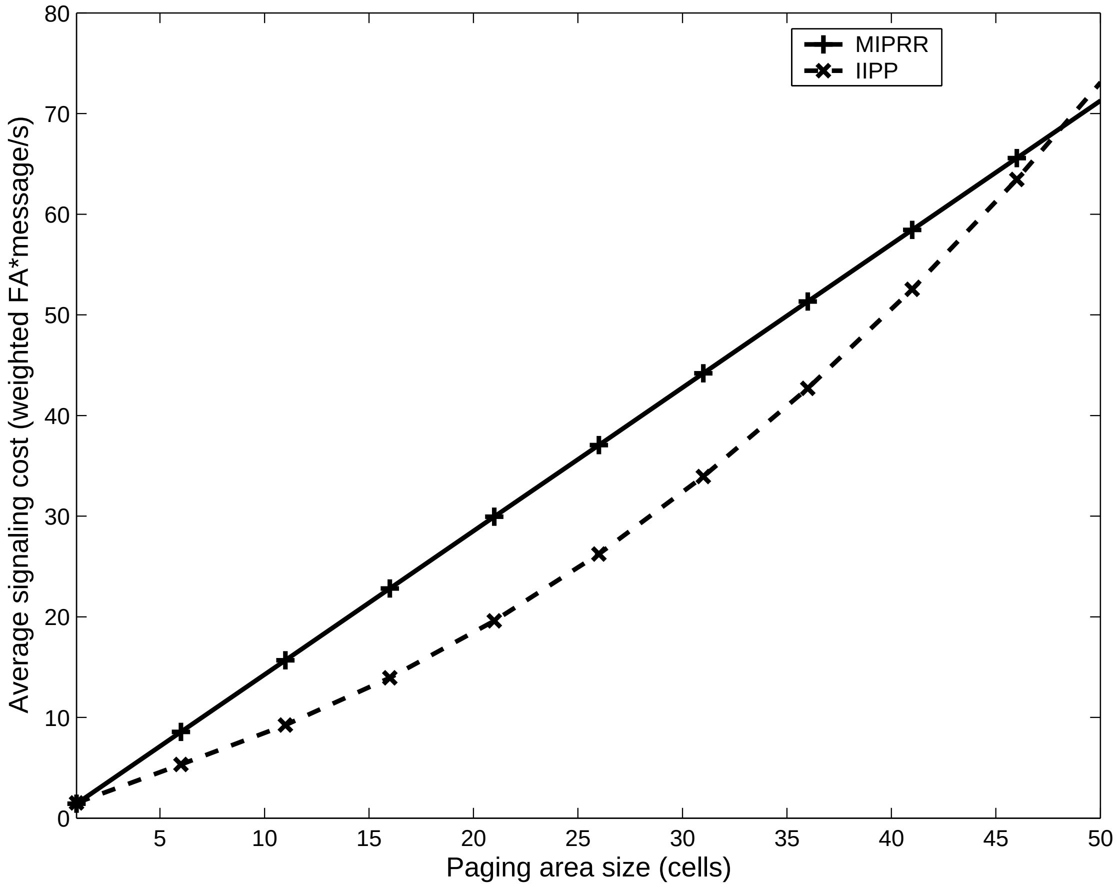

Figure 8: Signaling cost versus paging area size.

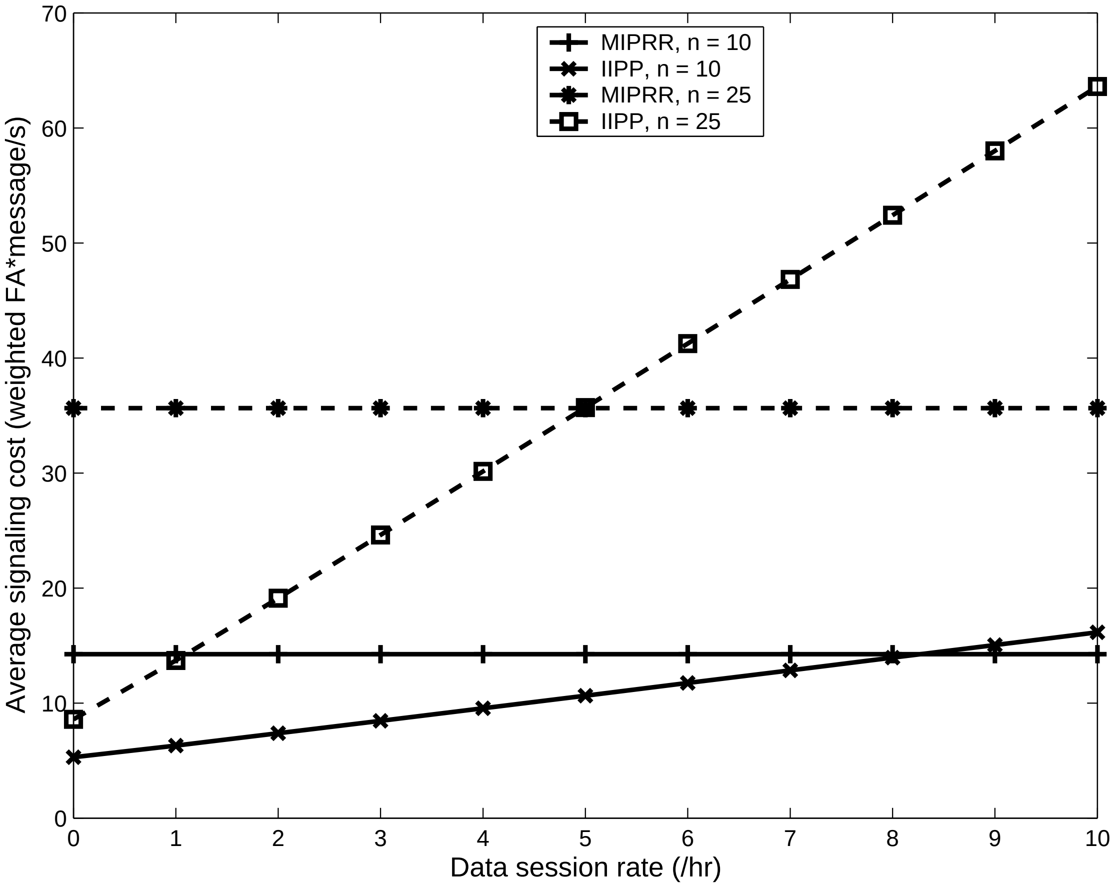

Figure 9: Signaling cost versus data session rate.

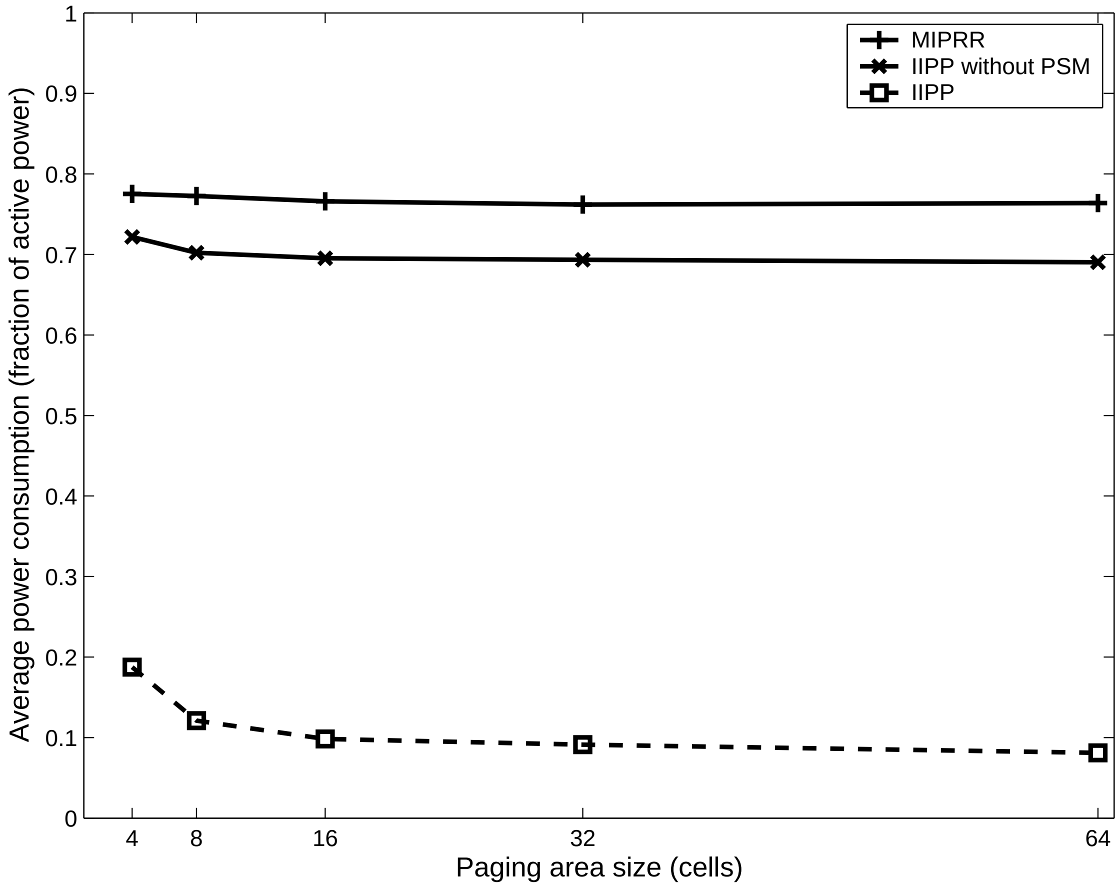

Figure 10: Average power consumption versus paging area size (simulation).

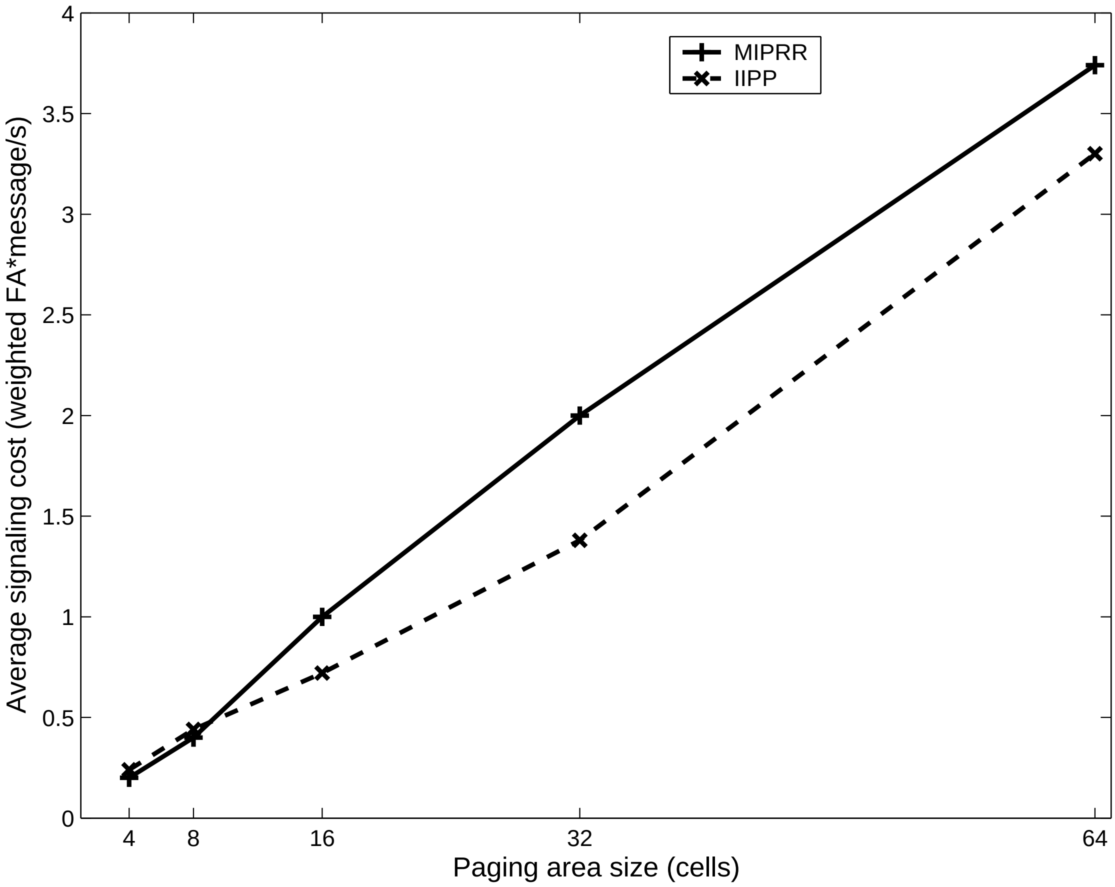

Figure 11: Signaling cost versus paging area size (simulation).