Paging and Power Saving in IEEE 802.11-enabled Networks - A Simulative Study

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ABSTRACT

Mobile communication systems increasingly adopt Internet Protocol solutions for transport of control and data traffic. To optimize scalability of the mobile communication infrastructure and to save mobile energy resources, mobile devices can set their network interface to power save mode, such as for instance supported by the IEEE 802.11 technology, and refrain from sending superfluous location information towards the network in case the device is idle. Such systems utilize paging to locate and reactivate mobile devices in power save mode. In this paper, we show how mobile terminal power saving efficiently complements IP paging in an IEEE 802.11-enabled network. By means of simulations, we evaluate and compare a mobile terminal's power consumption due to mobility management within a Mobile IPv6 network with and without paging and power save mode support. The results show that IP paging with complementary power save mode support harmonizes efficient location tracking with optimized energy resource usage, while taking requirements on routing delay constraints into account.

Categories and Subject Descriptors

C.2.1 [**Computer - Communication Networks**]: Network Architecture and Design—*network communications, wireless communication*; C.2.2 [**Computer - Communication Networks**]: Network Protocols—*routing protocols*; I.6.6 [**Simulation and Modeling**]: Simulation Output Analysis

General Terms

Design, Performance, Reliability

Keywords

Mobility Management, IP Paging, Power Saving, IEEE 802.11

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1. INTRODUCTION

Mobile communication systems increasingly adopt Internet Protocol solutions for mobility management. With IP-based mobility management protocols, such as Mobile IPv6 [6], a mobile terminal acquires a temporary IP address, which represents its current location. To maintain reachability, such protocols require the mobile terminal to update its routing state with a network mobility anchor (Home Agent) by means of location update signaling as soon as its IP address changes. A change of a mobile terminal's IP address can be due to its movement and associated change of its current access router. To save scarce radio bandwidth and to increase scalability of the network, mobile communication systems allow mobile terminals to enter a *dormant mode* and to refrain from sending frequent location updates in case they are idle. In addition, the mobile terminal might activate a power save mode to save local energy resources in case its network interface supports associated operation. Such systems utilize *paging* to locate a dormant mobile terminal and re-activate its resources in case data is to be forwarded to the mobile terminal.

Technology-specific paging solutions exist for nowadays 2^{nd} and 3^{rd} generation mobile communication systems. Following the trend to utilize technology independent and IP-based protocol solutions to support heterogeneous access networks, various architecture and protocol proposals exist for IP-based paging. The Internet Engineering Task Force (IETF) published a set of requirements for IP paging in RFC 3154 [7]. Following these requirements and taking additional design goals into account, we specified a *Flexible Paging Protocol* (FP^2), which strikes a balance between flexibility and protocol complexity.

The proposed paging architecture and protocol integrates well into various IP-based mobile communication networks. IP paging-related signaling components operate access technology independent, but allow efficient integration of various radio technologies in the access network by means of a *paging attendant*. The associated function performs mapping of IP paging protocol operation to technology-specific operation, hence allows the utilization of technology-specific paging and support of the technologies' power saving mode in case corresponding operation is supported.

In this paper, we focus on the evaluation of an IEEE 802.11-enabled Mobile IPv6 network with and without FP^2-based paging support. We propose how to efficiently integrate and utilize the IEEE 802.11 technology's power save mode with FP^2 to support paging. By means of simulation, we evaluate paging delay and power saving characteristics of FP^2 operation and compare relevant characteristics with standard Mobile IPv6 operation without paging support. Section 2 summarizes related work on IP paging protocols. Whereas a detailed signaling costs analysis of FP^2 operation in a Mobile IPv6 network can be found in [8], a summary of relevant paging protocol operation is covered in section 3, which includes details about FP^2 support in IEEE 802.11-enabled networks with and without activated power save mode. Section 4 focuses on the performance evaluation of paging delay and power saving characteristics of FP^2 operation with and without IEEE 802.11 power save mode support in a Mobile IPv6 network. Finally section 5 concludes this paper.

2. RELATED WORK

Aiming at a generic architecture and protocol proposal for IP paging, the solution should be capable of arranging with different classes of mobility management and be flexible enough to support efficiently different paging strategies and different access technologies. Some per-host routing based protocols, such as Cellular IP [13] and HAWAII [12], support protocol specific and built-in paging operation. Cellular IP utilizes paging caches in some routers to lessen per-host entries in individual routers' routing cache. Paging support is an integral part of the Cellular IP protocol and cannot be used for other mobility management schemes. HAWAII specifies a paging extension, which utilizes a multicast tree to perform paging, which makes it difficult to support individual and dynamic paging areas and disallows use of enhanced paging strategies.

P-MIP [14] has been specified as paging extension to the Mobile IPv4 protocol. It introduces a simple set of paging extensions and utilizes Mobile IPv4 Foreign Agents to coordinate the paging procedure. P-MIP is more flexible regarding the use of enhanced paging strategies and structuring of paging areas. However, this protocol assumes the existence of Foreign Agents.

Most IP paging protocols focus on the specification of architecture components and optimization of signaling costs without taking a mobile terminal's reduced activity into account. As a result, most proposals do not consider how to convey paging indications to dormant mobile terminals, which might not have a valid routable IP address or even entered a power save mode.

Operation of the standard IEEE 802.11 power save mode for dormant mobile terminals has been considered in [10]. This proposal uses an available paging extension for Hierarchical Mobile IPv6 and allows mobile terminals entering the IEEE 802.11 power save mode. The paper focuses on an analytical evaluation of the paging delay costs without specifying in detail how the mapping between the IP paging protocol operation and IEEE 802.11 traffic indication is achieved, which is a relevant conceptual detail to make this approach work. The actual paging protocol does not play any role in the evaluation and authors focus on the derivation of the IEEE 802.11 traffic indication delay based on the access point's standard operation without considering the entire paging system.

In [11], an Integrated IP Paging Protocol (IIPP) is proposed, which aims at reducing power consumption by means of synchronizing a network's access routers with mobile terminals and controlling active and sleep intervals from IP layer based on this synchronization. The proposal assumes that link-layer resources can be controlled entirely from IP layer regarding sleep periods, irrespective of any complexity to maintain a network interface's association with the infrastructure's access points. The work does not propose how to keep access routers synchronized among each other and with the mobile terminal. The evaluation of the gain in power saving simply derives from IP-layer activity, which is mapped to static power consumption on link-layer, resulting in a less accurate evaluation.

For an accurate evaluation of a mobile terminal's power consumption due to networking activity, the network interface's link-layer activity, power control and associated complexity should be taken into account. In this paper, we perform such an evaluation for a generic IP paging protocol and IEEE 802.11 access by means of simulations

3. FP^2 - A FLEXIBLE PAGING PROTOCOL

In this section, we describe the FP^2 architecture, as well as its integration and operation with Mobile IPv6, which represents the paging-enabled mobile communication platform for the subsequent simulative evaluation. Since this paper focuses on the gain in saving energy in IEEE 802.11-enabled networks, we propose how to efficiently operate power save mode (PSM) on a mobile terminal's interface while maintaining its reachability by means of FP^2. As an alternative, we describe how paging can be performed on an access link by means of IP-based signaling for access technologies without link-layer support for paging.

3.1 Protocol Operation

The FP^2 architecture comprises a *Paging Controller*, which implements tracking agent and paging agent functionality. The tracking agent function maintains information about a mobile terminal's coarse location (*paging area*), whereas the paging agent function coordinates the IP paging procedure. Furthermore, it comprises a function to buffer incoming user data packets and to forward the packets as soon as the routing states for the paged mobile terminal have been re-established. The architecture considers *paging attendant* functions, which are co-located with the network's access routers (AR). Such paging attendants perform mapping between the technology-independent IP paging protocol and access technology-specific operation as for control of link-specific paging indications. In case the access technology has no support for paging, the paging attendant generates IP-based signaling messages to perform paging a mobile terminal on the access interface.

Figure 1 illustrates a mobile terminal's registration with a Paging Controller (PC). When the mobile terminal decides to enter the dormant mode, the terminal sends a *DormantRequest* message to the paging attendant at its current access router. The attendant selects an appropriate PC and forwards the request to it. Various algorithms for PC selection can be supported, but details are out of the scope of this paper. The PC holds the mobile terminal's registration as long as it remains in dormant mode. The PC sends an associated *DormantReply* message back to the mobile terminal through the respective AR's paging attendant. With the reply message, the mobile terminal can learn about its PC and registers the PC with its Mobile IPv6 Home Agent as *alternate Care-of-Address*, which causes incoming packets being forwarded to the mobile terminal's PC to initiate a paging procedure.

To allow the tracking agent function in the PC maintaining a mobile terminal's coarse location information, the *DormantRequest* comprises information about the terminal's current *paging area*. In this paper, a paging area comprises multiple access routers. The terminal is now allowed to enter dormant mode and to move within

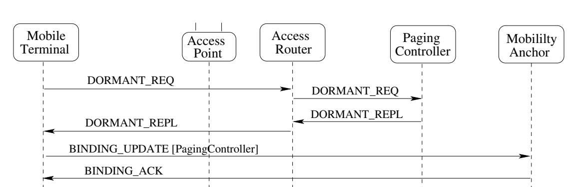

Figure 1: Mobile terminal dormant registration with the Paging Controller.

the registered paging area without sending location information to the PC. Only a change of the paging area is to be signaled to the PC, which is not considered in this study. Details about updating a paging area with the mobile terminal's PC can be found in [8].

In the event of arriving data packets trigger a paging procedure, the PC sends a *PagingRequest* message to all paging attendants being associated with the registered paging area. The study in this paper utilizes unicast packets to distribute *PagingRequest* signaling messages to the paging area's paging attendants individually, which allows using enhanced paging strategies. However, this study is based on the *blanket polling* paging strategy, which requests all paging attendants at once to page a mobile terminal, hence results in best performance regarding the effective paging delay. Individual paging attendants perform paging a mobile terminal on the access interface either by means of IP paging messages, which address the mobile terminal using IP multicast, or by means of link-layer support and associated paging indications on layer 2 (L2). Both approaches are described in the subsequent sections 3.2 and 3.3. The performance evaluation in section 4 investigates characteristics of both approaches.

3.2 IP multicast-based paging

In the event that a user data packet arrives at the PC, the packet is buffered until it can be forwarded to the destined mobile terminal after a successful paging procedure. The PC initiates the paging procedure and distributes the IP-based *PagingRequest* messages to all paging attendants of the registered paging area. Paging attendants are aware of the associated access technology and build an appropriate paging indication, which can be received and processed at the mobile terminal. In case there is no link-layer support for paging indications, the paging attendant delivers the *PagingRequest* to the mobile terminal by means of IP transport mechanisms (Figure 2). Due to the mobile's dormant mode, the network has no valid information about its routable IP address. Hence, paging attendants address the *PagingRequest* to the mobile terminal's Solicited Node Multicast Address [5].

Since a node's default Solicited Node Multicast Address comprises the least significant 3 byte of the associated interface's MAC address, the mobile terminal provides relevant MAC address bytes to its PC during the dormant registration. In the event of paging, the PC provides this information to the paging attendants as parameter of the *PagingRequest* messages. A proposal about how to embed multiple technologies' MAC information into a unique paging identifier (PID) is described in [8]. Individual paging attendants can derive the mobile's Solicited Node Multicast Address from the PID according to the supported access technology. After receiving the paging message, the mobile terminal deregisters with the PC by means of sending an *ActiveRequest* message to the PC through the paging attendant of its current access router. The *ActiveRequest* comprises the mobile terminal's current routable IP address, which allows the PC to forward the buffered data packet. Furthermore, the mobile terminal updates its current location with its Home Agent.

The Solicited Node Multicast Address-based paging approach, as described in this section, can be used in case a mobile terminal's interface does not support power save mode while the mobile is in dormant mode. In this case, the mobile terminal keeps all its networking resources active to be able to receive IP paging signaling. Hence, we assume the mobile terminal is able to receive Router Advertisements when it changes its access router in dormant mode and configures its IPv6 address accordingly by means of stateless address autoconfiguration. The only gain in saving power on the mobile terminal is that it refrains from sending frequent *Binding-Update* messages to the network.

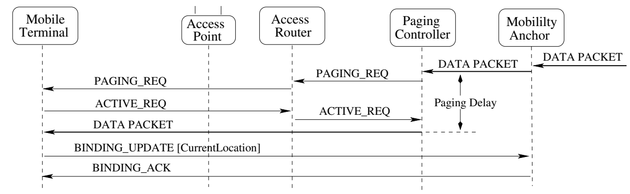

Figure 2: Solicited Node Multicast Address-based paging procedure.

3.3 Link-layer paging of terminals in PSM

The IEEE 802.11 MAC layer specification [3] comprises mechanisms for power saving as well as for associated *traffic indication* and delivery. Power saving is achieved by means of switching the mobile device's network interface to a *Doze* state. In *Doze* state, a network interface card (NIC) reduces activity of most hardware components and conserves a lot of energy. In PSM, the NIC is able to receive traffic only at regular intervals by means of switching its state periodically to *Idle*, where the NIC can receive (*Rx*) data. Transmitting (*Tx*) data is possible at any time. To enter PSM, the NIC must be associated and synchronized with an access point. After a mobile device has selected an access point, it performs an authentication and association procedure. Throughout the association procedure, the mobile device informs the access point about its *listen interval* (LI), which indicates the amount of beacon intervals (BI) a NIC in PSM remains unreachable before it is able to receive the next beacon. As a consequence of a successful association, the access point assigns an Association Identifier (*AID*) to the mobile terminal's interface.

According to the standard, the AID is used by access points to indicate the arrival of unicast traffic to an individual mobile device in PSM and represents a bit in the traffic indication bitmap (TIM), which is sent with each beacon. When entering PSM, a mobile device indicates its mode in an IEEE 802.11-specific frame control field. From now on, the access point listens to data packets destined to the mobile device's IP address. As soon as a packet for a mobile device in PSM arrives at the access point, the packet is buffered and traffic is indicated to the mobile device in subsequent beacons' TIM information element. As soon as a mobile device finds traffic indicated in a received TIM, it polls buffered data packets from the access point with an IEEE 802.11-specific Power Save Poll (PSP) message. Hence, in standard operation, an access point performs mapping of the mobile terminal's IP address to its AID and to the associated bit in the TIM, which is illustrated on the left side of Figure 3.

The standard IEEE 802.11 PSM relies strongly on the association between the mobile terminal and its current access point. An AID remains valid only as long as the mobile keeps its current as-

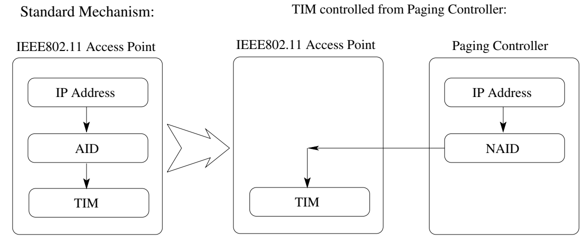

Figure 3: Relocation of NAID control and mapping functions to the Paging Controller.

sociation. In case the mobile terminal associates with a different access point, the AID changes as well. For mobile terminals in dormant mode having the NIC set to PSM, we propose utilizing the TIM to convey *paging indications* to the mobile terminal. Unlike mapping of a terminal's AID to the TIM as in standard PSM operation, we propose a *network association identifier* (NAID) for paging, which is valid as long as the mobile terminal remains in dormant mode, disregarding of a change in access points. The NAID is under control of the PC and assigned to the mobile terminal during the dormant registration (Figure 1). The associated *DormantReply* message conveys the NAID to the mobile terminal.

As a consequence, we relocate mapping of the terminal's IP address to the associated NAID from the access point to the PC to control dormant mobile terminals, as illustrated on the right side of Figure 3. In case the mobile terminal is paged, the *PagingRequest* carries the mobile terminal's NAID from the PC to the paging area's paging attendants. Paging attendants can now forward the *PagingRequest* to the IEEE 802.11 access point, which maps the embedded NAID to the associated bit in the TIM, as depicted in Figure 4. The mobile terminal finds its paging indication bit set in the TIM's virtual bitmap when its wakes up and processes the beacon at its next listen interval. This should cause the terminal to activate the NIC and to initiate deregistration with the PC to allow forwarding of buffered data packets.

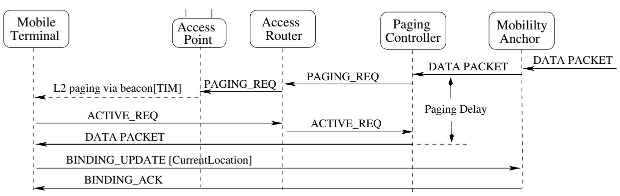

Figure 4: TIM-based link-layer paging procedure.

The proposed approach allows paging a dormant mobile terminal in PSM based on the arrival of data packets at the PC without the need to update the binding between the mobile's IP address and its AID at each access point. The approach is independent of the mobile terminal's location within the paging area and of its current access point and access router. The mobile remains reachable based on the IP address being registered with the PC.

To allow NAID-based paging indications to coexist with the standard's AID-based traffic indications within a beacon's TIM, we propose to split the TIM's partial virtual bitmap into two areas. Figure 5 depicts the TIM format. According to the standard, the TIM's virtual bitmap is transmitted only partially, starting with the first bit set and ending with the last bit set. This allows keeping the length of the periodically advertised TIM to a minimum. The TIM element's *Bitmap Control* field comprises offset information, which points to the first bit set in the partial virtual bitmap and allows unique association of individual bits of a bitmap with a mobile's AID and NAID respectively. The only requirement from access points is to keep the same separation between AID and NAID mapping space. To keep the length of the effectively used virtual bitmap short, access points could start assigning AID numbers from N backwards, whereas a PC could start assigning NAID numbers to registering terminals from (N+1) upward.

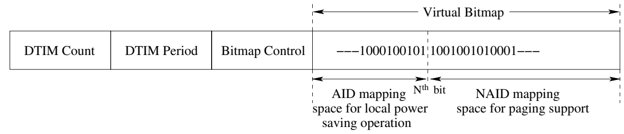

Figure 5: Combined AID and NAID mapping within an IEEE 802.11 Traffic Indication Map.

4. PERFORMANCE EVALUATION

This performance evaluation focuses on the gain in saving energy on the mobile terminal when using FP^2 with and without power save mode support, as well as on the reliability of routing initial data packets towards mobile and dormant terminals in an IEEE 802.11-enabled Mobile IPv6 network. Furthermore, paging delay characteristics are evaluated for both paging schemes, while taking different network load and PSM settings into account.

4.1 Simulation Environment and Models

For the simulative evaluation, we used the OMNeT++ simulation platform [2] and the associated IPv6 protocol suite [1], which provides an accurate simulation framework for IPv6, Mobile IPv6 and IEEE 802.11 wireless access. We implemented FP^2 support, which uses ICMPv6 formatting, with the IPv6 protocol suite. The IEEE 802.11 access point modules have been enhanced to be able to process received *PagingRequest* messages and to map the embedded NAID to a TIM element, which is distributed with periodically advertised beacons. On the terminal side, IEEE 802.11 power save mode has been added to support the *Doze* state and to periodically wake up to receive and process a beacon's TIM. To derive power consumption from a mobile terminal's IEEE 802.11 interface activity, we implemented a 4-state power model, which allows gathering data about how long a terminal remains in each state during CSMA/CA operation. The model refers to 4 clearly differential power consumption states during CSMA/CA operation, which is *Idle*, *Transmit*, *Receive* and *Doze*.

Figure 6 illustrates how the CSMA/CA operation enters different power states for link-layer activity, including periodic wake-up from *Doze* to *Idle* state in case the mobile has entered PSM. The average power P can be computed according to Eq. 1, where P_{Idle}, P_{Tx}, P_{Rx} and P_{Doze} represent the instantaneous power consumption in *Idle*, *Transmit*, *Receive* and *Doze* state respectively. To ease comparison of power consumption characteristics, this evaluation is based on exemplary but realistic instantaneous power consumption values, as referred to in Table 1.

$$P = \frac{P_{Idle} \cdot \sum t_{Idle} + P_{Tx} \cdot \sum t_{Tx} + P_{Rx} \cdot \sum t_{Rx} + P_{Doze} \cdot \sum t_{Doze}}{\sum t_{Idle} + \sum t_{Tx} + \sum t_{Rx} + \sum t_{Doze}} \quad (1)$$

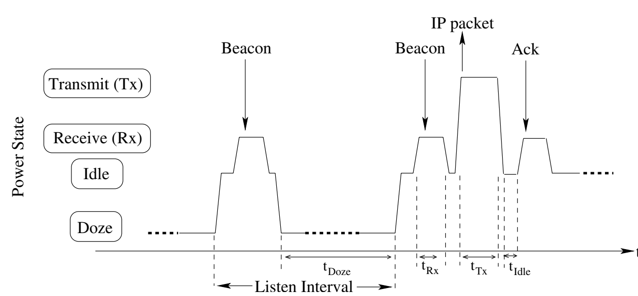

Figure 6: The 4-state power model to derive the average power consumption from a terminal's CSMA/CA operation.

Table 1: Instantaneous power consumption.

Power State	Power
Idle	0.90W
Tx	2.00W
Rx	1.20W
Doze	0.08W

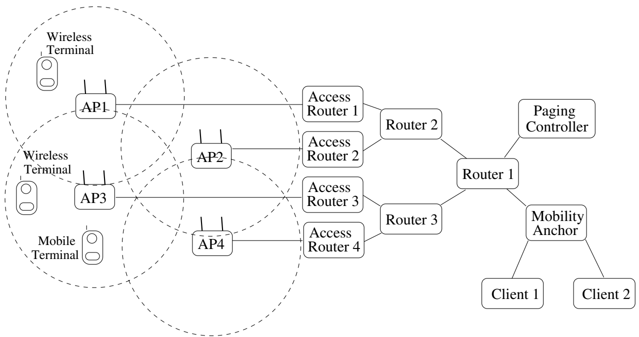

Figure 7: Architecture model for the simulative evaluation.

We performed all simulation scenarios in a network setup according to Figure 7, which comprises 4 wireless IEEE 802.11 access points (AP), each one being connected to a network infrastructure by means of an access router. The maximum wireless data rate is 11Mbps, whereas each wired link segment supports 100Mbps. The architecture comprises one Paging Controller and a Mobility Anchor, which operates as Mobile IPv6 Home Agent (HA). One *mobile terminal* supports the Mobile IPv6 protocol, whereas remaining stationary *wireless terminals* simply attach to the network through IEEE 802.11 access. The role of the network's stationary *Client 1* is to send data packets to the dormant mobile terminal, which causes initiation of the paging procedure, whereas *Client 2* is used to generate and receive background traffic. According to Mobile IPv6 operation, traffic from Client 1 towards the mobile terminal is always intercepted at the HA and tunneled either to the active mobile terminal or to the PC in case the terminal has entered dormant mode. Route optimization is disabled and return traffic is always reverse tunneled through the HA. Background traffic between Client 2 and wireless terminals is always routed directly without being tunneled by means of the HA.

In case the mobile terminal leaves the radio range of its current access point and the associated link-quality falls below a predefined threshold, the terminal scans for an alternative access point. For these experiments, we have chosen a handover threshold power of -90dBm. If the mobile is in dormant mode and has set its interface to PSM, it ascertains link quality from periodically received beacons every listen interval. Handover in PSM has been implemented as follows: The mobile terminal leaves PSM and the associated *Doze* state, performs scanning, authentication and association with the new access point according to the standard operation and re-enters PSM only after a successful association procedure.

4.2 Evaluation of the Paging Delay

We first studied the dependency of the paging delay characteristics, evaluating the average time a data packet is buffered at the PC before it can be forwarded after a successful paging procedure. To evaluate only the system characteristics without taking any dependency on handover into account, the paging delay evaluation considers a stationary case, where the mobile terminal remains as-

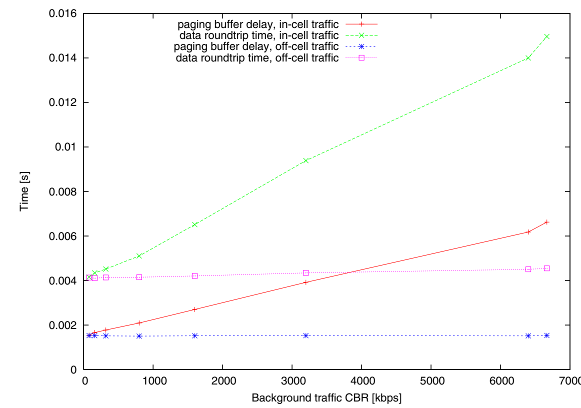

Figure 8: Paging delay for multicast-based paging.

sociated with AP3. Focusing on IP multicast paging first, Figure 8 illustrates the dependency of the paging delay for increasing downlink constant bit rate (CBR) background traffic from Client 2 to one wireless terminal. In one case, the wireless terminal is located in the same cell as the mobile terminal (in-cell) and associated with AP3, whereas in the other case it is associated with AP1 in a neighbor cell (off-cell). The diagram shows also the total round-trip time of the data packet from Client 1 to the mobile terminal and back to Client 1 including the paging delay (data round-trip time). Approaching 7000kbps background traffic, the paging delay samples do not converge anymore due to the saturation of the 11Mbps wireless link. The diagram shows that major contribution to the paging delay comes from effective wireless delay caused by medium contention and associated backoff mechanisms (in-cell graph), whereas increased off-cell traffic affects the paging delay only marginally.

Even though the paging delay can be kept small with multicast-based paging, the disadvantage is that the PC has to take care about retransmissions of *PagingRequest* messages in case the associated packet got lost on the wireless link. The probability that a collision occurs increases with load on the wireless link, in particular with increasing number of nodes contending for the wireless medium for uplink traffic. Since IEEE 802.11 supports MAC-level retransmissions only for unicast packets, the PC has to retransmit the *PagingRequest* in case it does not receive the *ActiveRequest* as reply within a certain time limit. Since the setting for the respective timeout at the PC affects the effective paging delay, Figure 9 depicts the *percentage* of paging request retransmissions due to collision instead of the absolute average paging delay. The diagram shows that the retransmission ratio increases exponentially with increased load and that the performance of multicast-based paging gets worse in case the number of uplink sources increases.

Link-layer paging of dormant mobile terminals in PSM by means of beacons is less sensitive against collisions, but implies a much larger paging delay due to the periodic wake-up each listen interval. The dependency on wireless downlink traffic may be less since beacons access the wireless medium with higher priority compared to IP traffic thanks to a smaller MAC inter-frame space. According to the procedure described in section 3.3, a terminal is able to receive a paging indication every listen interval. When a *PagingRequest* arrives at an access point, the remaining time until the mobile terminal's interface wakes up is probabilistic. Even though the paging procedure is expected to be more reliable, the average paging delay is much larger compared to multicast-based paging. Hence, we determine the probability, that the paging delay exceeds a certain delay constraint (T_c) for different listen interval settings. In

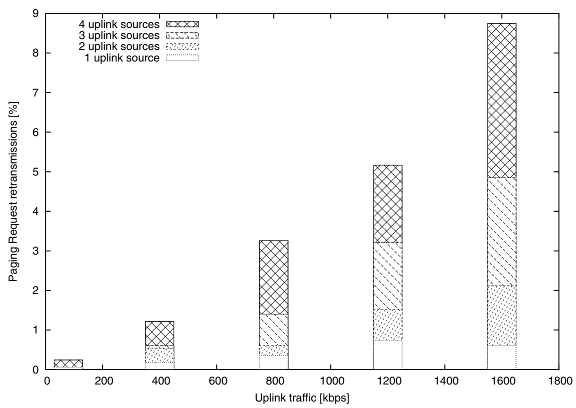

Figure 9: Paging retransmission rate for multicast-based paging.

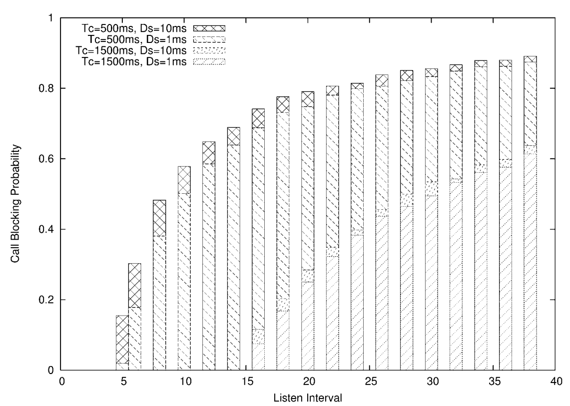

Figure 10: Call blocking probability for link-layer paging with enabled PSM.

this evaluation, the beacon interval is set to 100ms, which results for instance in a *Doze* period of 1 second with a listen interval set to 10. The paging delay contributes to the overall routing latency of initial data packets, which must be taken into account when the probability of a call block due to an application's timeout is to be determined. Figure 10 illustrates the *call blocking probability* for different listen interval settings and for an exemplary delay constraint of 500ms and 1500ms respectively. For each delay constraint, the call blocking probability has been evaluated with two different constant link delays for each wired link segment (D_s), which has been set to 10ms and 1ms respectively.

Since the above evaluation of the call blocking probability focuses on the dependency of system characteristics, any other contribution to the paging delay has to be added and taken into account for a system design. This includes additional time needed for address configuration after the mobile terminal receives a paging indication and reactivates its resources. The diagram shows also that the wired link segment delay D_s contributes marginally compared to the delay contributed by the PSM operation. However, since concatenated link segment delays between the PC and the access network contribute to the effective paging delay, keeping link and processing delay low in the relevant network parts remains an important design goal. Hence, the design of a system according to a particular delay constraint should take additional delay contributions into account to choose a mobile terminal's listen interval setting appropriately.

4.3 Evaluation of the Power Consumption

In this section, we focus on the evaluation of the mobile terminal's power consumption due to mobility management. Referring to Figure 7, we consider the four access points (AP1 - AP4) to cover a paging area. The evaluation of the power consumption focuses on signaling for IP-based mobility management, which includes Mobile IPv6 binding management and paging, IPv6 neighbor discovery and address configuration. Since we evaluate the power consumption based on link-layer activity, sending and receiving application data during a session affects the power consumption as well. However, such data has been kept small, as described below. On link-layer, standard IEEE 802.11 authentication and association has been considered in the evaluation in case the mobile terminal performs a handover between access points. Subsequent diagrams illustrate a mobile's average power consumption for CSMA/CA operation while modifying the handover ratio. The handover ratio derives from the distance of the paging area's access points and the mobile terminal velocity. Choosing equidistant locations for the access points and modifying the movement velocity for the mobile terminal, which moves clockwise between access points, according to the desired handover ratio suits the purpose of this evaluation.

Different diagrams are based on different data session characteristics. The mobile terminal is active throughout the session duration (SD) and enters dormant mode as soon as the session terminates. The session duration has been set to 30s in all cases. We simulated a worst case scenario, where the average session interval (SI) is 45s, and a more relaxed scenario with an average SI of 4750s. Since the power consumption during the 30s session is the same in all scenarios, we just configure Client 1 to send an initial data packet towards the mobile terminal with uniformly distributed inter-arrival time, which causes initiation of the paging procedure in case the terminal has entered dormant mode. After 30s, the mobile terminal enters dormant mode again. During a session and in case the mobile has not entered PSM while being dormant, the evaluation assumes the mobile's NIC to operate only in *Idle*, *Tx* or *Rx* power state respectively.

Figure 11 illustrates the power consumption of Mobile IPv6 and multicast-based IP paging and shows, that in a worst case scenario, the mobile terminal consumes slightly more power with paging. This is due to a short SI and the associated duration the mobile can remain in dormant mode after a session has terminated. Since dormant registration and deregistration requires additional signaling, the mobile terminal might decide to not enter dormant mode in case the ratio between SI and SD approaches 1. However, there is space for optimization when the PC can be co-located with the mobility anchor. In such a case, binding the PC address with the HA is needless and can be omitted, which saves additional signaling during dormant registration (Figure 1). The diagram shows, that the difference in power consumption is in the order of 50μW and even decreases with increasing handover ratio. Increasing the average SI to 4750s shows that the effect has been inverted (Figure 12) and FP^2 operation helps to conserve energy on the mobile terminal with increasing handover ratio and in particular with increasing ratio between SI and SD.

Even though FP^2 operation with multicast-based paging increases the scalability of mobile communication systems, as it has been shown in [8], the gain in saving power on the mobile terminal by means of reducing signaling is low and depends on the session- and mobility characteristics. Real benefit in saving energy can be achieved with paging and enabled power save mode as long as the mobile terminal remains dormant, as described in section 3.3. Figure 13 illustrates again the worst case scenario with a mean SI of 45s. Compared to standard Mobile IPv6, the average power

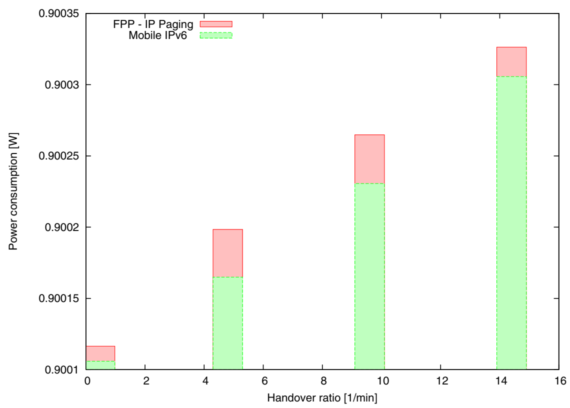

Figure 11: Power consumption of FP^2 with IP paging and an average SI of 45s.

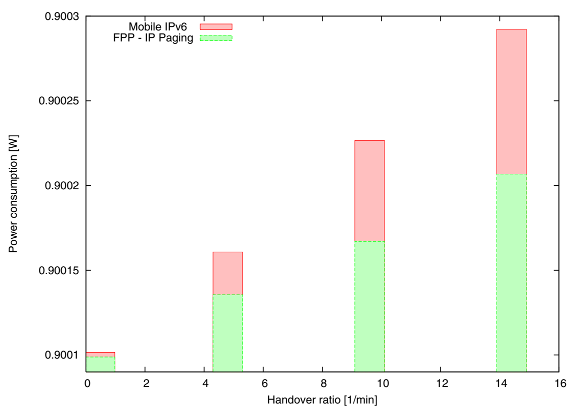

Figure 12: Power consumption of FP^2 with IP paging and an average SI of 4750s.

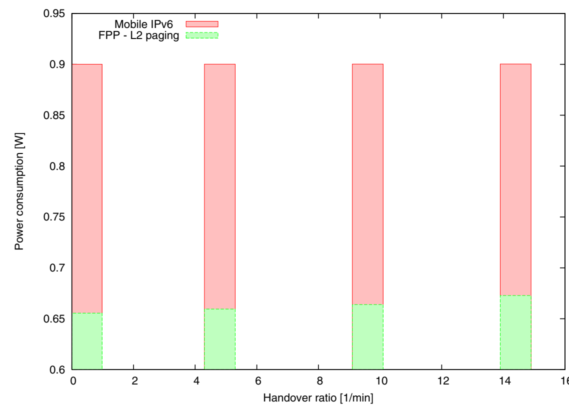

Figure 13: Power consumption of FP^2 with PSM support and an average SI of 45s.

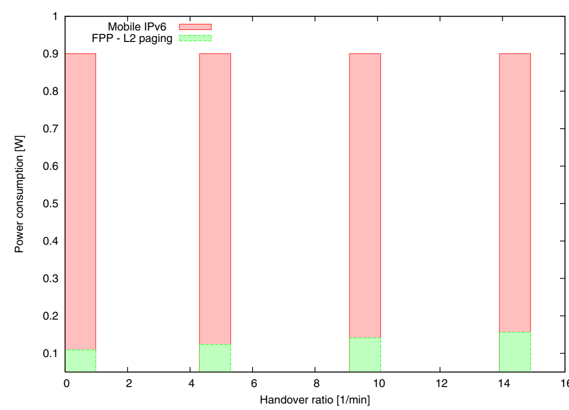

Figure 14: Power consumption of FP^2 with PSM support and an average SI of 4750s

consumption on the mobile terminal is about 250mW less in the paging-enabled scenario. Power consumption increases slightly with increasing handover ratio due to the remaining link-layer activity for access point probing, authentication and association during a handover.

Increasing SI allows the mobile terminal to remain in dormant mode for a longer time, which affects the average power consumption considerably. As illustrated in Figure 14, the gain in power saving is about 750mW.

4.4 Evaluation of the Data Drop Rate

Mobility implies handover between different points of attachment and associated temporary disconnection of a mobile terminal, which increases the probability of data packet loss. Various solutions are being discussed in standardization bodies to improve session continuity in handover scenarios. In this section, we focus on the reliability to deliver a session's initial data packet from the network to a mobile terminal and compare standard Mobile IPv6 operation with dormant mode and paging support. In a standard Mobile IPv6 scenario, the mobile terminal updates its location with its Home Agent after it has successfully attached with an access point and has configured a valid IPv6 care-of address. For this study, we enabled stateless address configuration, which relies on the reception of a Router Advertisement at the mobile terminal. We set the access routers' maximum advertisement interval to 1s, the minimal interval to 0.75s. Furthermore, we enabled Optimistic Duplicate Address Detection [9], which allows the immediate use of the IPv6 address after it has been configured.

In a standard Mobile IPv6 scenario, the mobility anchor forwards the data packet directly to the mobile terminal based on the latest location information. Large handover latency results in a steep increase in packet loss with increasing handover ratio, as illustrated in Figure 15. FP^2 support with multicast-based paging decreases pack loss to less than 10% of the Mobile IPv6 result. More reliability is achieved with paging since the initial data packet is buffered at the PC, which ensures first reachability of the mobile terminal by means of paging before forwarding the data packet. In case the mobile terminal is not connected with the network due to a handover, the PC retransmits the *PagingRequest* until the mobile terminal replies with the expected *ActiveRequest*, which proves reachability. Still, little packet loss occurs in case the mobile terminal initiates a handover just after the PC forwarded the buffered data packet.

Figure 16 illustrates that further decrease in data packet drop ratio can be achieved by means of link-layer paging. In the event of a paging procedure, a single *PagingRequest* causes the paged mobile terminal's bit in the TIM's virtual bitmap remains set for a configurable amount of beacon advertisements. The amount of subsequently advertised beacons until a bit in the TIM is reset could be

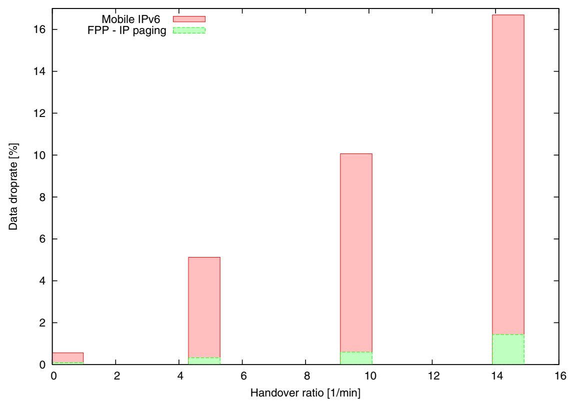

Figure 15: Data drop rate for Mobile IPv6 and IP paging.

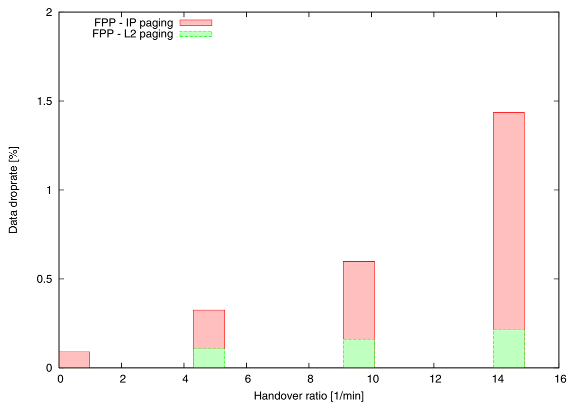

Figure 16: Data drop rate for IP paging and link-layer paging.

derived from the mobile terminal's listen interval. The mobile terminal receives the paging indication immediately after it has reassociated with the new access point and initiates deregistration with the PC after it has acquired a valid IP address.

5. CONCLUSION

In this paper, we proposed how to efficiently integrate and utilize the IEEE 802.11 power save mode with the IP paging protocol FP^2. In terms of the IP paging protocol, we described how the architecture's paging attendants can operate two different paging approaches on the access interface. One approach is appropriate for access technologies without paging support and utilizes IP-based paging signaling, which addresses the paged mobile terminal's Solicited Node Multicast Address. The second approach allows a dormant mobile terminal's interface to enter the power save mode and utilizes the IEEE 802.11 standard's Traffic Indication Map to page the mobile terminal based on a Network Association Identifier. The paper comprises a proposal for allowing combined mapping of the IEEE 802.11 standard's traffic indications and NAID-based paging indications within the Traffic Indication Map.

Based on a simulative performance evaluation, we compared both paging approaches' characteristics regarding paging delay, their efficiency to conserve power on the mobile terminal and reliability to route a session's initial data packet to a dormant mobile terminal. In earlier work, we proved the proposed IP paging protocol's efficiency to reduce signaling costs in mobile communication systems, hence to increase system scalability significantly. As a conclusion of this paper we find that the gain in saving power on the mobile terminal is marginal without link-layer support and depends highly on the mobile terminal's movement pattern and its session characteristics. If economic use of a mobile terminal's energy resources is required in addition to the gain in increasing system scalability, this evaluation shows that harmonized integration and use of an access technology's power save mode with FP^2 performs highly efficient.

In future extensions to the FP^2 concept, we would like to focus on the integration and efficient support of further technologies, such as WiMAX IEEE 802.16 access. Furthermore, based on the existing simulation framework, we plan to implement further concepts to optimize power consumption in the event of handover between IEEE 802.11 access points while the mobile is dormant. Such optimizations are based on omitting a complete association with an access point, but performing only downlink authentication and synchronization of the listen interval with access points and to perform a full association with an access point as soon as the mobile terminal has been paged. This approach can be evaluated regarding the tradeoff between conserving additional energy and increasing the paging delay.

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