

A Mobility Management Protocol for IP-Based Cellular Networks

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Abstract - Mobile IP is an IETF RFC that supports transparent host migration on the Internet. In the transition to IP-based cellular networks, it is widely agreed that Mobile IP provides an elegant solution for inter-domain, or macro-mobility management, but lacks critical aspects of mobility management needed within cellular networks. The shortcomings have led to the recent emergence of micro-mobility management protocols. This paper presents an IP-based mobility management protocol, μ -Mobile IP, based on two enhancements, proactive handoff and paging support, to an Internet Draft proposal Regional Registrations. A signaling cost analysis is used to justify the need for such enhancements. We show through simulations the protocol's suitability for supporting real-time communications.

1. Introduction

The move to third generation (3G) cellular network architectures is gathering pace. Both 3GPP and 3GPP2 introduced IP-based core network architectures that operate in parallel with legacy voice orientated circuit-switched networks. Though IP-based core networks form part of 3G standards, mobility management is still based on No.7 signaling, specifically GSM-MAP and ANSI-41, albeit enhanced versions. This is due to the lack of a standardized IP-based mobility management protocol.

In this paper we discuss the topic of an IP-based mobility management protocol suitable for deployment in future wireless networks [3]. The remainder of the paper is organized as follows: First a discussion of aspects of IP-based cellular networks is given. Next a proposed scheme termed Regional Registrations [1] is described. The main focus of the paper is the presentation of an integrated mobility management protocol, μ -Mobile IP, based on modifications and enhancements to the Regional Registrations draft. We present simulations run on ns2 [2] to show that μ MIP can support real-time communications, such as VoIP. Finally a signaling cost analysis is used to compare Regional Registrations and μ MIP in order to justify the need for protocol enhancements.

2. IP-Based Cellular Networks

The motivation for developing an IP-based mobility management protocol is in the simplification of network architecture. Expensive circuit-switched devices such as mobile switching center (MSC), location registers (HLR, VLR) and signal transfer points (STP) are replaced by off-the-shelf routers. Complex protocols such as ANSI-41

running over SS7 are replaced by additions to the current (v4) and future (v6) Internet Protocol, simple and well understood protocols.

2.1 Extending Mobile IP

The starting point for the design of an IP mobility management protocol is with Mobile IP, an IETF proposed standard [4]. Mobile IP provides a network layer solution to node mobility across IP networks. While roaming, a mobile node (MN) maintains two IP addresses, a permanent home address used in all transport layer connections, and a topologically correct care-of address (CoA) that reflects the current point of attachment. The CoA is obtained either through a Foreign Agent (FA) or auto-configuration process (i.e. is co-located in the MN). While home the MN uses its permanent home address. A location register on the home subnet, referred to as Home Agent (HA), maintains a mobility binding that maps the MN home address to a CoA. The HA acts as proxy on the home subnet, attracting packets addressed to the MN, and employing tunneling to re-direct packets to the MNs CoA. MNs send registration requests to inform the HA of any change in CoA or to renew a mobility binding. Mobile IP provides an elegant solution for node mobility when the MN moves infrequently. However, mobile IP introduces significant latency when used in a cellular environment simply because handoffs occur frequently and registration messages may travel large distances before packet redirection occurs. Thus there is a need for a specific micro-mobility protocol that interworks with mobile IP as the macro-mobility protocol.

2.2 Requirements for IP-Based Mobility Management

Before specifying a micro-mobility management protocol it is important to identify a generic set of requirements that must be met by any such proposal. Mobility management can be broadly decomposed into two functions: location management and handoff management [5]. Location management is concerned with maintaining approximate locality of the MN. Handoff management is concerned with maintaining connections as the MN moves across the coverage areas of different access points.

We can list the main requirements specific to an IP-based mobility management protocol as:

- Hierarchical architecture – to localize scope of location updates.
- Support fast handoffs – packet redirection with minimal latency
- Paging functionality to minimize network signaling and conserve battery power
- Provide compatibility with QoS/Context transfer protocols

Some pioneering proposals that provide such functionality include CellularIP [6] and HAWAII [7]. Various other proposals have been suggested that concentrate on one aspect of enhancing mobile IP such as [8,9,10] that discuss fast handoff mechanisms and [11] that discusses paging extensions to mobile IP.

2.3 Regional Registrations

Regional Registrations [1] is an IETF internet draft, and as such represents work in progress. Regional Registrations introduces a hierarchical network structure for an autonomous domain. The base proposal defines a two-layer hierarchy, where the gateway FA (GFA) is at the highest level with a single layer of regional FAs (RFA) below it. This is extendable to multiple levels. The protocol introduces extensions to mobile IP registration messages and two new message types: *regional registration request* and *regional registration reply*. Location management follows the mobile IP model. The GFA acts as border router and filters between registrations intended for the HA and those resulting from intra-domain movement. The GFA allocates a publicly routable IP address for use as the CoA for the MN throughout its visit. This is registered at the HA. RFAs are the building blocks of a Regional Registrations network. These FAs provide layer 2 interworking with wireless access points (AP), supplying local CoAs for routing packets to the MN. RFAs broadcast agent advertisements over the APs, providing at a minimum the CoA of the GFA. There are two phases of operation upon MN power-up. The first phase involves a mobile IP registration request sent to the HA to register the GFA CoA. The second phase involves sending regional registration request messages to establish a routing path from serving RFA to GFA. A change of RFA due to handoff alters the path and therefore requires regional registration request messages to be sent. This localized signaling is between MN-RFA-GFA only. Once successfully registered with its HA, the MN only sends home registration requests when an inter-domain handoff occurs or a HA binding renewal is required. A packet addressed to the MN home address is intercepted by the HA and tunneled to the GFA. The GFA will tunnel the packet down the hierarchy on the next hop towards the serving RFA. The serving RFA will decapsulate the packet and forward to the MN. Packets sent from the MN flow through the GFA to their destination.

2.4 μ -Mobile IP: An Integrated Micro-Mobility Management Protocol

We now proceed to outline μ MIP, an integrated micro-mobility management protocol, formulated to extend Regional Registrations to meet all the requirements of an IP-based mobility management protocol identified earlier. The details of μ MIP can be found in [12].

μ MIP implements the same hierarchical structure as Regional Registrations. The network architecture is based on a two-level hierarchy. At the highest level are the Gateway Mobility Agents (GMA) that perform the role of a border router, filtering between intra- and inter-domain signaling. At the second level is the Subnet Agent (SA) which interworks with a particular RAN consisting of APs or base stations (BS) that cover a specific geographic area. A group of SAs forms a multicast paging area group. The core network operates independently of the RAN technology. The RAN provides radio access and radio resource management, handling intra-SA handoffs. An Inter-Access Point Protocol (IAPP) may be employed for such handoffs. IP mobility management is only invoked for inter-SA handoffs. The SA will broadcast a beacon message over the radio access network (RAN) that includes the domain identifier, paging area identifier and GMA CoA. Figure 1 illustrates a typical μ MIP configuration.

2.4.1 Protocol Operation

On power-up a MN reads the beacon from the AP with the strongest signal strength. The advertised GMA CoA is registered at the HA. The MN also caches the network and paging area IDs and *active_state* timer value. Two new flags in the *registration request* message are defined in μ MIP, in addition to RFC2002 flags. They are N-new registration, P-paging update (note-the V bit is assumed redundant). Flag bits are used to distinguish message types to allow the same mobile IP messages to be used (i.e. reuse UDP port 434), with extensions applied to differentiate functionality. In a power-up registration the MN will set the N bit to 1 and P bit to 0.

This indicates to the network that the MN needs to perform a complete registration process which includes updating the HA. A security association between MN and HA is assumed to exist. The packet is addressed to the serving SA. The '*identification*' field is used as per RFC2002, for matching requests with replies and for replay protection.

On receiving the registration request, the SA will create a pending visitor entry. This cache will contain a mapping between the MN home address and a link layer identity (e.g. network access identifier-NAI).

An *active_state_timer* is initialized. The SA forwards the *registration request* message to the GMA identified in the CoA field. On reception a pending visitor entry is created in the GMA that maps the MN home address to the SA downlink interface IP address.

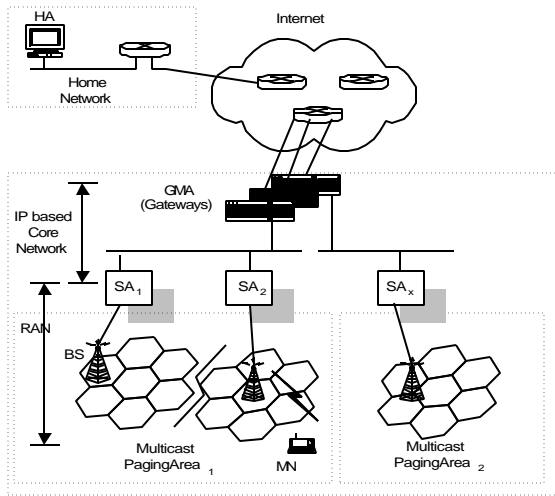


Figure 1 μMIP network configuration

The GMA associates each SA with a particular multicast paging group (MPG). These groups are assumed to be preconfigured. The MPG is noted against the cached MN profile. The GMA records the 'lifetime' field value. The *active_state* timer value is pre-configured in the GMA. The GMA examines the status of the flags to determine the next step in processing. A power-up registration is forwarded to the MNs HA without modification of the registration request portion. The HA performs the normal operations on receipt of a registration request and formulates a reply with the code field indicating the outcome. The reply is relayed back to the MN via GMA and SA. Both *active_state* and *lifetime* timers are activated on receipt of valid registration replies. Figure 2 illustrates information held in the network entities.

2.4.2 Handoff Support

In IP-based mobility management, handoffs involve redirecting IP packet flow to the MNs current point of attachment. The goal of any IP-based handoff scheme must be to:

- a) minimize packet loss
- b) minimize handoff latency

The handoff schemes discussed here are concerned with hard handoffs. Thus the process involves both link layer and IP layer re-establishment. Handoff time can be defined as the time between reception of the last packet through the old AP till reception of the first packet through the new AP.

Several handoff schemes have been suggested eliminate the L3 delay, thus reducing handoff time to the layer 2 delay.

In general handoff schemes can be classified as either proactive or reactive. Proactive handoffs employ link layer triggers to assist the MN in determining that a handoff is imminent and establish packet flow to the target AP prior to the handoff event i.e. requires link layer coupling.

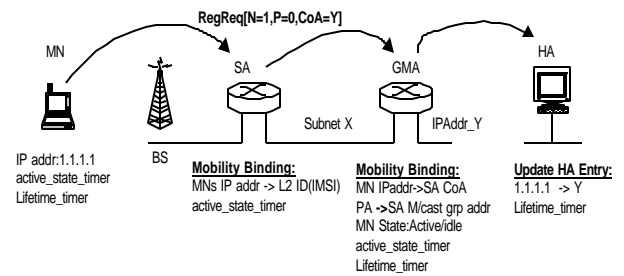


Figure 2 μMIP entity caches

This covers a hybrid of mobile assisted and mobile controlled handoff types. Reactive schemes simply follow the base mobile IP movement detection methods. Some suggested proactive (or fast) handoff schemes include:

- i) MN receives layer 2 handoff trigger and subsequently reads FA beacon through target AP. MN returns to serving FA and sends registration with the CoA set to target FA and requests 'bicasting' of IP packets. MN then completes layer 2 handoff [8].
- ii) Serving FA receives layer 2 handoff trigger and determines possible target FA through prior knowledge of network configuration. Serving FA establishes packet redirection to target FA, employing 'bicasting'. MN performs layer 2 handoff [9].
- iii) On each handoff MN sends additional messages to serving FA instructing that neighboring FAs join a multicast group. These m/cast groups receive and buffer the most recent few packets destined for MN. On handoff, first few packets are already buffered at target FA. New neighbors join and old neighbors leave the group based on MN movement [10].

μMIP employs handoff scheme (i) for the proactive mechanism to achieve low latency handoffs. In addition buffering is invoked in the GMA using a new 'handoff imminent' extension appended to the registration request message. This achieves the goal of minimizing packet loss. Reactive handoff support is also incorporated for fallback to base mobile IP. Figure 3 illustrates the operation.

2.4.3 Paging Support

Paging reduces the number of registrations generated for location management purposes. Paging introduces state into the MN. A MN is either in one of two states, idle or active. In idle state a MN camps on the beacon signal with the strongest strength, periodically awakening to read the beacon signal.

Idle state is governed by the *lifetime_timer* –as is the overall binding in GMA and HA. In the idle state a MN will not perform a registration until either a) it crosses a paging area boundary, b) it wishes to renew its binding, c) it is about to transmit data or d) is paged. The paging mechanism relies on manually configured SA MPGs. When a packet arrives for an idle MN, the GMA immediately begins to buffer all packets destined to that MN.

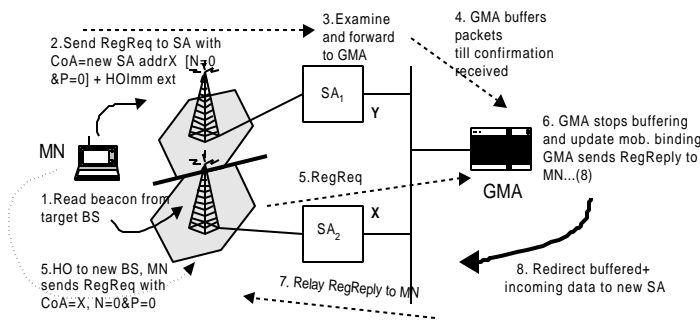


Figure 3 μ MIP proactive handoff support

The GMA uses multicast to send a *page solicitation* message, which is broadcast over APs. The paged MN responds by sending a *registration request*. The *registration request* has $N=0$ and $P=0$ and creates a binding in the new SA as well as updating the MN binding in the GMA. The GMA stops buffering and sends a *registration reply*.

3. Protocol Analysis

Analysis is split into two; firstly simulation results are presented that highlight the handoff performance of μ MIP. Secondly a signaling cost analysis compares μ MIP with Regional Registrations to justify the need for protocol extensions.

3.1 Handoff Performance

Simulations are conducted to investigate two critical performance issues, i.e. packet loss during handoffs and handoff latency, under a μ MIP environment. The simulations are run using *ns2 (v2.1b7a)* [2], which is widely used in the networking community to study IP networks. Use is made of the wireless and mobile IP extensions ported into the *ns2* environment.

Packet loss rates are critical when accessing suitability for supporting loss-sensitive data transactions such as FTP processes, where delay and jitter effects are more tolerable. As retransmissions are generally not employed for real-time communications, it is appropriate to minimise packet loss in order to prevent gaps in conversations.

The simulation environment consists of a correspondent node (CN) streaming audio (or VoIP) data over UDP to a MN. The CN acts as a CBR source, producing fixed length packets (200 bytes – typical of PCM coding schemes like G.711) at a rate of 50 pkts/s (corresponding to 20ms frames as, eg, in IS-95/cdma2000). There is an established packet flow prior to the handoff. The MN acts as a sink, receiving packets that arrive at a constant packet inter-arrival rate of α pkts/s. All the links are of fixed bandwidth and have an inherent propagation delay. Under a proactive handoff the MN will invoke buffering at the

GMA prior to handoff. Therefore for a given packet inter-arrival rate, α , the packet loss is directly proportional to the accumulated link propagation delay (L_i) over the wireless and wired portion from MN-AP-SA-GMA. Packet loss can be expressed by equation (1) below:

$$\text{Packet Loss} = \sum_{i=1}^3 L_i \times \alpha \quad \dots(1)$$

The simulated inter-arrival times were 25, 50 and 100pkts/s – corresponding data rates of 40, 80 and 160Kb/s, which covers PCM transmission rates plus higher rate internet audio streaming sources to represent some of the higher coding rates proposed for 3G systems. During each simulation the link delay between GMA and SA was varied between 0-100ms. All wired links consist of 10Mbps full-duplex connections. It is assumed that the wireless link presents an inherent delay at a given bit error rate to the packet stream, which is factored into *ns2*. Only traffic related to the CN-MN session and μ MIP signaling is carried on the links. Results from the simulations were obtained by examining resultant trace files. The packet loss count was taken to be the amount of packets sent by the GMA during the period of the MN transmitting a registration request and the GMA receiving the registration request. Figure 4 plots packet loss versus link delay results for varying packet inter-arrival rates. The simulation results closely match that predicted by equation (1), showing a linear relationship between link delay and packet loss. Under μ MIP, for a given average arrival rate, packet loss is a function of the link delay encountered. Given typical Wide-Area Network (WAN) delay figures of approximately 10-25ms, we see that under a μ MIP proactive handoff, packet loss is minimized to between 1-2 packets.

Handoff latency: For real-time communication, it has been shown that the handoff latency has an upper bound of 200ms - the maximum tolerable level of jitter for voice. In order to redirect packet flow through the new AP the MN must read the beacon signal broadcast, then formulate and send a registration message. In such a wireless environment the worst case delay is equal to the beacon period. The buffer period is defined to be the time between the GMA receiving a *registration request* with a *handoff imminent* extension via the serving AP and the GMA receiving the associated completion *registration request* message via the new AP.

The buffer capacity is also affected by the packet inter-arrival times and packet size. Adequate buffer space must be provided to cater for the worst-case handoff latency. The buffers are assumed to be FIFO. In the *ns2* simulation model, a hierarchical topology is configured that consists of two FAs (representing SAs) connected to a HA (representing the GMA). Attached to the HA via a wired link is a CN, a CBR audio source generating 200 Byte packets at 50 pkts/s as specified previously. The MN acts as the sink, and is initially within the coverage area of SA1. The MN is registered with SA1 and receives packets through SA1 prior to any movement. The MN then moves at 55 km/hr towards the coverage area of SA2.

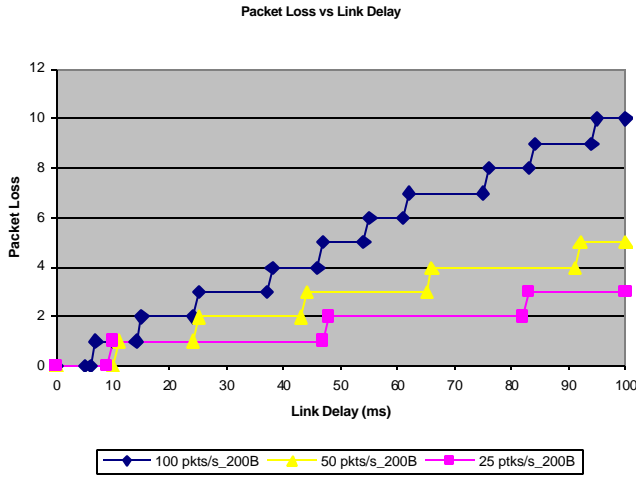


Figure 4 Packet loss during proactive handoff

On entering the coverage area of SA2, the MN performs a registration and the packet flow is re-directed though SA2. The coverage areas have a slight overlap. Wired link delays are set to 10ms. The simulation time is set to 70 seconds.

The primary goal of this analysis is to capture latency figures resulting from handoffs. Of interest is the beacon period frequency and the MNs ability to read and respond to the beacon, including the delay associated with signaling messages traversing between SA-GMA and vice versa. The beacon period was varied between 1ms and 1 second. Each measurement represents an average of several simulation runs. The results are plotted in Figure 5.

We see that beacon periods of 100ms result in handoff latencies well below the 200ms ceiling. At very low values of beacon period, the volume of protocol signal processing contributes significant delay. However this accurately reflects a real world situation where a trade-off exists between low values of beacon periods versus generated signaling load. Typically beacon periods would be around 100ms in a wide area cellular network.

3.2 Signaling Cost Analysis

This analysis is an adaptation of that reported in [11]. The model exposes the quantity of signaling related messages generated by each protocol under various mobility management procedures. The model derives two equations that represent signaling cost for each protocol. It is assumed that power-up registration procedures are completed. The network used in the model consists of a domain made up of a single paging area. A paging area consists of n SA coverage areas. A SA area consists of a given number of square-shaped cells. Each SA area has a perimeter l .

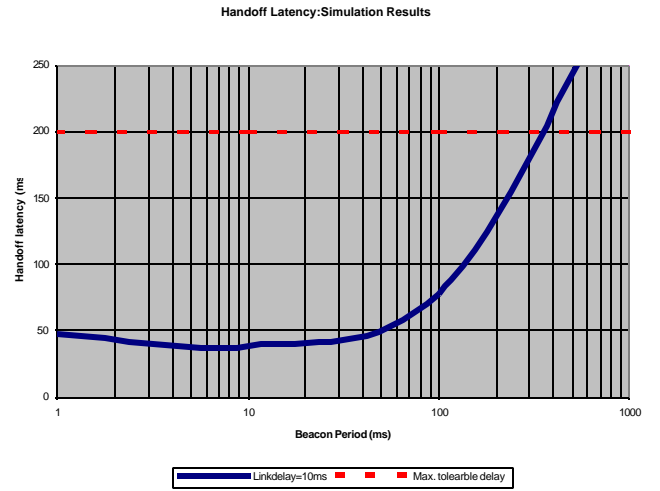


Figure 5 Handoff latency during proactive handoff

The SA areas and paging areas are also assumed to be square-shaped. The analysis does not extend to the cell level, as cell crossings *within* a SA area do not generate IP signaling messages for either Regional Registrations or μ MIP. User mobility is modelled using the fluid flow model. Users move with an average velocity v . The user density is given by r mobiles/ m^2 . The SA boundary-crossing rate is given by:

$$S = \frac{rvl}{p} \quad \dots (2)$$

For μ MIP, a large portion of the MN population will be in the idle state, implying the need to model the paging area boundary crossing rate. This is given by:

$$P = \frac{rvL}{p} \quad \dots (3)$$

where L is the paging area perimeter. For Regional Registrations the signaling cost is the accumulated effect of handoffs between FAs and registration renewals. The following terms are defined.

$d_{FA,GFA}$	Represents the number of hops between FA and GFA
$d_{FA,HA}$	Represents the number of hops between FA and HA
n	Number of cells in a SA area, $n \in \{1,4,9,16,\dots\}^*$
x	Number of SA areas in a paging area, $x \in \{1,4,9,16,\dots\}$
ρ	Mobile density (users/ m^2)
T_{Life}	MN registration Lifetime value (sec) (i.e renewal period)
N	Total MN pop. within domain (users) = ρ (Area of domain)

If the signaling cost is expressed in *hops*msg/sec* then an expression can be formulated as:

$$C_{RR} = d_{FAGMA} S + d_{FAHA} \left(\frac{N}{T_{Life}} \right) = d_{FAGMA} \left(\frac{rvlx}{p} \right) + d_{FAHA} \left[\frac{r^2 x}{16T_{Life}} \right] \quad \dots (4)$$

where the first term represents the rate of registration requests due to handoffs, the second being registration renewals.

For μ MIP, the equation derivation is more complicated due to the extra mobility management procedures i.e.

proactive handoff and paging functionality. μ MIP handoff signaling occurs only for active MNs, while paging updates only occur for idle MNs crossing PA. Renewals are independent of user mobility, as are registrations in response to incoming or outgoing data to/from an idle MN. The following new terms are defined:

$d_{SA,HA}$	Represents the number of hops between SA and HA
$d_{SA,GMA}$	Represents the number of hops between SA and GMA
ρ	Mobile density (users/m ²)
δ	Fraction of active MNs, idle population = (1 - δ)
λ_1	Outgoing data session rate from MN (/sec)
λ_2	Incoming data session rate to MN (/sec)

Expressing the signaling cost in *hops*msg/sec*, an expression can be formulated as:

$$C_{\mu MIP} = d_{SA,GMA} \left[2Sx\mathbf{d} + P(1-\mathbf{d}) + I_2(x+1)(1-\mathbf{d})N + I_1(1-\mathbf{d})N \right] + d_{SAHA} \left[\frac{N}{T_{life}} \right]$$

$$= d_{SA,GMA} \left[\frac{2rv\sqrt{x}}{p} \mathbf{d} + \frac{rv\sqrt{x}}{p} (1-\mathbf{d}) + \frac{r^2x}{16} (1-\mathbf{d}) [I_2(x+1) + I_1] \right] + d_{SAHA} \left[\frac{r^2x}{16T_{life}} \right]$$

...(5)

In equation (5), the first component of term one, models signaling cost due to proactive handoffs. The second models registrations from idle MNs crossing PA boundaries. The third models incoming packets to an idle MN. This component also models registrations due to outgoing packets from an idle MN. The second term models rate of renewal registrations.

3.2.1 Results

The results are divided into three sections. The first section compares performance by varying the paging area size. Then the average velocity of the MN population is varied. This is followed by varying the proportion of active users. The quantities used are based on the following values.

Quantity	Meaning	Value used in analysis
$d_{SA,HA}$	No. of hops between SA-HA	2
$d_{SA,GMA}$	No. of hops between SA-GMA	1
v	MN average velocity	20 m/sec
ρ	MN density	40 MN/km ² = 0.00004 MN/m ²
l	Perimeter of a cell	5000 m \rightarrow SA area of 1.56 km ²
T_{Life}	Renewal period	10 mins = 600 sec
x	No. of SA in paging area	16
δ	Portion of active users	5%
λ_1	Outgoing data session rate from MN	≈ 5 /hr = 0.0014 /sec
λ_2	Incoming data session rate to MN	≈ 2 /hr = 0.0005 /sec
P_{PA}	PA perimeter	20 km
A_D	Area of domain	20 km ²
N	No. of users in the domain	1000

Table 1 Parameter values used in analysis

Signaling Cost vs Paging Area Size

In this analysis the value of x was made variable. This is done to expose the effect of the size of the paging area on signaling. The results for the analysis are shown in Figure 6 below. The graph shows an optimised paging area size within which μ MIP out-performs Regional Registrations. This region exists for $1 < x < 25$. The reason is that while the paging area consists of only a small number of SAs the paging component remains proportionately small. Paging requires a single *Page Solicitation* message be multicast to all SAs in the MPG. As the number of SA increases this paging component becomes a significant contributor to the signaling load. This graph represents the cost of including paging functionality.

Signaling Cost vs MN Velocity

In this analysis the value of v was made variable. This is done to expose the effect of the MN velocity on signaling. The analysis assumes proactive handoff procedure. The results for the analysis are shown in Figure 7.

The graph shows that μ MIP out-performs Regional Registrations when the MN population's average velocity is greater than 10 ms⁻¹ (or 36kmh⁻¹). This can be attributed to the fact an increase in velocity implies an increase in boundary crossings, this in turn leads to an increase in registration due to SA crossings. Under μ MIP only active MNs register, but μ MIP also contains signaling components that are independent of MN velocity, i.e. outgoing/incoming session rates.

These components become less significant as the increase in velocity causes increased SA boundary crossings, thus pushing up the active populations' registration rate. Therefore this graph illustrates the cost of not introducing state (via paging functionality) into MNs.

Signaling Cost vs Active MN Population

In this analysis the value of \mathbf{d} is made variable. The results for the analysis are shown in Figure 8 below. Regional Registrations is unaffected by the active population, as all MNs are considered active. The results for μ MIP show that as the active MN population tends toward 100% the protocol simplifies to that of Regional Registrations, as no paging functionality is required. The difference then, stems from the handoff support mechanisms. Both proactive and reactive methods are shown for μ MIP. With proactive support in use, an active population below 20% results in a performance gain over Regional Registrations.

This is due to the overhead of having to send two registration requests for every handoff. With reactive support μ MIP offers a performance gain over Regional Registrations until the active population becomes 100%, at which point the protocols become identical.

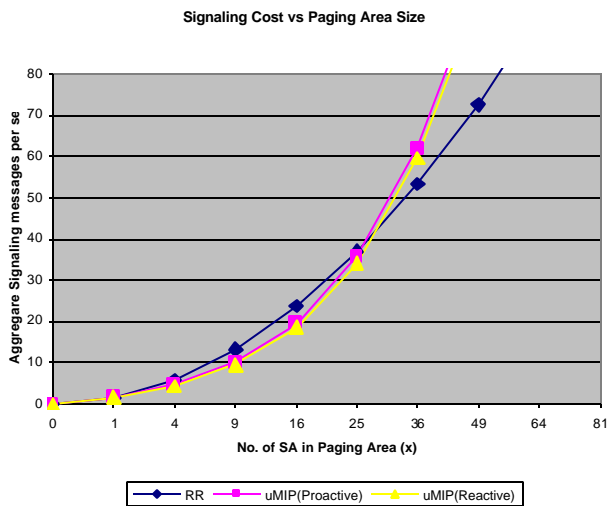


Figure 6 Signaling cost vs paging area size

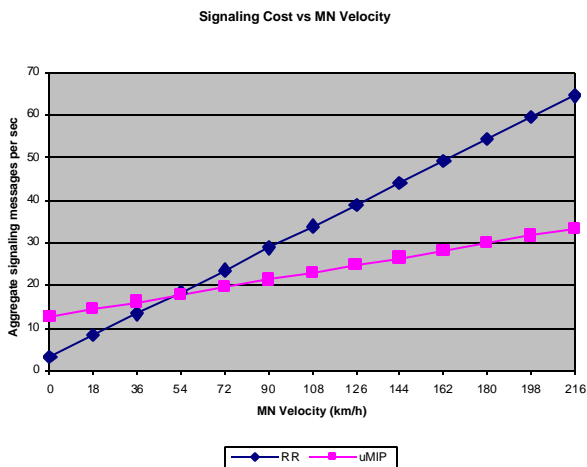


Figure 7 Signaling cost vs MN velocity

4. Conclusion

In this article we have discussed IP-based mobility management protocols. Regional Registrations, a draft IETF protocol was presented. Requirements for a micro-mobility management protocol were listed. This identified gaps in the Regional Registrations draft. Two key enhancements, support for proactive handoff and paging, were suggested and packaged under an integrated micro-mobility management protocol named μ MIP. We showed the suitability of this protocol for supporting real-time communications through simulations. It was shown that under a proactive handoff scheme μ MIP reduces packet loss to 1 packet in typical WAN scenarios. Handoff latency was shown to be in the order of 10ms with beacon periods of 100ms. In the final section a detailed signaling cost analysis was presented which supported claims that Regional Registrations must incorporate enhancements such as fast handoffs and paging in order to be capable of being deployed as a mobility management protocol in

future (4G) IP-based cellular networks. These issues continue to be addressed by the IETF's mobile IP working group.

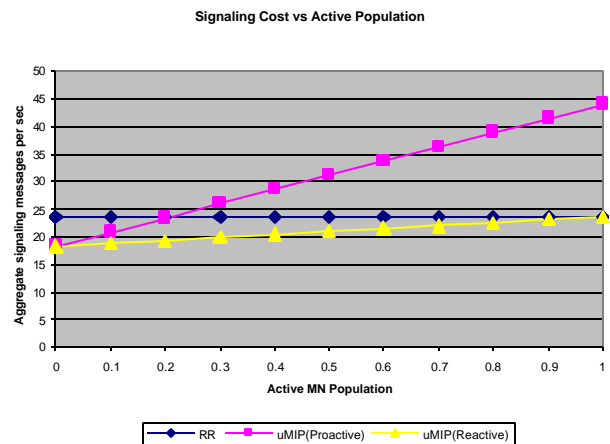


Figure 8 Signaling cost vs active MN population

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