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Mobility management support and performance analysis for wireless MPLS networks

Rami Langar,[1,]* Samir Tohme[2] and Nizar Bouabdallah[3]

[1]*GET-Telecom Paris, LTCI-UMR 5141 CNRS, 46 rue Barrault, 75634, Paris, France.*
[2]*PRiSM Laboratory, UMR 8144; 45, avenue des Etats-Unis, 78035, Versailles, France.*
[3]*INRIA, Campus Universitaire de Beaulieu; 35042 Rennes Cedex, France.*

SUMMARY

Multi-Protocol Label Switching (MPLS) is deployed in the Internet backbone to support service differentiation and traffic engineering. In recent years, there has been interest in extending the MPLS capability to wireless access networks for mobility management support. In this paper, we present analysis of Micro Mobile MPLS, a new micro-mobility management scheme which integrates the Mobile IP and MPLS protocols by using two-level hierarchy architecture. Our proposal supports two protocol variants. First, the fast handoff process, which anticipates the LSP procedure set-up with neighboring locations where a mobile node (MN) may move to, is provided to reduce service disruption. Second, a new mechanism based on the forwarding chain concept is proposed to track efficiently the host mobility within a domain. This concept can significantly reduce registration update costs and provide low handoff latency. Analytical models are developed and simulations are conducted to justify the benefits of our proposed mechanisms. Copyright © 2006 John Wiley & Sons, Ltd.

1. INTRODUCTION

Future wireless networks are expected to provide IP-based coverage and efficient mobility support with end-to-end Quality of Service (QoS) requirements. Mobile IP [1], which is a standard proposed by the Internet Engineering Task Force (IETF), can serve as the basic mobility management in IP-based wireless networks. However, it presents several drawbacks such as the long handoff latency and the large signaling load for frequent registration updates. Some enhancements to Mobile IP for MNs with frequent handoffs have been studied [2–6]. Most of these protocols adopt a hierarchical approach by dividing the network into domains. Mobile IP is used to support mobility between two domains, while intra-domain mobility is handled by micro-mobility scheme. Performance comparisons between some of these protocols can be found in Reference 7.

On the other hand, Multi-Protocol Label Switching (MPLS [8]) is deployed in the Internet backbone to support service differentiation and traffic engineering. In MPLS, each packet is prepended with a label. The label is the only information used to determine the packet's next hop. MPLS simplifies the forwarding process by means of label swapping. Other advantages of MPLS include the ease of creating virtual private networks, the support of traffic engineering via constraint-based routes, and path protection via fast reroute. These notable benefits of MPLS have inspired some studies on the use of this technology in the wireless infrastructure [9–16].

In view of this, reference 9 proposes a scheme to integrate the Mobile IP and MPLS protocols. This scheme, called Mobile MPLS, aims to improve the scalability of the Mobile IP data forwarding process by removing the need for IP-in-IP tunneling from Home Agent (HA) to Foreign Agent (FA) using Label

*Correspondence to: Rami Langar, GET-Telecom Paris, LTCI-UMR 5141 CNRS, 46 rue Barrault, 75634 Paris, France.
†E-mail: rami.langar@enst.fr

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Switched Paths (LSPs). However, such a scheme suffers from the non-applicability to micro-mobility (intra-domain mobility), as the scope of Mobile IP is more shifted toward the global mobility (inter-domain mobility). In reference 10, an enhanced label edge router (LER) called the label edge mobility agent (LEMA) is introduced to support intra-domain mobility using LSPs redirection. The scheme is scalable and suitable for QoS support. However, the algorithms for choosing the LEMAs for a particular MN are quite complex. H-MPLS [11] and several other schemes [12–16] try to ameliorate the performance of Mobile MPLS [9] by using different architectures. A Foreign Domain Agent (FDA) is introduced into each MPLS domain to support intra-domain mobility. However, these studies have not taken into account the fact that the signaling delay for the location update could be very long, which may cause service disruption for real-time services and will result in increasing the registration update cost, the loss of a large amount of in-flight packets and the degradation of QoS. Note that in-flight packets are those possibly lost during the handoff period. In addition, most of these studies have presumed that all base stations (BSs) are MPLS-aware equipments which may not be desired. The additional penalty that we have to pay is an enormous increase in cost and complexity inside the MPLS network.

To overcome these limitations, we propose in this paper a new protocol called Micro Mobile MPLS. Our proposal supports two protocol variants. In the first variant, called FH-Micro Mobile MPLS, we consider the fast handoff mechanism, which anticipates the LSP procedure setup with the neighboring subnets to reduce service disruption. In the second variant, called FC-Micro Mobile MPLS, the forwarding chain mechanism, which is a set of forwarding paths, is provided to track efficiently the host mobility within a domain. The forwarding chain can reduce registration update cost and provide low handoff latency. Analytical models are developed and simulations are conducted for performance analysis. The results show that our new proposals outperform other schemes (Mobile IP [1], Mobile MPLS [9], MIP-RR [3] and H-MPLS [11]) under various conditions.

The remainder of this paper is organized as follows. The next section introduces our proposed architecture along with a detailed description of the above-mentioned protocol variants. In the third section, we develop analytical models to derive the signaling cost function of registration updates and handoff performance for the underlying protocols. Numerical and simulation results are given in the fourth section. The final section contains our concluding remarks.

2. MICRO MOBILE MPLS AND ITS TWO VARIANTS

In this section, we describe our new scheme, called Micro Mobile MPLS, and its two variants. The aim is to achieve an efficient micro-mobility management protocol with continuous QoS support. As stated before, Micro Mobile MPLS is based on the integration of Mobile IP [1] and MPLS [8] protocols by using hierarchical architecture. A typical architecture for Micro Mobile MPLS networks is shown in Figure 1. We assume that an MPLS access network exists between the Label Edge Router Gateway (LERG) and the

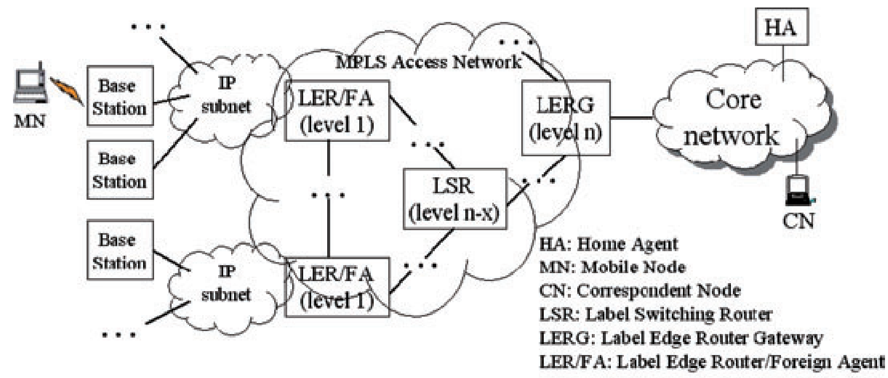

Figure 1. Architecture of a Micro Mobile MPLS wireless access network

Label Edge Router/Foreign Agents (LER/FAs). The network architecture is based on a two-level hierarchy. At the higher level is the LERG, which performs the role of an edge Label Switching Router (LSR) filtering between intra- and inter-domain signaling. At the second level is the LER/FA connected to several BSs that offer link-layer connectivity. We distinguish between link-layer functionalities of the air interface, which are handled by the BS, and IP-layer mobility (L3 handoff), which occurs when the MN moves between subnets served by different LER/FAs. Note that an LER/FA is the first IP-capable network element seen from the MN.

2.1 Registration Procedure in Micro Mobile MPLS

When an MN moves for the first time into a Micro Mobile MPLS foreign domain, it will send a Mobile IP Registration Request message to the nearest LER/FA. The latter records the MN home address in its routing table and then relays the registration message to the LERG of this domain. When the LERG gets the registration message and knows the Regional care-of address (RCoA) which corresponds to the IP address of the current LER/FA, it sends a registration message to the HA of the MN. The LERG uses its IP address as the care-of address (CoA) to perform the global registration for inter-domain mobility. Then the LERG establishes an LSP between it and the current LER/FA with the RCoA as a Forwarding Equivalence Class (FEC). Finally, the LERG relays the Registration Reply message, sent from the HA, to the MN along the established LSP. Note that MNs which are on the same subnet and which involve the same requirements of QoS can use the same established LSP.

Table 1 illustrates the label table of the LERG after registration. We assume that the MN home address is a.b.c.d, the CoA of the LERG is u.v.g.t and the RCoA of the LER/FA is w.x.y.z. The first row in Table 1 is the label binding for the LSP from the LERG to the LER/FA. Since the LERG is the ingress LSR for this LSP, it changes the row in its label table that uses the MN home address as FEC and sets the empty outgoing label and outgoing port entries to the values of the outgoing label and outgoing port of the LSP from the LERG to the current LER/FA. In this way, the LERG can relay packets destined for the MN home address to its current location in the foreign network. Figure 2 illustrates the registration procedure for the MN in Micro Mobile MPLS.

In. port	In. label	FEC	Out. port	Out. label
2	—	w.x.y.z	1	7
2	—	a.b.c.d	1	7
...	...	...	...	...

Table 1. Label table of the LERG after registration

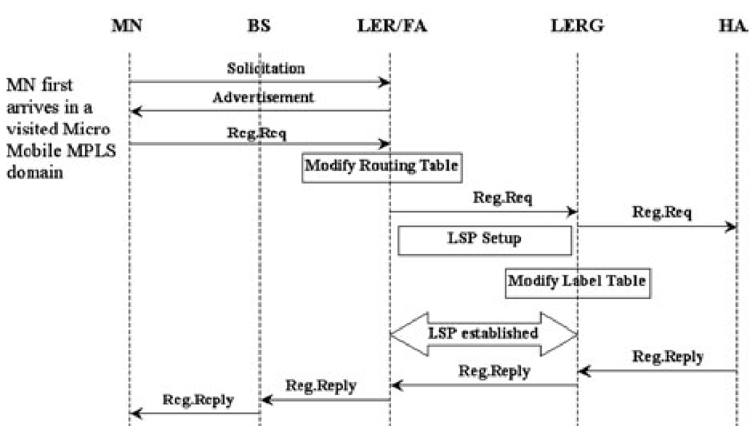

Figure 2. Mobile node registration in Micro Mobile MPLS

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2.2 *Handoff Support*

There are two types of handoff in our scheme: Intra-LER and Inter-LER handoffs. An Intra-LER handoff occurs when the MN moves between two BSs managed by the same LER/FA. An Inter-LER handoff occurs when a new BS and the old BS are under different LER/FAs. In this paper, the handoff latency is defined as the difference between the time at which the MN received the last packet from the old BS and the first packet from the new BS. To reduce the handoff latency, our scheme relies on the L2 (link-layer) trigger [17]. The L2 trigger is a signal from L2 to inform L3 (network-layer) of an imminent L2 handoff. That is, once the received signal strength from the current BS falls below the threshold level, the MN sends a Movement signaling message to the current LER/FA, to notify an imminent L2 handoff and initiate the buffering mechanism.

Intra-LER handoff
Once the association to the current BS is lost, the MN sends a Movement signaling message to the current LER/FA, which initiates the buffering mechanism and stores in-flight packets. Then, the MN will scan the air interface for a new BS. If it finds one, it will register at layer 2 with that BS and either wait for a Mobile IP Advertisement message sent from the LER/FA or it will issue a Mobile IP Solicitation message. In any case, the MN examines the LER/FA's IP address. This address is the same as before Intra-LER handoff, which means that the MN is under the same IP subnet. Therefore, the MN will issue a local interface-update message in the subnet to which the MN belongs, so that all stations in the same subnet, especially the current LER/FA, update their ARP cache (Address Resolution Protocol [18]). In this case, the current LER/FA will stop the buffering mechanism and forward in-flight packets destined for the MN toward the new BS. Note that an Intra-LER handoff is basically an L2 handoff. Note also that no message is sent to the LERG to take advantage of the common path between it and the LER/FA. The LERG will continue to use the old LSP between it and the current LER/FA to send packets to the MN. Table 2 illustrates the label table of an LER/FA after Intra-LER handoff.

Inter-LER handoff
In the case of an Inter-LER handoff, when the MN examines the LER/FA's IP address from the Advertisement message, it finds that this address differs from the old one, which means that the MN has entered a new IP subnet. In this case, the MN sends a Registration Request to the new LER/FA and performs identical steps as seen in the registration procedure. At the same time, the MN sends a handoff notification message to the old LER/FA (via the new LER/FA). Upon receiving the handoff notification message, the old LER/FA will stop the buffering mechanism and forward in-flight packets destined for the MN toward the new subnet. So in this case the MN may receive packets from the old LER/FA (via the new LER/FA) before the L3 handoff completes (i.e., before receiving the 'registration reply' message from the LERG). Note that no message is sent to the HA of the MN as only regional registration with the LERG is required. The HA is not notified unless the MN moves to another new domain or to refresh the binding if the global registration is about to expire. Table 3 illustrates the label table of the LERG after Inter-LER handoff. The previous RCoA of the old LER/FA is w.x.y.z and the RCoA of the new LER/FA is p.q.r.s. Figure 3 illustrates the signaling procedure of an Inter-LER handoff in Micro Mobile MPLS.

After the establishment of the new LSP, there would be a new row inserted in the LERG label table shown in Table 1, and the new table is shown in Table 3, in which the third row shows the label binding

In. port	In. label	FEC	Out. port	Out. label
1	5	w.x.y.z	—	—
...	...	...	...	...

Table 2. Label table of an LER/FA after intra-LER handoff

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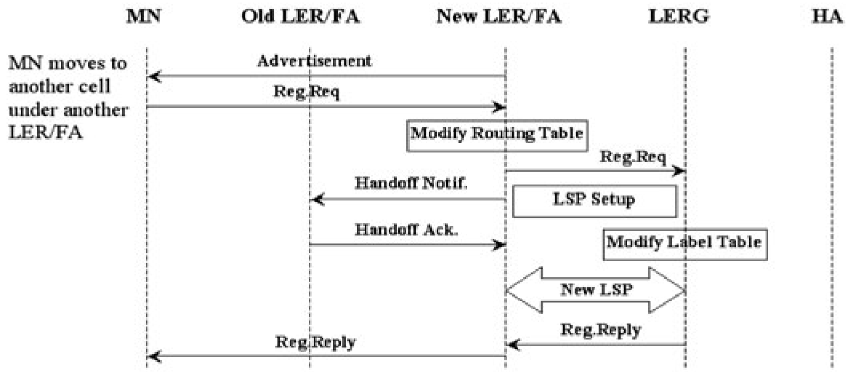

Figure 3. Inter-LER handoff procedure in Micro Mobile MPLS

In. port	In. label	FEC	Out. port	Out. label
2	—	w.x.y.z	1	7
2	—	a.b.c.d	~~1~~	~~7~~
			3	9
2	—	p.q.r.s	3	9
. . .	. . .	. . .	. . .	. . .

Table 3. Label table of the LERG after inter-LER handoff

for the LSP from the LERG to the new LER/FA. The outgoing port number and outgoing label value in the second row are changed to the corresponding values of the third one so that packets destined to the MN home address can be redirected to the new LER/FA.

The fast handoff mechanism: FH-Micro Mobile MPLS

The main idea behind FH-Micro Mobile MPLS [19] is to set up an LSP before the MN moves into a new subnet to reduce service disruption. In this context, we consider two types of LSP: active LSP and passive LSP. The active LSP is the one from the LERG to the current serving LER/FA. This LSP is currently used to transfer data. Passive LSPs are those from the LERG to the neighboring LER/FAs of the current serving FA. These LSPs are not currently used. The basic operations of the fast handoff mechanism are described below. Once the MN enters a new domain, it registers with the associated LERG by establishing an active LSP. At the same time, the LERG will also send label messages to the neighboring LER/FAs of the current serving FA in order to establish passive LSPs with the same requirements of QoS. When the MN moves into a neighboring subnet and knows the new RCoA, it will register to the LERG. Thus all the intermediate LSRs of the new path will change its LSP state from passive to active. By using the fast handoff mechanism, we can improve the handoff performance of Micro Mobile MPLS and reduce service disruption.

The forwarding chain mechanism: FC-Micro Mobile MPLS

The second protocol variant that we propose to handle efficiently local mobility is called FC-Micro Mobile MPLS. It is based on the forwarding chain concept (set of forwarding paths). In this technique, each time that the MN moves to a new subnet, the new RCoA will be registered at the old LER/FA instead of the LERG, as shown in Figure 4. By this procedure, a forwarding chain of FAs is constructed for each MN. In this regard, each MN keeps a buffer for storing IP addresses of the visited LER/FAs. Packets traveling toward this MN will be intercepted by the first FA in the chain (called master FA), taking advantage of the existing LSP between the LERG and the master LER/FA, and then forwarded along the chain of FAs to the MN. It is easy to see that such a scheme may cause unacceptable delays due to long chains.

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To avoid a long forwarding chain, we set a threshold on its length denoted by L_{th} (in terms of the number of movements). When the threshold is reached, the MN will register to the LERG and the MN forwarding chain will be renewed. Note that this scheme enables a significant reduction of the local registration update messages sent by the MN to the LERG. In this paper, we assume the optimal value of L_{th} is computed by the network operator.

The basic operation of the FC-Micro Mobile MPLS scheme is depicted in Figure 4. In this figure, an MN moves from subnet 1 to subnet 4. We assume that the threshold of the forwarding chain length is three. When the MN moves to subnet 2, it registers the new RCoA at the previous LER/FA1, which is the master LER/FA. Likewise, when the MN moves to subnet 3, it updates the new RCoA to the previous LER/FA2. In this case, data packets destined for the MN are intercepted by the LERG and switched to the master LER/FA using the existing LSP between the LERG and the LER/FA1. Then, the packets are forwarded along the chain of FAs to the MN. In view of this, the location update cost is drastically reduced since the distance between two neighboring LER/FAs is usually lower than the distance between an LER/FA and the LERG. The threshold of the forwarding chain length (L_{th}) is reached when the MN enters subnet 4. In this case, the MN will register to the LERG and updates its new RCoA to the root of the domain directly. The FC-Micro Mobile MPLS scheme can be described by the pseudo code in Table 4.

3. PERFORMANCE EVALUATION AND ANALYSIS

In this section, we derive the cost function of registration updates and the handoff performance metrics. Our previous studies [20–21] introduced the handoff performance of Micro Mobile MPLS without the fast handoff and the forwarding chain mechanisms. Here, we evaluate the signaling cost of registration updates and the handoff performance of FH- and FC-Micro Mobile MPLS using both analytical and simulation approaches. We compare our proposals with Mobile IP [1], Mobile MPLS [9], MIP-RR [3] and H-MPLS [11]. The simulations are run using our module developed under the Network Simulator NS-2

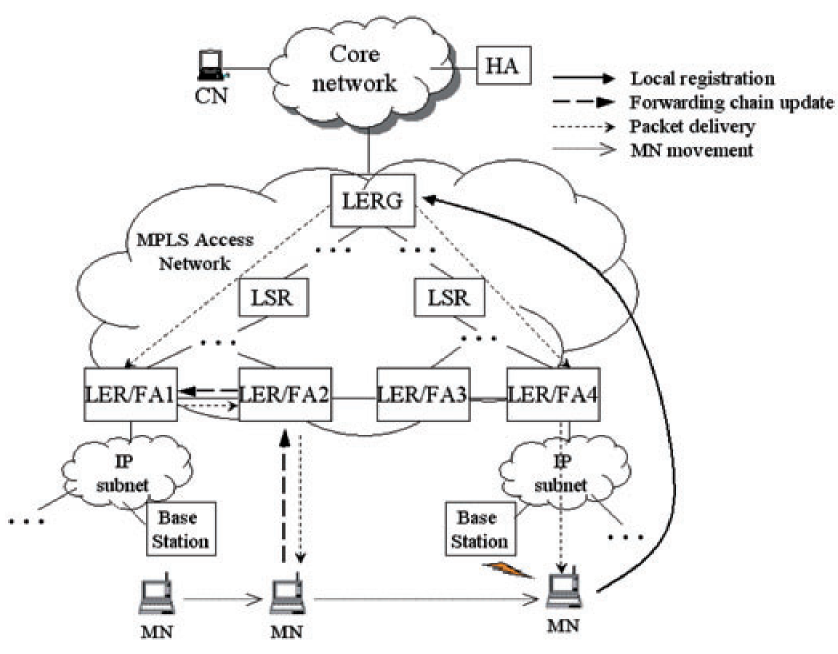

Figure 4. Operation of the FC-Micro Mobile MPLS scheme

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```
%Location registration procedures
Initialize i = 0;
IF (MN enters a new subnet)
   compare the address of the new LER/FA to the addresses in buffer;
   IF (the new address already exists in buffer)
      Extract the rank (rg) of the subnet from buffer;
      i = rg;
   ELSE
      record the new LER/FA address in buffer;
      i = i + 1;
   ENDIF
   IF (i < L_th)
      New LER/FA registers to the old LER/FA;
   ELSE
      New LER/FA registers to the LERG;
      MN notifies the old LER/FA of the handoff;
      Delete all the addresses in buffer;
      i = 0;
   ENDIF
ENDIF
%Packet delivery procedures
IF (packets for the MN are intercepted by the LERG)
   Switch the packets to the master LER/FA using label swapping;
   IF (the LER/FA is not the MN's current serving LER/FA)
      Reswitch the packets to the next LER/FA of the forwarding chain;
   ENDIF
   The current serving LER/FA strips off the label and sends the packets to the MN;
ENDIF
```

Table 4. FC-Micro Mobile MPLS scheme

[22]. We model the MN's mobility as a two-dimensional (2D) random walk. Thus an MN may move to one of the neighboring subnets with equal probability. We assume also that the MN is moving in a uniform direction across the wireless cells. Similarly to reference 23, we define the following parameters that will be used in the analysis.

3.1 Parameters

t_s	average session connection time
t_r	average cell resident time
T_{life}	MN's home registration lifetime value
T_{ad}	time interval for an FA to send agent advertisements
N_h	average number of handoff during a session (i.e., $N_h = t_s/t_r$)
N_r	average number of renewals of the home registration update during a session (i.e., $N_r = t_s/T_{life}$)
N_f	average number of renewals of the forwarding chain during a session (i.e., $N_f = N_h/L_{th}$)
s_u	average size of a signaling message for the registration update
s_l	average size of a label message for LSP set-up
h_{x-y}	average number of hops between x and y in the wired network
B_w	bandwidth of the wired link
B_{wl}	bandwidth of the wireless link
L_w	latency of the wired link (propagation delay)
L_{wl}	latency of the wireless link (propagation delay)
P_t	routing or label table lookup and processing delay

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λ_d downlink packet transmission rate
T_{inter} data packet inter-arrival time

Let $t(s, h_{x-y})$ denote the time that takes a message of size s to be forwarded from x to y via the wired and wireless links. $t(s, h_{x-y})$ can be expressed as follows:

$$t(s,h_{x-y}) = c + h_{x-y} \times \left(\frac{s}{B_w} + L_w\right) + (h_{x-y}+1) \times P_t$$

$$\text{where } c = \begin{cases} \frac{s}{B_{wl}} + L_{wl} & \textit{if } x = MN \\ 0 & \textit{otherwise} \end{cases}$$

3.2 Signaling Cost of Registration Updates during a Session

The total signaling cost of registration updates during a session is denoted by C_u. It is the accumulative traffic load related to the exchange of signaling messages (hop × message size) at every L3 handoff during the MN's communication session. For each movement to a new subnet, the home registration update with the HA is performed in both Mobile IP and Mobile MPLS. In MIP-RR and H-MPLS a local registration update with the root of the domain is performed. In FH-Micro Mobile MPLS, both local registration update with the LERG and LSPs procedure set-up with the neighboring subnets are performed. However, considering FC-Micro Mobile MPLS, only a forwarding chain update with the previous LER/FA is performed since the new RCoA will be registered at the previous LER/FA. The local registration update with the LERG can occur in FC-Micro Mobile MPLS only when the forwarding chain is renewed (i.e., when the threshold of the forwarding chain length is reached). Note that the home registration procedure is performed in MIP-RR, H-MPLS, FH- and FC-Micro Mobile MPLS only when the binding update in the HA is renewed. Let N_g denote the remaining non-notified neighboring LER/FAs of the new serving LER/FA when handoff occurs. We have

$$C_u(\text{Mobile IP}) = 2s_u \times h_{MN-HA} \times N_h$$

$$C_u(\text{Mobile MPLS}) = 2N_h \times (s_u \times h_{MN-HA} + s_1 \times h_{FA-HA})$$

$$C_u(\text{MIP-RR}) = 2s_u \times h_{MN-GFA} \times N_h + 2s_u \times h_{MN-HA} \times N_r$$

$$C_u(\text{H-MPLS}) = 2s_u \times h_{MN-LERG} \times N_h + 2s_1 \times h_{FA-LERG} \times N_h + 2s_u \times h_{MN-HA} \times N_r$$

$$\begin{aligned} C_u(\text{FH-Micro Mobile MPLS}) = & -2s_u \times (h_{MN-LERG} + h_{FA-FA}) \times N_h + 2s_1 \times h_{FA-LERG} \times N_g \times N_h \\ & + 2s_u \times h_{MN-HA} \times N_r \end{aligned}$$

$$\begin{aligned} C_u(\text{FC-Micro Mobile MPLS}) = & \, 2s_u \times (h_{MN-FA} + h_{FA-FA}) \times N_h + 2N_f \times (s_u \times h_{MN-LERG} + s_l \times h_{FA-LERG}) \\ & + 2s_u \times h_{MN-HA} \times N_\tau \end{aligned}$$

3.3 Average Handoff Time

According to our definition of the handoff latency and assuming that data packets destined to the MN are sent at a constant bit rate, the average handoff time (T_h) can be written as the sum of three terms: disruption time (T_d), establishment time (T_e) and $T_{inter}/2$.

(1) *Disruption time calculation.* The disruption time (T_d) is the average time that an MN spends without connection to any LER/FA during the handoff process. In other words, it is the time between the moment that the MN disconnects from the old FA to the moment that it connects to the new one. It is easy to see

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that the disruption time becomes null when the overlapping area is large enough. The worst case value for this quantity is equal to the beacon period (T_{ad}). T_d can be given by the following expression:

$$T_d = \begin{cases} 0 & \text{if } T_{\text{overlap}} \geq T_{ad} \\ \dfrac{1}{T_{\text{ad}}} \displaystyle\int_0^{T_{\text{ad}}-T_{\text{overlap}}} f(t)\,dt & \text{otherwise} \end{cases}$$

where T_{overlap} denotes the time spent by the MN in the overlapping area and $f(t) = T_{\text{ad}} - T_{\text{overlap}} - t$. Hence, T_d is equal to

$$T_{\text{d}} = \begin{cases} 0 & \text{if } T_{\text{overlap}} \geq T_{ad} \\ \dfrac{T_{\text{ad}}}{2} + \dfrac{T_{\text{overlap}}{}^2}{2T_{\text{ad}}} - T_{\text{overlap}} & \text{otherwise} \end{cases}$$

(2) *Establishment time calculation.* The establishment time (T_e) is the time to establish the new route to the MN and to receive the first forwarded data packet (denoted by p^*) through the new path. In this paper, we assume that the distance between the LERG and the new LER/FA is equal to the distance between the LERG and the old LER/FA. We have:

$$h_{\text{oldFA-LERG}} = h_{\text{newFA-LERG}} = h_{\text{FA-LERG}}.$$

Calculation of T_e for the underlying protocols

In Mobile IP and Mobile MPLS, owing to the lack of any buffering and forwarding techniques, the referred packet (p^*) will be sent by the HA. However, in MIP-RR and H-MPLS, p^* will be sent by the root of the domain. That is, the T_e value of these four schemes can be given as follows:

$$T_{\text{e}}(\text{Mobile IP}) = 2t(s_{\text{u}}, h_{\text{MN-HA}}) + T_{\text{inter}}/2$$

$$T_{\text{e}}(\text{Mobile MPLS}) = 2[t(s_{\text{u}}, h_{\text{MN-HA}}) + t(s_1, h_{\text{FA-HA}})] + T_{\text{inter}}/2$$

$$T_{\text{e}}(\text{MIP-RR}) = 2t(s_{\text{u}}, h_{\text{MN-GFA}}) + T_{\text{inter}}/2$$

$$T_{\text{e}}(\text{H-MPLS}) = 2[t(s_{\text{u}}, h_{\text{MN-LERG}}) + t(s_1, h_{\text{FA-LERG}})] + T_{\text{inter}}/2$$

where $T_{\text{inter}}/2$ is the mean waiting time to receive data packets at the root of the domain. Recall that data packets destined to the MN are assumed to be sent at a constant bit rate.

Calculation of T_e for the FH-Micro Mobile MPLS scheme

The T_e value in FH-Micro Mobile MPLS is more complicated. In this scheme, upon receiving the handoff notification message from the new LER/FA, the old LER/FA will divert the possible in-flight packets destined for the MN to the new subnet. In this case, the MN may receive packets from the old LER/FA (via the new LER/FA) before the L3 handoff completes (i.e., before receiving the 'registration reply' message from the LERG).

To evaluate the average establishment time of FH-Micro Mobile MPLS, we compute the handoff latency (T_h) when $T_d = 0$. That is, the overlapping area is large enough. According to this approach, let us denote by t_0 the time that the MN receives the last packet from the old LER/FA before handoff occurs. Let x denote the time interval between the last packet arrival and the reception of the agent advertisement message from the new LER/FA. Since we have assumed that $T_d = 0$ (i.e., the MN is in the overlapping area when handoff occurs), it will be easy to see that x ranges between 0 and T_{inter}. The LERG (respectively the old LER/FA) will receive the registration related update message at $[t_0 + x + t(s_u, h_{\text{MN-LERG}})]$ (respectively $[t_0 + x + t(s_u, h_{\text{MN-FA}} + h_{\text{FA-FA}})]$). Two cases are to be distinguished: (a) $T_{\text{inter}} \leq 2t(s_u, h_{\text{MN-LERG}})$ and (b) $T_{\text{inter}} > 2t(s_u, h_{\text{MN-LERG}})$.
For convenience, we denote:

$$\beta_1 = T_{\text{inter}} - 2t(s_{\text{u}}, h_{\text{MN-LERG}}),$$

$$\beta_2 = T_{\text{inter}} - t(s_{\text{u}}, h_{\text{MN-FA}}) - t(s_{\text{u}}, h_{\text{MN-FA}} + h_{\text{FA-FA}}),$$

$$\gamma = T_{\text{inter}} + t(s_{\text{u}}, h_{\text{FA-FA}})$$

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and

$$\psi = x + 2t(s_u, h_{MN-FA} + h_{FA-FA})$$

Case a. In this case, data packets from the old path arrive before packets from the new path. Two subcases are also to be considered. The first subcase makes the assumption that the old LER/FA receives the handoff notification message from the new FA before receiving in-flight packets (i.e., $0 \le x < \beta_2$). In this subcase, T_h is simply equal to γ. Therefore, $T_e = \gamma - x$. The second subcase occurs if the buffer located at the old LER/FA already contains in-flight packets when receiving the handoff notification message (i.e., $\beta_2 \le x < T_{inter}$). Hence, T_h is equal to ψ and $T_e = \psi - x$.

Case b. In this case, a similar analysis can be performed. The main difference with the above case (Case a) is that the L3 handoff may be successfully completed without having any in-flight packets along the old path (i.e., $0 \le x < \beta_1$). Since we have assumed that $h_{oldFA\text{-}LERG} = h_{newFA\text{-}LERG}$, the T_h value in this particular subcase will be equal to T_{inter}. Then T_e is equal to $T_{inter} - x$.
We summarize the expression of T_e for each case as follows:

$$T_e(a) = \begin{cases} \gamma - x & \text{if } 0 \le x < \beta_2 \\ \psi - x & \text{if } \beta_2 \le x < T_{inter} \end{cases}$$

$$T_e(b) = \begin{cases} T_{inter} - x & \text{if } 0 \le x < \beta_1 \\ \gamma - x & \text{if } \beta_1 \le x < \beta_2 \\ \psi - x & \text{if } \beta_2 \le x < T_{inter} \end{cases}$$

As a result, the T_e value of FH-Micro Mobile MPLS for each case is defined as

$$\begin{cases} T_e(a) = \dfrac{1}{T_{inter}} \displaystyle\int_0^{\beta_2} \gamma \, dx + \dfrac{1}{T_{inter}} \int_{\beta_2}^{T_{inter}} \psi \, dx - \dfrac{T_{inter}}{2} \\ T_e(b) = \beta_1 + \dfrac{1}{T_{inter}} \displaystyle\int_{\beta_1}^{\beta_2} \gamma \, dx + \dfrac{1}{T_{inter}} \int_{\beta_2}^{T_{inter}} \psi \, dx - \dfrac{T_{inter}}{2} \end{cases}$$

Considering the h_{x-y} values shown in Figure 5, the average establishment time of FH-Micro Mobile MPLS is

$$T_e(\text{FH-Micro Mobile MPLS})_a \approx \frac{T_{inter}}{2} + L_w + \frac{9}{2} \times \frac{L_w{}^2}{T_{inter}}$$

$$T_e(\text{FH-Micro Mobile MPLS})_b \approx \frac{T_{inter}}{2} + \frac{25}{2} \times \frac{L_w{}^2}{T_{inter}}$$

Calculation of T_e for the FC-Micro Mobile MPLS scheme
In FC-Micro Mobile MPLS, data packets destined to the MN are forwarded from the old LER/FA to the new one when the forwarding chain update message is received at the old FA. The same above analysis can be performed here. The old LER/FA will receive the forwarding chain update message at $[t_0 + x + t(s_u, h_{MN\text{-}FA} + h_{FA\text{-}FA})]$. Two cases are also to be considered: (c) $T_{inter} \ge t(s_u, h_{MN\text{-}FA}) + t(s_u, h_{MN\text{-}FA} + h_{FA\text{-}FA})$ and (d) $T_{inter} < t(s_u, h_{MN\text{-}FA}) + t(s_u, h_{MN\text{-}FA} + h_{FA\text{-}FA})$.
Case c. In this case, the analysis is similar to that in the previous Case a. Two subcases are also to be considered. The first subcase makes the assumption that the old LER/FA receives the forwarding chain update message before receiving in-flight packets (i.e., $0 \le x < \beta_2$). Therefore, T_h will be equal to γ and $T_e = \gamma - x$. The second subcase occurs if the buffer located at the old LER/FA already contains in-flight packets when receiving the forwarding chain update message (i.e., $\beta_2 \le x < T_{inter}$). Hence, T_h is equal to ψ and $T_e = \psi - x$.

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Case d. In this case, the buffer always contains in-flight packets. Then $T_e = \psi - x$.
We summarize the expression of T_e for each case as follows:

$$T_e(c) = \begin{cases} \gamma - x & \text{if } 0 \le x < \beta_2 \\ \psi - x & \text{if } \beta_2 \le x < T_{\text{inter}} \end{cases}$$

$$T_e(d) = \psi - x \qquad \forall\, 0 \le x < T_{\text{inter}}$$

As a result, the T_e value of FC-Micro Mobile MPLS for each case is defined as

$$\begin{cases} T_e(c) = T_e(a) \\ T_e(d) = \dfrac{1}{T_{\text{inter}}}\displaystyle\int_0^{T_{\text{inter}}} \psi\, dx - \dfrac{T_{\text{inter}}}{2} \end{cases}$$

Considering the h_{x-y} values shown in Figure 5, the average establishment time of FC-Micro Mobile MPLS is

$$T_e(\text{FC-Micro Mobile MPLS})_c \approx \frac{T_{\text{inter}}}{2} + L_w + \frac{9}{2} \times \frac{L_w{}^2}{T_{\text{inter}}}$$
$$T_e(\text{FC-Micro Mobile MPLS})_d \approx 4L_w$$

3.4 *Total Packet Loss during a Session*

The total packet loss (*Pkt_loss*) during a session is defined as the sum of lost packets per MN during all handoffs. In Mobile IP, Mobile MPLS, MIP-RR and H-MPLS, all in-flight packets will be lost during the handoff time due to the lack of any buffering mechanism. In our proposed schemes, in-flight packets would be lost until the buffering mechanism is initiated.*Pkt_loss* for each scheme can be expressed as follows:

$$Pkt\_loss(\text{Mobile IP}) = T_h(\text{Mobile IP}) \times \lambda_d \times N_h$$
$$Pkt\_loss(\text{Mobile MPLS}) = T_h(\text{Mobile MPLS}) \times \lambda_d \times N_h$$
$$Pkt\_loss(\text{MIP-RR}) = T_h(\text{MIP-RR}) \times \lambda_d \times N_h$$
$$Pkt\_loss(\text{H-MPLS}) = T_h(\text{H-MPLS}) \times \lambda_d \times N_h$$
$$Pkt\_loss((\text{FH/FC})\text{-Micro Mobile MPLS}) = t(s_u, h_{\text{MN-FA}}) \times \lambda_d \times N_h$$

3.5 *Buffer Size Requirement*

The buffer to store in-flight packets is located at the LER/FA in our proposed schemes. The buffering mechanism is activated from the moment when the Movement signaling message notifying an imminent L2 handoff is received to the moment when the registration related update message is received. In FH-Micro Mobile MPLS, the update message corresponds to the handoff notification message. In FC-Micro Mobile MPLS, it corresponds to the forwarding chain update message. Thus both these schemes require the same size of buffer space. The buffer size requirement (*Buf_size*) for FH- and FC-Micro Mobile MPLS is listed as follows:

$$Buf\_size((\text{FH/FC})\text{-Micro Mobile MPLS}) = [T_d + t(s_u, h_{\text{MN-FA}} + h_{\text{FA-FA}})] \times \lambda_d$$

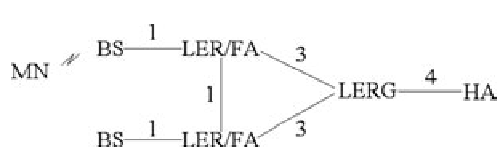

Figure 5. Relative distances in hops in the simulated network

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4. NUMERICAL AND SIMULATION RESULTS

In this section, we compare all underlying protocols. We consider the Inter-LER handoff scheme. A stream of 48 bytes UDP over IP packets is used to simulate voice traffic. The packet inter-arrival time is constant and equal to 6 ms. The parameter settings in our experiments are listed in Table 5. The settings of the $h_{x\text{–}y}$ values are shown in Figure 5.

Figure 6 presents the different registration costs when parameters have their default settings. MIP-RR and FC-Micro Mobile MPLS can significantly reduce the registration updates cost, particularly when the MN handoffs frequently (i.e., when the cell resident time is short). FC-Micro Mobile MPLS provides the lowest registration cost since some local registration updates are replaced by low-cost forwarding chain updates. In fact, as the previous LER/FAs are usually close to the new ones, the location update cost to the old LER/FA is usually less than that to the LERG. We notice also that the registration updates cost of FC-Micro Mobile MPLS increases when the threshold of the forwarding chain length (L_{th}) decreases,

Parameter	Value	Parameter	Value
t_s	1000 s	B_w	100 Mbps
t_r	5~50 s (default 20)	B_{wl}	11 Mbps
T_{life}	500 s	L_w	1 ms
T_{ad}	1 s	L_{wl}	2 ms
s_u	48 bytes	P_t	10^{-6} s
s_l	28 bytes	N_g	1
L_{th}	1~20 (default 10)	λ_d	64 kps

Table 5. Parameter settings

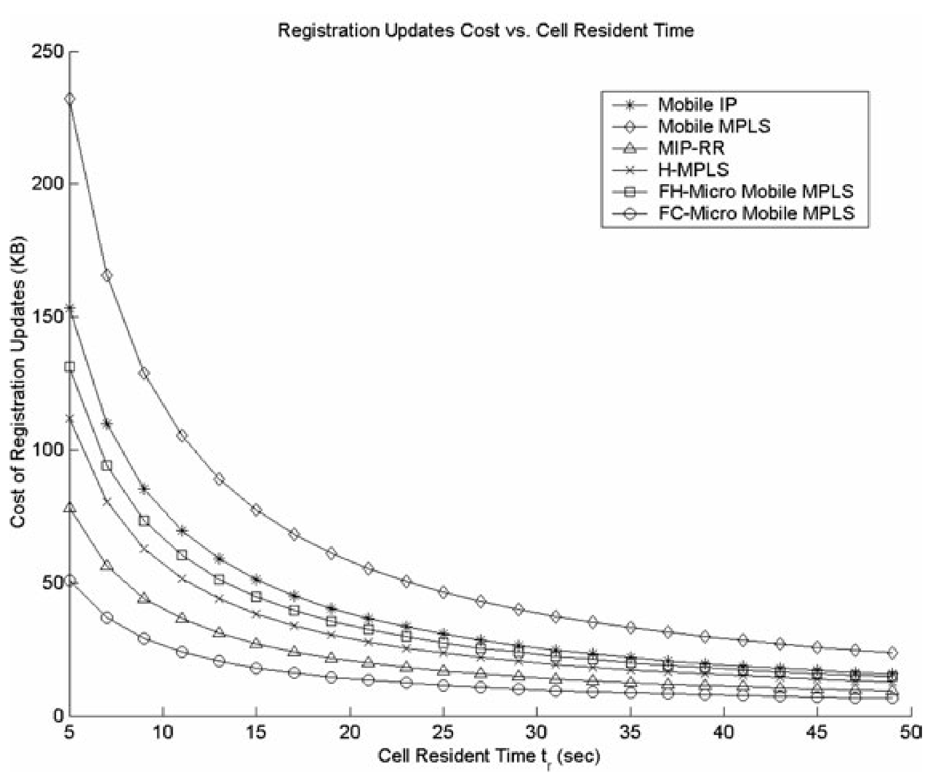

Figure 6. Registration updates cost

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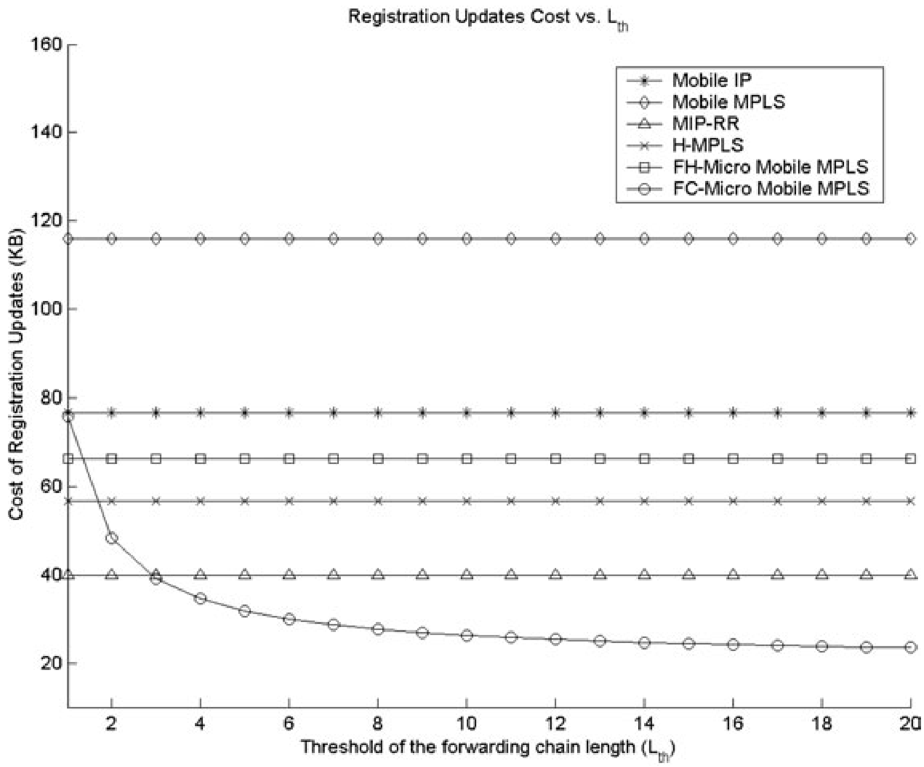

Figure 7. Effect of L_{th} on the registration updates cost

since the local registration updates with the LERG become more frequent (see Figure 7). The FH-Micro Mobile MPLS scheme has a higher registration updates cost than FC-Micro Mobile MPLS, MIP-RR and H-MPLS, since this scheme anticipates the LSPs procedure set-up with the remaining non-notified neighboring locations where the MN may move to.

Figure 8 shows the impact of the ratio $r = \dfrac{T_{overlap}}{T_{ad}}$ on the average handoff time (T_h) for different schemes. It is easy to see that T_h decreases with the increasing ratio r. In fact, when r is large, the MN can maintain the connection with the old BS for relatively long periods. We also observe that T_h takes small values when the MN spends at least a time period equal to T_{ad} in the overlapping area. This result is expected since in this case the disruption time is null. Moreover, as can be seen, FH- and FC-Micro Mobile MPLS have the same value of handoff latency since T_{inter} used in our analysis and simulations satisfies the following inequations: $T_{inter} \geq t(s_u, h_{MN\text{-}FA}) + t(s_u, h_{MN\text{-}FA} + h_{FA\text{-}FA})$ and $T_{inter} \leq 2t(s_u, h_{MN\text{-}LERG})$. In addition, these schemes provide the lowest average handoff time thanks to the buffering and forwarding techniques. Note that analytical results practically coincide with the simulation ones, which illustrates the accuracy of our models.

Figure 9 shows the amount of lost packets during the whole connection session for different schemes when $r \geq 1$ (i.e., $T_d = 0$). Both Mobile IP and Mobile MPLS have a large amount of lost packets especially when the MN handoffs frequently. The H-MPLS scheme has a larger amount of lost packets than MIP-RR since the time needed to establish an LSP between the domain's root and the new serving FA is relatively long. In contrast, both FH- and FC-Micro Mobile MPLS provide the smallest amount of lost packets thanks to the buffering mechanism. In this case, the maximum buffer size requirement for each MN is about 4.016 kB. This means that a memory of size 128 MB can handle over than 30 000 MNs.

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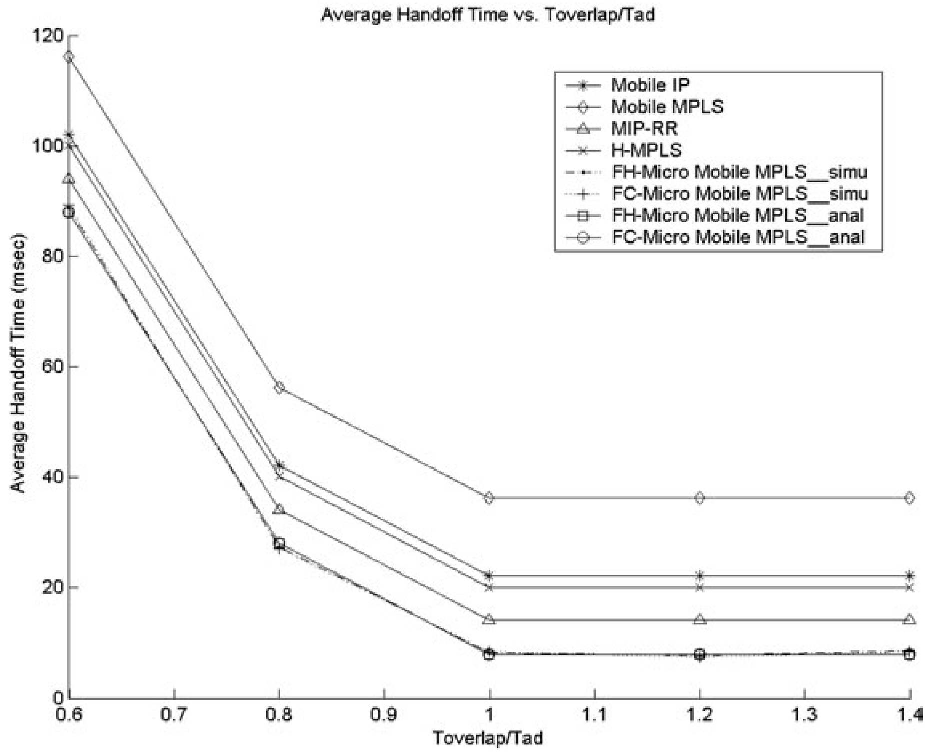

Figure 8. Average handoff time

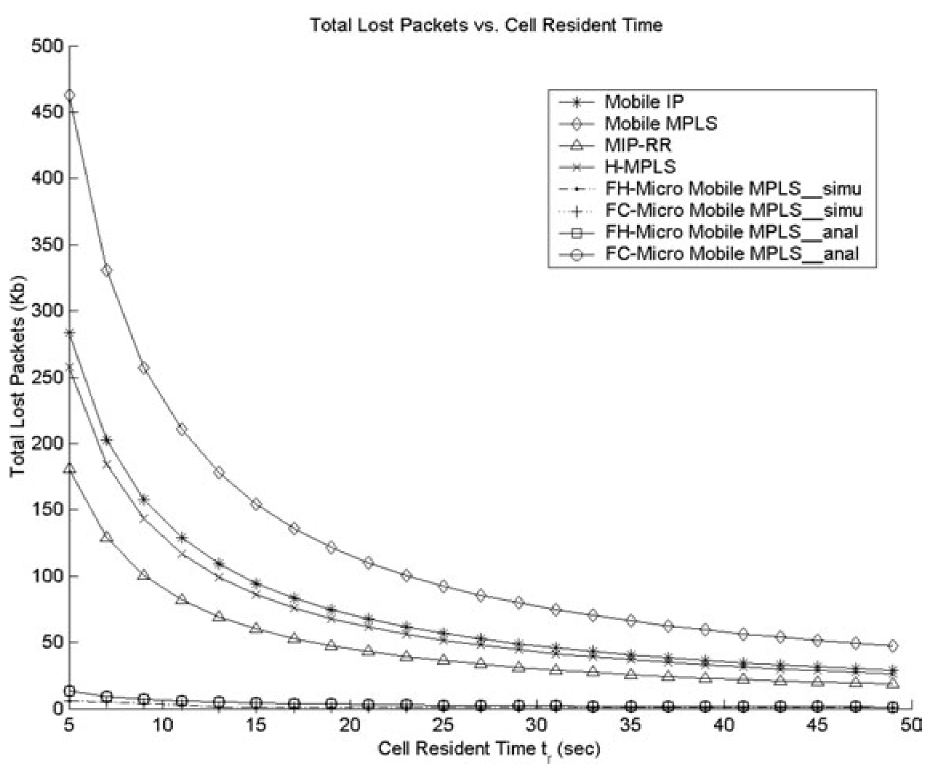

Figure 9. Total lost packets during a session

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5. CONCLUSION

In this paper, we proposed a practical approach called Micro Mobile MPLS to handle efficiently the local mobility in wireless MPLS access networks. We consider two protocol variants: the FH- and FC-Micro Mobile MPLS schemes. In FH-Micro Mobile MPLS, we suggest setting up an LSP before the MN moves into a new subnet to reduce service disruption. In FC-Micro Mobile MPLS, we propose to track the MN's movement by using the forwarding chain. The forwarding chain can restrict the registration messages into a local scope and then reduce the registration updates cost and provide low handoff latency. A performance comparison between our proposals and existing protocols (Mobile IP, Mobile MPLS, MIP-RR and H-MPLS) was given. Results show that our mechanisms provide the lowest handoff latency and have the smallest signaling cost of registration updates.

REFERENCES

1. Perkins C. IP Mobility Support for IPv4. *RFC 3220*, January 2002.
2. Campbell A, Gomez J, Kim S, Turanyi Z, Valko A, Wan C-Y. Design, implementation and evaluation of cellular IP. *IEEE Personal Communications* 2000; **7**: 42–49.
3. Gustafsson E, Jonsson A, Perkins C. Mobile IPv4 regional registration. draft-ietf-mip4-reg-tunnel-00.txt, November 2005, (in press).
4. Ramjee R, Varadhan K, Salgarelli L *et al.* HAWAII: a domain-based approach for supporting mobility in wide-area wireless networks. *IEEE/ACM Transactions on Networking* 2002; **10**(3): 396–410, June 2002.
5. Das S, Misra A, Agrawal P, Das SK. TeleMIP: telecommunications-enhanced Mobile IP architecture for fast intradomain mobility. *IEEE Personal Communications* 2000; **7**(4): 50–58; August 2000.
6. Misra A, Das S, Dutta A, Mcauley A, Das SK. IDMP-based fast handoffs and paging in IP-based 4G mobile networks. *IEEE Communications* 2002; **40**(3): 138–145; March 2002.
7. Campbell A, Gomez J, Kim S, Turanyi Z, Wan C-Y, Valko A. Comparison of IP micro-mobility protocols. *IEEE Wireless Communications* 2002; **9**: 2–12.
8. Rosen E, Viswanathan A, Callon R. Multiprotocol label switching architecture. *Internet IETF RFC 3031*, January 2001.
9. Ren Z, Tham C, Foo C, Ko C. Integration of Mobile IP and multi-protocol label switching. In *IEEE International Conference on Communications (ICC)*, Finland, June 2001.
10. Chiussi FM, Khotimsky DA, Krishnan S. A network architecture for MPLS-based micro-mobility. In *IEEE WCNC'02*, Orlando, FL, 2002.
11. Yang T, Dong Y, Zhang Y, Makrakis D. Practical approaches for supporting micro mobility with MPLS. In *IEEE International Conference on Telecommunications (ICT)*, Beijing, China, June 2002.
12. Kim H, Wong KD, Chen W, Lau WC. Mobility-aware MPLS in IP-based wireless access networks. In *IEEE Globecom*, San Antonio, TX, 2001.
13. Xie K, Wong V, Leung V. Support of micro-mobility in MPLS-based wireless access networks. In *IEEE WCNC*, New Orleans, LA, March 2003.
14. Nguyen HM, Li F, Xie Q. Integration of micro-mobility with QoS in IP/MPLS-based radio access networks. In *IEEE 57th VTC—Spring 2003*, Korea, April 2003.
15. Vassiliou V, Owen HL, Barlow DA, Grimminger J, Huth H-P, Sokol J. M-MPLS: micromobility-enabled multiprotocol label switching. In *IEEE ICC*, Alaska, May 2003.
16. Sethom K, Afifi H, Pujolle G. Wireless MPLS: a new layer 2.5 micro-mobility scheme. In *ACM MobiWac 2004*, Philadelphia, PA, October 2004.
17. El Malki K. Low latency handoffs in Mobile IPv4. IETF, draft-ietf-mobileip-lowlatency-handoffs-v4-09.txt, October 2005 (in press).
18. Plummer D, Ethernet Address Resolution Protocol: or converting network protocol addresses to 48.bit Ethernet address for transmission on Ethernet hardware. *STD 37, RFC 826*, November 1982.
19. Langar R, Tohme S, Bouabdallah N, Pujolle G. Performance analysis of micro mobile MPLS for future wireless networks. In *16th IEEE PIMRC 2005*, Berlin, September 2005.
20. Langar R, Tohme S, Le Grand G. Micro mobile MPLS: a new scheme for micro-mobility management in 3G All-IP networks. In *10th IEEE Symposium on Computers and Communications (ISCC)*, Spain, June 2005.

DOI: 10.1002/nem

21. Langar R, Le Grand G, Tohme S. Micro mobile MPLS: a solution for micro-mobility management in next generation networks. In *12th IEEE MASCOTS*, Volendam, The Netherlands, October 2004.
22. ns2 home page. http://www.isi.edu/nsnam/ns [29 October 2005].
23. Lo SC, Lee G, Chen WT, Liu JC. Architecture for mobility and QoS support in All-IP wireless networks. *IEEE Journal on Selected Areas in Communications* 2004; **22**(4): 691–705; May 2004.

AUTHOR'S BIOGRAPHIES

Rami Langar received the B.S. degree in telecommunications engineering from Ecole Supérieure des Communications (Sup'Com), Tunis, Tunisia, in 2001. He received the M.S. degree in network and computer science from the University of Paris VI, France, in 2002. He is currently working toward the Ph.D. degree from the Ecole Nationale Supérieure des Télécommunications, ENST, Paris, France. He also works as teaching and research assistant at the Ecole Normale Supérieure de Cachan, France. His research interests include 4G visions, mobility management, performance evaluation and quality of service support.

Samir Tohmé was born in Damascus, Syria, in 1949. He graduated from the Ecole Supérieure d'Electricité, Paris, France, in 1975, and received the Ph.D. degree from the Ecole Nationale Supérieure des Télécommunications, ENST, Paris, in 1979. He is currently a professor at the University of Versailles, France and director of the PRiSM laboratory. His main research activities concern high-speed networks, traffic control, and next generation networks. Pr. Tohme is the French Representative to the IFIP Technical Committee TC6 and the Chairman of the IFIP WG 6.2 on Broadband Communication. He is also a member of the IEEE IAC Communications Society.

Nizar Bouabdallah received the B.S. degree in telecommunications engineering from Ecole Supérieure des Communications (Sup'Com), Tunis, Tunisia, in 2001. He received the M.S. and Ph.D. degrees in network and computer science from the University of Paris VI, France, in 2002 and 2004, respectively. He joined Alcatel Research Labs, Marcoussis, France, in 2002, where he achieved his Ph.D. In 2005, he was a visitor researcher at North Carolina State University. He is currently a researcher at INRIA, France. His research interests include optical networking, performance evaluation, network planning and modeling, as well as control and management architectures.

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