On the Analysis of Mobility Mechanisms in Micro Mobile MPLS Access Networks

Rami Langar[¶‡], Nizar Bouabdallah[τ] and Samir Tohme[†]
(¶) School of Computer Science, University of Waterloo ; 200 University Ave. W., Waterloo, ON, Canada
(‡) GET-Telecom Paris, LTCI-UMR 5141 CNRS ; 46, rue Barrault, 75634 Paris, France
(τ) INRIA, Campus universitaire de Beaulieu ; 35042 Rennes Cedex, France
(†) PRiSM Laboratory, UMR 8144 ; 45, avenue des Etats-Unis, 78035 Versailles, France
E-Mail: rami.langar@enst.fr ; nizar.bouabdallah@inria.fr ; Samir.Tohme@prism.uvsq.fr

***Abstract*—One of the major challenges for the next-generation mobile systems is related to efficient mobility management issue. In this paper, we propose a new micro-mobility management scheme, called Micro Mobile MPLS, that supports both mobility and quality-of-service (QoS) management in wireless networks. Our proposal includes two protocol variants. In the first variant, called FH-Micro Mobile MPLS, we consider the fast handoff (FH) mechanism, which anticipates the LSP (Label Switched Path) procedure setup with an adjacent neighbor subnet that an MN is likely to visit. This mechanism is proposed to reduce service disruption by using the link-layer (L2) functionalities. In the second variant, called FC-Micro Mobile MPLS, the forwarding chain (FC) concept is provided to track efficiently the host mobility within a domain. This concept is more suitable for MNs with high mobility rate. In order to assess the efficiency of our proposals, all underlying protocols are compared. To achieve this, we develop analytical models to evaluate the link usage cost, the registration updates cost, the handoff latency and the packet loss rate. Numerical and simulation results show that the proposed mechanisms can significantly reduce the registration updates cost and provide low handoff latency and packet loss rate under various scenarios.**

***Index Terms*—Mobile IP, MPLS, mobility tracking and modeling, micro-mobility, fast handoff, forwarding chain, wireless systems.**

I. INTRODUCTION

Mobile operators are transitioning toward third-generation networks and beyond in order to provide high-speed data access and sophisticated services, predominantly based on the Internet Protocol (IP). The IP-based wireless networks have the advantages of directly applying IP techniques and applications written for wired networks to wireless ones [1].

Two important problems still remain to be solved even if the IP techniques are adopted in the next-generation networks: how to maintain the network connectivity and how to assure the provisioning of enough network resources to MNs. Mobility management in mobile communication systems is an important task in order to keep connectivity with roaming users at anytime. Mobile IP [2], which is a standard proposed by the Internet Engineering Task Force (IETF), can serve as the basic mobility management in IP-based wireless networks. For the resource provisioning, there are three different architectures to provide network resources for quality-of-service (QoS) guarantees in the Internet: Integrated Services (Intserv) [3], Differentiated Services (Diffserv) [4] and Multiprotocol Label Switching (MPLS) [5].

Mobile IP specified a mechanism to enable an MN to change its point of attachement without changing its IP address. Both Mobile IPv4 and Mobile IPv6 are discussed in the IETF. Though our work is based on Mobile IPv4, the similar modification can be deployed in IPv6 framework. In Mobile IP, an MN is assigned with a permanent homem address in its home network, and will borrow a temporary care-of address (CoA) in any foreign network [6]. The home agent (HA) in the MN's home network will maintain the mapping between the home address to the CoA. The CoA is often the IP address of the foreign agent (FA) in the current visited foreign network.

Packets which are sent from a correspondent node in the Internet and destined to an MN are first intercepted by the MN's HA, and then tunneled to the current serving FA using the MN's CoA. The FA then decapsulates the packets and forwards them to the MN. This routing path will increase the packet delivery cost and is mostly criticized as a triangular routing problem. In addition, Mobile IP has other problems such as long handoff latency and large signaling load for frequent registration updates. Some enhancements to Mobile IP for MNs with frequent handoffs have been studied in [7]– [14].

On the other hand, the notable benefits of MPLS [5] in terms of QoS, traffic engineering and support of advanced IP services, such as virtual private networks, inspire some works to use this technology in the wireless infrastructure [15]– [23]. In fact, using MPLS tunnels called label switched paths (LSPs), an overlay network will be efficiently created and managed. In MPLS, tunnel redirection happens quickly at the change of a label in a single node in the network.

This paper is based on "On the analysis of Micro Mobile MPLS access networks: the fast handoff and the forwarding chain mechanisms," by R. Langar, S. Tohme, N. Bouabdallah and G. Pujolle, which appeared in the Proceedings of the 3rd IEEE Consumer Communications and Networking Conference (CCNC), Las Vegas, NV, USA, Jan. 2006.

The design and integration of mobility management and QoS provisioning in the wireless networks is a real challenge. In this paper, we propose a new micro-mobility management scheme, called Micro Mobile MPLS, that supports both mobility and QoS management in wireless networks. Our proposal supports three protocol variants. In the first variant called FH-Micro Mobile MPLS, we consider the fast handoff (FH) mechanism, which anticipates the LSP procedure setup with an adjacent subnet that an MN is likely to visit. This mechanism is proposed to reduce service disruption by using the L2 functionalities. In the second variant called FC-Micro Mobile MPLS, the forwarding chain (FC) mechanism, which is a set of forwarding path, is provided to track efficiently the host mobility within a domain. The forwarding chain mechanism fits the wireless environment with high mobility rate, where packets must be quickly redirected to their new locations. To gauge the effectiveness of our proposed mechanisms, we derive analytical expressions of the signaling cost, link usage, and handoff performance metrics (i.e., handoff latency and packet loss rate). Numerical and simulation results show that our proposals can significantly reduce the registration updates cost and provide low handoff latency and packet loss rate when compared to the existing schemes (FMIP [10], MIP-RR [9], Mobile MPLS [15], H-MPLS [18]) under various scenarios.

The remainder of this paper is organized as follows. Section II gives a brief survey of the previous work. Section III introduces our proposed architecture along with a detailed description of the above mentioned protocol variants. In section IV, we develop analytical models to derive the signaling cost function of registration updates, the link usage and the handoff performance for all underlying protocols. Numerical and simulation results are given in section V. Finally, section VI contains our concluding remarks.

II. Related Works

There have been several works on micro-mobility in wireless IP networks [7]– [23], each with different advantages and disadvantages.

Specifically, authors in [9] propose the regional registration protocol (MIP-RR) to reduce the number of signaling messages to the home network and the signaling delay by performing registrations locally in a regional network. This scheme which is based on the hierarchical mobility management makes most of registration updates hidden from the HA. The registration updates end at the gateway FA (GFA) of the current visited domain (or region). The structure can be extended to include multiple hierarchy levels of FAs beneath the GFA level. However, recursive tunnelling has to be applied, which results in longer latencies and affects the flexibility of the system [24].

[7] proposes a distributed dynamic regional location management scheme for Mobile IP to reduce the overall signaling cost. They assume that every FA has the functionality of a FA and a GFA. However, this assumption is not realistic. Authors in [8] showed the limitations of this approach due to its limited applicability. Note that this scheme can be seen as an extension of the IETF regional registration protocol [9].

In [10], a fast handoff mechanism for Mobile IP is proposed. This scheme, so-called FMIP, enables an MN to quickly discover that it has moved to a new subnet and receive data as soon as its attachment is detected by the new access router. This approach has a significant effect on the performance of real-time and QoS sensitive applications. However, the location update cost in FMIP can be excessive, especially for the mobile nodes with relatively high mobility and long distance to their HAs.

[15] 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 to Foreign Agent using Label Switched Paths (LSPs). However, such a scheme suffers from the non-applicability to micro-mobility, as the scope of Mobile IP is more shifted towards the global mobility.

In [16], [17], a framework associated with signaling for intra-domain mobility using LSP redirection in a traffic engineered network has been proposed. An enhanced LER called the label edge mobility agent (LEMA) is introduced to support chained LSP-redirection. An MPLS domain is augmented to support micro-mobility by adding the LEMA functionality to a subset of the existing MPLS nodes. 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 [18] and several other schemes ([19–23]) try to ameliorate the performance of Mobile MPLS [15] by using different architectures. A Foreign Domain Agent (FDA) is introduced into each MPLS domain to support intra-domain mobility. However, these works 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 updates cost, the loss of a large amount of in-flight packets and the degradation of QoS. Note that the in-flight packets are the packets possibly lost during the handoff period. In addition, with high mobility rate, the system performance is critically affected by frequent registrations with the FDA, resulting in excessive signaling traffic and long service delay. Moreover, most of these works 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 the cost and the complexity inside the MPLS network.

III. Proposed Approach: Micro Mobile MPLS

In this section, we describe our new scheme called Micro Mobile MPLS and its three variants. Micro Mobile MPLS is based on the integration of MIP-RR [9] and MPLS [5] protocols. A typical architecture for Micro Mobile MPLS networks [25] is shown in figure 1. We assume that an MPLS access network exists between the Label Edge Router Gateway (LERG) and the Label Edge Router/Foreign Agents (LER/FAs). The network architecture is based on a two-level hierarchy. At the higher level is the LERG that 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 access points (APs) that offer link-layer connectivity. We distinguish here between link-layer functionalities of the air interface, which are handled by the AP, 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.

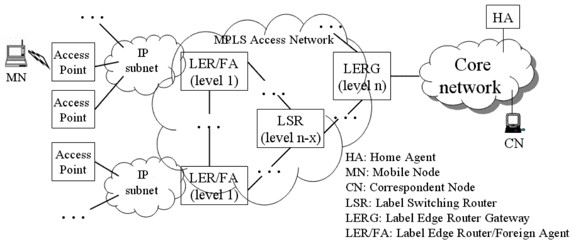


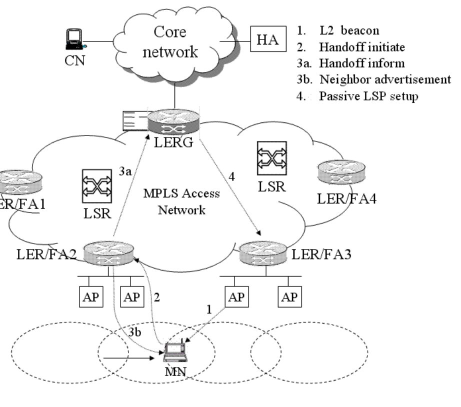
Figure 1. Architecture of a Micro Mobile MPLS wireless access network

In this paper, the handoff latency is defined as the time elapsed from the moment the handoff event is detected to the moment the first packet is received from the new subnet. There are two types of handoff in wireless access network: Intra-LER and Inter-LER handoffs [25]. An Intra-LER handoff occurs when the MN moves between two APs managed by the same LER/FA. This kind of handoff is basically L2 (link-layer) handoff. On the other hand, an Inter-LER handoff occurs when a new AP and the old AP are under different LER/FAs. This kind of handoff is typically L3 (network-layer) handoff. In this work, we focus on Inter-LER handoff since it has the most important effect on the handoff performance. As a first main specification of our scheme, the old LER/FA will be notified to buffer in-flight packets at each handoff occurrence. This operation is common for all the protocol variants. Indeed, to reduce the packet loss during handoff, our scheme relies on the L2 trigger [26]. The L2 trigger is a signal from L2 to inform L3 an imminent L2 handoff. That is, once the received signal strength from the current AP falls below the threshold level, the MN sends a "Movement signaling message" to the current LER/FA, to notify an imminent L2 handoff. According to our scheme, as soon as the current LER/FA receives this message, it initiates the buffering mechanism. In what follows, we present the specific operation of each protocol variant, namely, FH- and FC-Micro Mobile MPLS.

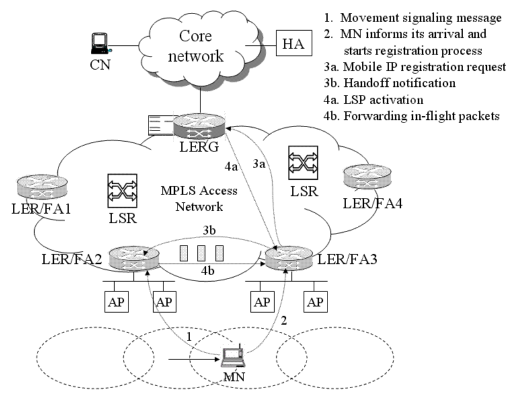
A. The Fast Handoff mechanism: FH-Micro Mobile MPLS

The main idea behind FH-Micro Mobile MPLS is to anticipate the L3 Inter-LER handoff using the L2 functionalities and to setup an LSP before the MN moves really 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. On the other side, a passive LSP is the one from the LERG to the neighboring subnet to which the MN is moving to. This LSP is not currently used until its activation.

The FH-Micro Mobile MPLS scheme employs a link-layer movement detection scheme to predict the possible MN's next location. In other words, as can be seen in figure 2a, once the MN enters an overlapped area of the boundary cells of two subnets, it receives a L2 beacon from the possible new AP (step 1). Immediately, the MN notifies the current LER/FA for the possible handoff by sending a *handoff initiate* signaling message, which contains the MAC address of the new AP (step 2). Note that in this case, the MN is not yet connected to the radio link of the new subnet and is still in connection with the old AP. Each LER/FA has a *neighbor mapping table* that binds IP and MAC addresses of its entire neighbor APs. Hence, when the current LER/FA receives the *handoff initiate* signaling message, it looks into its neighbor mapping table to get the new LER/FA's IP address and then informs the LERG for the possible handoff operation (step 3a). Immediately, the LERG initiates the LSP procedure set up with the new LER/FA before the L3 handoff occurs (i.e., before the MN receives the Mobile



(a) Before handoff



(b) During handoff

Figure 2. Operation of the FH-Micro Mobile MPLS scheme

IP advertisement message from the new FA). That is, the FH-Micro Mobile MPLS will pre-establish an extra passive LSP between the LERG and the new subnet that the MN is likely to visit (step 4). At the same time of step 3a, the current LER/FA informs the MN for the new Regional Care-of-Address (RCoA: the IP address of the new possible LER/FA) by sending a *Neighbor Advertisement* signaling message (step 3b). This allows the MN to be able to start registration process with the LERG before receiving the new Mobile IP advertisement message from the new FA (i.e., the L3 beacon). Note that the MN's registration to the LERG is initiated only when the L2 handoff is performed. Specifically, the L2 handoff is launched by the MN when the received signal strength from the current AP falls below the threshold level. In this case, the MN notifies the current LER/FA to initiate the buffering mechanism by sending a Movement signaling message (see figure 2b, step 1). Once the L2 handoff is accomplished, the L3 handoff is initiated by the MN even before it receives the new Mobile IP advertisement message from the new FA since the MN is already aware of the new RCoA (step 2). The new FA forwards the Mobile IP registration request message to the LERG (step 3a) and notifies the old LER/FA for the handoff event (step 3b). As soon as the LERG receives the Mobile IP registration request, it activates the pre-established passive LSP and traffic will be delivered through the activated LSP (step 4a). On the other hand, once the old LER/FA is notified (step 3b), the in-flight packets are forwarded to the MN through the new FA (step 4b). By using the fast handoff mechanism, we can improve the handoff performance of Micro Mobile MPLS and reduce service disruption.

B. The Forwarding Chain mechanism: FC-Micro Mobile MPLS

The second protocol variant that we propose to handle efficiently the 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 3. By this procedure, the existing LSP between the LERG and the old subnet will be extended from the old FA to the new one. As a result, a forwarding chain of FAs will be constructed for each MN. To do so, each MN keeps a buffer for storing IP addresses of the visited LER/FAs. Packets traveling towards 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.

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 delete all the addresses in its buffer. That is, the MN forwarding chain will be renewed and the new visited LER/FA becomes the new master FA. Note that this scheme enables a significant reduction of the registration update messages sent by the MN to the LERG. These LERG registrations are replaced by simple forwarding chain updates (local registrations). In addition, such a scheme is appropriate for MNs with high mobility rate, where data packets must be forwarded quickly to their new locations.

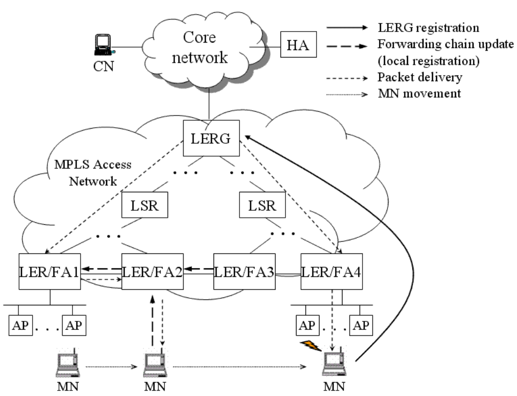


Figure 3. Operation of the FC-Micro Mobile MPLS scheme

The basic operation of the FC-Micro Mobile MPLS scheme is depicted in figure 3. In this case, the 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 notifies the new RCoA to the previous LER/FA2. In this case, data packets destined to the MN are intercepted by the LERG and sent 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. Doing so, 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. At the same time, the new LER/FA4 becomes the master FA of the next forwarding chain. The FC-Micro Mobile MPLS scheme can be described by the pseudocode in table I [27].

IV. PERFORMANCE EVALUATION & ANALYSIS

In this section, we develop analytical models to derive the link usage, the handoff performance and the cost function of registration updates. This analysis includes our two protocol variants (FH- and FC-Micro Mobile MPLS) and competing schemes. Indeed, we compare our proposals with respect to the FMIP [10], MIP-RR [9], Mobile MPLS [15] and H-MPLS [18] schemes.

For analytical simplicity, we consider a full binary tree with the LERG as a root, as shown in figure 4. The depth ℓ of a full binary tree with N nodes is $\lfloor \log_2 N \rfloor + 1$.

TABLE I.
FC-MICRO MOBILE MPLS SCHEME

```
%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
```

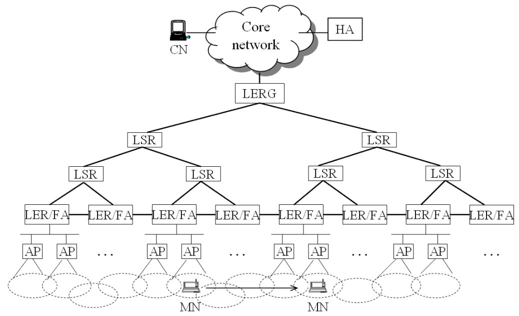


Figure 4. A full binary tree access network of depth $\ell = 4$

That is, a full binary tree of depth ℓ has $2^\ell - 1$ nodes (including the LERG, LSRs and LER/FAs), $\ell \geq 1$, and the number of subnets or leaf nodes (LER/FAs) is $2^{\ell-1}$. Moreover, we assume that the mobility of mobile nodes is restricted to two directions (forward and backward). That is, an MN which is in subnet i, can only move to two neighboring subnets $i+1$ or $i-1$ with equal probability p ($p = \frac{1}{2}$). Examples include roads, tunnels, train and train stations. Below, we introduce the parameters that will be used in the analysis.

Parameters:

- t_s average session connection time
- t_r average FA resident time
- T_{ad} time interval for a FA to send agent advertisements
- N_h average number of L3 handoff during a session (i.e., $N_h = t_s/t_r$)
- N_f average number of renewals of the forwarding chain during a session (i.e., $N_f = N_h/L_{th}$)
- 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
- λ downlink packet transmission rate
- s_u average size of a signaling message for the registration update
- s_l average size of a label message for LSP setup
- h_{x-y} average number of hops between x and y in the wired network
- C_{fh} location update cost between an FA and the HA (hop $\times$ message size)
- C_{fg} location update cost between an LER/FA and the LERG (hop $\times$ message size)
- C_{ff} location update cost between two neighboring LER/FAs (hop $\times$ message size)
- l_{fh} traffic load related to LSP setup procedure between an FA and the HA (hop $\times$ message size)
- l_{fg} traffic load related to LSP setup procedure between an LER/FA and the LERG (hop $\times$ message size)
- l_{ff} traffic load related to LSP setup procedure between two neighboring LER/FAs (hop $\times$ message size)

C_i and l_i parameters can be written as:

$$\begin{cases} C_{fg} = 2s_u h_{FA-LERG} = 2s_u(\ell - 1) \\ C_{fh} = 2s_u h_{FA-HA} = 2s_u h_{HA-LERG} + 2s_u(\ell-1) \\ C_{ff} = 2s_u h_{FA-FA} = 2s_u \\ l_{fg} = 2s_l h_{FA-LERG} = 2s_l(\ell-1) \\ l_{fh} = 2s_l h_{FA-HA} = 2s_l h_{HA-LERG} + 2s_l(\ell-1) \\ l_{ff} = 2s_l h_{FA-FA} = 2s_l \end{cases} \tag{1}$$

A. Framework: Modeling Mobility Behavior of an MN

Let $X(t)$ be the distance (in terms of number of hops) between the subnet in which the MN is located at time t (current serving LER/FA) and the master LER/FA. The residence time of the MN in subnet i is assumed to be exponentially distributed with the mean $1/\mu$. $\{X(t), t \geq 0\}$ forms a Continuous-Time Markov Chain (CTMC) with state space $S = 0, 1, 2, ..., (L_{th} - 1)$ as depicted in figure 5.

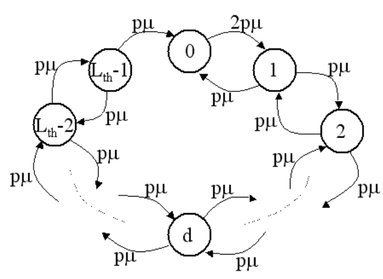


Figure 5. CTMC of the proposed mobility model of an MN

Let $\Pi_d = \lim_{t\to\infty} Prob[X(t) = d], d \in E1$, be the stationary probability distribution of $X(t)$. Based on figure 5, the balance equations can be derived as follows:

$$\begin{cases} 2p\,\mu\,\Pi_0 = p\,\mu\,\Pi_1 + p\,\mu\,\Pi_{L_{th}-1} \\ 2p\,\mu\,\Pi_1 = 2p\,\mu\,\Pi_0 + p\,\mu\,\Pi_2 \\ 2p\,\mu\,\Pi_d = p\,\mu\,\Pi_{d-1} + p\,\mu\,\Pi_{d+1} \quad \forall\, 2 \le d \le (L_{th}-2) \\ 2p\,\mu\,\Pi_{L_{th}-1} = p\,\mu\,\Pi_{L_{th}-2} \\ \sum_{d=0}^{L_{th}-1} \Pi_d = 1 \end{cases} \tag{2}$$

Solving these equations, we obtain:

$$\begin{cases} \Pi_0 = \dfrac{1}{L_{th}} \\ \Pi_d = \dfrac{2(L_{th}-d)}{L_{th}^2} \quad \forall\, 1 \le d \le (L_{th}-1) \end{cases} \tag{3}$$

B. Link Usage in the MPLS access network

Let LU denote the link usage in the MPLS access network, which is the number of links used for packet delivery between the MN and the LERG. Recall that, in FMIP, MIP-RR, Mobile MPLS, H-MPLS and FH-Micro Mobile MPLS schemes, packet are delivered using the shortest path routing. Hence, packets exchanged between the LERG and any FA traverse $(\ell-1)$ hops. However in FC-Micro Mobile MPLS, packets have to traverse the connection binding the LERG to the master FA and the forwarding chain binding the master FA to the MN. The mean value of LU for FC-Micro Mobile MPLS can thus be given by:

$$\begin{aligned} &LU(\text{FC-Micro Mobile MPLS}) \\ &= \sum_{i,j \in E1} Prob(MN \in j | MN \in i) \times \Pi_i \times LU_{|MN \in\, j} \\ &= \ell - 1 + \Big(\sum_{d=1}^{L_{th}-1} d\,\Pi_d \Big) \end{aligned} \tag{4}$$

where the first term $(\ell-1)$ is the number of links from the LERG to the master LER/FA and the second term is the mean path length used to forward packets from the master LER/FA to the current serving LER/FA (i.e., average forwarding chain size).

C. Registration Updates Cost

Let C_u denote the signaling cost of registration updates when a L3 handoff occurs. It is the traffic load of signaling messages (hop $\times$ message size) exchanged in the network when the MN moves to a new subnet. In FMIP, the MN only performs a home registration update with the HA. In Mobile MPLS, we have to take into consideration the additional cost associated to the LSP procedure setup with the new FA. In MIP-RR, only a LERG registration update with the root of the domain is required. Additional cost, associated to the LSP procedure setup with the new FA, is to be considered in H-MPLS. In FH-Micro Mobile MPLS, a LERG registration update and a handoff notification to the old LER/FA (in order to forward in-flight packets) are performed at every L3 handoff. Note that in this case, the LSP binding the LERG and the new LER/FA already exists and only needs activation. In FC-Micro Mobile MPLS, a local registration is required as long as the forwarding chain length does not reach the threshold. Otherwise, a LERG registration is performed. This happens when the distance of the current serving LER/FA from the master FA is $(L_{th}-1)$, and the MN moves in the direction that increases this distance (which happens with probability p). We summarize the expression of registration updates cost for all underlying protocols as follows:

$$\begin{cases} C_u(\text{FMIP}) = C_{fh} \\ C_u(\text{MIP-RR}) = C_{fg} \\ C_u(\text{Mobile MPLS}) = C_{fh} + l_{fh} \\ C_u(\text{H-MPLS}) = C_{fg} + l_{fg} \end{cases} \tag{5}$$

$$\begin{cases} C_u(\text{FH-Micro Mobile MPLS}) = C_{fg} + C_{ff} + l_{ff} \\ C_u(\text{FC-Micro Mobile MPLS}) \\ \quad = 2p\,\Pi_0\,(C_{ff}+l_{ff}) + \sum_{d=1}^{K-2} p\,\Pi_d\,(C_{ff}+l_{ff}) \\ \quad\quad + p\,\Pi_{L_{th}-1}\,(C_{fg}+l_{fg}) \\ \quad = p\,(1+\Pi_0-\Pi_{L_{th}-1})\,(C_{ff}+l_{ff}) \\ \quad\quad + p\,\Pi_{L_{th}-1}\,(C_{fg}+l_{fg}) \end{cases} \tag{6}$$

Hereafter, we define the call-to-mobility ratio (CMR) as the ratio of the packet arrival rate to the mobility rate, i.e., $CMR = \psi = \lambda\, t_r$. Then, using the equations (1) and (3), the unit time cost of registration updates ($C_u^{'} = C_u/t_r$) for all underlying protocols can be expressed as:

$$\begin{cases} C_u^{'}(\text{FMIP}) = \dfrac{2\,s_u\,\lambda}{\psi} \times \big(\ell - 1 + h_{HA-LERG}\big) \\ C_u^{'}(\text{MIP-RR}) = \dfrac{2\,s_u\,\lambda}{\psi} \times (\ell-1) \\ C_u^{'}(\text{Mobile MPLS}) = \dfrac{2\,\lambda}{\psi}\,(s_u+s_l)\big(\ell - 1 + h_{HA-LERG}\big) \\ C_u^{'}(\text{H-MPLS}) = \dfrac{2\,\lambda}{\psi}\,(s_u+s_l) \times (\ell-1) \end{cases} \tag{7}$$

$$\begin{cases} C_u^{'}(\text{FH-Micro Mobile MPLS}) = \dfrac{2\,\lambda}{\psi} \times (s_l + \ell\, s_u) \\ C_u^{'}(\text{FC-Micro Mobile MPLS}) \\ \quad = \dfrac{2p\,\lambda}{\psi} \times (s_u+s_l) \times \big(1 + \dfrac{1}{L_{th}} - \dfrac{2}{L_{th}^2}\big) \\ \quad\quad + \dfrac{4p\,\lambda}{\psi} \times \dfrac{\ell-1}{L_{th}^2} \times (s_u+s_l) \end{cases} \tag{8}$$

D. Average handoff time

For convenience, let $t(s, h_{x-y})$ denote the time that takes a message of size s to be forwarded from x to y

via both the wired and wireless links. $t(s, h_{x-y})$ can be expressed as follows:

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

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

The average handoff time (T_h) can be expressed as the sum of two terms: disruption time (T_d) and completion time (T_c).

Disruption time (T_d): It is the average time that spends an MN 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 that the disruption time becomes null when the overlapping area is large enough. The worst case value for this quantity is equal to the L3 beacon period (T_{ad}). T_d can be given by the following expression:

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

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

$$T_d = \begin{cases} 0 & \text{if } T_{overlap} \geq T_{ad} \\ \frac{T_{ad}}{2} + \frac{T_{overlap}^2}{2T_{ad}} - T_{overlap} & \text{otherwise} \end{cases} \quad (9)$$

Note that with FMIP and FH-Micro Mobile MPLS schemes, the disruption time (T_d) corresponds to the physical disconnection from the old AP until the connection to the new one. As soon as the MN establishes a physical connection with the new AP, it starts receiving in-flight packets through the new FA.

Completion time (T_c): It is the time to complete the registration update. We summarize the T_c value corresponding to each scheme as follows:

$$\begin{cases} T_c(\text{FMIP}) = 2\, t(s_u, h_{MN-HA}) \\ T_c(\text{MIP-RR}) = 2\, t(s_u, h_{MN-GFA}) \\ T_c(\text{Mobile MPLS}) = 2\, t(s_u, h_{MN-HA}) + 2\, t(s_l, h_{FA-HA}) \\ T_c(\text{H-MPLS}) = 2\, t(s_u, h_{MN-LERG}) + 2\, t(s_l, h_{FA-LERG}) \end{cases} \quad (10)$$

$$\begin{cases} T_c(\text{FH-Micro Mobile MPLS}) \\ \quad = 2\, t(s_u, h_{MN-LERG} + h_{FA-FA}) \\ T_c(\text{FC-Micro Mobile MPLS}) \\ \quad = 2\, t(s_u, h_{MN-FA} + h_{FA-FA}) + 2\, t(s_l, h_{FA-FA}) + \\ \quad 2 \times \frac{N_f}{N_h} \times \left[t(s_u, h_{MN-LERG}) + t(s_l, h_{FA-LERG}) \right] \end{cases} \quad (11)$$

E. 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 MIP-RR, Mobile MPLS and H-MPLS, all in-flight packets will be lost during the handoff time due to the lack of any buffering mechanism. In FMIP, FH-, and FC-Micro Mobile MPLS, in-flight packets would be lost till the buffering mechanism is initiated. As mentioned before, the L2 trigger is used in FMIP as well as in our proposed schemes. Pkt_loss for each scheme can be expressed as follows:

$$\begin{cases} Pkt\_loss(\text{FMIP}) = t(s_u, h_{MN-FA}) \times \lambda \times N_h \\ Pkt\_loss(\text{MIP-RR}) = T_h(\text{MIP-RR}) \times \lambda \times N_h \\ Pkt\_loss(\text{Mobile MPLS}) = T_h(\text{Mobile MPLS}) \times \lambda \times N_h \\ Pkt\_loss(\text{H-MPLS}) = T_h(\text{H-MPLS}) \times \lambda \times N_h \\ Pkt\_loss(\text{(FH/FC)-Micro Mobile MPLS}) \\ \qquad = t(s_u, h_{MN-FA}) \times \lambda \times N_h \end{cases} \quad (12)$$

F. Buffer size requirement

According to our schemes, a buffer is required at the old LER/FA to store in-flight packets during each handoff operation. Note that in the FMIP case, the buffer is located at the new access router. As stated before, the buffering mechanism is activated in our schemes when the current LER/FA receives the Movement signaling message. This message notifies an imminent L2 handoff occurrence. On the other side, the buffering mechanism is disabled when the current LER/FA is notified by the new FA to forward in-flight packets. In FH-Micro Mobile MPLS, the signaling message used to notify the old FA corresponds to the handoff notification message. In FC-Micro Mobile MPLS, it corresponds to the forwarding chain update message. The buffer size requirement (Buf_size) for FMIP, FH-, and FC-Micro Mobile MPLS is listed as follows:

$$\begin{cases} Buf\_size(\text{FMIP}) = [\ T_d + t(s_u, h_{MN-FA})\ ] \times \lambda \\ Buf\_size(\text{(FH/FC)-Micro Mobile MPLS}) \\ \qquad = \ [\ T_d + t(s_u, h_{MN-FA} + h_{FA-FA})\ ] \times \lambda \end{cases} \quad (13)$$

V. NUMERICAL & SIMULATION RESULTS

In this section, we compare all underlying protocols using both analytical and simulation approaches. The parameter settings in our experiments are listed in table II.

TABLE II.
PARAMETER SETTINGS

Parameter	Value	Parameter	Value
t_s	1000 sec	$h_{HA-LERG}$	4
t_r	5 ∼ 50 sec (default 20)	P_t	10^{-6} sec
T_{ad}	1 sec	B_w	100 Mbps
L2 Beacon	100 msec	B_{wl}	11 Mbps
s_u	48 bytes	L_w	1 msec
s_l	28 bytes	L_{wl}	2 msec
L_{th}	1 ∼ 15 (default 4)	λ	64 Kbps

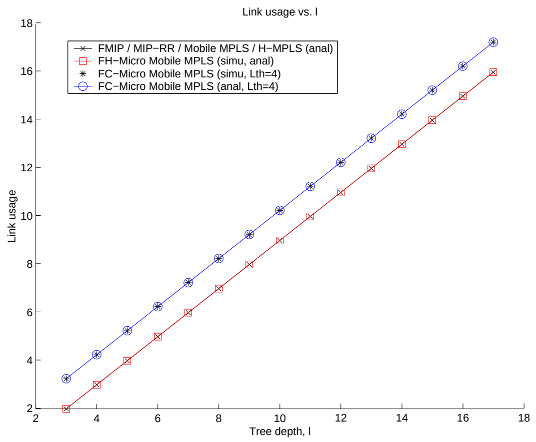


Figure 6. Link usage cost

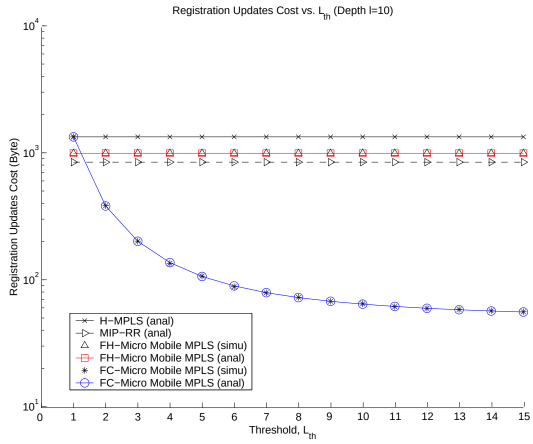


Figure 8. Effect of L_{th} on the registration updates cost in FC-Micro Mobile MPLS

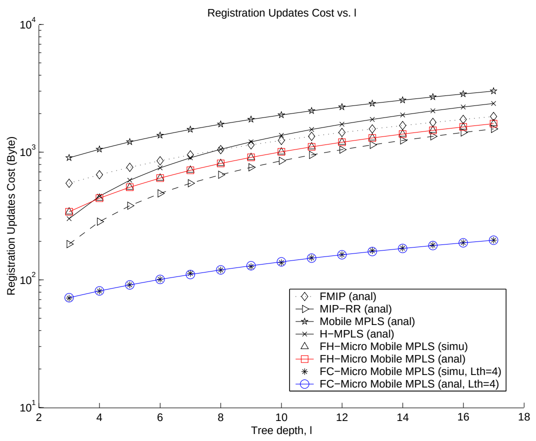


Figure 7. Registration updates cost at every L3 handoff

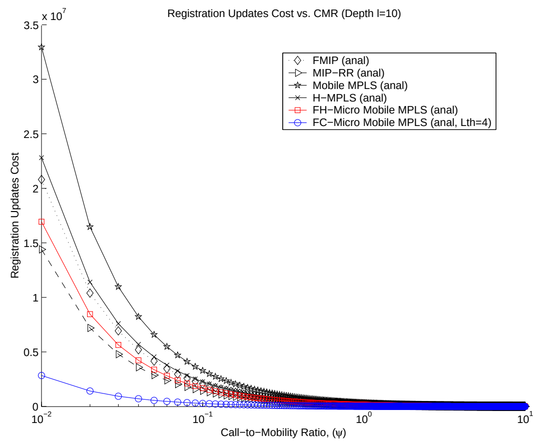


Figure 9. Effect of CMR (ψ) on the registration updates cost

Figure 6 represents the link usage cost of all underlying protocols. We can see that the cost of FC-Micro Mobile MPLS is higher than that of the remaining protocols. This slight difference is due to the additional cost introduced by the forwarding chain.

Figure 7 plots the different registration updates costs at every L3 handoff. The FH-Micro Mobile MPLS scheme exhibits a lower registration cost than FMIP, Mobile MPLS and H-MPLS protocols, since the required LSP between the LERG and the new LER/FA already exists. However, it has a higher registration cost than MIP-RR, due to the extra signaling messages sent to the old subnet to forward in-flight packets. FC-Micro Mobile MPLS, on the other hand, provides the lowest registration cost since some expensive LERG registration updates are replaced by low-cost local registrations. Note that the LERG registration updates cost increases with the depth ℓ of the tree. In view of this, the FC gain, with respect to the remaining solutions, increases with this parameter. Notice that analytical results practically coincide with the simulation ones, which illustrates the accuracy of our models.

Figure 8 depicts the registration updates cost of all underlying protocols as a function of the threshold L_{th}. We can observe that the registration updates cost of FC-Micro Mobile MPLS decreases with L_{th}. Indeed, the expensive LERG registrations become less frequent. They are replaced by low-cost (1 hop) local registrations. However, we note that the threshold value will be limited by delay constraint. Typically, delay sensitive applications, such as video or voice services, will require small values of L_{th} to ensure acceptable end-to-end delay. Finally, we point out that the variation of L_{th} does not affect the performance of the other studied protocols (FMIP, MIP-RR, Mobile MPLS, H-MPLS, and FH-Micro Mobile MPLS). Thus, the results presented in figures 6 and 7 for these schemes are L_{th}-independent.

Figure 9 shows the effect of the CMR parameter on the registration updates cost for different schemes. In this figure, we observe that when the CMR is small (i.e., when the MN handoffs frequently), the FH-Micro Mobile MPLS scheme generates less signaling traffic than the FMIP, Mobile MPLS and H-MPLS schemes, which are more suitable for mobile users with high CMR. We notice also that FC-Micro Mobile MPLS can significantly reduce the registration updates cost mainly when the CMR

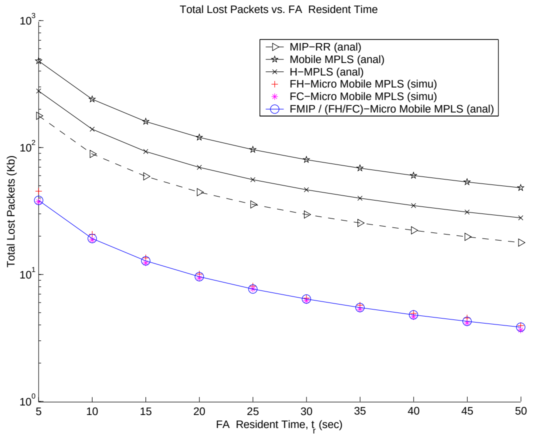


Figure 10. Total lost packets during a session

value is low. Our results demonstrate that this scheme can reduce the MIP-RR signaling cost by 70% when the CMR is small. Note that, this considerable gain is obtained with respect to the MIP-RR scheme, which exhibits the best cost among the existing protocols. According to these results, the FC mechanism is the best strategy for MNs with high mobility rate.

TABLE III.
AVERAGE HANDOFF TIME IN MSEC

FMIP	30.198
MIP-RR	22.159
Mobile MPLS	56.256
H-MPLS	40.199
FH-Micro Mobile MPLS	24.171
FC-Micro Mobile MPLS	18.136

The average handoff time values for different schemes are listed in table III. Each value was obtained by averaging 100 consecutive simulations. These results are obtained considering a non-null overlapping distance between cells. The simulated access network consists of a full binary tree of depth $\ell = 10$ and $L_{th} = 4$. Every leaf node (LER/FA) is connected to one AP. During simulations, the MN moves periodically between neighboring APs and receives downlink packets. The simulations are run using the Network Simulator NS-2 [28]. As can be seen, FH-Micro Mobile MPLS improves the handoff performance when compared with FMIP, Mobile MPLS and H-MPLS since the registrations are performed within a local domain and the required active LSP between the root and the new subnet already exists. Furthermore, FC-Micro Mobile MPLS provides the lowest average handoff time. Recall that in this case, the registrations are often carried out with the previous FA instead of the LERG. This enables shorter delay to complete the registration updates.

Figure 10 shows the amount of lost packets during the whole connection session for different schemes according to the same scenario. We observe that the total lost packets for all approaches increases when the MN handoffs frequently (i.e., when the FA resident time is short). Notice that Mobile MPLS has the largest amount of lost packets. In contrast, FMIP, 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 thousands of MNs.

VI. Conclusion

In this paper, we proposed a new micro-mobility management scheme, called Micro Mobile MPLS, that supports both mobility and quality-of-service (QoS) management in wireless access networks. We considered two protocol variants: the FH- and FC-Micro Mobile MPLS schemes. In FH-Micro Mobile MPLS, we suggested to anticipate the LSP establishment before the MN moves really into a new subnet to reduce service disruption by using the L2 functionalities. In FC-Micro Mobile MPLS, we proposed to track the MN's movement by using the forwarding chain concept. This new concept limits the range of handoff signaling messages to a local area. Doing so, we avoid the relatively long distance discussions with the root of the domain. We exhibited how this mechanism reduces the registration updates cost and provide low handoff latency and small packet loss rate. To achieve this, a comparison between our proposals and existing solutions (FMIP, MIP-RR, Mobile MPLS and H-MPLS) was given. We analytically derived the registration updates cost, the link usage and the handoff performance for all underlying protocols. We proved, through analysis and simulations, that our proposed mechanisms achieve a substantial signaling cost gain and improve the handoff performance at the price of a slight increase of the link usage cost.

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Rami Langar received the B.S. degree in telecommunications engineering from the Ecole Supérieure des Communications (Sup’Com), Tunis, Tunisia, in 2001. He received the M.S. degree from the University of Paris VI, France, in 2002, and the Ph.D. degree from the Ecole Nationale Supérieure des Télécommunications, ENST-Paris, France, in 2006, both in Network and Computer Science. He is currently a Postdoctoral research fellow in the School of Computer Science at the University of Waterloo, ON, Canada. His research interests include 4G visions, mobility management, resource management, performance evaluation and quality of service support.

Nizar Bouabdallah received the B.S. degree in telecommunications engineering from the 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.

Samir Tohme 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.