Mobility Modeling and Handoff Analysis for IP/MPLS-Based Cellular Networks

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Abstract— **One of the major challenges for the wireless networks 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 cellular networks. Our proposal includes two protocol variants. In the first variant, called FC-Micro Mobile MPLS, the forwarding chain (FC) concept is provided to track efficiently the host mobility within a domain. This concept fits mobile nodes (MNs) with high mobility rate. The second protocol variant, called Master Forwarding Chain (MFC)-Micro Mobile MPLS, aims to reduce the total signaling cost by controlling the number of registration updates with the root of the domain. In order to assess the efficiency of our proposals, the aforesaid protocols are compared with respect to the existing solutions. To achieve this, we develop analytical models to evaluate both registration updates and link usage costs. 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.**

I. 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. In this regard, several enhancements to Mobile IP for MNs with frequent handoffs have been studied in [2]– [7].

Specifically, authors in [2] propose a distributed dynamic regional location management scheme for Mobile IP to reduce the overall signaling cost. They assume that every Foreign Agent (FA) has the functionality of a FA and Gateway Foreign Agent (GFA). However, this assumption is not realistic and there is no provision for end-to-end QoS support. Authors in [3] showed the limitations of this approach due to its limited applicability. In [4], a fast handoff mechanism for Mobile IP, called FMIP, is proposed. 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 Home Agents (HAs).

On the other hand, the notable benefits of MPLS [8] 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 [9] – [14].

In view of this, [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 the HA to the FA 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 [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] [13] [14]) 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 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.

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 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. On the other hand, the second protocol variant, called Master Forwarding Chain (MFC)-Micro Mobile MPLS, aims to reduce the total signaling cost by controlling the number of registration updates to the root of the domain. To gauge the effectiveness of our proposed mechanisms, we derive analytical expressions of both registration updates and link usage costs. Numerical and simulation results show that our proposals can significantly reduce the registration updates cost and also provide low handoff latency and packet loss rate when compared to the existing schemes (FMIP [4], MIP-RR [5], Mobile MPLS [9], H-MPLS [11]) under various scenarios.

The remainder of this paper is organized as follows. Section II introduces our proposed architecture along with a detailed description of the above mentioned protocol variants. Section III describes the system model used to evaluate the performance of the proposed schemes. In section IV, we develop analytical models to derive the signaling cost function of registration updates and the link usage for all underlying protocols. Numerical and simulation results are given in section

V. Finally, section VI contains our concluding remarks.

II. MICRO MOBILE MPLS AND ITS TWO VARIANTS

In this section, we describe our new scheme called Micro Mobile MPLS and its two variants. Micro Mobile MPLS [15] is based on the integration of Mobile IP Regional Registration [5] and MPLS [8] protocols. 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 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. Note that an LER/FA is the first IP-capable network element seen from the MN.

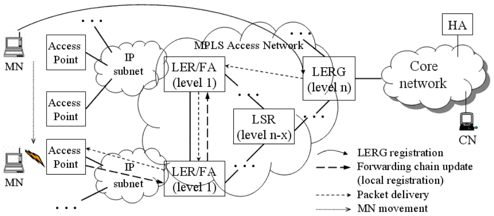

Fig. 1. Architecture of a Micro Mobile MPLS wireless access network

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As a first main specification of our scheme, when an Inter-LER handoff occurs, the old LER/FA will be notified to buffer in-flight packets. This operation is common for the two protocol variants. Indeed, to reduce the packet loss during handoff, our scheme relies on the L2 trigger [16]. 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 and initiate the buffering mechanism. In what follows, we present the specific operation of each protocol variant, namely, FC-, and MFC-Micro Mobile MPLS.

A. FC-Micro Mobile MPLS

The first protocol variant that we propose to handle efficiently the local mobility is called Forwarding Chain (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 Regional Care-of-address (RCoA: the IP address of the new LER/FA) will be registered at the old LER/FA instead of the LERG, as shown in figure 1. 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 could be appropriate for MNs with high mobility rate, where data packets must be forwarded quickly to their new locations.

B. MFC-Micro Mobile MPLS

The second proposed mechanism is called Master Forwarding Chain (MFC)-Micro Mobile MPLS. This protocol can be seen as an extension of the FC-Micro Mobile MPLS in cellular networks. In fact, in this technique, the MN registers with the LERG only when its distance, in terms of number of hops instead of movements, from the master FA reaches a threshold K. To illustrate the differences between FC and MFC mechanisms, we consider the simple example presented in figure 2. Assume that the MN's trajectory is $\{S_1, S_2, S_3, S_4, S_5, S_6\}$. Note that S_1 is the master FA. According to the FC scheme, the forwarding chain is $\{S_1, S_2, S_3, S_4, S_5, S_6\}$. Whereas, in the MFC case, the resulting forwarding chain is $\{S_1, S_3, S_6\}$, which is the shortest path between the master FA and the MN. It is easy to see that the MFC scheme reduces the forwarding chain size. In other words, considering the same threshold (i.e., $K = L_{th}$), the registration updates with the LERG are more frequent in the FC case than in the MFC one. In addition, the end-to-end delay is reduced with the MFC scheme thanks to the relatively shorter forwarding chain.

The second main difference between both schemes is related to the local registration. Considering the MFC scheme, each time that the MN moves to a new subnet, the new RCoA will be registered at the master FA instead of the old LER/FA, as long as the threshold is not reached. Henceforth, this kind of registration will be called local registration as opposed to the LERG registration. Specifically, the local registration is always done through only one hop in the FC case, whereas it can be done through up to $K - 1$ hops in the MFC case.

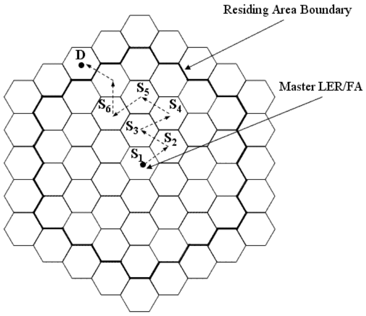


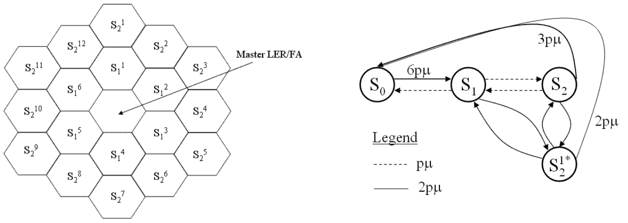
Fig. 2. Movement path of an MN with $K = 4$ and $L_{th} = 7$

According to the MFC mechanism, as long as the MN remains in a *residing area* around the master FA, regardless of the taken trajectory, it carries out a local registration (see figure 2). Once it leaves this area, it performs a LERG registration and the new serving LER/FA becomes the new MN's master FA. In the example of figure 2, the threshold K is set equal to 4. This figure shows the MN's trajectory. The LERG registration will be performed by the MN at location D since its distance to the master FA reaches the threshold K. Note that, unlike the MFC case, the LERG registration in the FC case depends mainly on the MN's trajectory.

III. SYSTEM MODEL

In this section, we study the MN's mobility. Our aim is to determine the position of an MN with respect to its master FA in order to be able to predict the MN's evolution. To do so, we develop Markovian models. The obtained results will be used, in a later stage, to derive the protocol performance metrics such as the registration updates cost and the link usage.

We consider polygon-based 2-D model. Typically, each LER/FA covers an hexagon area. This model is broadly used in the literature. In this case, each subnet is surrounded by six neighbors (see figure 3a). The MN can move to one of the neighboring subnets with equal probability p ($p = \frac{1}{6}$). For simplicity, we only present in this section the Markovian chain corresponding to the mobility behavior of an MN in the MFC-Micro Mobile MPLS case. Hence, in the remainder of this section we only consider the MFC case.



(a) Mobility model for the MFC scheme ($K = 3$)

(b) State transition diagram of the aggregated Markov chain for $K = 3$

Fig. 3. Mobility model and state transition diagram for $K = 3$

Figure 3a represents the *residing area* of an MN for the case $K = 3$. The *residing area* contains the master FA's subnet surrounded by $2 = K - 1$ loops of subnets. Each subnet is referenced by the loop label and its position inside that loop, which determines the exact MN's position with respect to the current master FA. For example, subnets belonging to loop 1 are referenced by S_1^j, $1 \leq j \leq 6$, those belonging to loop 2 are referenced by S_2^j, $1 \leq j \leq 12$, and so on and so forth. To generalize, let i ; $i = 0, 1, \ldots, (K - 1)$ designate the ith loop away from the master FA. The master FA's subnet is denoted by S_0^0. Subnets belonging to loop i are referenced by S_i^j, $1 \leq j \leq 6\,i$. Note that the loop label represents the distance between the MN and the master FA.

Let $X(t)$ be the MN's location within the residing area at time t. The residence time of an MN in each subnet S_i^j is assumed to be exponentially distributed with the mean $1/\mu$. $\{X(t), t \geq 0\}$ is therefore a Markov process with continuous time and finite state space $E = \{S_i^j \mid 0 \leq i \leq (K-1)\ ,\ 1 \leq j \leq 6\,i\}$. Recall that our main objective is to determine the MN's position within the *residing area* in order to predict its evolution. According to its next location, the MN can perform either a local registration or a LERG registration. In the latter case, the master FA will be updated and its associated *residing area* will be created.

The resolution of the Markovian chain $X(t)$, as defined above, is time-consuming. Moreover, this chain suffers from the state space explosion problem, mainly when the threshold K takes high values. To avoid this issue, we extract a new chain $Y(t)$ from $X(t)$ by aggregating its states. In other words, all the sates where the MN exhibits exactly the same behavior will be aggregated. Hence, the size of the state space E will be drastically reduced. To achieve this, we profit from the symmetric property of the 2-D model. In what follows, we describe the algorithm to perform state aggregation.

1) As before, S_i^j denotes the MN's position in the *residing area*. As presented in figure 3a, the state S_i^1 is chosen to be the one at the top of state S_{i-1}^1. Afterwards, each loop i consists of $6\,i$ subnets labeled in a clockwise direction as $S_i^1, \ldots, S_i^{6\,i}$. Let S_i^{j*} denote the new aggregated state, where i always designates the loop reference, and $j*$ the state label inside the loop.

2)

```
Start with i = 1;
until $(i = K - 1)$
Repeat{
    set $S_i^{0*} = S_i = \bigcup_{0 \leq n \leq 5} S_i^{n \times i + 1}$
    If $(i \neq 1)$ {
        set $L = \lceil \frac{i-1}{2} \rceil$;
        For $m = 1$ to $m = L$
            set $S_i^{m*} = \bigcup_{0 \leq n \leq 5} S_i^{n \times i + m + 1} + \bigcup_{1 \leq n \leq 6} S_i^{n \times i - m + 1}$
    }
    $i = i + 1$;
}
```

Let $F = \{S_0, S_1, S_i, S_i^{1*}, \ldots, S_i^{m*}, \ldots, S_i^{L*}, S_{i+1}, \ldots\}$ ($i = 2, 3, \ldots, K-1$) designate the state space of the new chain $Y(t)$ obtained by aggregation of the initial Markovian chain $X(t)$. We can demonstrate that the resulting aggregated process $Y(t)$ is also Markovian. Due to space limitation, we do not provide the proof of this result.

Steady state probabilities

Based on the state transition diagram of the aggregated Markov chain (see figure 3b where $K = 3$), we can obtain the steady state probability for state $F_i, (i = 1, \ldots, M)$, where M is the set size (i.e., $M = K + \sum_{i=2}^{K-1} \lceil \frac{i-1}{2} \rceil$). Denote by Π_i and $\Pi_i^{(m)}$ $\Big(i = (0, 1, \ldots, K-1)$ and $m = (1, \ldots, L)\Big)$ the stationary probability of the system for the aggregated state S_i and S_i^{m*}, respectively. The balance equations for the aggregated Markov chain are obtained recursively as follows:

$$\begin{cases} \Pi_0 = p\Pi_1 + 3p\Pi_{K-1} + 2p \displaystyle\sum_{j=1}^{\lceil \frac{K-2}{2} \rceil} \Pi_{K-1}^{(j)} \\ \Pi_1 = 6p\Pi_0 + 2p\Pi_1 + p\Pi_2 + 2p\Pi_2^{(1)} \\ \Pi_2 = p\Pi_1 + p\Pi_3 + 2\,p\Pi_2^{(1)} + p\Pi_3^{(1)} \\ \Pi_{K-1} = p\Pi_{K-2} + p\Pi_{K-1}^{(1)} \\ \forall\ \ 3 \leq i \leq K-2 \\ \qquad \Pi_i = p\Pi_{i-1} + p\Pi_{i+1} + p\Pi_i^{(1)} + p\Pi_{i+1}^{(1)} \end{cases} \tag{1}$$

$$\begin{cases} \Pi_2^{(1)} = 2p\Pi_2 + 2p\Pi_1 + p\Pi_3^{(1)} \\ \Pi_3^{(1)} = 2p\Pi_3 + 2p\Pi_2 + 2p\Pi_2^{(1)} + p\Pi_3^{(1)} + p\Pi_4^{(1)} + 2p\Pi_4^{(2)} \\ \Pi_4^{(1)} = 2p\Pi_4 + 2p\Pi_3 + 2p\Pi_4^{(2)} + p\Pi_3^{(1)} + p\Pi_5^{(1)} + p\Pi_5^{(2)} \\ \forall\ \ 5 \leq i \leq K-1 \\ \qquad \Pi_i^{(1)} = 2p\Pi_i + 2p\Pi_{i-1} + p\Pi_i^{(2)} + p\Pi_{i-1}^{(1)} + \\ \qquad\qquad + \alpha\, p\Pi_{i+1}^{(1)} + \alpha\, p\Pi_{i+1}^{(2)} \end{cases} \tag{2}$$

$$\text{where } \alpha = \begin{cases} 1 & \text{if } 5 \leq i \leq K-2 \\ 0 & \text{if } i = K-1 \end{cases}$$

$$\begin{cases} \forall \ 6 \leq i \leq K-1 \text{ and } 2 \leq j \leq \lceil \frac{i-1}{2} \rceil - 1 \\ \quad \Pi_i^{(j)} = p\Pi_i^{(j-1)} + \beta_1 \, p\Pi_i^{(j+1)} + p\Pi_{i-1}^{(j-1)} + p\Pi_{i-1}^{(j)} + \\ \quad\quad + \beta_2 \, p\Pi_{i+1}^{(j)} + \beta_2 \, p\Pi_{i+1}^{(j+1)} \end{cases} \tag{3}$$

$$\text{where } \beta_1 = \begin{cases} 1 & \text{if } i \text{ is odd} \\ 1 & \text{if } i \text{ is even and } 2 \leq j \leq (\lceil \frac{i-1}{2} \rceil - 2) \\ 2 & \text{if } i \text{ is even and } j = (\lceil \frac{i-1}{2} \rceil - 1) \end{cases}$$

$$\text{and } \beta_2 = \begin{cases} 1 & \text{if } 6 \leq i \leq K-2 \\ 0 & \text{if } i = K-1 \end{cases}$$

$$\begin{cases} \forall \ 2 \leq n \leq \dfrac{K-1}{2} \\ \quad \Pi_{2n}^{(n)} = p\Pi_{2n}^{(n-1)} + p\Pi_{2n-1}^{(n-1)} + \gamma_1 \, p\Pi_{2n+1}^{(n)} \end{cases} \tag{4}$$

$$\text{where } \gamma_1 = \begin{cases} 0 & \text{if } n = \frac{K-1}{2} \\ 1 & \text{otherwise} \end{cases}$$

$$\begin{cases} \forall \ 2 \leq n \leq \dfrac{K-2}{2} \\ \quad \Pi_{2n+1}^{(n)} = p\Pi_{2n+1}^{(n-1)} + p\Pi_{2n+1}^{(n)} + p\Pi_{2n}^{(n-1)} + \\ \quad\quad + 2p\Pi_{2n}^{(n)} + \gamma_2 \, p\Pi_{2n+2}^{(n)} + \gamma_2 \, 2 \, p\Pi_{2n+2}^{(n+1)} \end{cases} \tag{5}$$

$$\text{where } \gamma_2 = \begin{cases} 0 & \text{if } n = \frac{K-2}{2} \\ 1 & \text{otherwise} \end{cases}$$

$$\sum_{i=0}^{K-1} \Pi_i + \sum_{i=2}^{K-1} \sum_{m=1}^{\lceil \frac{i-1}{2} \rceil} \Pi_i^{(m)} = 1 \tag{6}$$

Given the balance equations (1-5) and the normalization equation (6), the steady state probabilities of the aggregated Markov chain can be derived. Note that obtained results will be used in the next section to derive the signaling cost functions of registration updates and the link usage.

IV. PERFORMANCE EVALUATION & ANALYSIS

In this section, we develop analytical models to derive the link usage and the cost function of registration updates. We compare our two protocol variants (FC- and MFC-Micro Mobile MPLS) with respect to the FMIP [4], MIP-RR [5], Mobile MPLS [9] and H-MPLS [11] schemes. The following parameters are used in our 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
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)
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 × message size)
C_{fg}	location update cost between an LER/FA and the LERG (hop × message size)
C_{ff}	location update cost between two neighboring LER/FAs (hop × message size)
l_{fh}	traffic load related to LSP setup procedure between an FA and the HA (hop × message size)
l_{fg}	traffic load related to LSP setup procedure between an LER/FA and the LERG (hop × message size)
l_{ff}	traffic load related to LSP setup procedure between two neighboring LER/FAs (hop × message size)

C_i and l_i parameters can be written as:

$$\begin{cases} C_{fh} = 2s_u h_{FA-HA} & ; \quad C_{fg} = 2s_u h_{FA-LERG} \\ C_{ff} = 2s_u h_{FA-FA} & ; \quad l_{fh} = 2s_l h_{FA-HA} \\ l_{fg} = 2s_l h_{FA-LERG} & ; \quad l_{ff} = 2s_l h_{FA-FA} \end{cases} \tag{7}$$

A. 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. For simplicity, we assume that the distance between the LERG and any FA is the same and equal to δ. In FMIP, MIP-RR, Mobile MPLS and H-MPLS, packet are delivered using the shortest path routing. Hence, packets exchanged between the LERG and any FA traverse δ hops. In both FC and MFC cases, we have to take also into account the mean forwarding chain size. Based on the analysis of section III, the mean forwarding chain size for the MFC case is given by:

$$f(K) = 6p\,\Pi_0 + \sum_{i=1}^{K-2} \Pi_i (i + 2p) + \sum_{i=2}^{K-2} \sum_{m=1}^{\lceil \frac{i-1}{2} \rceil} i \, \Pi_i^{(m)} + \ 2p\,(2K-3) \sum_{m=1}^{\lceil \frac{K-2}{2} \rceil} \Pi_{K-1}^{(m)} \ + \ p\,(3K-4)\,\Pi_{K-1} \tag{8}$$

Hence, the mean value of LU for MFC-Micro Mobile MPLS is given by:

$$LU(\text{MFC-Micro Mobile MPLS}) = \delta + f(K) \tag{9}$$

In the FC case, the movement of MNs in a 2-D area is not a Markovian process since the MN's evolution depends on its mobility history. In other words, the MN's next registration (i.e., LERG or local registration) depends not only on its current position, but also on its entire trajectory since it has left the master FA. This increases the complexity of analysis. Therefore, the link usage parameter of FC-Micro Mobile MPLS will be evaluated only through simulations.

B. Registration Updates Cost

Let C_u denote the signaling cost of registration updates when a L3 (network-layer) handoff occurs. It is the traffic load of signaling messages (hop × 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 both FC and MFC-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. Using the results of section III, the expression of registration updates cost for MFC-Micro Mobile MPLS can be written as follows:

$$
\begin{aligned}
&C_u(\text{MFC-Micro Mobile MPLS}) \\
&\quad = 2(s_u+s_l)\Pi_0 + \sum_{i=1}^{K-2} 2(s_u+s_l)(i+2p)\Pi_i \\
&\quad + \sum_{i=2}^{K-2} \sum_{m=1}^{\lceil \frac{i-1}{2} \rceil} 2i\,(s_u+s_l)\,\Pi_i^{(m)} \\
&\quad + \ 4p\,(s_u+s_l)\,(2K-3+\delta)\Big(\sum_{m=1}^{\lceil \frac{K-2}{2} \rceil} \Pi_{K-1}^{(m)}\Big) \\
&\quad + \ 2p\,\Pi_{K-1}\,(s_u+s_l)\,(3K-4+3\delta) \qquad (10)
\end{aligned}
$$

In FC-Micro Mobile MPLS, the registration updates cost will be derived only through simulations since the movement of MNs in a 2-D area is not a Markovian process. The expression of registration updates cost for the remaining schemes can be given by :

$$
\begin{cases}
C_u(\text{FMIP}) = C_{fh} \\
C_u(\text{MIP-RR}) = C_{fg} \\
C_u(\text{Mobile MPLS}) = C_{fh} + l_{fh} \\
C_u(\text{H-MPLS}) = C_{fg} + l_{fg}
\end{cases} \qquad (11)
$$

V. NUMERICAL & SIMULATION RESULTS

In this section, we compare all underlying protocols using both analytical and simulation approaches. In addition to the analysis given above, simulations are conducted to investigate two critical performance issues: packet loss during a session and handoff latency. The simulations are run on the NS-2 simulator [17]. The parameter settings in our experiments are listed in table I.

TABLE I

PARAMETER SETTINGS

Parameter	Value	Parameter	Value
t_s	1000 sec	$h_{HA-LERG}$	4
t_r	5 $\sim$ 50 sec (default 20)	B_w	100 Mbps
T_{ad}	1 sec	B_{wl}	11 Mbps
L2 Beacon	100 msec	L_w	1 msec
λ	64 Kbps	L_{wl}	2 msec
δ	2 $\sim$ 16 (default 9)	s_u	48 bytes
ϕ (L_{th} or K)	1 $\sim$ 15 (default 4)	s_l	28 bytes

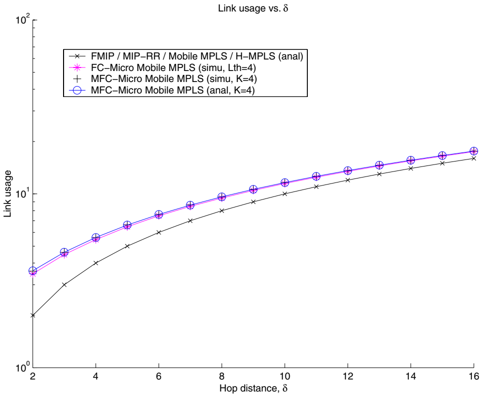


Fig. 4. Link usage cost

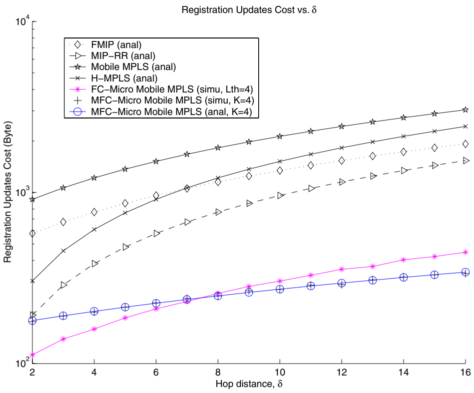


Fig. 5. Registration updates cost at every L3 handoff

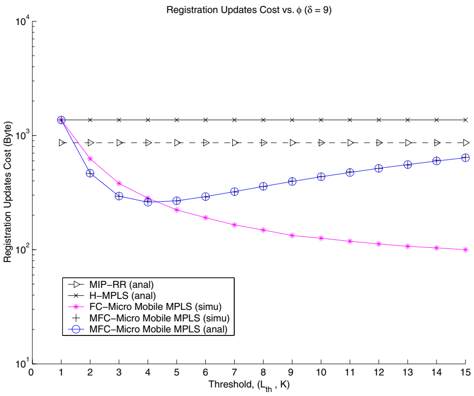


Fig. 6. Effect of L_{th} and K on the registration updates cost in (FC/MFC)-Micro Mobile MPLS

Figure 4 represents the link usage cost of all underlying protocols. We can see that FC- and MFC-Micro Mobile MPLS have almost the same cost. This cost is higher compared to the remaining protocols. This slight difference is due to the additional cost introduced by the forwarding chain.

Figure 5 plots the different registration updates cost. We can observe that both FC and MFC schemes exhibit always the smallest cost. However, the minimum registration cost is obtained by different strategies according to the value of δ (i.e., the distance between an LER/FA and the LERG). In this particular case (i.e., $K = L_{th} = 4$), the FC scheme stands out as the best choice when $\delta \leq 7$, otherwise the MFC scheme provides the best cost. In fact, considering the same threshold (i.e. $K = L_{th}$), the expensive registration updates with the LERG are more frequent in the FC case than in the MFC one. However, the local registration cost in the FC strategy is cheaper than the MFC one. In this regard, when δ is large, the LERG registration cost is a dominant cost. Hence, the MFC mechanism stands out as the best choice. Otherwise, when δ is relatively small, the FC mechanism becomes the best choice. Notice that analytical results (figures 4 and 5) practically coincide with the simulation ones, which illustrates the accuracy of our study.

Figure 6 depicts the registration updates cost of FC- and MFC-Micro Mobile MPLS as a function of their respective thresholds. We can observe that the registration updates cost of MFC-Micro Mobile MPLS is a convex function of K, where the minimum cost is obtained for K_{opt} (in this example $K_{opt} = 4$). In fact, the LERG registration frequency decreases with the increase of the threshold $\phi = K$. That is, more

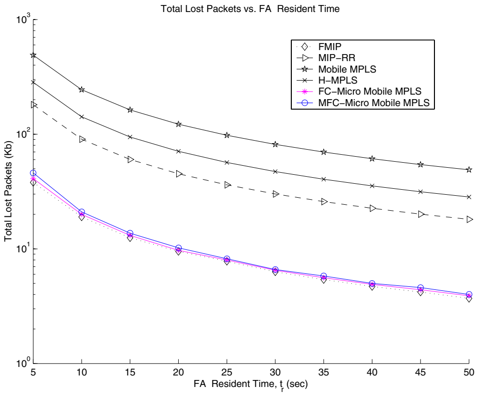


Fig. 7. Total lost packets during a session

and more expensive LERG registrations are replaced by local registrations. On the other hand, the local registration cost increases with the threshold, since the average distance between the MN and the master FA increases. In view of this, the optimal signaling cost is a trade-off between these two opposite requirements. Specifically, the registration updates cost of MFC-Micro Mobile MPLS can be written as follows:

$$\begin{aligned} & C_u(\text{MFC-Micro Mobile MPLS}) \\ & \quad = f(K) \times (\text{cost between two neighboring FAs}) \\ & \quad + \frac{1}{g(K)} \times (\text{LERG registration cost}) \\ & \quad = f(K)\ (C_{ff} + l_{ff}) + \frac{1}{g(K)}\ (C_{fg} + l_{fg}) \end{aligned}$$

where $f(K) = \circ(K)$ denotes the average distance (in terms of number of hops) between the MN and the master FA and $g(K) = \circ(K)$ denotes the average number of visited subnets during a cycle (i.e., inside the *residing area*). This formula exhibits clearly the convex behavior of the MFC registration updates cost. Finally, we also notice that analytical results practically coincide with the simulation results, which illustrates the accuracy of our study.

On the other side, in FC-Micro Mobile MPLS, the registration updates cost decreases with the threshold $\phi = L_{th}$. 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 ϕ (i.e., K or L_{th}) does not affect the performance of the other studied protocols (FMIP, MIP-RR, Mobile MPLS and H-MPLS). Thus, the results presented in figures 4 and 5 for these schemes are ϕ-independent.

TABLE II

AVERAGE HANDOFF TIME IN MSEC

FMIP	30.198	MIP-RR	22.159
Mobile MPLS	56.256	H-MPLS	40.199
FC mechanism	18.136	MFC mechanism	20.145

The average handoff time values for different schemes are listed in table II. Each value was obtained by averaging 100 consecutive simulations. During simulations, the MN moves randomly between neighboring APs. The parameters used in our experiments have their default settings as depicted in table I. As can be seen, FC-Micro Mobile MPLS provides the lowest average handoff time. This is because registrations in FC-Micro Mobile MPLS are often carried out with the previous FA instead of the LERG, which enable shorter delay to complete the registration updates. The handoff delay increases slightly with MFC compared to FC, since the MN performs registrations with the master FA instead of the previous FA.

Figure 7 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, FC- and MFC-Micro Mobile MPLS, provide the smallest amount of lost packets thanks to the buffering mechanism.

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 cellular networks. We considered two protocol variants: the FC- and MFC-Micro Mobile MPLS schemes. Both schemes use the forwarding chain concept, which limits the range of handoff signaling messages to a local area. We exhibited how these two mechanisms reduce 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 and the link usage 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.

REFERENCES

[1] C. Perkins, IP Mobility Support for IPv4, RFC 3220, January 2002.
[2] J. Xie and I. F. Akyildiz, “A distributed dynamic regional location management scheme for mobile IP”, IEEE Infocom 2002.
[3] W. Ma and Y. Fang, “Dynamic Hierarchical Mobility Management Strategy for Mobile IP Networks”, IEEE J. Select. Areas Commun., vol. 22, pp. 664-676, May 2004.
[4] R. Koodli, Ed., Fast Handovers for Mobile IPv6, RFC 4068, July 2005.
[5] E. Gustafsson, A. Jonsson and C. Perkins, “Mobile IPv4 Regional Registration”, draft-ietf-mip4-reg-tunnel-01.txt, Nov. 2005, work in progress.
[6] A. Campbell, J. Gomez, S. Kim, Z. Turanyi, A. Valko and C-Y Wan, “Design, Implementation and Evaluation of Cellular IP”, IEEE Pers. Commun. Mag., August 2000.
[7] R. Ramjee, K. Varadhan, L. Salgarelli et al., “HAWAII: a Domain-based Approach for Supporting Mobility in Wide-area Wireless Networks”, IEEE/ACM Transactions on Networking, vol. 10, pp. 396-410, June 2002.
[8] E. Rosen, A. Viswanathan, and R. Callon, “Multiprotocol Label Switching Architecture”, Internet IETF RFC 3031, January 2001.
[9] Z. Ren, C. Tham, C. Foo, and C. Ko, “Integration of Mobile IP and Multi-Protocol Label Switching”, IEEE ICC 2001, Finland, June 2001.
[10] F.M. Chiussi, D.A. Khotimsky, and S. Krishnan, “A Network Architecture for MPLS-based Micro-Mobility”, IEEE WCNC’02, Orlando, USA.
[11] T. Yang, Y. Dong, Y. Zhang, and D. Makrakis, “Practical Approaches for Supporting Micro Mobility with MPLS”, IEEE International Conference on Telecommunications (ICT), Beijing, China, June 2002.
[12] K. Xie, V. Wong and V. Leung, “Support of Micro-Mobility in MPLS-based Wireless Access Networks”, IEEE WCNC’03, March 2003.
[13] V. Vassiliou, H. L. Owen, D. A. Barlow, J. Grimminger, H-P Huth, and J. Sokol, “M-MPLS: Micromobility-enabled Multiprotocol Label Switching”, IEEE ICC, Alaska, USA, May 2003.
[14] K. Sethom, H. Afifi, G. Pujolle, “Wireless MPLS: a new layer 2.5 micro-mobility scheme”, ACM MobiWac, Philadelphia, PA, USA, Oct. 2004.
[15] R. Langar, S. Tohme, N. Bouabdallah, “Mobility management support and performance analysis for wireless MPLS networks”, the ACM/WILEY International Journal of Network Management, vol. 16 issue 4, pp. 279-294, July 2006.
[16] K. El Malki, “Low Latency Handoffs in Mobile IPv4”, IETF, draft-ietf-mobileip-lowlatency-handoffs-v4-11.txt, October 2005, work in progress.
[17] ns2 home page, http://www.isi.edu/nsnam/ns