Adaptive Mobility Management for IP/MPLS-Based Wireless Networks: a Proposal and Analysis

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***Abstract*—In this paper, we propose a new adaptive MPLS-enabled micro-mobility management scheme designed to track efficiently the mobility of nodes so as to minimize both handoff latency and total signaling cost while ensuring the mobile node's QoS requirements. To achieve this, we introduce a new concept called *residing area*. Accordingly, the micro-mobility domain is divided into virtual *residing areas* where the MN limits its signaling exchanges within this local region instead of communicating with the relatively far away root of the domain at each handoff occurrence. One of the key distinguishing features of our solution from existing literature is its adaptive nature since the virtual residing areas are constructed according to the current network state and the QoS constraints. To evaluate the efficiency of our proposal, we compare our scheme with existing solutions using both analytical and simulation approaches. Numerical and simulation results show that our proposed scheme can significantly reduce registration updates and link usage costs and provide low handoff latency under various scenarios.**

I. Introduction

Future wireless networks are expected to provide IP-based coverage and efficient mobility support with end-to-end QoS guarantees. Two enabling factors are considered as crucial: (i) maintaining the network connectivity during node mobility (i.e., service continuity) and; (ii) provisioning the network resources required by the Mobile Node (MN) in all the visited subnetworks.

Mobility management protocols are key for service continuity in mobile networks. Mobile IP [1], the Internet Engineering Task Force (IETF) standard, 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, many enhancements to Mobile IP for MNs with frequent handoffs have been proposed in the literature [2]– [7] to ensure service continuity.

Specifically, [2] proposes a fast handoff scheme, called FMIP, for Mobile IP in order to alleviate the high handoff latency. To tackle the inherent problem of Mobile IP regarding the high signaling cost, the authors in [3] propose a distributed dynamic location management scheme. This scheme can be seen as an extension of the IETF regional registration protocol (MIP-RR [4]) in order to improve its flexibility and adaptability. Another approach to reduce the signaling cost is the "pointer forwarding" technique used in [5], [6] and [7].

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, inspired some works to use this technology in the wireless infrastructure [9] – [13].

To meet the requirement of next generation mobile networks, we propose in this paper a new adaptive micro-mobility management scheme called adaptive Master Residing Area (MRA) which alleviates the limitations of previous works in terms of flexibility and adaptability and in the same time benefits from MPLS resource provisioning capability. The key idea behind our proposal is to manage adaptively the node mobility according to its current state and the QoS constraints. Indeed, to track efficiently the mobility of nodes within a domain, we introduce a new concept called the *Master Residing Area*. This concept can reduce registration updates cost (i.e., volume of signaling messages exchanged during handoff operations), provide low handoff latency and support QoS thanks to MPLS capabilities.

To gauge the effectiveness of our proposed scheme, we develop a new analytical model based on Markov chains. We, explicitly, derive the expressions of the signaling cost function of registration updates and the link usage cost for a general two-dimensional (2-D) random walk mobility model. Numerical and simulation results show that our proposal can improve significantly the network performance when compared to existing schemes (Fast Mobile IP [2], MIP-RR [4], Pointer Forwarding (PF) [6], Mobile MPLS [9] and M-MPLS [13]) under various scenarios.

The remainder of this paper is organized as follows. Section II describes our proposed adaptive micro-mobility management scheme. Section III introduces the analytical model used to evaluate the performance of our proposal. In section IV, a comparison between our proposal and existing solutions is drawn using both analytical and simulation results. Finally, section V concludes this paper.

II. Adaptive MPLS-enabled MRA

In this section, we describe our proposed adaptive MRA scheme. As mentioned earlier, our ultimate aim is to overcome the limitations of existing schemes in terms of high signaling cost and in the same time benefit from the QoS support capability of MPLS networks. In the following, we describe the architecture of adaptive MRA.

A. Proposed architecture

Adaptive MRA relies on our proposed Micro Mobile MPLS architecture [14], which is based on the integration of MIP-RR [4] and MPLS [8] protocols. A typical architecture for adaptive MRA networks is shown in Fig. 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 by the MN.

Two types of handoff are defined: Intra-LER and Inter-LER handoffs. 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.

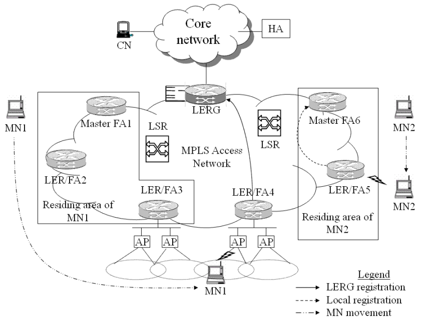


Fig. 1. Architecture of a Micro Mobile MPLS wireless access network

B. Handoff operation

As stated before, our approach is based on the adaptive residing area (RA) concept and can be considered as a new alternative to track efficiently the mobility of nodes instead of the pointer forwarding technique, in an MPLS environment. Accordingly, the micro-mobility domain is divided into virtual RAs where the MN limits its registration updates within this local region, instead of communicating to the far away LERG node. Explicitly, a specific node called master FA (MFA) will be delegated by the LERG to manage the mobility of nodes inside the current virtual RA. Each time the MN moves to a new subnet inside the current RA, it registers with the MFA instead of the LERG, as shown in Fig. 1. Consequently, the existing LSP (with QoS requirements) between the LERG and the MFA will be extended to the new visited FA. Packets traveling towards this MN will be intercepted first by the MFA, taking advantage of the existing LSP, and then forwarded along the new added LSP to the MN. The MN keeps registering with the MFA instead of the LERG as long as it moves inside the RA (see Fig. 1). Once the MN goes outside this area, it registers to the LERG. Hence, a new LSP between the LERG and the new subnet will be established and the new visited LER/FA becomes the new MFA.

It is easy to see that such a scheme may cause unacceptable delays due to the eventual long radius of the RA. To fulfill the delay constraint, the virtual RA around a specific MFA is constructed adaptively according to both the relative position of the current MFA with the LERG and the delay constraint. Assume that the maximum tolerable delay inside the micro-mobility domain is D_{max}. For the sake of simplicity, D_{max} will be expressed in terms of hops. Each time the MN moves to a new subnet, it compares the length of its indirect path to the LERG through the current MFA with D_{max}. If this distance is equal or less than D_{max}, the MN can register locally to the MFA. Otherwise, it registers directly to the LERG and the new FA becomes the MFA of the new RA. Moreover, to minimize the signaling cost, a second condition must be verified before performing a local registration instead of a LERG registration. Specifically, a local registration with the MFA is achieved as long as it is cheaper than a LERG registration. Indeed, each time the MN moves to a new subnet, the new LER/FA compares the signaling cost (in terms of hop $\times$ message size) of a registration update to the MFA with that to the LERG. In other words, once the distance between the new visited FA and the LERG is equal or less than the distance between the new FA and the MFA, a LERG registration is preferred. Thus, the new FA is considered as not belonging to the previous MFA residing area.

To illustrate the residing area (RA) concept, we consider the simple example presented in Fig. 2, where the LERG node is located at the center of a domain with a radius $R = 3$. We assume that $D_{max} = 4$. It is worth noting that D_{max} must be at least equal to R. Assume that the current MFA is the subnet S_1. The associated RA will be composed of nine subnets as shown in Fig. 2. These FAs satisfy both conditions regarding the delay and registration cost. Accordingly, as long as the MN remains in this area (i.e., it fulfills the delay constraint and a local registration is cheaper than a LERG one), it carries out a local registration with the MFA. Once it leaves this RA, it performs a LERG registration and the new serving LER/FA becomes the new MN's MFA.

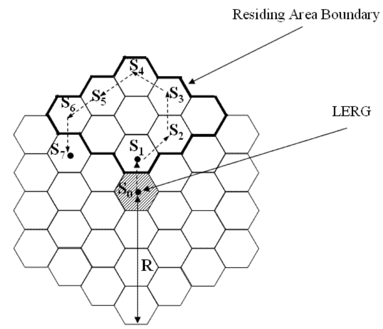


Fig. 2. Residing area of a MN when $R = 3$ and $D_{max} = 4$

III. Analytical Model

In this section, we develop a new analytical model using Markov chains to evaluate the performance of our adaptive MRA scheme in terms of registration updates and link usage costs. The elaborated model will be also used to derive the performance metrics for the existing solutions FMIP, Mobile MPLS, MIP-RR and M-MPLS. In the PF case, we will use simulations.

In our study, we consider a general 2-D random walk model. Typically, the wireless network is divided into subnetworks as shown in Fig. 3. Each subnet is covered by one LER/FA, called base station in cellular networks. This model is widely used in the literature. In this case, each subnet is surrounded by six neighbors. The MN can move to one of the neighboring subnets with equal probability p ($p = \frac{1}{6}$).

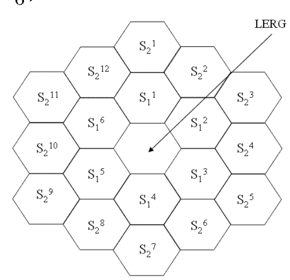


Fig. 3. Two-dimensional mobility model

Figure 3 represents a micro-mobility domain with a radius $R = 2$ in a two dimensional space. The domain contains the LERG node surrounded by 2 rings of subnets. Each subnet is referenced by the ring label and its position inside that ring, which determines the exact MN's position with respect to the LERG of the domain. For example, subnets belonging to ring 1 are referenced by S_1^j, $1 \leq j \leq 6$, those belonging to ring 2 are referenced by S_2^j, $1 \leq j \leq 12$, and so on and so forth. To generalize, let i ; $i = 0, 1, \ldots, R$ designate the ith ring away from the LERG node. The LERG node subnet is denoted by S_0^0. Subnets belonging to ring i are referenced by S_i^j, $1 \leq j \leq 6\,i$. Note that the ring label represents the distance between the MN and the LERG.

Let $X(t)$ be the MN's state within the micro-mobility domain at time t defined by the tuple (S_i^j, S_n^m), where S_i^j is the current subnet location and S_n^m is the current MN's MFA. The residence time of a 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

$\mathcal{S} = \{ (S_i^j, S_n^m) \mid 0 \le i \le R \ , 1 \le j \le 6\, i \ , S_n^m \in E_{S_i^j} \}$, where $E_{S_i^j}$ is the set of possible MFAs that a MN can register to when it is located in the subnet S_i^j. In other words, $S_n^m \in E_{S_i^j}$ if and only if the subnet S_i^j belongs to the RA managed by S_n^m, i.e., it satisfies the following relation:

$$S_n^m \in E_{S_i^j} \text{ if and only if} \begin{cases} d(S_i^j, S_n^m) < d(S_i^j, \mathit{LERG}) \\ \qquad \& \\ d(S_i^j, S_n^m) + d(S_n^m, \mathit{LERG}) \le D_{max} \end{cases} \quad (1)$$

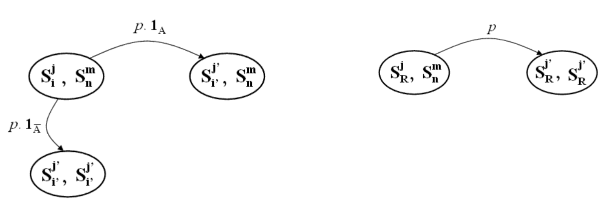
where $d(x, y)$ denotes the shortest path distance (in terms of number of hops) between subnets x and y. Note that the first condition in (1) ensures that a local registration cost is cheaper than a LERG one. The second condition ensures that the MN fulfills the delay constraint.

According to our adaptive MRA scheme, the MN's state at time t is completely defined by the tuple $X(t) = (S_i^j, S_n^m)$. Using that information, we can predict exactly the MN's evolution. According to its next location (i.e., visited subnet), the MN can perform either a local registration or a LERG registration. In the latter case, the MFA will be updated and its associated RA will be created.

In the following, we consider the discrete-time transition matrix derived from the Markov chain $X(t)$ to calculate the steady state probabilities. To derive the transition probabilities when leaving a generic state (S_i^j, S_n^m), we distinguish between two cases: either the current MN's subnet S_i^j is located at the ith ring far away from the LERG node with $1 \le i \le R - 1$ or it is located at the boundary of the micro-mobility domain (i.e., $i = R$). In the latter case, the MN may leave the current domain and enters a new one. The transition probabilities regarding each case are derived as follows.

1) Case1: S_i^j is not a boundary subnet (i.e., $i \neq R$)

Let $S_{i'}^{j'}$ denote the next visited subnet by the MN. $S_{i'}^{j'}$ is one of the six neighbors that surrounds the current subnet S_i^j. Hence, the MN moves to subnet $S_{i'}^{j'}$ with a probability p. According to whether $S_{i'}^{j'}$ belongs or not to the current RA managed by the MFA S_n^m, we can identify the next MN's state. Specifically, if it is the case (i.e., $S_n^m \in E_{S_{i'}^{j'}}$), the MN will transit to the state $(S_{i'}^{j'}, S_n^m)$ as shown in Fig. 4(a). In this case, the MN performs a local registration to the current MFA S_n^m. Henceforth, we denote by $\mathcal{A}$ the event that $S_n^m \in E_{S_{i'}^{j'}}$ (see (1)). On the other hand, if $\mathcal{A}$ is not satisfied (i.e., $\bar{\mathcal{A}} = S_n^m \notin E_{S_{i'}^{j'}}$), the MN registers to the LERG and the new FA becomes the MFA of the new RA. As such, the MN transits to state $(S_{i'}^{j'}, S_{i'}^{j'})$ as shown in Fig. 4(a). Note that $1_{\mathcal{A}}$ (respectively $1_{\bar{\mathcal{A}}}$) is the indicator function of the condition $\mathcal{A}$ (respectively $\bar{\mathcal{A}}$), i.e., it is equal to 1 if the condition $\mathcal{A}$ (respectively $\bar{\mathcal{A}}$) is true and 0 otherwise.



(a) S_i^j is not a boundary subnet (b) S_i^j is a boundary subnet

Fig. 4. Transition probabilities from a generic state (S_i^j, S_n^m)

2) Case2: S_i^j is a boundary subnet (i.e., $i = R$)

In this case, the MN may leave the current micro-mobility domain. Accordingly, we distinguish between two sub-cases:

2.a: The MN remains in the same domain

In this case, the MN behaves in a similar way to case1 and we get the same transition diagram shown in Fig. 4(a).

2.b: The MN moves to an adjacent domain

Let $S_{i'}^{j'}$ denote the next visited subnet by the MN located in the adjacent micro-mobility domains. In our study, we assume that all the domains have the same radius R. So, likewise the old subnet S_R^j, the new visited subnet $S_{i'}^{j'}$ will be R hops far away from the new LERG (i.e., again at the boundary of the new domain, thus $i' = R$). As such, the MN moves to the subnet $S_R^{j'}$ with a probability p. When the MN enters the new domain, it registers to the new LERG and the new visited subnet becomes the new MFA. As a result, the MN transits to the state $(S_R^{j'}, S_R^{j'})$ with a probability p as shown in Fig. 4(b).

Based on the different cases listed above, we derive the transition probability matrix $P = [p_{ij}]$. Then, the steady state probability vector $\Pi = [\Pi_s]$, containing all the steady probabilities of states $s = (S_i^j, S_n^m) \in \mathcal{S}$, is obtained by resolving the following system:

$$\Pi P = \Pi \text{ and } \sum_{s \in \mathcal{S}} \Pi_s = 1 \quad (2)$$

Using these results, we evaluate hereafter the performance of our proposed adaptive MRA scheme. Building on these results, we can also evaluate analytically the existing solutions (i.e., FMIP, Mobile MPLS, MIP-RR and M-MPLS) except the PF scheme, which will be studied using simulations as shown in the next section.

A. Link Usage Cost

Let LU denote the link usage in the micro-mobility domain, which is the average number of links used for packet delivery between the MN and the LERG. In our adaptive MRA case, packets exchanged between the MN and the LERG have to pass-through the MFA. Hence the LU can be written as follows:

$$\begin{aligned} &LU(\text{Adaptive MRA}) \\ &\quad = \sum_{s \in \mathcal{S}} \Pi_s \Big(d(\mathit{Subnet(s)}, \mathit{MFA(s)}) + d(\mathit{MFA(s)}, \mathit{LERG}) \Big) \\ &\quad = V_{LU} \times \Pi \end{aligned} \quad (3)$$

where $s = (\mathit{Subnet(s)}, \mathit{MFA(s)}) = (S_i^j, S_n^m)$ and V_{LU} denotes the link usage vector of all states $s \in \mathcal{S}$.

Recall that in PF, packets have to traverse both the connection binding the LERG to the MFA and the forwarding chain binding the MFA to the MN. The LU metric in PF will be derived through simulations. In FMIP, Mobile MPLS, MIP-RR and M-MPLS schemes, packets are delivered using the shortest path routing between the LERG and the MN. Hence, the link usage is the same and can be given by:

$$\begin{aligned} &LU(\text{FMIP}) = LU(\text{Mobile MPLS}) = LU(\text{MIP-RR}) = LU(\text{M-MPLS}) \\ &\quad = \sum_{\substack{0 \le i \le R \\ 1 \le j \le 6\, i}} \pi(S_i^j) \times d(S_i^j, \mathit{LERG}) = \sum_{\substack{0 \le i \le R \\ 1 \le j \le 6\, i}} i \times \pi(S_i^j) \end{aligned} \quad (4)$$

where $\pi(S_i^j)$ denotes the steady probability that the MN is located at the physical subnet S_i^j. $\pi(S_i^j)$ can be expressed as follows, using the steady state probabilities $\Pi_s = \Pi(S_i^j, S_n^m)$ of the states $s = (S_i^j, S_n^m)$:

$$\pi(S_i^j) = \sum_{S_n^m \in E_{S_i^j}} \Pi(S_i^j, S_n^m) \quad (5)$$

B. 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 adaptive MRA, a local registration followed by a LSP procedure setup between the MFA and the new FA are required as long as the MN remains in the same RA. Otherwise, a LERG registration with a new LSP setup between the root of the domain (i.e., LERG) and the new subnet is performed. Additional registration to the MN's HA is also needed, each time the MN moves to a new domain. In this case, the new LERG forwards the registration request received from the MN to the HA.

In this regard, the average registration updates cost when transiting to a state $s = (\textit{Subnet(s)}, \textit{MFA(s)}) = (S_i^j, S_n^m)$ can be written as follows, using the transition probability matrix P and the steady state probability vector Π.

$$cost(s) = \begin{cases} \dfrac{\sum_{i \in \mathcal{S}} P(i,s) \times \Pi_i \times \mathcal{C}(i,s)}{\sum_{i \in \mathcal{S}} P(i,s)\Pi_i} & \text{if } \textit{Subnet(s) = MFA(s)} \\ C_{local}(s) & \text{otherwise} \end{cases} \quad (6)$$

where

$$\mathcal{C}(i,s) = \begin{cases} C_{lerg}(s) + C_{home} & \text{if } \textit{Subnet(s) = Subnet(i)} \\ C_{lerg}(s) & \text{if } (\textit{Subnet(s)} \neq \textit{Subnet(i)}) \\ & \text{ and } (\textit{MFA(s)} \neq \textit{MFA(i)}) \\ 0 & \text{otherwise} \end{cases}$$

$$\text{with} \quad \begin{cases} C_{home} = 2\ m_u\ d(\textit{LERG}, \textit{HA}) \\ C_{lerg}(s) = 2\ (m_u + m_l)\ d\big(\textit{Subnet(s)}, \textit{LERG}\big) \\ C_{local}(s) = 2\ (m_u + m_l)\ d\big(\textit{Subnet(s)}, \textit{MFA(s)}\big) \end{cases}$$

and m_u is the average size of signaling messages for the registration updates and m_l is the average size of a label message for LSP setup. The total registration updates cost can be thus written as:

$$C_u(\text{Adaptive MRA}) = \sum_{s \in \mathcal{S}} \Pi_s cost(s) = V_{C_u} \times \Pi \quad (7)$$

where $V_{C_u} = [cost(s)]$ denotes the registration updates cost vector of all states $s \in \mathcal{S}$.

It is worth noting that in FMIP, the MN performs a home registration update with its HA at each L3 handoff. In Mobile MPLS, we have to take into consideration the additional cost associated to the LSP procedure setup between the new FA and the HA. In MIP-RR, only a GFA registration (i.e., LERG registration) is required. Additional cost associated to the LSP procedure set up between the LERG and the new FA, is to be considered in M-MPLS. Finally, in the PF case, a local registration between the new and the old FAs is performed as long as the forwarding chain length does not exceed the threshold K. Otherwise a LERG registration is required. The average registration updates cost for all underlying protocols, except for PF, can be expressed as follows using (4) and (5). In PF, simulations will be used to evaluate the registration cost.

$$\begin{cases} C_u(\text{FMIP}) = 2\ m_u\ LU(\text{FMIP}) + C_{home} \\ C_u(\text{Mobile MPLS}) = 2\ (m_u + m_l)\ LU(\text{Mobile MPLS}) \\ \qquad\qquad + C_{home} + L_{home} \\ C_u(\text{MIP-RR}) = 2\ m_u\ LU(\text{MIP-RR}) + \alpha\ C_{home} \\ C_u(\text{M-MPLS}) = 2\ (m_u + m_l)\ LU(\text{M-MPLS}) + \alpha\ C_{home} \end{cases} \quad (8)$$

where $L_{home} = 2\ m_l\ d(\textit{LERG}, \textit{HA})$ is the signaling cost needed to setup a LSP between the HA and the LERG, and $0 \leq \alpha \leq 1$ denotes the probability of moving out of a micro-mobility domain. This probability can be derived using the elaborated model as shown below.

$$\alpha = \sum_{s \in \mathcal{S}} \Pi_s H(s) \quad (9)$$

where $H(s)$ denotes the probability of entering a new domain when transiting to the state s. It corresponds also to the probability of performing a home registration in the adaptive MRA case when the MN moves to the state s. $H(s)$ can be written as:

$$H(s) = \begin{cases} \dfrac{\sum_{i \in \mathcal{S}} P(i,s) \times \Pi_i \times h(i,s)}{\sum_{i \in \mathcal{S}} P(i,s)\Pi_i} & \text{if } \textit{Subnet(s) = MFA(s)} \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

$$\text{where} \quad h(i,s) = \begin{cases} 1 & \text{if } \textit{Subnet(s) = Subnet(i)} \\ 0 & \text{otherwise} \end{cases}$$

IV. Numerical & Simulation Results

In this section, we compare our proposal with respect to the FMIP [2], MIP-RR [4], Pointer Forwarding (PF) [6] Mobile MPLS [9] and M-MPLS [13] schemes through both simulations and analytical approaches. To evaluate the link usage and registration updates cost by simulations, we develop our own discrete-event simulator. We also derive by simulations the handoff latency for the different protocols. In this case, the ns-2 simulator [15] is used.

The simulation environment consists of a cellular network formed by several micro-mobility domains with equal size as shown in Fig. 5. As before, we denote by R the radius of each micro-mobility domain. The mobility of nodes is simulated using a random walk model. According to each management policy, the average registration cost per handoff and the link usage are calculated. All the simulation results given below have been achieved with very narrow 97.5% confidence intervals. The parameter settings in our experiments are listed in table I, where t_s denotes the average session connection time. t_r is the average FA residency time. T_{ad} is the time interval for an FA to send agent advertisements (L3 beacon). B_w and B_{wl} are the bandwidth of the wired and wireless links, respectively, and L_w and L_{wl} are the latency of the wired and wireless links, respectively.

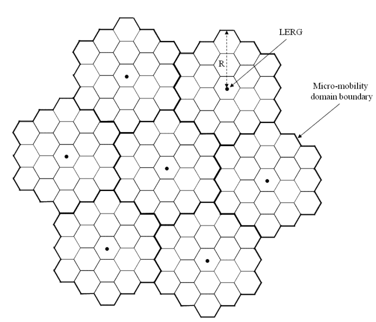
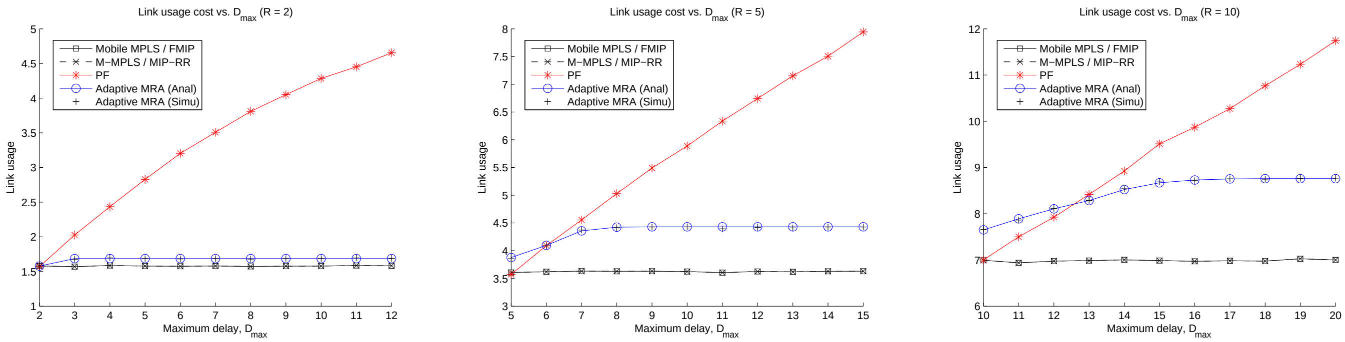
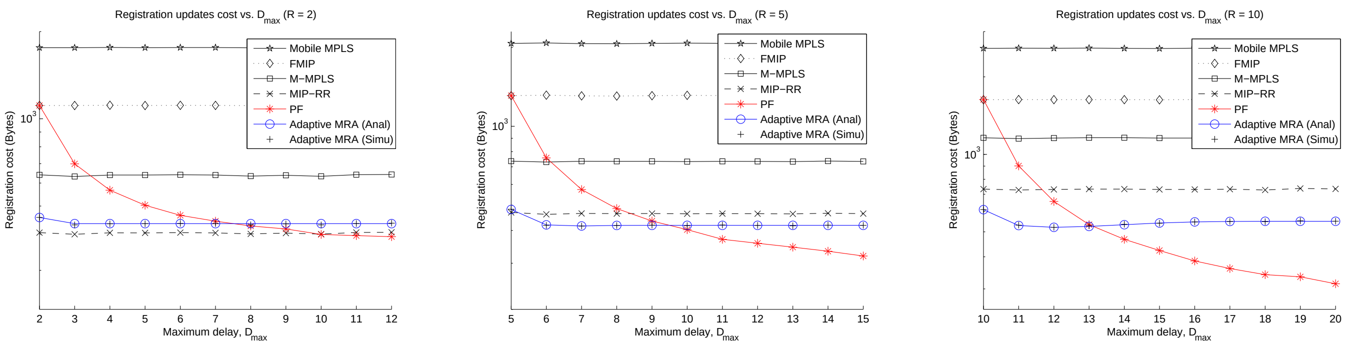


Fig. 5. A model of the simulated cellular network with $R = 2$



(a) Radius $R = 2$ (b) Radius $R = 5$ (c) Radius $R = 10$

Fig. 6. Link usage cost vs. Maximum delay D_{max}



(a) Radius $R = 2$ (b) Radius $R = 5$ (c) Radius $R = 10$

Fig. 7. Registration updates cost vs. Maximum delay D_{max}

TABLE I

PARAMETER SETTINGS

Parameter	Value	Parameter	Value
t_s	1000 sec	$d(HA, LERG)$	10
t_r	$5 \sim 50$ sec	T_{ad}	1 sec
m_u	48 bytes	B_w	100 Mbps
m_l	28 bytes	B_{wl}	11 Mbps
R	$2 \sim 10$	L_w	1 msec
D_{max}	$2 \sim 20$	L_{wl}	2 msec

In all figures of this section, we can see that the analytical and simulation curves regarding our adaptive MRA coincide, which illustrates the accuracy of our study. We note that simulation results overlap also analytic data in the FMIP, Mobile MPLS, MIP-RR and M-MPLS cases. In view of this, we only present the simulation curves for these schemes.

Figure 6 depicts the link usage cost of all underlying protocols as a function of the maximum tolerable delay inside the micro-mobility domain $D_{max} \geq R$. We considered three values of the radius R, $R = 2$, $R = 5$ and $R = 10$ as shown in Fig. 6(a), 6(b) and 6(c), respectively. These values of R are representative of small, medium and large micro-mobility domains. We can observe in Fig. 6 that the link usage cost with FMIP, Mobile MPLS, MIP-RR and M-MPLS schemes is the same and insensitive to D_{max} since, in these cases, packets are delivered using the shortest path from the LERG node to the current serving LER/FA. As such, the link usage cost is minimal. In the PF case, the link usage cost increases due to the additional cost introduced by the forwarding chain. This increase grows dramatically with D_{max}. Indeed, increasing D_{max} allows longer forwarding chains to be formed. In our adaptive MRA case, the link usage cost is also higher than the minimal cost. This is because packets are not directly forwarded between the LERG and the MN. Packets have to pass-through the MFA of the current MN residing area. However, compared to the PF scheme, the MRA protocol reduces considerably the link usage cost, notably when D_{max} is large. Indeed, the additional cost introduced by the residing area is less important than the one introduced by the PF forwarding chain, whose length can reach $D_{max} - R$. In contrast, the maximum length introduced by the residing area is $R - 1$. As such, the longest path between the MN and the LERG in the MRA case is $2R - 1$. In view of this, the link usage cost in MRA remains constant for values of $D_{max} \geq 2R - 1$ as shown in Fig. 6.

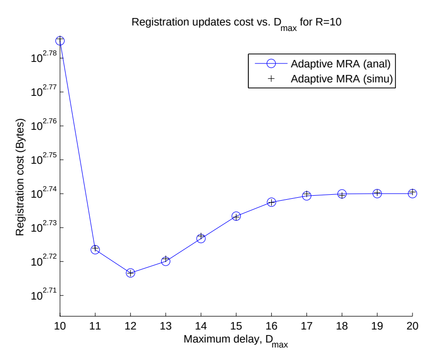


Fig. 8. Registration updates cost of adaptive MRA vs. D_{max}: Case $R = 10$

Figure 7 plots the different registration updates cost at every L3 handoff as a function of the maximum tolerable delay D_{max}. As before, we consider three values of R (i.e., 2, 5 and 10). Likewise the link usage, the registration updates costs in FMIP, Mobile MPLS, MIP-RR and M-MPLS are insensitive to D_{max}. In these cases the shortest path between the LERG and the

MN is always used to forward the registration update packets at each L3 handoff. The Mobile MPLS (respectively M-MPLS) has a higher cost than FMIP (respectively MIP-RR), due to the additional signaling cost needed to establish a LSP between the HA (respectively LERG) and the new visited FA at each L3 handoff.

Adaptive MRA, on the other hand, reduces the registration cost since some expensive LERG registrations are replaced by low-cost local registrations. In this case, the registration updates for MRA is a convex function of D_{max}, where the minimum cost is obtained for a given D_{max}^{opt}. For instance, when $R = 10$, $D_{max}^{opt} = 12$ as shown in Fig. 7(c) and more clearly in Fig. 8. The reason is as follows. Given a domain radius R, the LERG registration frequency decreases with the increase of D_{max}, due to the increase of the average residing area size. As such, more and more expensive LERG registrations are replaced by local registrations. On the other hand, the local registration cost increases with D_{max}, since the average residing area size increases. Hence, the average distance between the MN and the MFA increases with D_{max}. In view of this, the optimal cost is a trade-off between these two opposite requirements.

The rational behind such finding is as follows. Assume that maximal tolerable delay inside the micro-mobility domain is $D_{max} > D_{max}^{opt}$. In this case, it is better for the network administrator to regulate its MRA management protocol according to D_{max}^{opt} instead of D_{max}. In doing so, it respects the D_{max} constraint since $D_{max}^{opt} < D_{max}$. Moreover, it minimizes the registration updates cost as well as the link usage cost.

Revisiting Fig. 7, we notice also that the cost of registration updates in the PF case decreases strongly with D_{max}, since expensive HA registrations are replaced by low-cost local registrations. Figure 7 shows that the PF and MRA schemes lead always to the smallest registration cost. However, the minimal cost is obtained by different strategies according to the value of D_{max}. In the particular case where $R = 5$ (see Fig. 7(b)), the MRA scheme stands out as the best choice when $D_{max} < 10$, otherwise the PF scheme provides the best cost. This is because the local registrations become more frequent with the increase of D_{max}. These local registrations are cheaper in the PF case than with MRA scheme. Indeed, the local registrations are performed with the previous FA (i.e., through only one hop) in the PF case, whereas they are performed with the MFA, which is generally multiple hops far away, in the MRA case. However, the gain of PF over MRA when D_{max} is large is achieved at the expense of a great penalty on the link usage cost as shown in Fig. 6. In contrast, for moderate and small values of D_{max}, our MRA scheme enables the lowest registration updates cost. Hence, the MRA scheme stands out as the best solution from signaling cost perspective for delay sensitive applications.

The average handoff time values for different schemes are reported in table II. The simulated access network consists of multiple adjacent micro-mobility domains with radius $R = 10$ and D_{max} is set equal to 10, 12 and 20 respectively. Every LER/FA is connected to one AP. During simulations, the MN moves randomly between neighboring APs and receives downlink packets. A correspondent node (CN) is attached to the LERG via a wired link and it generates a constant bit rate traffic to the MN. Generated packets have a fixed size of 200-bytes. The generation rate is set equal to 40 packets/s corresponding thus to uncompressed data rate of 64 kb/s.

We can see in table II that both adaptive MRA and PF schemes provide the lowest average handoff time since registration updates are often carried out locally (i.e., with the master FA in the MRA case and with the previous FA in the PF case) instead of the relatively far away LERG or HA nodes. This enables the MRA scheme to outperform the remaining solutions although an extra time is needed in this case to setup LSP paths at each L3 handoff. Note that the handoff delay in PF is lower than in the MRA scheme when D_{max} takes large values. In this case, the local registrations become more frequent. Recall that the time needed to achieve a local registration is shorter in the PF case than with the MRA scheme. In the former case, the MN performs registration with the previous FA instead of the relatively far away MFA. However, this happens at the cost of considerable increase in the link usage cost.

TABLE II

AVERAGE HANDOFF TIME IN MSEC

D_{max}	10	12	20
Mobile MPLS	69.8016	70.3187	71.4239
FMIP	38.9828	38.2416	38.7950
M-MPLS	35.3039	35.2712	35.1563
MIP-RR	21.3693	21.4086	21.2694
PF	40.1176	19.8281	12.5569
Adaptive MRA	22.1752	19.4276	20.2310

V. CONCLUSION

This paper described a new micro-mobility management scheme, called adaptive MRA, that supports both mobility management and QoS resource provisioning in IP/MPLS-based wireless access networks. Our proposal limits the range of signaling messages to a local area called residing area. This area is constructed adaptively according to both the current mobile node position and the delay constraints. Doing so, we avoid the relatively long distance negotiations with the root of the domain at each handoff occurrence. Using both analytical and simulation approaches, we compared our proposal with existing solutions (FMIP, Mobile MPLS, MIP-RR, M-MPLS and PF). We found that the proposed scheme achieves substantial signaling cost and link usage reduction and improves the handoff latency, which are crucial for supporting real-time applications. In particular, we showed that our proposed scheme provides the lowest registration cost and handoff latency when the maximum tolerable delay inside a micro-mobility domain has moderate or small values. As such, our protocol stands out as the best choice for delay sensitive applications.

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