Evaluating the Performance of Fast Handover for Hierarchical MIPv6 in Cellular Networks

Li Jun ZHANG and Samuel PIERRE
Mobile Computing and Networking Research Laboratory (LARIM)
Department of Computer Engineering and Software Engineering
École Polytechnique de Montréal, Montréal, Canada
Email: {lijun.zhang, samuel.pierre}@polymtl.ca

***Abstract*— Next-Generation Wireless Networks (NGWNs) present an all-IP-based architecture integrating existing cellular networks with Wireless Local Area Networks (WLANs), Wireless Metropolitan Area Networks (WMANs), ad hoc networks, Bluetooth, etc. This makes mobility management an important issue for users roaming among these networks/systems. On one hand, intelligent schemes need to be devised to empower mobile users to benefit from the IP-based technology. On the other hand, new solutions are required to take into account global roaming among various radio access technologies and support of real-time multimedia services. This paper presents a comprehensive performance analysis of Fast handover for Hierarchical Mobile IPv6 (F-HMIPv6) using the fluid-flow and random-walk mobility models. Location update cost, packet delivery cost and total cost functions are formulated based on the proposed analytical models. We investigate the impact of several wireless system factors such as user velocity, user density, mobility domain size, session-to-mobility ratio on these costs, and present some numerical results.**

***Index Terms*— next-generation wireless network, mobility management, fast handover, hierarchical mobile IPv6, performance analysis**

I. INTRODUCTION

In the new era of Internet, mobile users freely change their point of attachment to the network. Under this circumstance, mobility management is a crucial issue to keep track of the users' current locations and correctly deliver packets to them. So far, a number of schemes have been proposed to address this issue within the Internet Engineering Task Force (IETF). Several schemes are still in progress. The baseline mobility management protocol is called Mobility support in IPv6 (MIPv6) [1] which handles the routing of IPv6 packets to Mobile Nodes (MNs) when they are away from their home network. To do so, a Home Address (HoA) is assigned to each MN as a permanent identity. While located in a visiting network, an MN acquires a Care-of-Address (CoA) on the new link. This address, configured either stateless [2] or stateful [3], is used to identify the MN's present location within the Internet.

The MN needs to perform the Duplicate Address Detection (DAD) procedure [4] to verify the uniqueness of the CoA. In order to correctly transport packets to a roaming MN, a binding cache is managed by a mobility agent called the Home Agent (HA). Consequently, each time an MN changes its location, it has to update this binding at its designated HA. As a consequence, packets destined to the MN are intercepted by the HA and tunneled to the MN's current location. This procedure is called MIPv6 with tunnel mode. In addition, MIPv6 also enables Correspondent Nodes (CNs) to bind MNs' HoAs to CoAs. This enables direct routing of packets from an CN to an MN's current location via the Route Optimization (RO) mode. However, for security concerns, a Return Routability (RR) procedure is required between the MN and each CN before updating the binding cache at the CN. This RR test consists of verifying whether or not the specific MN possesses the proclaimed HoA and CoA, and ensuring authorization of subsequent Binding Updates (BUs) to the CN.

It is universally recognized that the mobility management procedure in MIPv6 involves long handover latency and high signaling overhead, which need to be addressed to meet the requirements of future wireless networks. In this context, Hierarchical Mobile IPv6 (HMIPv6) [5], [6] and Fast handovers for MIPv6 (FMIPv6) [7], [8] are proposed by separate working groups of IETF.

HMIPv6 is designed to reduce the signaling cost and location update delay outside a local mobility domain. A domain is managed by a network entity called Mobility Anchor Point (MAP). While entering a MAP domain, an MN receives router advertisements containing information about local MAPs from Access Routers (ARs) within range. Then the MN obtains two CoAs: an on-link Local CoA (LCoA) and a Regional CoA (RCoA) within the selected MAP domain. Afterwards, a *Local Binding Update (LBU)* message is sent to the MAP to bind the MN's LCoA with its RCoA. Upon receipt of a successful *Binding Acknowledgment (BA)*, the MN updates the binding of its RCoA with the HoA at the HA and each CN. As a result, packets destined to the MN are intercepted by the MAP, encapsulated and forwarded to the MN's on-link address. A movement within the MAP domain merely incurs LBUs at the MAP without further propagation to the HA and every CN, thus significantly reducing the signaling load and micro-mobility related handoff delays.

Due to the lengthy handoff procedure, MIPv6 is re-

This work was supported in part by NSERC/Ericsson Industrial Research Chair under Grant IRC252720-01.

garded as inappropriate for fast handover support in IPv6-based mobile networks. Under this circumstance, FMIPv6 is designed to enable an MN to rapidly detect its movements and to obtain a prospective IP address with a new AR while being connected to a current AR. This protocol also offers the MN an opportunity to utilize available link layer event notification (triggers) to accelerate network layer handoff [9]. Hence, delays due to network prefix discovery and new CoA generation are completely eliminated during handoff. Moreover, a bidirectional tunnel is setup between the Previous AR (PAR) and the New AR (NAR) to avoid packet drops. The PAR binds an MN's previous CoA with its new CoA. Therefore, packets addressed to the MN are intercepted by the PAR, tunneled to the NAR, and no BUs are necessary to the HA and each CN during handoff. However, due to the utilization of pre-handover triggers, the performance of FMIPv6 depends dramatically on the trigger time. It becomes unreliable when the pre-handoff trigger is delivered too closely to the actual link switch [9].

Both FMIPv6 and HMIPv6 are designed in their own way to improve the MIPv6 performance in terms of signaling overhead and handover. The two schemes can be combined together. However, simple superimposition of FMIPv6 over HMIPv6 brings unnecessary processing overhead for re-tunneling at the PAR and inefficient usage of network bandwidth [10]- [13]. An effective integration, called Fast handover for Hierarchical MIPv6 (F-HMIPv6), has been designed to enable an MN to exchange handoff signaling messages with a local MAP and to establish a tunnel between the MAP and NAR, instead of between the PAR and NAR [10]- [13].

Upon receiving layer two (L2) handoff anticipation or triggers, the MN sends a *Router Solicitation for Proxy Advertisement (RtSolPr)* message to the selected MAP [13]. This message includes information about a potential NAR's MAC address or identifier. It is assumed that the MAP already knows the network prefixes and MAC addresses of the ARs within its domain. In return to the RtSolPr, the MAP sends a *Proxy Router Advertisement (PrRtAdv)* message to the MN. The message contains either the NAR's network prefix or a New on-link Local CoA (NLCoA). The former allows the MN stateless auto-configuration an IPv6 address for its interface [2] while the latter is used for stateful address configuration [3]. Subsequently, the MN sends a *Fast Binding Update (FBU)* message to the MAP indicating its Previous Local CoA (PLCoA) and the NAR's IP address.

After receiving the FBU message from the MN, the MAP sends a *Handover Initiate (HI)* message to the NAR to establish a bidirectional tunnel. In response, the NAR sets up a host route entry for the MN's PLCoA and then responds with a *Handover Acknowledge (HACK)* message. As a result, a bidirectional tunnel is established between the MAP and NAR.

The MAP sends a *Fast Binding Acknowledgment (FBACK)* message toward the MN over its PLCoA and NLCoA. Then, the MAP begins to forward the packets

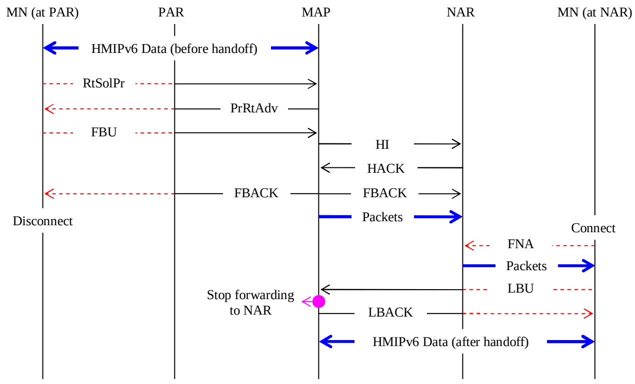

Figure 1. Location Update Procedure in F-HMIPv6 [13]

destined to the MN to the NAR using the established tunnel. Once attached on the new link, the MN sends a *Fast Neighbor Advertisement (FNA)* message to the NAR, which then delivers the buffered packets to the MN.

Afterwards, the MN follows normal the HMIPv6 operations by sending a *Local Binding Update (LBU)* to the MAP via the NAR. When the MAP receives the new LBU with a NLCoA from the MN, it stops forwarding packets to the NAR and removes the established tunnel for fast handover. In response to the LBU, the MAP sends a *Local Binding Acknowledgment (LBACK)* to the MN. As a result, the remaining data path follows the HMIPv6 procedures [13]. Figure 1 shows the location update procedure of F-HMIPv6.

Even though F-HMIPv6 is an efficient scheme, its performance in wireless networks is largely dependent on various system parameters such as the user mobility model, user density, session-to-mobility ratio. It is crucial to analyze the performance while F-HMIPv6 being deployed in IPv6-based cellular networks.

The rest of this article is organized as follows. Section II presents analytical models based on the fluid-flow and random-walk mobility models. Section III formulates the location update cost and packet delivery cost functions using the proposed mobility models. Section IV presents detailed numerical results to show the impact of different system parameters on the performance. Section V concludes the article and outlines future work.

II. Mobility Models

IPv6-based wireless cellular networks are used to evaluate the performance of roaming users. We assume that mobile service areas are partitioned into cells of equal size. Each cell is surrounded by rings of cells, except for cells in the outermost ring. Each domain is composed of n rings of the same size. We name the inmost cell "0", the central cell. Cells labeled "1" constitute the first ring around cell "0", and so on. Each ring is labeled in accordance with the distance to the cell "0". We assume that each cell is managed by one AR. Figure 2 shows an example of a MAP domain with three rings.

There are two mobility models proposed in the literature: the fluid-flow and random-walk models [14]. The

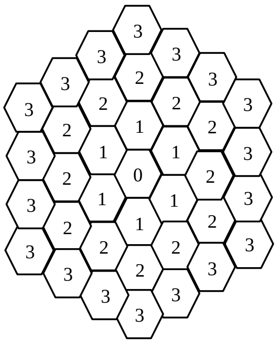

Figure 2. An Example of a MAP Domain with 3 Rings

former is more appropriate for mobile users with high mobility, sporadic speed and direction changes. The latter is often used for pedestrian mobility, which is mostly limited to small geographical areas such as residential sites or premises.

A. The Fluid-flow Model

Using the fluid-flow mobility model, the movement direction of an MN within a MAP domain is distributed uniformly in the range of $(0, 2\pi)$. Let v be the average speed of an MN (m/s); R the cell radius (m); L_c, L_d the perimeters of a cell and a MAP domain with n rings (m), ρ the user density in a cell, i.e. the average number of mobile users per square meter $(/m^2)$; R_c and R_d be the cell and domain crossing rates, R_c and R_d denote the average number of crossings of the boundary of a cell and a domain per unit of time $(/s)$. They are expressed as follows:

$$R_c = \frac{\rho \times v \times L_c}{\pi} = \frac{\rho \times v \times (6R)}{\pi} \tag{1}$$

$$R_d = \frac{\rho \times v \times L_d}{\pi} = \frac{\rho \times v \times (12n + 6)R}{\pi} \tag{2}$$

B. The Random-walk Model

Under the random-walk model, the next position of an MN is determined by its previous position plus the value of a random variable with an arbitrary distribution. Assuming that an MN is located in a cell of ring r, the probability of moving forward to a cell of ring $r + 1$ or backward to a cell of ring $r - 1$ is expressed as follows:

$$p^+(r) = \frac{1}{3} + \frac{1}{6r} \tag{3}$$

$$p^-(r) = \frac{1}{3} - \frac{1}{6r} \tag{4}$$

We present the random-walk model with a one-dimensional Markov chain in which the state is defined as the distance between the current cell located the MN and central cell. Thus an MN is in state r if and only if it is now residing in a cell of ring r. Figure 3 shows the state transition diagram of this Markov chain.

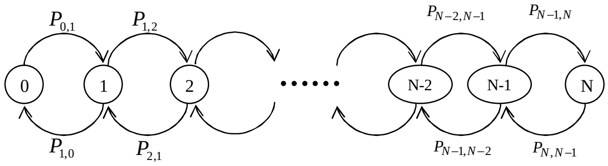

Figure 3. State Diagram for the Random-walk Model

Assuming that the probability for an MN to stay in the current cell is q, the probability for the MN to move to another cell is $1 - q$. The transition probability $P_{r,r+1}$ and $P_{r,r-1}$ represent the probabilities that an MN moves from its current state r to the state $(r + 1)$ or $(r - 1)$. They are expressed as follows:

$$P_{r,r+1} = \begin{cases} 1 - q & if r = 0 \\ (1 - q) \times (\frac{1}{3} + \frac{1}{6r}) & if 1 \le r \le n \end{cases} \tag{5}$$

$$P_{r,r-1} = (1 - q) \times (\frac{1}{3} - \frac{1}{6r}) \tag{6}$$

Let $\Phi_{r,n}$ be the steady-state probability of state r within a MAP domain of n rings. Using the transition probabilities in Equations 5 and 6, $\Phi_{r,n}$ is expressed as:

$$\Phi_{r,n} = \Phi_{0,n} \prod_{i=0}^{r-1} \frac{P_{i,i+1}}{P_{i+1,i}} \tag{7}$$

As $\sum_{r=0}^{n} \Phi_{r,n} = 1$, $\Phi_{0,n}$ can be expressed as:

$$\Phi_{0,n} = \frac{1}{1 + \sum_{r=1}^{n} \prod_{i=0}^{r-1} \frac{P_{i,i+1}}{P_{i+1,i}}} \tag{8}$$

III. Cost Functions

To analyze the performance of F-HMIPv6, we define the total cost as the sum of the location update cost and the packet delivery cost.

A. Location Update Cost

Generally, an MN performs two types of movements: intra-domain and inter-domain. The former are movements within a MAP administrative domain while the latter implies movements between domains. Accordingly, two location update procedures are carried out for F-HMIPv6: the intra-domain case, shown in Figure 1, and inter-domain case which includes the intra-domain F-HMIPv6 and legacy MIPv6 location update procedures. The location update procedure for MIPv6 is shown in Figure 4.

We assume that the distance between the PAR and MAP equals the one between the NAR and MAP and that F-HMIPv6 supports route optimization. Let κ, τ denote the unit transmission cost on a wireless, wired link, d_{x-y} the hop distance between network elements x

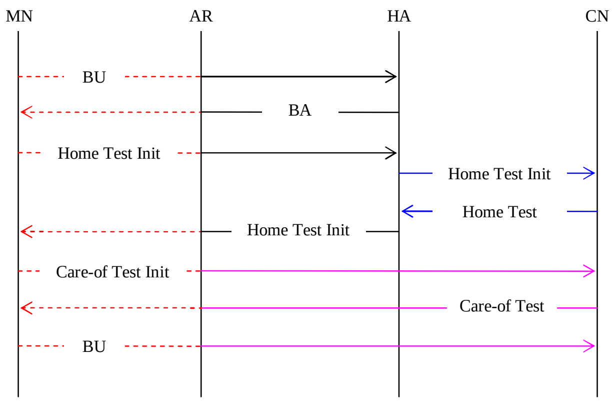

Figure 4. Location Update Procedure in MIPv6

and y, the F-HMIPv6 signaling load functions for intra-domain S_{intra} and inter-domain S_{inter} location update are expressed as follows:

$$S_{intra} = 7\kappa + 9\tau \times d_{AR-MAP} \tag{9}$$

$$S_{inter} = S_{intra} + S_{MIPv6,RO} \tag{10}$$

Equation 9 implies that seven messages are exchanged between the MN and AR via a radio link during handover, the signaling cost for each message is represented by κ. In addition, nine messages are exchanged between the MAP and AR via a wired link, the signaling cost for each message is presented by $\tau \times d_{AR-MAP}$. The same principles apply to Equations 11 and 12.

As shown in Figure 4, the location update procedure for MIPv6 with the tunnel mode consists of a pair of messages (BU and BA) exchanged between the MN and HA. Besides this, MIPv6 with RO support includes the RR procedure and a BU sent to the CN. Overall, the location update cost for MIPv6 is given as follows:

$$S_{MIPv6,tunnel} = 2\kappa + 2\tau \times d_{AR-HA} \tag{11}$$

$$S_{MIPv6,RO} = S_{MIPv6,tunnel} + N_{CN} \times (S_{RR} + S_{BU}) \tag{12}$$

Where the signaling cost for the RR procedure is given by: $S_{RR} = 4\kappa + 2\tau \times (d_{AR-HA} + d_{HA-CN} + d_{AR-CN})$. The signaling cost for sending out a BU to one CN is given by: $S_{BU} = \kappa + \tau \times d_{AR-CN}$.

Based on the signaling load functions: S_{intra} and S_{inter}, the location update cost per MN for F-HMIPv6 with the fluid-flow mobility model is expressed as follows:

$$C^l = \frac{R_d S_{inter} + (N_{AR} \times R_c - R_d) S_{intra}}{\rho \times A_d} \tag{13}$$

Where N_{AR} is the number of ARs in a MAP domain, A_d is the area of a MAP domain (m^2), ρ is the user density in a cell ($/m^2$), R_c and R_d are the cell and domain crossing rate ($/s$), respectively.

Assuming that a MAP domain is composed of n rings, and each cell is controlled by an AP integrating the functionality of an AR. The probability for an MN to perform an inter-domain location update P is expressed as follows:

$$P = \Phi_{n,n} \times P_{n,n+1} \tag{14}$$

Where $\Phi_{n,n}$ is the steady-state probability of the state n, $P_{n,n+1}$ is the probability that the MN moves from a cell in ring n to a cell in ring $n+1$.

Therefore, based on the signaling load functions and inter-domain roaming probability P, the location update cost per MN for F-HMIPv6 with the random-walk model is calculated as follows:

$$C^l = \frac{P \times S_{inter} + (1-P) \times S_{intra}}{E(T)} \tag{15}$$

Where $E(T)$ is the average cell residence time.

B. Packet Delivery Cost

Let P_z be the processing cost at network entity z, C_T the packet transmission cost from a CN to the MN, the packet delivery cost for F-HMIPv6 is expressed as follows:

$$C^p = P_{MAP} + P_{HA} + C_T \tag{16}$$

In F-HMIPv6, a MAP maintains a binding cache table for translation between MNs' RCoAs and LCoAs, same as HA managing a binding between MNs' HoAs and CoAs. All packets addressed to an MN are intercepted by the MAP and tunneled to the MN's LCoA. Hence the processing cost at the MAP can be further divided into the lookup cost and routing cost. The lookup cost is proportional to the size of the binding cache table, thus proportional to the number of MNs in a MAP domain. In addition, the routing cost is proportional to the logarithm of the number of ARs in a MAP domain [15]. Therefore, the processing cost at the MAP can be further expressed as:

$$P_{MAP} = \lambda_s \times [\alpha \times N_{AR} \times \rho \times A_c + \beta \times log_2(N_{AR})] \tag{17}$$

Where λ_s denotes the session arrival rate (packets per second), α is a proportionality factor showing the relationship between the MAP's lookup cost and size of the binding cache table, β is a weighting factor indicating the relationship between routing cost of a MAP and number of ARs in a MAP domain, A_c is the area of a cell (m^2), ρ is the user density in a cell ($/m^2$) and N_{AR} is the number of ARs in a MAP domain.

We assume that F-HMIPv6 supports route optimization to resolve the triangle routing problem. Only the first packet of a session is transmitted to the HA to detect whether or not an MN is away from its home network. All successive packets of the session are directly routed to the MN's new location. Let λ_p denote the first packet arrival rate of a session which also assumes to be the average packet arrival rate (p/s), θ_{HA} is a unit packet processing cost at the HA (s/p), the processing cost at the HA is given by:

$$P_{HA} = \lambda_p \times \theta_{HA} \tag{18}$$

Let λ_s, λ_p denote the session arrival rate and packet arrival rate, d_{x-y} the distance between network elements x and y, the packet transmission cost C_T is calculated as follows:

$$C_T = \kappa \times \lambda_s + C_{direct} + C_{indirect} \qquad (19)$$

Where C_{direct} indicates the transmission cost for the delivery of session packets directly from a CN to an MN, which is given by: $C_{direct} = \tau(\lambda_s - \lambda_p)(d_{CN-MAP} + d_{MAP-AR})$ and $C_{indirect}$ is the transmission cost for session packets through a triangle route via the HA, which is given by: $C_{indirect} = \tau\lambda_p(d_{CN-HA} + d_{HA-MAP} + d_{MAP-AR})$.

IV. Numerical Results

This section analyzes the impact of various wireless system parameters on the aforementioned costs. The parameter values are taken from [15]- [17], i.e. $\alpha = 0.1$, $\beta = 0.2$, $\lambda_s = 1$, $\lambda_p = 0.1$, $\theta_{HA} = 20$, $\tau = 1$, $\kappa = 2$, $N_{CN} = 2$, $L_c = 120$ m, the network topology is shown in Figure 5. The hop distance between different domains is assumed to be identical, i.e. $d_{HA-CN} = f = 6$, $d_{CN-MAP} = d = 4$, $d_{HA-MAP} = c = 6$, $d_{AR-MAP} = b = 2$, $d_{AR1-AR2} = d_{PAR-NAR} = 2$. All links are assumed to be full-duplex in terms of capacity and delay.

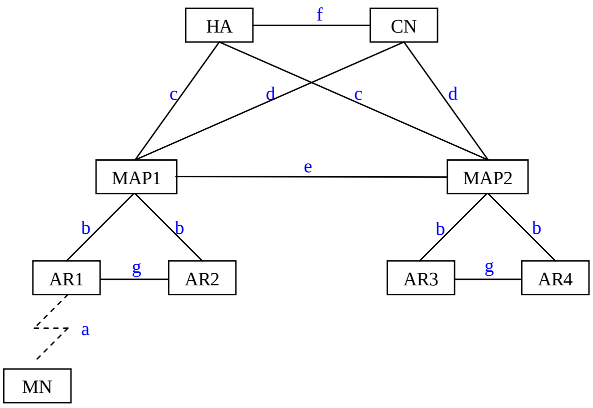

Figure 5. Network Topology Used for Performance Analysis

A. The Impact of User Velocity on Location Update Cost

Figures 6 and 7 demonstrate the relationship between the location update cost and user's average velocity for MAP domains of one ring and six rings, using the fluid-flow model. The user density is set to 0.0002. A lower velocity leads to a lower cell/domain crossing rate and results in less location update cost. In addition, F-HMIPv6 requires more signaling overhead than HMIPv6 (37.17% more for $n = 1$ and 111.57% more for $n = 6$); compared to MIPv6 with tunnel, F-HMIPv6 presents 342.86% more location update cost for $n = 1$ and 127.56% more for $n = 6$; compared to FMIPv6, F-HMIPv6 presents 453.57% more location update cost for $n = 1$ and 184.45% more

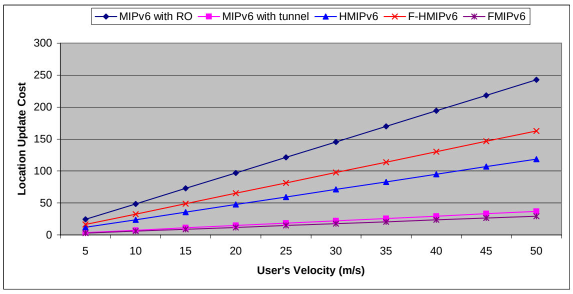

Figure 6. Location Update Cost vs. User's Velocity ($n = 1$)

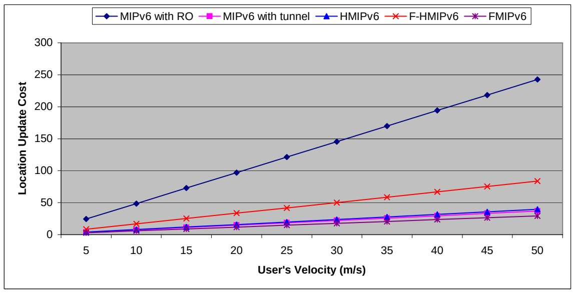

Figure 7. Location Update Cost vs. User's Velocity ($n = 6$)

for $n = 6$. However, it also requires less location update cost than MIPv6 with RO (32.90% lower for $n = 1$ and 65.52% lower for $n = 6$). Comparing the two figures, we find that increasing the MAP size leads to significant reduction of location update cost in case of HMIPv6 and F-HMIPv6. This is because an MN served by a MAP with smaller domain size is more likely to perform inter-domain movements. Furthermore, we also observe that increasing domain size has no impact on the performance of MIPv6 and FMIPv6.

B. The Impact of Cell Residence Time on Location Update Cost

Figures 8 and 9 show the relationship between the location update cost and average cell residence time for MAP domains of one ring and six rings, using the random-walk model. The probability for an MN to stay in the current cell q is set to 0.2. The longer an MN remains in a current cell, the lower the location update cost. We explain this as the MN is less likely to move between subnets. In addition, F-HMIPv6 requires less location update cost than MIPv6 with RO (26.84% less for $n = 1$ and 59.46% less for $n = 6$); compared to MIPv6 with tunnel, F-HMIPv6 presents 382.86% more location update cost for $n = 1$ and 167.56% more for $n = 6$. And F-HMIPv6 also requires more location update cost than HMIPv6 (45.06% higher for $n = 1$ and 127.60% higher for $n = 6$). F-HMIPv6 also needs more location update cost than FMIPv6 (503.57% higher for $n = 1$ and 234.45% higher for $n = 6$). Comparing the two figures, we find that increasing the MAP domain size leads to significant reduction of location update cost in case of

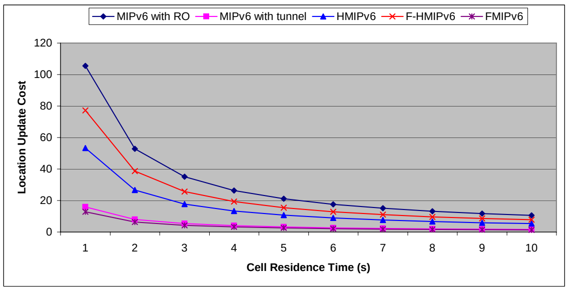

Figure 8. Location Update Cost vs. Cell Residence Time ($n = 1$)

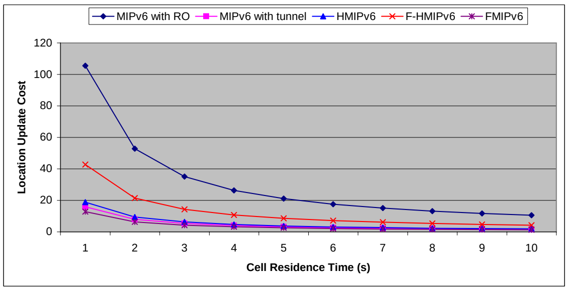

Figure 9. Location Update Cost vs. Cell Residence Time ($n = 6$)

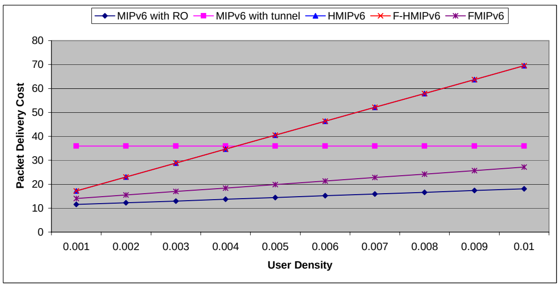

Figure 10. Packet Delivery Cost vs. User Density ($n = 1$)

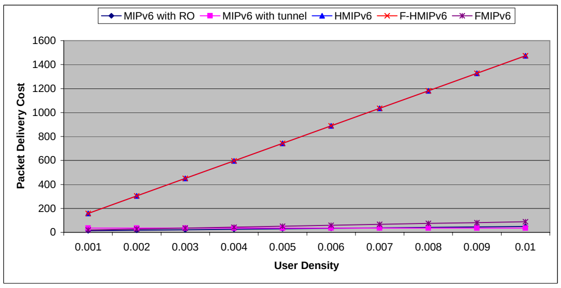

Figure 11. Packet Delivery Cost vs. User Density ($n = 3$)

HMIPv6 and F-HMIPv6. This is because an MN moves in a domain with larger size is less likely to perform inter-domain movements. Furthermore, Figure 9 shows that HMIPv6 tends to deliver the same performance as MIPv6 with tunnel; this means increasing the domain size can considerably reduce location update cost.

C. The Impact of User Density on Packet Delivery Cost

Figures 10 and 11 show the variation of packet delivery cost as the average user density changes for MAP domains with one ring and three rings, under the fluid-flow model. Packet delivery cost increases linearly as the user density augments for HMIPv6 and F-HMIPv6; this is because the processing cost at the MAP, especially the lookup cost to check the binding cache table, is proportionally to the number of MNs in a MAP domain. The two figures also show that increasing the MAP domain size leads to a rapid augmentation of packet delivery cost for F-HMIPv6 and HMIPv6, but has no influence on MIPv6 and FMIPv6; this is because the processing cost at the MAP, especially the routing cost, which is proportional to the logarithm of the number of ARs in a MAP domain. Moreover, Figure 10 shows that when the user density is larger than 0.003, both F-HMIPv6 and HMIPv6 have higher packet delivery cost than MIPv6. However, F-HMIPv6 always delivers the same performance as HMIPv6 in terms of packet delivery cost.

D. The Impact of Session-to-Mobility ratio on Total Cost

Figures 12 and 13 illustrate the variation of total cost as the average session-to-mobility ratio changes for a MAP domain with one ring, using the fluid-flow model. The Session to Mobility Ratio (SMR) is defined as the ratio of the session arrival rate to the user mobility ratio, it is analogous to the Call-to-Mobility Ratio (CMR) used in cellular networks. Under the fluid-flow model, the SMR is defined as λ_s/R_c, i.e. the session arrival rate divided by the cell crossing rate. As the value for ρ and v is fixed, and $R_c = \dfrac{\rho \times v \times L_c}{\pi}$, this leads to a fixed value of cell crossing rate, as a result, the augmentation of the SMR implies an increase of the session arrival rate, so the total cost increases. In case of $SMR \leq 1$, i.e. $\lambda_s \leq R_c$, the location update cost is more dominant than packet delivery cost over the total cost, shown in Figure 12. Under this circumstance, MIPv6 with RO has the highest total cost amongst all schemes. The total cost in descent order is MIPv6 with RO, F-HMIPv6, HMIPv6, MIPv6 with tunnel and FMIPv6. Moreover, as $SMR \geq 1$, the impact of location update cost on the total cost reduces while packet delivery cost becomes more important over the total cost. The higher SMR, the more important is the packet delivery cost over the total cost. As a result, MIPv6 with tunnel has the highest total cost as the SMR increases. In addition, we observe that FMIPv6 yields the best performance amongst all schemes, due to no additional processing cost at the MAP.

Figures 14 and 15 also show the relationship between the total cost and average session-to-mobility ratio for a MAP domain with six rings, using the fluid-flow model. The total cost increases as the SMR augments, the same observation applies to Figures 12 and 13, except that increasing the MAP domain size leads to an augmentation of total cost for HMIPv6 and F-HMIPv6, yet no impact

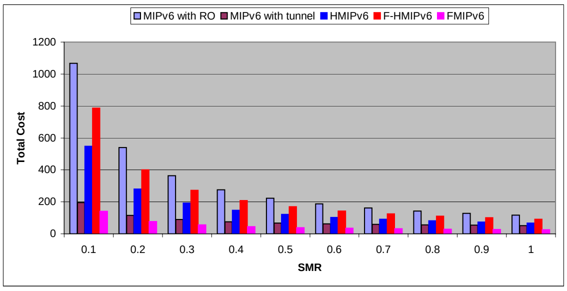

Figure 12. Total Cost vs. SMR ($n = 1$, $SMR \leq 1$)

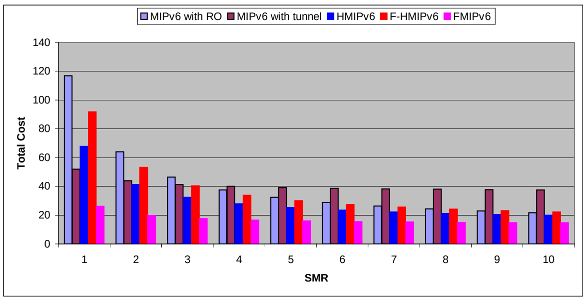

Figure 13. Total Cost vs. SMR ($n = 1$, $1 \leq SMR \leq 10$)

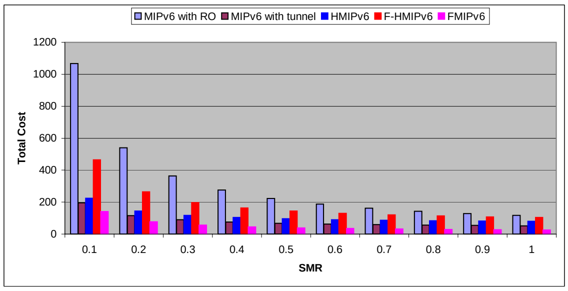

Figure 14. Total Cost vs. SMR ($n = 6$, $SMR \leq 1$)

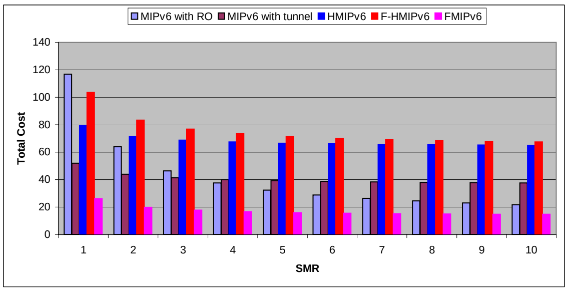

Figure 15. Total Cost vs. SMR ($n = 6$, $1 \leq SMR \leq 10$)

on MIPv6 and FMIPv6. In case of $SMR \leq 1$, the total cost in descent order is MIPv6 with RO, F-HMIPv6, HMIPv6, MIPv6 with tunnel and FMIPv6, shown in Figure 14. However, with $SMR \geq 1$, the total cost in descent order is F-HMIPv6, HMIPv6, MIPv6 with RO, MIPv6 with tunnel and FMIPv6, shown in Figure 15. This because the impact of packet delivery cost over total cost dramatically increases. Besides, the processing cost at the MAP largely increases as the number of ARs within a domain augments. We also observe that F-HMIPv6 tends to deliver the same performance as HMIPv6, shown in Figure 15.

V. Conclusion

This article presented a comprehensive performance analysis of Fast handover for Hierarchical MIPv6 (F-HMIPv6) using analytical models based on the fluid-flow and random-walk mobility models. The impact of various wireless system parameters on the cost functions is evaluated. We find that F-HMIPv6 requires more signaling cost for location update, however, it delivers the same performance as HMIPv6 in terms of packet delivery cost. Generally, F-HMIPv6 is suitable for intra-domain roaming since it requires higher signaling overhead compared with HMIPv6 and FMIPv6. Further study will be carried out to evaluate the performance in terms of handoff blocking probability, handoff latency and packet loss rate.

Acknowledgment

The authors would like to thank the anonymous reviewers for the insightful and constructive feedback on our manuscript.

References

[1] D. Johnson, C. Perkins and J. Arkko, "Mobility support in IPv6", *IETF RFC 3775*, June 2004.
[2] S. Thomson, T. Narten and T. Jinmei, "IPv6 stateless address autoconfiguration", *IETF RFC 4862*, September 2007.
[3] R. Droms, J. Bound, B. Volz, T. Lemon, C. Perkins and M. Carney, "Dynamic host configuration protocol for IPv6 (DHCPv6)", *IETF RFC 3315*, July 2003.
[4] T. Narten, E. Nordmark, W. Simpson and H. Soliman, "Neighbor discovery for IP version 6 (IPv6)", *IETF RFC 4861*, September 2007.
[5] H. Soliman, C. Castelluccia, K. El Malki and L. Bellier, "Hierarchical mobile IPv6 mobility management (HMIPv6)", *IETF RFC 4140*, August 2005.
[6] H. Soliman, C. Castelluccia, K. El Malki and L. Bellier, "Hierarchical mobile IPv6 mobility management (HMIPv6)", *IETF draft*, draft-soliman-mipshop-4140bis- 01.txt, October 2006.
[7] R. Koodli, "Fast handovers for mobile IPv6", *IETF RFC 4068*, July 2005.
[8] R. Koodli, "Mobile IPv6 fast Handovers", *IETF draft*, draft-ietf-mipshop-fmipv6-rfc4068bis-03.txt, October 2007.
[9] J. Kempf, J. Wood and G. Fu, "Fast mobile IPv6 handover packet loss performance: measurements for emulated real time traffic", in *Proc. IEEE WCNC 2003*, New Orleans, USA, Mar. 2003, pp. 1230-1235.
[10] H. Y. Jung, H. Soliman, S.J. Koh and N. Takamiya, "Fast handover for hierarchical MIPv6 (F-HMIPv6)", *IETF draft*, draft-jung-mipshop-fhmipv6-00.txt, October 2005.
[11] H.Y. Jung and S.J. Koh, "Fast handover support in hierarchical mobile IPv6", in *Proc. IEEE ICACT 2004*, Phoenix Park, Korea, February 2004, pp. 551-554.
[12] H.Y. Jung, E.A. Kim, J.W. Yi and H.H. Lee, "A scheme for supporting fast handover in hierarchical mobile IPv6 networks", *ETRI Journal*, vol. 27, no. 6, pp. 798-801, December 2005.
[13] H.Y. Jung, H. Soliman, S.J. Koh and J.Y. Lee, "Fast

handover for hierarchical MIPv6 (F-HMIPv6)", *IETF draft*, draft-jung-mobopts-fhmipv6-00.txt, April 2005.
[14] I.F. Akyildiz and W. Wang, "A dynamic location management scheme for next-generation multiuser PCS systems", *IEEE Transactions on Wireless Communications*, vol. 1, no. 1, pp. 178-189, January 2002.
[15] S. Pack and Y. Choi, "Performance analysis of hierarchical mobile IPv6 in IP-based cellular networks", in *Proc. IEEE PIMRC 2003*, Beijing China, Sep. 2003, pp. 2818-2822.
[16] M. Woo, "Performance analysis of mobile IP regional registration", *IEICE Transactions on Communications*, vol. E86-B, no. 2, pp. 472-478, February 2003.
[17] X. Zhang, J.G. Castellanos and A.T. Campbell, "P-MIP: paging extensions for mobile IP", *Mobile Networks and Applications*, vol. 7, no. 2, pp. 127-141, April 2002.

Li Jun ZHANG received a M.Sc degree in Computer Engineering (2007) from the École Polytechnique de Montréal, Montréal, Canada and a B.Sc in Mathematics (1993) from Jilin University, Changchun, China. She is now pursuing a Ph.D. in Computer Engineering and Software Engineering Department at École Polytechnique de Montréal.

From July 1993 to May 2001, she worked as Software Engineer, System Analyst, System Administrator, System Integrator, Network Administrator and Database Engineer at China Construction Bank, Dalian, China. Since September 2003, she has been working as Graduate Research Assistant at Mobile Computing and Networking Research Laboratory (LARIM) and Intern Research Assistant at Ericsson Research Canada, since January 2004. She works as Teaching Assistant at the Department of Computer Engineering and Software Engineering of the École Polytechnique de Montréal. She served as a reviewer for several conference and journal papers.

Her current research interests include mobile and wireless networking architectures, mobility management and wireless network security for next-generation heterogeneous networks. She has applied three seamless handoff related patents in USA, one book chapter, and has published several peer-reviewed conference papers.

Dr. Samuel Pierre is currently a Professor of Computer Engineering at École Polytechnique de Montréal where he is Director of the Mobile Computing and Networking Research Laboratory (LARIM) and NSERC/Ericsson Industrial Research Chair in Next-generation Mobile Networking Systems. He is the author or coauthor of 6 books, 19 book chapters, 17 edited books and conference proceedings, as well as over 300 other technical publications including journal and proceedings papers.

Dr. Pierre received the Best Paper Award of the 9th International Workshop in Expert Systems & their Applications (France, 1989), Distinguished Paper Award from OPNETWORK'2003 (Washington, USA), special mention from Telecoms Magazine (France, 1994) for one of his coauthored books, Télécommunications et transmission de données (Eyrolles, 1992), among others. His research interests include wireline and wireless networks, mobile computing, performance evaluation, and electronic learning. He is a Fellow of Engineering Institute of Canada, senior member of IEEE, a member of ACM and IEEE Communications Society. He is an Associate Editor of IEEE Communications Letters, IEEE Canadian Journal of Electrical and Computer Engineering, and IEEE Canadian Review. He is also a Regional Editor of Journal of Computer Science, and he serves on the editorial board of Telematics and Informatics published by Elsevier Science.