

# Architecture for Mobility and QoS Support in All-IP Wireless Networks

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## ABSTRACT

Mobility management and quality-of-service (QoS) provisioning are the important tasks on the future development of wireless networks. The high host mobility makes these tasks more challenging. In this paper, we propose an architecture which supports both mobility and QoS management in IP-based wireless networks. In mobility management, the fast handoff, which the packets are forwarded in advance to the neighboring locations where a mobile node may move to, is provided to reduce the service disruption. Also, the fast location lookup, which the routing information about a mobile node is replicated to some routers, is provided to avoid the triangular routing problem incurred by the protocol of Mobile IP. In QoS provisioning, we enable the end-to-end QoS guarantee by using the RSVP (Resource reSerVation Protocol) signaling. In particular, the RSVP aggregation technique is used to avoid the scalability problem. Also, the technique of passive resource reservation is used to reduce the influence of host mobility on the resource reservation delay. We emphasize the integration of mobility and QoS management in the architecture design. A performance analysis is given to justify the benefits of our proposed architecture.

Keywords: Mobility Management, QoS Provisioning, Mobile IP, RSVP, RSVP Aggregation

## 1. INTRODUCTION

There has been an evolutionary trend in mobile communication systems toward the four-generation (4G) ones. The future 4G systems will be heterogeneous networks, which include a large number of different access networks [4]. For instance, the network services are provided by the cellular radio systems for outdoor environments and by the wireless LAN (Local Area Net-

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work)/wireless PAN (Personal Area Network) systems for indoor ones. A mobile node (MN) equipped with a software-based terminal can connect to the Internet via the base station of the access network nearby. One promising feature of 4G networks is to provide an all-IP (Internet Protocol) architecture and the connectivity to anywhere at anytime. The IP-based wireless networks have the advantages of directly applying IP techniques and applications written for wired networks to wireless ones [20].

Two important problems still remain to be solved even if the IP techniques are adopted in the 4G wireless networks: how to maintain the network connectivity and how to assure the provisioning of enough network resources to MNs. Mobility management in mobile communication systems is an important task in order to keep connectivity with roaming users at anytime. It consists of two components: location management and handoff management. The location management corresponds to the registration updates of MNs' current points of attachment to the Internet, which enables any MN to be reached at anytime. The handoff management enables an MN to keep the network connectivity when changing its point of attachment. Mobile IP (MIP) [25], which is a standard proposed by the Internet Engineering Task Force (IETF), can serve as the basic mobility management in IP-based wireless networks. For the resource provisioning, there are two general models to provide network resources for quality-of-service (QoS) guarantees in the Internet: *Integrated Services* (IntServ) and *Differentiated Services* (DiffServ) models [23]. While IntServ can provide quantitative QoS guarantees to individual flows, DiffServ can provide qualitative QoS guarantees to multiple flows in an aggregate way.

MIP specified a mechanism to enable an MN to change its point of attachment without changing its IP address. Both MIPv4 and MIPv6 are discussed in the IETF. Though our work is based on MIPv4, the similar modification can be deployed in IPv6 framework. In MIP, an MN is assigned with a permanent home address in its home network, and will borrow a temporary care-of address (CoA) in any foreign network. The home agent (HA) in the MN's home network will maintain the mapping between the home address to the CoA. The CoA can be the IP address of the foreign agent (FA) in the current visited foreign network or can be acquired from the local address pool using protocols such as Dynamic Host Configuration Protocol (DHCP) [12]. The former case of getting the CoA is used throughout the paper.

Packets which are sent from a corresponding node (CN) in the Internet and destined to an MN are first intercepted by the MN's HA, and then tunneled to the current serving FA using the MN's CoA. The FA then decapsulates the tunneled packets and forwards them to the MN. This routing

path will increase the packet delivery cost and is mostly criticized as a triangular routing problem. In addition, MIP has other problems [10] such as long handoff latency and large signaling load for frequent registration updates. Some enhancements to MIP for MNs with high mobility have been studied in [7][8][10][14][20][27][28][30].

RSVP (Resource reSerVation Protocol) [5] is a resource setup protocol designed for the IntServ model. The needed resource can be reserved by RSVP along the data path between the sender and the receiver. RSVP performs poorly due to the host mobility in wireless mobile networks [18]. The delay of reserving resource along the new data path after the MN's movement may cause the service disruption for real-time services. Some RSVP extensions for wireless mobile networks were surveyed in [18]. Moreover, RSVP has the scalability problem, since per-flow reservation states have to be periodically refreshed. RSVP aggregation [3] with the facilities for aggregation of individual reserved sessions into a common class can avoid the scalability problem. Though the DiffServ model has a good scalability, only the soft (or qualitative) QoS can be guaranteed.

The design and integration of mobility management and QoS provisioning in the wireless networks is a real challenge. The integration of MIP and DiffServ was investigated in [21][33]. However, the end-to-end QoS can not be guaranteed. In this paper, we propose a hierarchical architecture which supports both MIP-based mobility management and RSVP-based QoS provisioning. We reduce not only the registration cost, but also the packet delivery cost through the mechanisms of fast handoff and fast location lookup. The proposed resource reservation mechanism which takes advantage of the proposed mobility architecture and RSVP aggregation can widely reduce the maintenance cost.

The remainder of this paper is organized as follows. Section 2 gives a brief survey of the previous work. Section 3 introduces our proposed architecture. The detailed descriptions of our provided mechanisms are given in Section 4. The performance evaluations are shown in Section 5. Finally, we present the conclusion in Section 6.

## **2. RELATED WORK**

### **2.1. Techniques of Mobility Management**

MIP provides a basic solution to the location management problem in IP-based wireless networks. However, MIP suffers from the performance degradation due to the MN's specific movement patterns. The movement patterns can be classified into three categories according to the

moving scope [7][10]: local mobility (movement between base stations on the same subnet), intra-domain mobility (movement across different subnets within the same domain), and inter-domain mobility (movement among different domains).

To handle local and intra-domain mobility, frequent and possible long distant registration updates to the HA may happen in MIP. To reduce the registration cost for local mobility, the ARP (Address Resolution Protocol) is used in [7]. The base stations should be configured as network-layer routers first. Then, the MN can keep the same CoA in the same subnet and the actual point of attachment to a particular base station is managed by the gratuitous and proxy features of the ARP.

On the other hand, the regional registration [14] can reduce the registration cost for intra-domain mobility. The regional registration which is based on the hierarchical mobility management makes most of registration updates hidden from the HA. The registration updates end at the GFA (Gateway FA) of the current visited domain (or region) as the MN moves within the same domain (or region). The optimal setting of the domain size was discussed in [34]. At the HA, the address of the current serving GFA of the MN will be recorded. The packet delivery from the GFA to the current visited subnet (or base station<sup>1</sup>) of the MN can be done by the host-specific routing [8][27] or the tunneling [10][20].

In the host-specific routing, packets are forwarded to the current visited subnet hop by hop via the forwarding entries in the routing tables. For example, HAWAII [27] directly maintains the routing path by a signaling protocol, while Cellular IP [8] learns the routing path indirectly by snooping incoming and outgoing packets at base stations. In the tunneling, packets are tunneled to the current visited subnet using the CoA acquired. For example, TeleMIP [10] and IDMP [20] provide local CoAs within a domain and these local CoAs use the address space of local scope not to deplete the address space of global scope.

In handoff management, the handoffs can be classified into hard and soft ones depending on whether two or more simultaneous connections to an MN exist during handoff. Recently, the fast (or seamless) handoff mechanisms are widely discussed in reducing the service disruption during hard handoff for real-time applications. The fast handoff aims at having low handoff latency and low packet loss. The handoff latency is the time elapsed from the moment the handoff event is detected to the moment the first packet is received from the new link. Pre-registration [13],

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<sup>1</sup> The mobility management may have base-station-level or subnet-level granularity. In the subnet-level granularity, the packet delivery within a subnet is broadcast natured. In the base-station-level granularity, the base stations should be network-layer routers.

Post-registration [13], and IDMP rely on the L2 (link-layer) trigger to reduce the handoff latency. The L2 trigger is a signal from L2 to inform L3 (network-layer) an imminent L2 handoff. In Pre-registration, the L2 and the L3 handoffs can proceed at the same time. In Post-registration, the MN can receive packets from the new link (these packets are forwarded from the old FA) before the L3 handoff completes. Both Pre-registration and Post-registration require the FA to be aware of the IP address identifier of the neighboring FA. In IDMP, all possible new FAs for an MN will buffer the “in-flight” packets. The in-flight packets are the packets possibly lost in the air during the handoff period. After the L3 handoff completes, the MN can immediately receive the buffered packets from the new FA.

The low packet loss during handoff is commonly achieved by the buffering mechanism which stores in-flight packets at some place. The buffering mechanism can be a unicast-based or a multicast-based one. In the unicast-based buffering, in-flight packets can be buffered in the old FA or the GFA (e.g.,  $\mu$ MIP [30]) and then be forwarded to the new FA. In the multicast-based buffering, all the surrounding FAs of the current serving FA of the MN will buffer the in-flight packets which are multicasted from the GFA in IDMP.

## **2.2. Techniques of QoS Provisioning**

In IntServ, two factors cause RSVP some problems: IP tunneling and host mobility. The IP tunneling operated in MIP makes RSVP messages invisible to the routers along the tunnel. One solution is to create a RSVP session over the tunnel using explicit signaling messages [32]. The host mobility causes the service disruption in providing real-time services. The passive or advance resource reservation is generally used to deal with this problem. The passive resources are reserved in advance along the possible new data paths after handoff for the MN. The passive resource can be temporarily used by other MNs to alleviate the resource occupation problem.

There are several ways to make the advance resource reservations. In [31], these reservations are made along the paths from the sender to all locations where the MN (as a receiver) is expected to visit. This approach occupies too much resource. In [6], these reservations are made from the sender toward the neighboring locations of the current visited one of the MN. The signaling messages are sent by multicasting, which incurs high maintenance cost on dynamic multicast trees. In [19], these reservations are made only along the new branch path toward the new visited location by using a crossover router discovery scheme. However, this scheme is limited to the tree-based network topology. In [17][24], these reservations are made from the current visited location to the

neighboring locations. Moreover, the forwarding chain is used to trace the MN's movement. However, the maintenance of forwarding chains and the effect of a different maintaining way on the resource reservation cost are not discussed.

In DiffServ, most research efforts are made at the QoS provisioning within the access network (or the administrative domain). The *Bandwidth Broker* (BB) is commonly charged with the resource allocation and the call admission control within the access network. The resource commitments are based on how many connections for each service class are allowed in that access network. In [9], the BB only allocates the wireless resources of base stations. The base station plays the role in performing the traffic conditioning and marking as a typical edge router does in DiffServ. In [21], the BB will configure the resources allocated to different service classes on different paths as well as the resources on the possible new paths for handoff MNs. The above two schemes only provide the soft QoS guarantee within the access network, but not a strict end-to-end QoS guarantee across different access networks. The end-to-end QoS guarantee using DiffServ was discussed in [33], which encounters the same scalability problem as in IntServ.

### **3. MOBILITY AND QoS ARCHITECTURE**

The *Intra-Domain Mobility Management Protocol* (IDMP) presented in [11][20] is based on the TeleMIP architecture [10]. IDMP has some outstanding features as pointed out in [10] over other schemes like HAWAII and Cellular IP. In this paper, we will propose some mechanisms to enhance the performance and ability of IDMP by reducing the packet loss and the data delivery cost, and providing the end-to-end QoS guarantee.

#### **3.1. An Introduction to IDMP**

IDMP is based on a two-level generalization of the MIP architecture (see Fig. 1). Each access network composed of several subnets is viewed as a domain. The mobility management in IDMP has the subnet-level granularity. There are two types of agents (in addition to the HA) in supporting the mobility management: *Mobile Agent* (MA) and *Subnet Agent* (SA). An access network is distributed with some MAs and a subnet is associated with a single SA. Moreover, each SA should be associated with at least one MA in that domain. An MA is capable of handling several SAs. For example, SA<sub>1</sub> and SA<sub>3</sub> are served by MA<sub>1</sub>, while SA<sub>2</sub> is served by MA<sub>2</sub>. An MA acts as a domain-level point of attachment and provides global CoAs (GCoA) for the registered MNs in that domain. An SA acts as a subnet-level point of attachment and provides local CoAs (LCoA) for the

registered MNs in that subnet. The MA and the SA are functionally similar to the GFA and the FA, respectively.

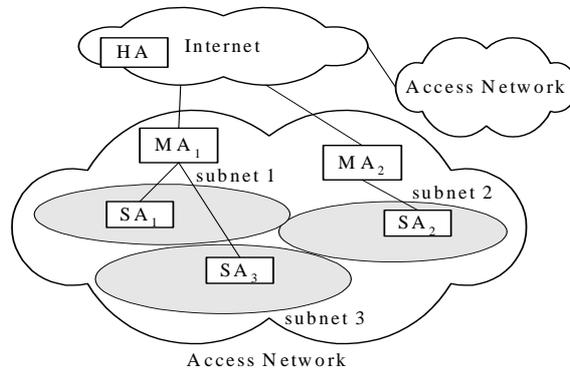


Fig. 1. IDMP network architecture.

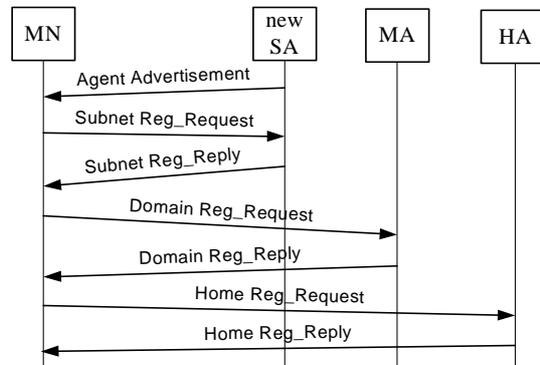


Fig. 2. Signaling flow during inter-domain movement in IDMP.

An SA will periodically broadcast the agent advertisement containing the domain identifier to advertise its present. An MN can determine whether it is in a new subnet or in a new domain by listening to the agent advertisement. Whenever the MN changes domains, it first obtains an LCoA by performing a subnet-specific registration update to the serving SA. The serving SA assigns the MN a designated MA. Then the MN performs a domain-specific registration update by communicating its current LCoA to the designated MA. The designated MA replies to the registration with a GCoA. Finally, the MN performs a home registration update by communicating its current GCoA to the HA. The above signaling flow is shown in Fig. 2. Whenever the MN changes subnets within the same domain, the MN only communicates its new LCoA to the serving MA. Note that the serving MA remains the same in this circumstance. In other words, the GCoA remains unchanged. Packets destined to an MN are intercepted by the MN's HA, and then tunneled to the MA using the MN's GCoA, and then tunneled to the SA using the MN's LCoA.

IDMP provides fast handoff and paging support. Fig. 3 shows the functional layout of IDMP, where there is only one serving MA in a domain. IDMP's fast handoff mechanism works as fol-

lows. It is assumed that on each handoff/movement, the MN is changing to a different subnet. When a prospective handoff is detected by the L2 trigger, IDMP requires either the MN or the old SA (say SA<sub>2</sub>) to generate a MovementImminent message to the serving MA. The MA then multicasts all inbound packets (destined to the MN) to the neighboring SAs (SA<sub>1</sub> and SA<sub>3</sub> in this case). Each of these neighboring SAs buffers such arriving packets in per-MN buffers. After the MN registers with a new SA (say SA<sub>3</sub>), the new SA can immediately forward the buffered packets to the MN.

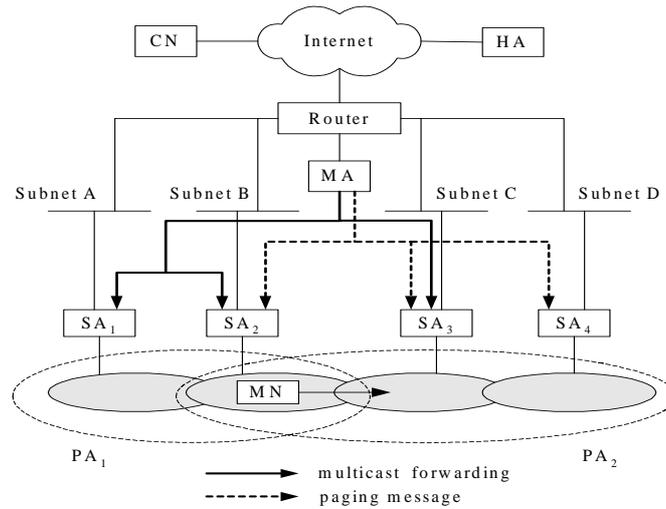


Fig. 3. IDMP functional layout.

The frequency of intra-domain registration updates is reduced in IDMP by the paging mechanism. Subnet areas are grouped into several *Paging Areas* (PAs) as depicted in Fig. 3. The PAs (PA<sub>1</sub> and PA<sub>2</sub>) in the figure are overlapped to avoid the problem of ping-ponging (rapid back and forth movement between two neighboring PAs). When an MN in the idle mode (with no active connection session) changes its subnet of attachment (say SA<sub>2</sub> to SA<sub>3</sub>), no registration update is performed as long as the MN stays within the same PA (PA<sub>2</sub>). When the MA receives packets for an MN which is in the idle mode, the MA multicasts a paging message to all the subnets within the MN's current visited PA. After the MN receives the paging message and re-registers with the MA, the MA tunnels the packets to the MN's current serving SA.

The QoS provisioning using DiffServ in the IDMP environment was discussed in [21]. The BB located in each access network will configure the local resource allocation. Also, the BB will configure the resource for handoff MNs. In summary, IDMP has two disadvantages: (1) a large amount of multicast addresses is used in the fast handoff and the paging operations; (2) the end-to-end QoS issue is not considered. If RSVP is used, in order to reduce the influence of host mobility on the resource reservation, RSVP messages would be rather terminated at the MA than

terminated at the MN itself as pointed out in [10]. The reason is that the path from the CN to the MA is less changed than the one from the CN to the MN under the MN's mobility.

### 3.2. Our Proposed Architecture

Based on the IDMP's architecture, we propose a more efficient one for both QoS and mobility management. Our proposed architecture (called FCAR) is based on the concepts of *Forwarding Chain* and *Aggregate Reservation*. FCAR supports paging, fast handoff, fast location lookup, and resource reservation services. The protocol design is based on the MN-initiated control scheme. Moreover, the QoS provisioning in the access network is based on the IntServ model with the combination of RSVP and RSVP aggregation [3].

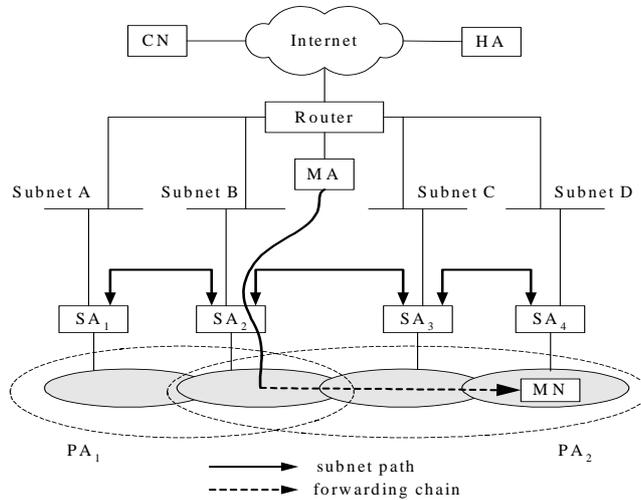


Fig. 4. FCAR functional layout.

Fig. 4 shows a snapshot of FCAR. FCAR uses the same two-level hierarchical architecture as IDMP. We use the subnet-level granularity in the mobility management for the easy comparison with IDMP, though it will be the base-station-level granularity in the future all-IP architecture. FCAR supports the same paging mechanism as IDMP too. However, we use a different approach to manage the MN's mobility within a domain. We anchor the MN's connection to a fixed SA (called anchored SA) and use a forwarding chain (set of forwarding paths) to track the host mobility within a domain. For example, the MN shown in Fig. 4 is traced by the forwarding chain linked from SA<sub>2</sub> (anchored SA) to SA<sub>3</sub>, and to SA<sub>4</sub>. The tunneled packets using the LCoA are decapsulated at the anchored SA and then are forwarded to the MN along the forwarding chain.

To avoid a long forwarding chain during subsequent movements, two types of forwarding

schemes can be used: *region-based* and *movement-based* schemes<sup>2</sup>. In the region-based forwarding (abbreviated as R-FCAR), we restrict the forwarding paths for an MN to be concatenated within the same PA. When an MN handoffs to one other PA, the forwarding chain is renewed. That is, a registration update to the MA is performed and the new visited SA in that PA becomes the new anchored SA. In the movement-based forwarding (abbreviated as M-FCAR), we restrict the maximal length of the forwarding chain (in terms of the number of movements) to a certain threshold. The forwarding chain is renewed when the number of MN's movements just exceeds the threshold value. By comparison, the first visited SA in a new PA becomes the new anchored SA in R-FCAR, while the next visited SA becomes the new anchored SA in M-FCAR just after the number of MN's movements has reached the threshold value. Note that there is no forwarding path between different domains in both schemes, since each domain may use its own address space of local scope. In other words, the forwarding chain is forced to be renewed when the MN moves to a different domain. The determination of renewal of a forwarding chain is by listening to the PA's identifier in R-FCAR or by recording the number of MN's movements in M-FCAR. Here one movement for an MN is equivalent to one handoff.

The series of registration updates (subnet-specific, domain-specific and home ones) during inter-domain movement in FCAR is the same as that in IDMP. However, there are two differences in the registration updates during intra-domain movement. First, the MN will additionally issue a forwarding request message to create a forwarding path between the new and the old SAs. Second, only when the forwarding chain is being renewed, a new LCoA should be obtained and a domain-specific registration update should be performed. The above signaling flow is shown in Fig. 5.

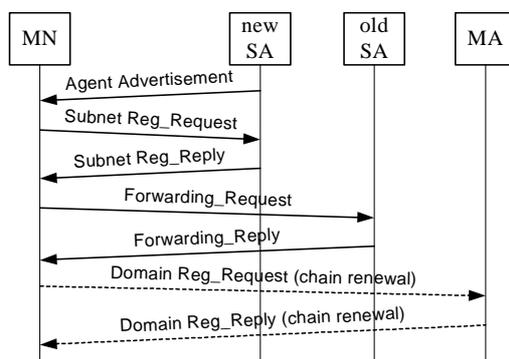


Fig. 5. Signaling flow during intra-domain movement in FCAR.

<sup>2</sup> Another possible scheme is the distance-based one as proposed in [2]. The implementation cost of this scheme is high, since the geographic distance information between SAs (or FAs) should be known apriori.

The usage of forwarding chains may cause that most of data packets are conveyed between SAs. To provide the QoS guarantee for data delivery on the forwarding chain, we establish a bi-directional and QoS guaranteed path (called *subnet path*) between any two neighboring SAs within a domain. The subnet path is established either over the direct edge between the neighboring SAs or through the host which is the least common ancestor of the two neighboring SAs. The subnet path can be considered as a common channel which conveys the packets between SAs. We maintain the resource reservations on subnet paths in an aggregate manner. The reserved resource can be shared among the traffic flows on a subnet path.

Below, we show how to provide a variety of services based on the proposed architecture. More detailed descriptions about these services are given in the next section.

*Fast Handoff.* We provide the similar fast handoff mechanism as IDMP. The main difference is that the buffered packets are sent from the old SA instead of the serving MA during handoff. That is, once an imminent handoff for an MN occurs, the MN sends a MovementImminent message to the old SA. The old SA then sends all inbound packets destined to the MN to neighboring SAs via the subnet paths. The neighboring SA buffers such arriving packets in per-MN buffers. After the MN registers with a new SA, the MN sends a forwarding request message to the old SA (via the new SA). Upon receiving the forwarding request message, the old SA stops sending packets to the neighboring SAs and forwards future packets for the MN toward the new SA via the subnet path.

*Fast Location Lookup.* MIP has the triangular routing problem that may cause a long call setup delay in the voice over IP applications. The reason is that the call request from the caller to the callee (assumed an MN) should be sent to the HA first where the callee's CoA is inquired. Here, we borrow the location lookup technique [29] used in cellular networks to reduce the call setup delay. We replicate the address mapping of an MN (<MN's home address, MN's GCoA>), which is usually stored in the HA, to the MA. Any call request (or data stream) to an MN locating in one other access network can be directly delivered from the local MA by looking up the replica to the remote MA without the intervention of the HA.

*QoS Guarantee.* In FCAR, we anchor the MN's connection to the anchored SA during movement within a domain. As a result, the connection path from the CN to the anchored SA becomes less changed, so we can terminate the per-flow resource reservation using RSVP at the anchored SA. Note that the technique of RSVP over IP tunnels [32] should be applied between the HA and the MA, and between the MA and the anchored SA. Since the forwarding chain to track the host mo-

bility is established over subnet paths with pre-configured resources, the resource provisioning can be quickly and easily extended from the anchored SA to the MN's current serving SA. Therefore, we can achieve the end-to-end QoS guarantee conveniently.

## 4. PROPOSED MECHANISMS

### 4.1. Fast Handoff Support

We explain the fast handoff procedure associated with the maintenance of forwarding chains. Fig. 6 shows an example of using the R-FCAR scheme. Suppose that an MN is in the active mode (with more than one connection session) and can only move vertically or horizontally. First, we discuss the case when the MN is a receiver. Assume that SA<sub>2</sub> is the anchored SA for the MN in PA<sub>1</sub>. SA<sub>2</sub> will have a forwarding entry for the MN indicating that the MN is now in SA<sub>2</sub>. The forwarding entry contains three fields. The first field is the MN's permanent IP address and the second field indicates whether the MN is in or out of the subnet. The third field indicates the next forwarding node if the MN is out of the subnet, or the current visited node if the MN is in the underlying subnet.

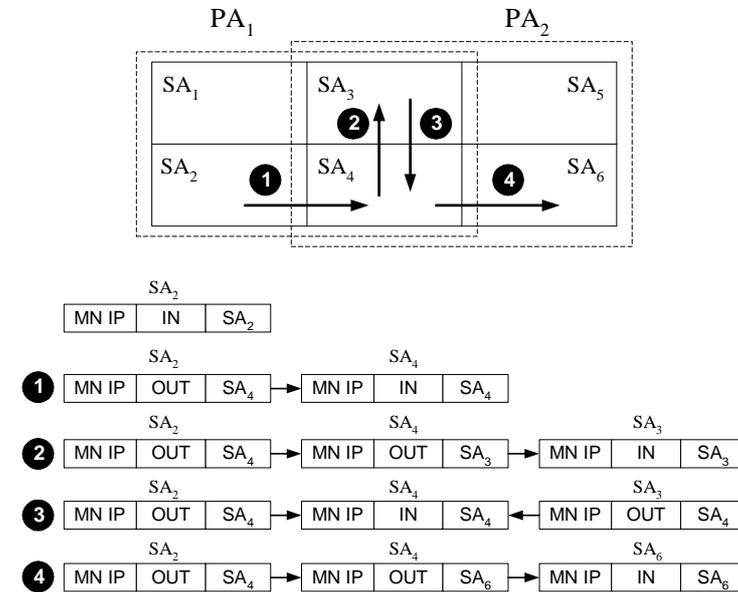


Fig. 6. The creation of the forwarding chain in R-FCAR.

When the MN is about to move from SA<sub>2</sub> to SA<sub>4</sub> (movement 1), it sends a MovementImminent message to SA<sub>2</sub>. SA<sub>2</sub> adds a new option indicating the request of packet buffering into each header of all inbound packets (after decapsulating the packets) for the MN, and then sends these packets to the neighboring SAs (SA<sub>1</sub> and SA<sub>4</sub>). The neighboring SAs will buffer such packets. When the

MN moves to SA<sub>4</sub>, it performs the subnet-specific registration update to SA<sub>4</sub> and issues a forwarding request message to SA<sub>2</sub>. SA<sub>4</sub> adds a new forwarding entry for the MN and SA<sub>2</sub> updates its forwarding entry indicating that the MN is now in SA<sub>4</sub>. SA<sub>2</sub> will stop sending packets to the neighboring SAs and forwards the future packets for the MN to SA<sub>4</sub>. The buffered packets stored in SA<sub>1</sub> will be removed upon time out to save the buffer space. One further mechanism to improve the buffer utilization is to control the amount of in-flight packets sent to neighboring SAs according to the likelihood of the MN to handoff to a particular SA. This issue will be discussed in Section 5.

When the MN moves from SA<sub>4</sub> to SA<sub>3</sub> (movement 2), the forwarding path SA<sub>4</sub>→SA<sub>3</sub> is created. When the MN backs to SA<sub>4</sub> (movement 3), SA<sub>4</sub> updates its forwarding entry indicating that the MN is in the current subnet. Packets sent from SA<sub>2</sub> will be delivered to SA<sub>4</sub> through the direct forwarding path SA<sub>2</sub>→SA<sub>4</sub> instead of the loop one SA<sub>2</sub>→SA<sub>4</sub>→SA<sub>3</sub>→SA<sub>4</sub>. The forwarding path SA<sub>3</sub>→SA<sub>4</sub> can still forward those old packets routed to SA<sub>3</sub> to SA<sub>4</sub>. Consequently, there is always no loop route on the forwarding chain<sup>3</sup>. Finally, the MN moves to SA<sub>6</sub> in PA<sub>2</sub> (movement 4). The forwarding chain is renewed and SA<sub>6</sub> becomes an anchored SA. The old forwarding chain from SA<sub>2</sub> to SA<sub>6</sub> can continue forwarding packets to the MN before the domain-specific registration update is finished at the serving MA.

When the MN switches from the active mode to the idle mode, a domain-specific registration update should be performed, and no forwarding path will be created in the idle mode. To reclaim obsolete forwarding entries in SAs, we can remove these entries by a timeout mechanism. We can associate a timestamp filed with the forwarding entry and update the filed each time when the forwarding entry is looked up. Those forwarding entries having not been used for over a certain time period will be deleted.

When the MN is a sender, we maintain the similar forwarding chain with opposite direction to the case when the MN is a receiver. The outbound packets from the MN are forwarded to the anchored SA along the forwarding chain. Then the anchored SA uses the reverse tunneling [22] to deliver these packets to the serving MA. The reverse tunneling can reduce the change of data path due to the movement of a sender node. The serving MA then decapsulates and sends these outbound packets to the CN.

We summarize the jobs of an SA when it receives an inbound (or outbound) packet as follows:

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<sup>3</sup> Hence, when neighboring SAs are not directly linked but have a common ancestor, packets will not go down and up along the same path.

1. If the inbound packet is a packet with an IP option indicating the request of packet buffering, the SA buffers this packet in per-MN buffers. The SA will forward such buffered packets to the corresponding MN once it is in the underlying subnet.
2. If the inbound (or outbound) packet is a forwarded packet destined to (or originated from) an MN, the SA either forwards the packet to the MN directly or forwards the packet to the next forwarding node according to the forwarding entry.

The proposed fast handoff mechanism offers several advantages over IDMP:

- During handoff, the MovementImminent message is sent to the old SA instead of the MA. Consequently, in-flight packets are sent from the old SA instead of the MA toward the neighboring SAs. This can reduce the number of hosts/routers involving in the packet delivery. Also, the buffering mechanism can be initiated more early than that in IDMP, so packet loss can be reduced.
- The domain-specific registration update is performed for each movement in IDMP, but is performed when the forwarding chain is being renewed in FCAR. Before the forwarding chain is renewed, we update the forwarding path for each movement by exchanging messages between the old and the new SAs. The incurred signaling overhead would be small as compared with IDMP.

## 4.2. Fast Location Lookup Support

The fast location lookup can provide a convenient way to find the MN's location by using the data replication. In our mobility architecture, any outgoing packet from an access network would be routed to the MA first. If we replicate the address mapping of an MN to the MA, any connection setup (or data stream) from that MA can easily reach this MN without the intervention of the HA. However, once the address mapping in the HA is updated, the replicated address mapping at the MA should be updated too. Hence, we reduce the routing cost at the expense of the update cost of data replication.

The location lookup problem is to find the best placement of the replicated address mappings among the MAs such that the cost savings are maximal. Shivakumar et al. [29] provides a per-user replication scheme on this problem. We can map their proposed solution into our one as follows. A replica of the address mapping of an MN at an MA is judicious if the cost saving due to replication exceeds the cost incurred. Hence, it is judicious to replicate the address mapping of  $MN_i$  at  $MA_j$  if:

$$\alpha \times C_{ij} \geq \beta \times U_i$$

$\alpha$  is the cost saving achieved when a local lookup succeeds as opposed to a remote route.  $\beta$  is the cost of updating a replicated address mapping.  $C_{ij}$  is the expected number of connection setups which come from the area served by  $MA_j$  and are destined to  $MN_i$  over a certain time period.  $U_i$  is the expected number of registration updates with respect to  $MN_i$  at the HA over a certain time period.

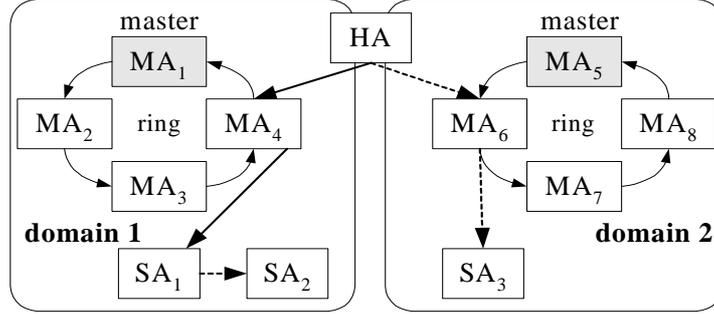


Fig. 7. The fast location lookup in FCAR.

We illustrate the design of the fast location lookup based on our mobility architecture. As shown in Fig. 7, we connect MAs in the same domain using a virtual token ring. Each domain has one MA serving as *master* MA. Each MA should maintain the expected number of outgoing connection setups from its serving area on a per-MN basis over a time period  $T$ . Once the expected number of connection setups to an MN exceeds the threshold value (*local-threshold*) before the MA gets a valid replicated address mapping, this MA sends an AddressSolicitation message to the next MA in the token ring and waits for a reply before a timeout. The AddressSolicitation message is for inquiring an MN's address mapping. An MA will reply to this message with the MN's GCoA if the MN is currently registering with this MA, or will relay the message to the next MA in the token ring. A reply to the inquiry message is expected when the two end nodes of the connection setup locate in the same domain. The expected number of connection setups is recounted when it has reached the *local\_threshold* value or when a valid replicated address mapping becomes available.

Also, the master MA will approximate the total expected number of connection setups on a per-MN basis by listening to the AddressSolicitation messages issued by other non-master MAs over a time period  $T$ . That is, the total expected number is supposed to be over  $n \times local\_threshold$ , given  $n$  AddressSolicitation messages are listened to in the token ring. Once the total expected number of connection setups to an MN exceeds the threshold value (*global-threshold*) and meanwhile the master MA does not listen to any reply to the latest AddressSolicitation message with

respect to the MN within the time period  $T$ , the master MA sends an AddressSolicitation message to the MN's HA. It happens when the two end nodes of the connection setup locate in different domains. The master MA will propagate the reply from the HA to other MAs via the token ring. All these MAs in the token ring will keep the replicated address mappings in their local caches. These replicated address mappings in the caches are valid for a certain period of time and will be removed when becoming invalid. This replication scheme can facilitate an MN who frequently makes a call to a certain MN and moves around in the same domain.

Take Fig. 7 as an example. Suppose that the MN is currently located in  $SA_1$ .  $SA_1$  and  $SA_2$  are served by  $MA_4$  and  $SA_3$  is served by  $MA_6$ . Suppose that  $MA_2$  in domain 1 and all MAs in domain 2 have the replicated address mapping of the MN. Any connection setup to the MN from  $MA_2$  or from one of MAs in domain 2 will be routed to  $MA_4$  directly<sup>4</sup>. As the MN moves to  $SA_2$ , the connection setup using the replicated address mapping can still reach the MN via the forwarding chain from  $SA_1$  to  $SA_2$ . As the MN moves to  $SA_3$  and registers with  $MA_6$ , the MN will be unreachable if the replicated address mapping is referred to.

We need a process to update the replicated address mappings in the caches. The HA will keep a log for those master MAs which have valid replicated address mappings. Once a registration update for a certain MN is performed at the HA (indicating an inter-domain movement), the HA sends an AddressUpdate message, which carries the new address mapping, to those master MAs ( $MA_5$  in our example) with a valid replicated address mapping for the MN. The master MA will propagate the AddressUpdate message to other MAs via the token ring. Also, the HA will send the same AddressUpdate message to the old registered MA ( $MA_4$  in our example). Then, the old registered MA propagates this message to other MAs in the token ring. These steps ensure that all replicated address mappings for the MN either acquired from the HA (propagated by the master MA) or from a companion MA in the token ring can be updated.

### 4.3. Resource Reservation Support

To provide network resources for QoS guarantees in the wireless networks, two kinds of reservations need to be made: (1) on the connection path over the wireless link and (2) on the connection path over the wired links. The wireless link is shared to the MNs and its usage can be efficiently managed by the mechanisms such as *Class Based Queueing* (CBQ) [24]. Here, we put

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<sup>4</sup> Without apriori knowledge of the node type, time-out events will always occur in the proposed mechanism when the connection setup is to a fixed node in the Internet.

emphasis on the resource reservations over wired links.

In IntServ, the RSVP messages: Path and Resv are periodically exchanged between the sender and the receiver for subscribing a service type with appropriate resource allocation. Two service types with QoS guarantees are provided in IntServ: *Guaranteed* and *Control Load* services. RSVP has the scalability problem as mentioned before. To solve this problem, RSVP aggregation [3] is proposed by the IETF. This new technique can aggregate other RSVP reservations using a single RSVP reservation. Flows using the same aggregate reservation are marked with the same *Differentiated Services Code Point* (DSCP) in the packet header. In RSVP aggregation, two aggregate reservations should be made, which correspond to the guaranteed and the control load services in IntServ.

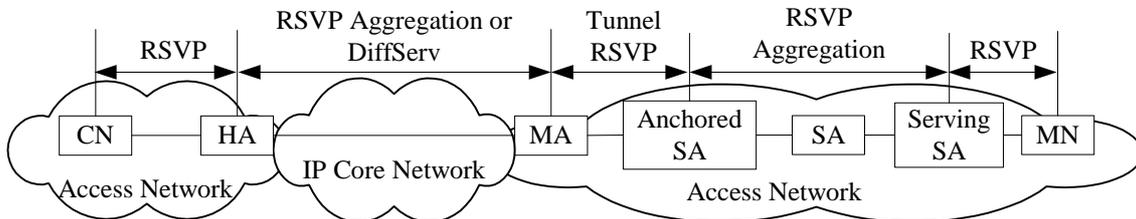


Fig 8. The end-to-end QoS scenario.

In our mobility architecture, the connection path from the CN to the MN can be divided into two parts: (1) from the CN to the anchored SA and (2) from the anchored SA to the MN's current serving SA. The first part is less affected by the MN's mobility than the second part, so the resource reservation on the first part is suitably managed by RSVP. The second part is established over the subnet paths and its resource reservation is suitably managed by RSVP aggregation. The end-to-end QoS scenario is shown in Fig. 8. The QoS provisioning in the core network may be based on the IntServ over DiffServ architecture [1] or based on the aggregated RSVP [15]. When the CN is an MN, the diagram in the left access network is the same as that in the right one in Fig. 8.

In the following, we explain the design of end-to-end QoS in our mobility architecture. We distinguish the signaling messages used in RSVP, RSVP over tunnel, and RSVP aggregation by preceding the terms "E2E", "Tunnel", and "Aggregated" on the name of the message. As shown in Fig. 9, the original E2E Path message from the sender (CN) is tunneled twice before reaching the anchored SA. The anchored SA decapsulates the E2E Path message and replaces the protocol ID of this message with RSVP-E2E-Ignore (as defined in [3]). The E2E Path message after replacement will be carried through the subnet paths transparently. Finally, the serving SA restores the E2E Path message and forwards this message to the receiver (MN). The receiver selects the ser-

vice type desired and informs the sender about its selection by sending out the E2E Resv message.

The SAs on the subnet paths will trigger aggregated messages to initiate RSVP aggregations when receiving the E2E Resv message. The anchored SA reversely tunnels the E2E Resv message to the serving MA where RSVP over tunnel is initiated. The serving MA either reversely tunnels the E2E Resv message to the HA or directly delivers this message to the sender depending on whether the E2E Path message is tunneled from the HA. The latter case happens when the fast location lookup is used. Any error encountered in delivering the signaling message above will be reported to the sending node of the message and be relayed back to the end host.

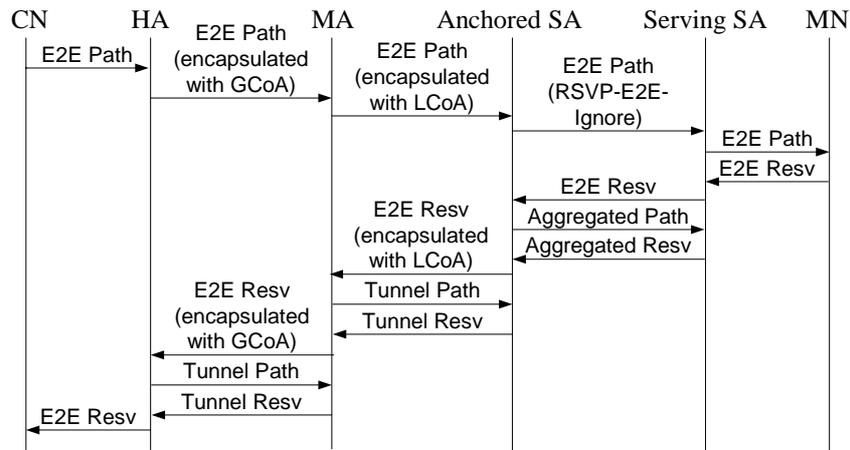


Fig. 9. Signaling flow during the end-to-end RSVP session.

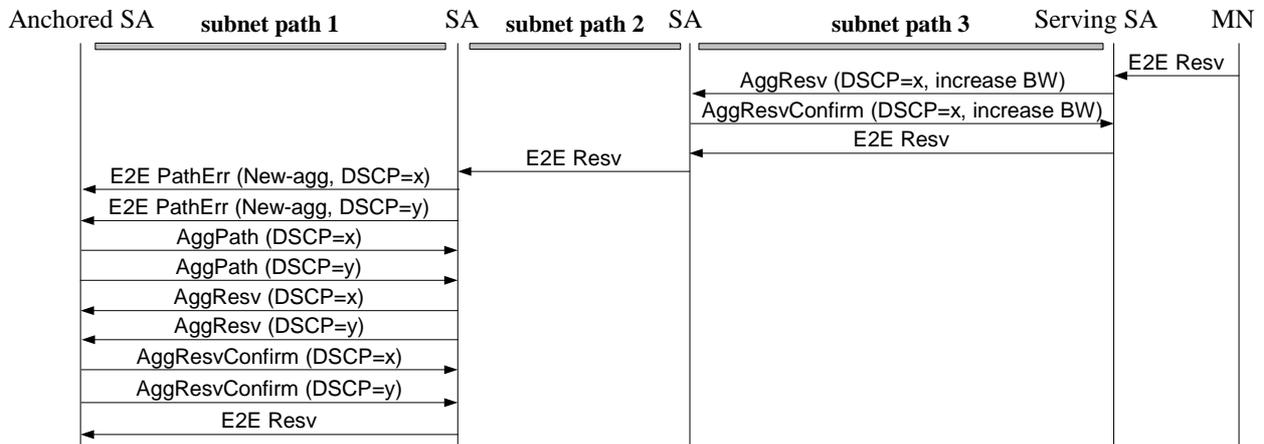


Fig. 10. Signaling flow during the aggregated RSVP.

Below, we explain the resource maintenance on the subnet paths using RSVP aggregation. The aggregate resources are managed on a per-subnet-path basis. The two end nodes (i.e., SAs) of a subnet path will act as an aggregator and a deaggregator, respectively to intercept E2E messages and then trigger aggregated ones. Fig. 10 shows the case when the E2E Resv message is transmitted back along a forwarding chain which is composed of three subnet paths. Each subnet path

shows a different reservation case.

Subnet path 1 shows the case where the aggregate reservation is first initiated. Two aggregate reservations distinguished by DSCPs  $x$  and  $y$  are made together. The MN in the example uses the aggregate reservation with DSCP  $x$ . Subnet paths 2 and 3 show the cases where there already exist aggregate reservations with and without sufficient reserved resources for new flows, respectively. In subnet path 2, no aggregated message is triggered. In subnet path 3, aggregated messages are triggered to increase the bandwidth of the aggregate reservation with DSCP  $x$ . To reduce the signaling overhead on maintaining aggregate resources, we can resize (increase or decrease) an aggregate resource with  $n$  units each time. The resource of  $n$  units can satisfy more than one E2E resource reservation.

To reduce the resource reservation delay after handoff, we also provide the passive or advance resource reservation. We make advance resource reservations along possible new paths after handoff for the MN. Under this scheme, the resources in use can be categorized into two types: active and passive ones. Active resources are currently used by the MNs, while passive ones are reserved for the incoming handoff MNs. We can use two types of signaling messages (e.g., Active Path and Passive Path) to manage the active and the passive resources. The implementation of RSVP with passive reservation was discussed in [24][31].

Fig. 11 shows sequent scenarios of reservations in R-FCAR as the MN moves within a domain. Assume that  $SA_2$  is the anchored SA for the MN. One active reservation is established using RSVP (actually, RSVP over tunnel) toward  $SA_2$ . Besides, two passive aggregate reservations are made using RSVP aggregation along the neighboring subnet paths as shown in Fig. 11a. When the MN moves to  $SA_1$ , the passive aggregate reservation between  $SA_2$  and  $SA_1$  becomes active, and the passive aggregate reservation between  $SA_2$  and  $SA_4$  will be released. This scenario further continues as shown in Fig. 11b. When the MN stays in  $SA_3$  (see Fig. 11c), which is a boundary SA of  $PA_1$ , two passive aggregate reservations are made. Besides, one passive reservation from the serving MA to  $SA_5$  is made using RSVP, since  $SA_5$  may become a new anchored SA if the MN crosses to  $PA_2$ .

In summary, different types of passive resources are reserved in FCAR depending on whether the forwarding chain is about to be renewed. The forwarding chain is about to be renewed when the MN resides in one of the boundary SAs of a PA in R-FCAR, or when the number of movements has reached the limit in M-FCAR. When it is the case, we make passive reservations using RSVP along the paths from the current serving MA to all the possible new anchored SAs. Other-

wise, we make passive aggregate reservations using RSVP aggregation on the subnet paths from the current serving SA to the neighboring SAs. We do not consider the passive reservation as the MN crosses the domain boundaries here.

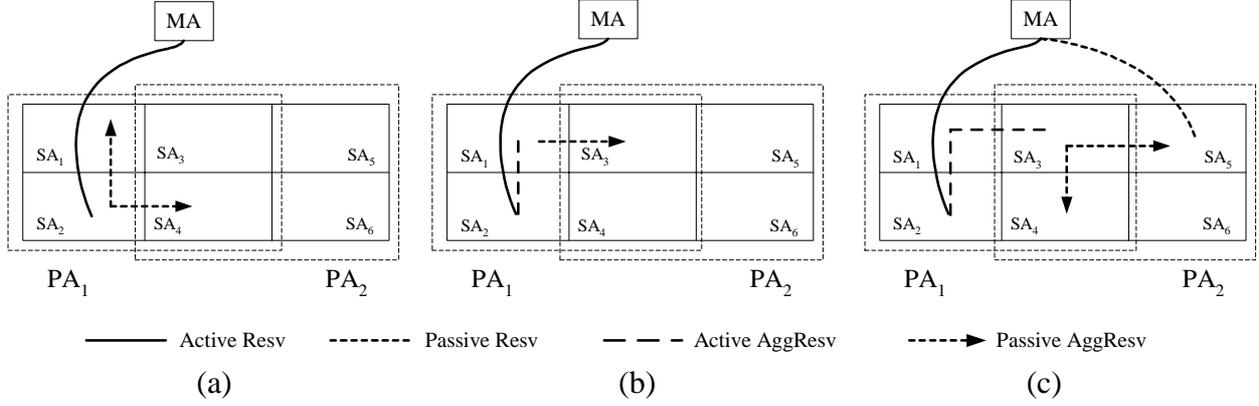


Fig. 11. Active/Passive resource reservations in R-FCAR.

To efficiently utilize the limited resource, the maintenance of passive resources should be further considered. Reserving too much resource or putting the reserved resource idle too long will cause the waste. As the buffer management in the fast handoff, we can reserve the passive resource according to the likelihood of the MN to handoff to a particular SA. This issue will be discussed later. Moreover, we can dynamically adjust the size of passive resource required by a handoff MN according to the residual time of the MN staying in the current SA. In [26], the size of passive resource is getting large as the probability of being handoff increases.

Our proposed resource reservation mechanism offers several advantages over other schemes:

- FCAR uses aggregate reservations on parts of the connection path. This can reduce the maintenance cost on reserved resources. The proposed scheme in [24] which uses the forwarding chain but maintains the per-flow reservation on the whole connection path will perform worse than FCAR. The proposed scheme in [17] which only makes advance resource reservation on a forward one-step path is restricted as compared with FCAR.
- The per-flow passive reservations are made using RSVP only when the forwarding chain is about to be renewed in FCAR, while they are made as the MN moves each time in [6][24][31]. Moreover, the passive reservations are made toward the possible new anchored SAs in FCAR, but toward all the neighboring SAs in other schemes.

## 5. PERFORMANCE EVALUATIONS

In order to evaluate the performance of FCAR, we study the costs of resource reservation, fast

handoff, and fast location lookup during intra-domain movement. We consider a network environment with a single domain made up of  $16 \times 16$  square-shaped subnets. The whole domain is served by a single MA and each subnet is served by a single SA. A paging area (square-shaped area) consists of  $R \times R$  subnets. We model the MN's mobility as a two-dimensional (2-D) random walk. In a 2-D random walk, an MN may move to one of four neighboring subnets with equal probability 0.25. However, the MN's mobility may exhibit spatial locality in the real world. To capture this phenomenon, we assume that an MN will decide to stay in the same subnet with probability  $q$  when going to cross one of the PA's boundaries.

## 5.1. Cost Analysis

We will analyze the signaling costs of mobility management and QoS provisioning in FCAR. The signaling cost is the accumulative traffic load on exchanging signaling messages (hop  $\times$  message size) during the MN's communication session. Below, we introduce the parameters that will be used in the analysis.

### Parameters.

$t_s$ : average session connection time.

$t_r$ : average SA resident time.

$N_m$ : average number of movements during a session (i.e.,  $N_m = t_s/t_r$ ).

$N_r$ : average number of renewals of the forwarding chain during a session.

$s_u$ : average size of a signaling message for the registration update.

$s_r$ : average size of a signaling message for the resource reservation.

$d_{x,y}$ : average number of hops between  $x$  and  $y$ .

$L_{limit}$ : maximal number of movements before the renewal of the forwarding chain.

$L_{forwarding}$ : average length of a forwarding chain.

$B_w$ : bandwidth of the wired link.

$B_{wl}$ : bandwidth of the wireless link.

$L_w$ : latency of the wired link (propagation delay and link layer delay).

$L_{wl}$ : latency of the wireless link (propagation delay and link layer delay).

$P_t$ : routing table lookup and processing delay.

$T_{ad}$ : time interval for an SA to send agent advertisements.

$\lambda_d$ : downlink packet transmission rate.

Let  $t(s, d_{x,y})$  denote the transmission delay of a message of size  $s$  sent from  $x$  (an MN always) to  $y$

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

$$t(s, d_{x,y}) = (s/B_{wl} + L_{wl}) + d_{x,y} \times (s/B_w + L_w) + (d_{x,y} + 1) \times P_t.$$

### 5.1.1 Analysis on mobility management

#### A. Signaling cost of registration updates

The total signaling cost of registration updates during a session is denoted by  $C_u$ . We compare our proposed schemes (R-FCAR and M-FCAR) with other schemes (MIP [25] and IDMP [20]). We assume that all these schemes are based on the same implementation method which has the subnet-specific registration update<sup>5</sup>. For each movement in the simulated environment, both the subnet-specific and home registration updates are performed in MIP, and both the subnet-specific and domain-specific registration updates are performed in IDMP, and both the subnet-specific registration and forwarding chain updates are performed in FCAR. The domain-specific registration update is performed in FCAR only when the forwarding chain is renewed.

$$C_u(\text{MIP}) = 2s_u \times (d_{MN\_SA} + d_{MN\_HA}) \times N_m$$

$$C_u(\text{IDMP}) = 2s_u \times (d_{MN\_SA} + d_{MN\_MA}) \times N_m$$

$$C_u(\text{FCAR}) = 2s_u \times (d_{MN\_SA} + d_{MN\_SA} + d_{SA\_SA}) \times N_m + 2s_u \times d_{MN\_MA} \times N_r$$

#### B. Average handoff time

The average handoff time ( $T_h$ ) is defined as the sum of two terms: discovery time ( $T_d$ ) and completion time ( $T_c$ ).  $T_d$  is the time for an MN to discover that it has moved into a new SA's serving area. This kind of discovery is indicated by receiving an agent advertisement from the new SA. Hence,  $T_d$  is equal to  $1/2T_{ad}$ .  $T_c$  is the time to complete the registration update. We summarize the  $T_c$  value of each scheme as follows:

$$T_c(\text{MIP}) = 2t(s_u, d_{MN\_SA}) + 2t(s_u, d_{MN\_HA})$$

$$T_c(\text{IDMP}) = 2t(s_u, d_{MN\_SA}) + 2t(s_u, d_{MN\_MA})$$

$$T_c(\text{FCAR}) = 2t(s_u, d_{MN\_SA}) + 2t(s_u, d_{MN\_SA} + d_{SA\_SA}) + 2t(s_u, d_{MN\_MA}) \times N_r / N_m$$

#### C. Total packet loss

The total packet loss ( $Pkt\_loss$ ) during a session is defined as the sum of lost packets during all handoffs while the MN is receiving the downlink data packets. In MIP, all in-flight packets will be lost during the handoff time due to the lack of any buffering mechanism. In IDMP and FCAR, in-flight packets are lost till the buffering mechanism is initiated. As mentioned before, the L2

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<sup>5</sup> The subnet-specific registration update can be avoided by associating the registration related information with the agent advertisement.

trigger is used both in IDMP and FCAR. It is assumed that the packet loss begins when the L2 handoff is detected.

$$Pkt\_loss(MIP) = (1/2T_{ad} + T_c(MIP)) \times \lambda_d \times N_m$$

$$Pkt\_loss(IDMP) = t(s_u, d_{MN\_MA}) \times \lambda_d \times N_m$$

$$Pkt\_loss(FCAR) = t(s_u, d_{MN\_SA}) \times \lambda_d \times N_m$$

#### D. Buffer size requirement

The buffers to store in-flight packets are located at the MA and the SA in IDMP and FCAR, respectively. The buffering mechanism activates from the moment when the MovementImminent message is received to the moment when the registration related update request is received. The update request is with the domain-specific registration in IDMP and is with the forwarding chain update in FCAR. The buffer size requirements (*Buf\_size*) for IDMP and FCAR are listed as follows. We can find that both these schemes require the buffer space of same size.

$$\begin{aligned} Buf\_size(IDMP) &= [1/2T_{ad} + 2t(s_u, d_{MN\_SA}) + t(s_u, d_{MN\_MA}) - t(s_u, d_{MN\_MA})] \times \lambda_d \\ &= [1/2T_{ad} + 2t(s_u, d_{MN\_SA})] \times \lambda_d \end{aligned}$$

$$\begin{aligned} Buf\_size(FCAR) &= [1/2T_{ad} + 2t(s_u, d_{MN\_SA}) + t(s_u, d_{MN\_SA} + d_{SA\_SA}) - t(s_u, d_{MN\_SA} + d_{SA\_SA})] \times \lambda_d \\ &= [1/2T_{ad} + 2t(s_u, d_{MN\_SA})] \times \lambda_d \end{aligned}$$

#### E. Fast location lookup

Suppose that the cost of the fast location lookup is measured by the number of hops. We now consider the judicious condition to replicate the address mapping within a domain. In our simulated environment,  $\alpha$  is the difference in hops between the two paths from the local MA to the remote MA with and without the relay of the HA.  $\beta$  is the update propagation cost from the HA to the master MA, and then to the other MAs in the token ring. Let  $N_{MA}$  denote the average number of MAs in a token ring.

$$\alpha = 2d_{MA\_HA} - d_{MA\_MA}$$

$$\beta = d_{MA\_HA} + N_{MA} \times d_{MA\_MA}$$

### 5.1.2 Analysis on resource reservation

The total signaling cost of resource reservations during a session is denoted by  $C_r$ .  $C_r$  includes the cost on establishing both the active and passive reservations, and is expressed as follows for a particular reservation scheme:

$$C_r(\text{Scheme}) = C_{active}(\text{Scheme}) + C_{passive}(\text{Scheme})$$

We compare the reservation cost of FCAR with that of MRSVP. MRSVP is a representative

term to represent those schemes which establish passive reservations along all possible new paths (or subpaths as compared with the original path) from the sender. The schemes proposed in [6][31] belong to MRSVP. Under the same mobility architecture, MRSVP will make passive reservations along the paths from the MA to all the neighboring SAs of the current serving SA. IDMP which configures the resources along the possible new paths by the BB would have the same reservation cost as MRSVP. We only measure the reservation cost from the MA to the current serving SA, since the reservation cost from the CN to the MA is the same for different schemes.

In MRSVP, an active reservation is established from the MA to the current serving SA and passive reservations are established from the MA to the neighboring SAs of the current serving one. Let  $N_h$  denote the average number of neighboring SAs of an SA, which is four in our simulated environment. The reservation cost of MRSVP is:

$$C_{active}(\text{MRSVP}) = 2s_r \times d_{SA\_MA} \times N_m$$

$$C_{passive}(\text{MRSVP}) = 2s_r \times N_h \times d_{SA\_MA} \times N_m$$

In FCAR, an active reservation is established from the MA to the current anchored SA and the active aggregate reservation is extended along the forwarding chain. The passive aggregate reservations are established on the subnet paths from the current serving SA to the neighboring SAs (excluding the previous visited one). Besides, passive reservations will be established from the MA to the possible new anchored SAs when the forwarding chain is about to be renewed. Assume that all the aggregate resources on the subnet paths have been initiated. Let  $\rho$  denote the probability that a passive aggregate reservation needs to be resized when triggered.  $N_a$  denotes the average number of possible new anchored SAs, which is the same as  $N_h$  in M-FCAR and is at most two in R-FCAR if  $R > 1$ . The reservation cost of FCAR is:

$$C_{active}(\text{FCAR}) = 2s_r \times N_r (d_{SA\_MA} + L_{forwarding})$$

$$C_{passive}(\text{FCAR}) = s_r ((N_h - 1) \times \rho \times 4d_{SA\_SA} \times N_m + N_a \times 2d_{SA\_MA} \times N_r)$$

### 5.1.3 Analysis on buffer/resource allocation

In FCAR, we forward in-flight packets and establish passive aggregate reservations to all surrounding SAs of the current serving one. If we know apriori the likelihood of the MN to handoff to a particular SA, we can reduce or avoid the resource requirement (buffer space and bandwidth) at some surrounding SAs with low likelihood. The probability of an MN to handoff to the  $i$ th ( $1 \leq i \leq N_h$ ) neighboring SA (denoted as  $P_i$ ) can be obtained by the mobility prediction algorithm [16]. Let  $B_r$  denote the amount of the actual resource requirement for an incoming handoff MN. Assume

that we only reserve resource of  $w_i \times B_r$  ( $0 \leq w_i \leq 1$ ) units at the  $i$ th neighboring SA. The negative effect due to such resource allocation comes from two possibilities:

- (1) insufficient resource amounted to  $(1-w_i) \times B_r$  units, if the handoff MN does appear in the  $i$ th neighboring SA.
- (2) wasted resource amounted to  $w_i \times B_r$  units, if the handoff MN does not appear in the  $i$ th neighboring SA.

Let  $\theta$  ( $0 \leq \theta \leq 1$ ) denote the ratio of the cost incurred by possibility 1 to the cost incurred by possibility 2. Our goal is to find the setting of  $w_i$  such that the total negative effect ( $F$ ) is minimal:

$$F = \theta \sum_{i=1}^{N_h} P_i (1-w_i) B_r + \sum_{i=1}^{N_h} (1-P_i) w_i B_r$$

Since  $N_h$  of the  $w_i$ 's can be set independently, we need to minimize the following formula:

$$f = \theta P_i (1-w_i) B_r + (1-P_i) w_i B_r = \theta P_i B_r + (B_r - (1+\theta) P_i B_r) w_i$$

$f$  is a linear function, so the minimal value occurs as  $w_i = 0$  or  $1$ . We can set  $w_i$  using the rule:

$$\begin{cases} w_i = 0, & \text{if } B_r(1-P_i) > \theta P_i B_r. \text{ That is, } P_i < \frac{1}{1+\theta} \\ w_i = 1, & \text{if } B_r(1-P_i) \leq \theta P_i B_r. \text{ That is, } P_i \geq \frac{1}{1+\theta} \end{cases}$$

Therefore, when  $P_i$  is no less than  $1/(1+\theta)$ , we reserve resource of  $B_r$  units and forward all in-flight packets to the  $i$ th neighboring SA. Otherwise, nothing needs to be performed. This is an all-or-nothing policy on the resource provisioning.

## 5.2. Simulation Results

The parameter settings in our experiments are listed in Table 1. Parts of the parameter values are referred to the paper [28]. The settings of the  $d_{x,y}$  values are represented by Fig. 12.

Table 1. Parameter settings.

Parameter	Value	Parameter	Value
$R$	2, 4, 8, 16 (default 4)	$L_w$	0.5 msec
$L_{limit}$	2 ~ 20 (default 10)	$L_{wl}$	2 msec
$q$	0 ~ 1 (default 0.4)	$P_t$	0.001 msec
$t_s$	1000 sec	$T_{ad}$	1 sec
$t_r$	2 ~ 40 sec (default 20)	$\lambda_d$	64 Kbps
$s_u$	48 bytes	$N_h$	4
$s_r$	38 bytes	$N_a$	2(R-FCAR), 4(M-FCAR)
$B_w$	100 Mbps	$\rho$	0 ~ 1 (default 0.8)
$B_{wl}$	11 Mbps	$N_{MA}$	4

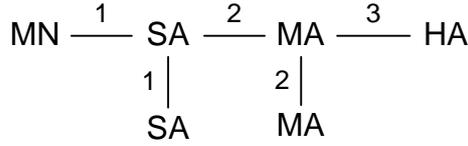


Fig. 12. Relative distances in hops in the simulated network.

Fig. 13 shows the comparison of registration costs. The domain-based approaches (IDMP and FCAR) can significantly reduce the registration cost particularly when the MN handoffs frequently (i.e., when the SA resident time is short). The FCAR-based approach has the less registration cost than IDMP, since some domain-specific registration updates are replaced by low-cost forwarding chain updates. Fig. 14 shows the comparison of resource reservation costs. Both R-FCAR and M-FCAR perform better than MRSVP under different settings of the parameter  $\rho$ . The cost savings are from the resource management in an aggregate way and from the low-cost passive reservations. The smaller the parameter  $\rho$  is, the more the cost saving is.

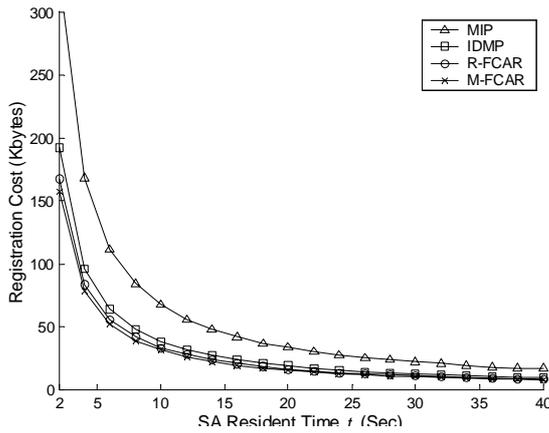


Fig. 13. Registration cost.

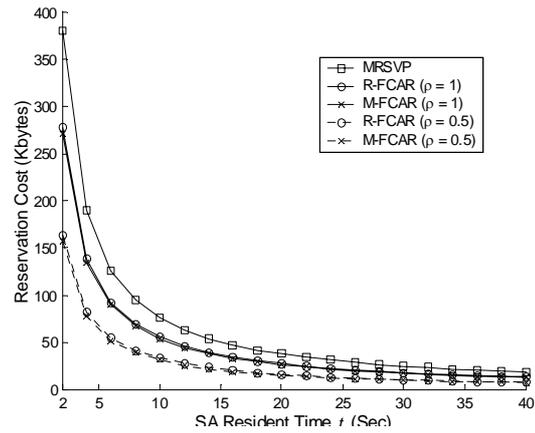


Fig. 14. Resource reservation cost.

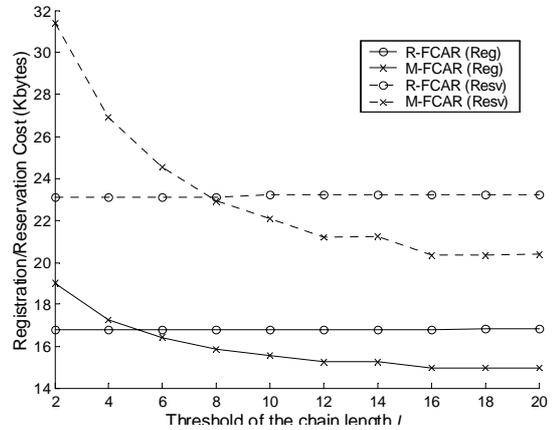
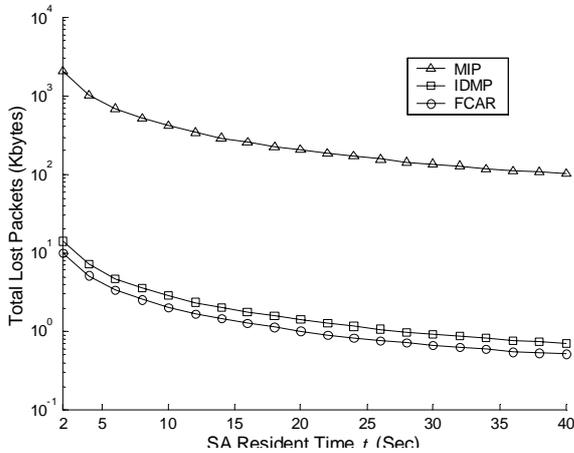


Fig. 15. Total lost packets.

Fig. 16. Effect of the length of the forwarding chain.

Fig. 15 shows the amount of lost packets during the whole connection session for different approaches. MIP without the buffering mechanism has the largest amount of lost packets. The FCAR-based approach which initiates the buffering mechanism more early than IDMP has the smallest amount of lost packets. Notice that R-FCAR and M-FCAR have the same amount of lost packets. The buffer size requirement for each MN is about 4.04 Kbytes in IDMP and FCAR. This means that over 20 thousands of MNs can be provided with the buffering mechanism if a node is equipped with a memory of size 100 Mbytes. The average handoff time values for different approaches are listed in Table 2. MIP would have a longer handoff time than what is shown if we take the transmission delay across the wide area Internet into account. For example, the MN is far away from its home network. The FCAR-based approach always performs the forwarding chain update regardless of whether the domain-specific registration update is performed. This manner can reduce the packet loss but incurs a little bit overheads particularly in R-FCAR which involves more domain-specific registrations than M-FCAR.

Table 2. Average handoff time in seconds.

MIP	IDMP	R-FCAR	M-FCAR
0.515196	0.512172	0.512327	0.511732

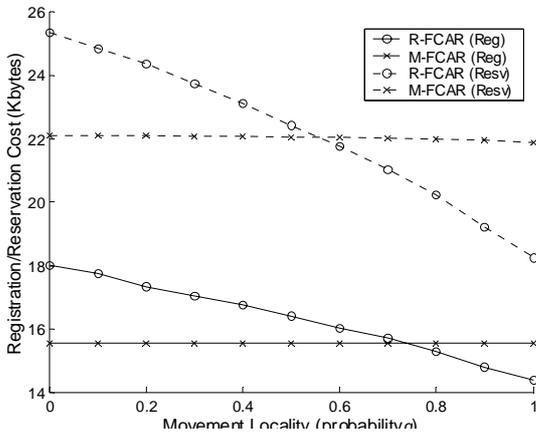


Fig. 17. Effect of locality in movement.

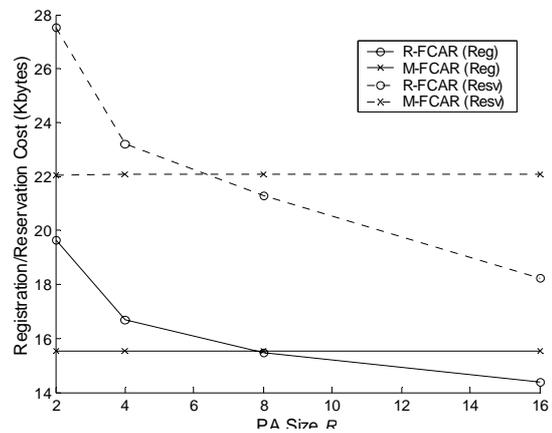


Fig. 18. Effect of the size of the paging area.

In the following, we compare the differences between R-FCAR and M-FCAR. The registration and the resource reservation costs of the FCAR-based approach are mainly affected by the frequency of the renewal of the forwarding chain. As the limit of the maximal length of the forwarding chain (denoted by  $L_{limit}$ ) increases, the renewal frequency in M-FCAR becomes low. Hence,

the cost decreases with the increasing value of  $L_{limit}$  as shown in Fig. 16. On the contrary, the low renewal frequency happens in R-FCAR when the MN has a high locality in movement (corresponding to a large value of  $q$ ) or when the size of the paging area (controlled by  $R$ ) is large. These situations are shown in Figs. 17 and 18. Notice that the paging cost increases with the increasing size of the paging area. To compete with each other between R-FCAR and M-FCAR, we can adjust the parameters  $R$  and  $L_{limit}$ . Fig. 19 shows the average length of the forwarding chain with the changes of these parameters. To match with the opposite, the average length in R-FCAR would be larger than that in M-FCAR after tuning the parameters (e.g.,  $R = 8$  and  $L_{limit} = 10$ ). Since a long forwarding chain will increase the end-to-end transmission time, we prefer tuning  $L_{limit}$  in M-FCAR to tuning  $R$  in R-FCAR for a good performance. In summary, R-FCAR is only suitable for the MN with high locality in movement, while M-FCAR can fit in more general cases. However, M-FCAR needs an extra overhead on recording the number of movements, while R-FCAR does not need any extra overhead.

For a judicious replication in our fast location lookup, there should have a sufficient number of connection setups from  $MA_j$  to a particular  $MN_i$ . Fig. 20 shows the minimal requirement for the number of connection setups under different numbers of home registration updates. The  $C_{ij}$  value is 2.66 times on average the  $U_i$  value. The  $C_{ij}$  value shown in the figure also indicates the setting of the *global\_threshold* value in the determination of sending the AddressSolicitation message to the HA. The *local\_threshold* value can be set to  $global\_threshold/N_{MA}$ .

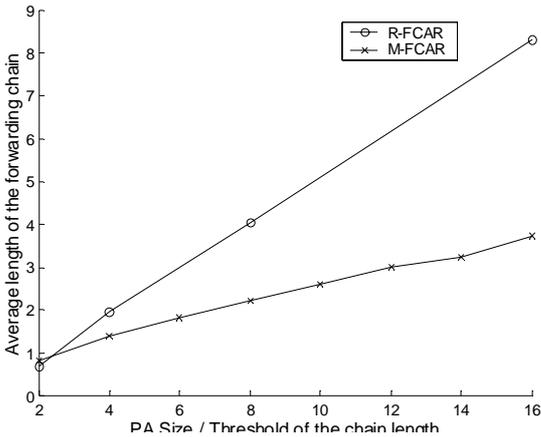


Fig. 19. Average length of the forwarding chain

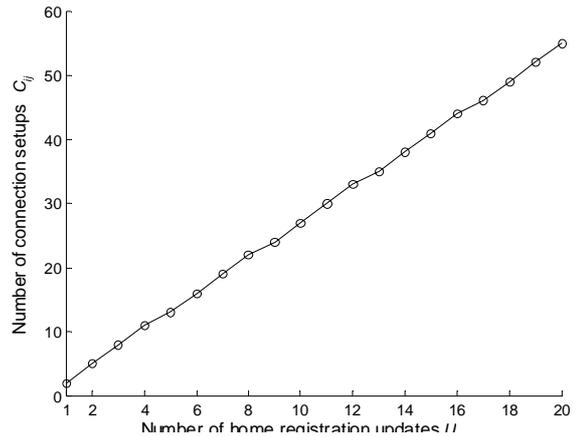


Fig. 20. The judicious condition for the address replication.

## 6. CONCLUSION

In this paper, we propose a hierarchical architecture for both mobility and QoS support in

IP-based wireless networks. The proposed architecture has several advantages and provides excellent solutions to the problems raised by mobility and by the wireless environment. We establish a static subnet path between any two neighboring subnets. These subnet paths are configured with resource reservations in an aggregate manner. The aggregate reservation has a good scalability with the increasing number of mobile nodes. We buffer in-flight packets during handoff and make advance resource reservations along neighboring subnet paths to reduce the packet loss and the service disruption. Also, we track the mobile node's movement within a domain by using the forwarding chain. The forwarding chain can restrict the registration and the resource reservation related messages into a local scope. Two types of maintenance on forwarding chains are discussed. The movement-based approach performs better than the region-based one in most cases. Besides, the fast location lookup can reduce the data delivery cost in MIP. We have discussed the judicious condition for the replication of address mappings. The performance evaluations have justified the benefits of our proposed mechanisms. In the future, we plan to implement these mechanisms and measure the performance in a real system. Also, we will discuss the security issue on the proposed architecture.

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