HiMIP-NEMO: Combining Cross-layer Network Mobility Management and Resource Allocation for Fast QoS-Handovers

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***Abstract*—Network mobility introduces a new communication paradigm that provides sets of mobile hosts (MH) moved collectively as a unit with high-mobility. Efficient network mobility handover design is essential to meet QoS requirements for real-time VoIP-like applications. IETF MIPv6-NEMO design has some problems and introduces extra overheads on packet header and tunnel processing, and added transmission delays due to additional routing legs. Inflexible execution sequence between tasks in MIPv6-NEMO causes negative effect on handover latency performance. In this work, we combine the designs of routing and resource allocation with network mobility management, and introduce the notion of *foreign mobility agent* in a hierarchical backhaul packet forwarding architecture, referred to as *HiMIP-NEMO*, to facilitate *QoS-handovers* and reduce latency and packet loss during handover. Under the architecture, a QoS-incorporated registration protocol and handover protocol with several new layers 2 and 3 message types are also proposed. Both the analytical and simulation results are presented. The results show the effectiveness of the proposed integrated designs in the support of QoS-handover and significant improvements in latency and packet loss performances.**

***Keywords:* Mobile IPv6, Network Mobility, Qos Handover**

I. Introduction

Recent advances in wireless access technology has made it possible that a transportation vehicle (such as car, bus or train) may have one or more computing and communication devices (called *mobile hosts* or MH), either carried by passengers or installed on the vehicle. On these devices, a wide range of Internet applications from web-based information retrieval to real-time VoIP communications may be supported. Meeting different communication requirements of applications and services on mobile vehicles requires a new network structure design that can support non-stop, high bandwidth and high quality wireless communication services.

Network mobility refers to a set of mobile hosts (MH) move collectively as a unit. It introduces a new communication paradigm of sets of mobile hosts with high-mobility. In this paradigm, an entire mobile network changes its point of attachment to the Internet as one unit. All data packets sent to and from the mobile network are transmitted via one or more mobile routers (MR). A major advantage of network mobility is that it reduces the number of handovers of individual hosts and the power consumption of MH [1]. Fig. 1 shows an example network deployment to support network mobility services. There are two important requirements must be met in network mobility service provisioning. For instance, an MH inside a bus moving within the coverage of its wireless Internet service operator may subscribe a VoIP service. He/she would like to be able to access the service by placing and receiving calls while the bus moves. This *global Internet reachability* gives one of the basic requirements of network mobility. Similar to Mobile IP and Mobile IPv6, it requires that an MH can always be reached by some unique identifier anywhere the bus roams. Another important requirement is that the communication quality, especially for VoIP-like sessions must not be affected by handovers when the vehicle moves from one coverage area of a base station (BS) to another. Hence, the speed of QoS re-negotiation on the new route and fast and reliable packet redirection from old to the new path during handover becomes critical to assure no disruption and performance degradation of the on-going services. In other words, this requires resources necessary to sustain the service quality of all on-going communication instances be reserved in time at the new route to ensure a successful QoS-handover, not just network connectivity establishment. In this work, we

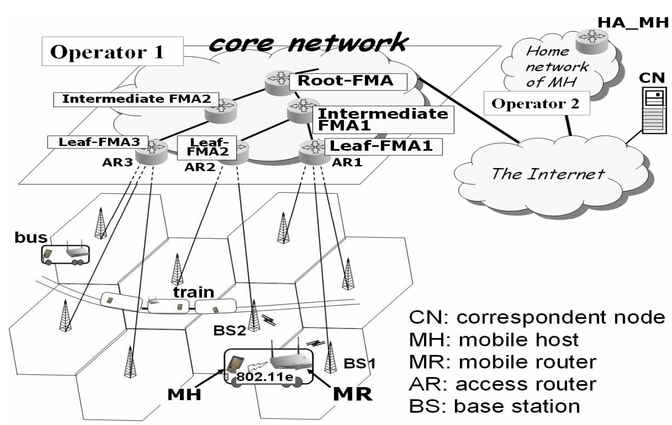

Figure 1. Network Mobility architecture

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combine the designs of routing and resource allocation with network mobility management, and introduce the notion of *foreign mobility agent* in a hierarchical backhaul packet forwarding architecture, referred to as HiMIP-NEMO, to facilitate QoS-handovers and reduce latency and packet loss during handover. Under the architecture, a QoS-incorporated registration protocol and a QoS-handover protocol with several new layer 2 and layer 3 message types are also proposed.

Mobile IPv6 [2] was initially designed for single host mobility. IETF sets up the Network Mobility (NEMO) working group to study issues in network mobility [3][4], and has published the basic support protocol [5] (hereafter called MIPv6-NEMO [6]). MIPv6-NEMO aims to provide a transparent network mobility support to the attached MHs with no modification necessary to the existing protocol stacks on the MH. Its design however raises some problems. First, it requires that traffic to/from the MH go through a bi-direction tunnel between the MR and its home agent (HA_MR). This introduces extra overheads on packet header and tunnel processing, and additional routing legs, resulting in added transmission delays. Second, MIPv6-NEMO is a framework in which many tasks must be performed to complete the handover process. Tasks such as the duplicate address detection (DAD) and re-registration operations as well as inflexible sequence between tasks (e.g., resulting in additional waiting time for route advertisement message) have negative effect on handover latency performance. In [9], they propose a method called fast handover for Mobile IPv6 (FMIPv6) to improve the handover delay. But this method may cause undesirable fluctuation of packet delays; it also has the problem of when should the fast binding update (FBU) be sent. There are two works which apply the FMIPv6 method to the IEEE 802.16e and 3G/CDMA contexts [10][11]. In these documents, they still do not resolve the delay fluctuation problem.

A number of network mobility management schemes, such as PSBU [7] and MIRON [8], have been proposed to address the problems like packet header overhead, handover efficiency, and route optimization. The performances of PSBU and MIRON depend on how fast the new care-of address/prefix can be configured and re-registered. Basically, according to IETF specification [13], DAD must be performed before the newly configured care-of address can be released regardless whether the address is provided by the DHCPv6 server. Additionally, there are other processes like re-registration, proxy DAD, return routability (RR) and binding update procedure with CN need to be completed. Each of these processes incurs extra delay in handover. There are also application-layer solutions for efficient handover such as SIP-NEMO [6]. This approach relies on lower layer movement detection to trigger application-level handover procedure, and thus requires cooperation between layers.

The issue of global reachability for network mobility can be achieved by passing foreign network prefix information by the MR to the MH (including visiting and local mobile host) (such as in [12]). In [7], they propose a scheme that the MR will send aggregate binding updates for local fixed nodes to achieve route optimization. Here, we adopt the same approaches in the proposed HiMIP-NEMO operations.

When an MR attaches to a new BS, the aggregate QoS requirements of all existing communication instances through the MR must be submitted to the new BS to initiate resource allocation at the intermediate switching nodes along the new routing path from MR to each individual MH's CN. It is essential that the resources needed for the existing services must be reserved in time at the new cell to ensure a successful QoS-handover, not just network connectivity establishment. According to our knowledge, no existing handover schemes on network mobility simultaneously consider QoS parameter passing and how to speed up QoS re-allocation to support rigid QoS requirements for real-time application like VoIP in the network mobility paradigm.

Traditional layered protocol reference model can no longer be efficient to support fast QoS-handover for network mobility service, where individual protocol layers are independently designed and functionally they do not cooperate. For example, during handover, the radio link attachment procedure to a new BS in a subnet may have been completed while the network-layer handover procedure is still waiting for the reconfiguration of MHs' IP addresses. This inefficiency dictates a combined cross-layer mobility management and resource allocation design to reduce latency and packet loss during handovers. In this paper, we propose a QoS-handover architecture, HiMIP-NEMO, which combines the designs of routing and resource allocation with network mobility management and introduces the notion of foreign mobility agent to facilitate fast and reliable QoS handovers. A QoS-incorporated registrastion protocol and a QoS-handover protocol with several layer 2 and layer 3 messages are also proposed to assure no disruption and performance degradation of the existing services in network mobility services.

The remainder of this paper is organized as follows. Section II presents the proposed HiMIP-NEMO architecture and the two QoS-incorporated protocols. In Section III, we present analyses and simulation results of HiMIP-NEMO. Then, in Section IV, we conclude.

II. HIMIP-NEMO: COMBINED CROSS-LAYER MOBILITY MANAGEMENT, ROUTE-REDIRECTION AND RESOURCE ALLOCATION FOR QOS-HANDOVERS

Consider an MH adopting Mobile IPv6 and having an IPv6 home address. When attached to an MR, it listens for router advertisement (RA) from the MR (RA_{MR}), and uses the embedded network prefix to generate its care-of address (CoA) which is geographically meaningful and will be used to optimize the routing of packets. Once connected, the MH may for example place a VoIP call.

A. System Architecture Overview

To achieve fast and QoS-guaranteed handover, we propose the use of *Foreign Mobility Agent* (FMA) in a hierarchical routing architecture, called HiMIP-NEMO. Using Fig. 1 as an example, FMAs are functional modules residing in the routers of the service domain and are connected by a high speed wired network to facilitate their fast communications to support QoS-handover. The *switching-FMA* (SWF) refers to the cross-point of the old and new transmission paths of a handover instance.

A main function of FMAs is to maintain routing tables for all the MRs attached to their child BSs. In this paper, we focus on the handover procedure between BSs in different subnets. Similar procedures can be also applied to handover between BSs in the same subnet.

We distinguish two types of handover in the HiMIP-NEMO operations: *reactive* and *proactive* to speed up the handover process. Two layer 2 messages from the wireless access network are used to trigger HiMIP-NEMO handover operations. When attaching to a BS, an MR will send BS a registration message (MRreg) containing its information. The BS then sends a HiMIP-NEMO defined layer 3 message, MRinfo, to its connecting leaf-FMA, indicating the present of the MR. An MRinfo may lead to a HiMIPv6-NEMO *reactive handover*. The other is the handover indication (HOind) message which is sent by an MR when it is about to disconnect from the current serving BS and hand over to a target BS. When receives the HOind message, a HiMIP-NEMO defined layer 3 message, handover notification (MRHOnotify), will be sent by the serving BS to the target BS. During this message forwarding, based on the prefixes of the serving and target BSs, a route optimization is performed to find their nearest common ancestor (i.e. the SWF) in the hierarchical Mobile IP backhaul network. This refers to HiMIPv6-NEMO *proactive handover*. The REG-REQ and MOB_HO-IND messages defined in the IEEE 802.16e have similar functionalities as MRreg and HOind used here. But they do not provide similar functions of the MRinfo and MRHOnotify messages here whereby the BSs and FMAs in the hierarchical Mobile IP backhaul network cooperate to speed up optimal routing and resource allocation in efficient QoS-handover. In the proposed HiMIP-NEMO architecture, a QoS-incorporated registration process is performed whenever an MR enters the network mobility service domain.

B. The QoS-incorporated Registration Process

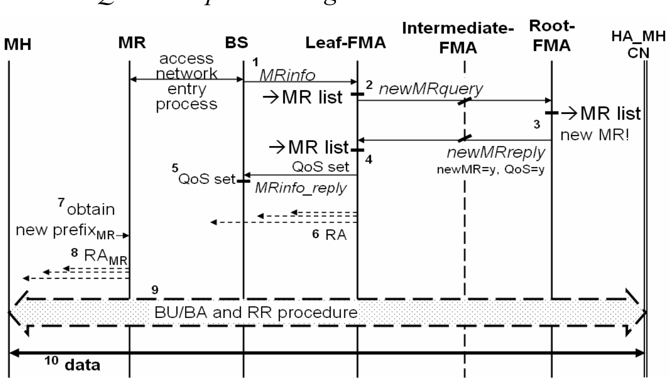

Figure 2. The QoS-incorporated registration process for MR

To support QoS-handover, a registration process is proposed. The messages exchanged during the process are shown in Fig. 2. When an MR moves into a network mobility service domain, it first establishes radio link with a BS. In HiMIP-NEMO, during MR's registration, an extra field is defined in the registration message (MRreg) to carry MR's prefix (prefix$_{MR}$). The MR then computes the aggregate QoS requirements of its attached MH(s), and sends the information to the BS.

If the serving BS does not have QoS and handover related information of the MR, it will send an MRinfo to its leaf-FMA containing the MAC address (MAC_MR), the prefix$_{MR}$, and the QoS parameters of the MR (QoS$_{MR}$). The leaf-FMA then searches its MR list. If not found, the leaf-FMA creates a new record for the MR and records all the information into it including the QoS requirements. It then sends a HiMIP-NEMO defined message, newMRquery, to the root-FMA (step 2.) with MAC_MR, prefix$_{MR}$, and QoS$_{MR}$. In the meantime, each intermediate FMA on the path will also search its MR list for a record of the MR. If not found, a new one is created and the information in the newMRquery is copied into the record. When the root-FMA receives the message and does not find a record on its MR list, it replies a newMRreply message with the *newMR* and the *QoS_reservation_confirm* fields set to "true" to the leaf-FMA (step 3).

On the way of passing the newMRreply from the root-FMA back to the leaf-FMA, when an intermediate FMA reads the true value of the QoS_reservation_confirm field, it will retrieve the QoS$_{MR}$ information from its MR list and make corresponding QoS reservation for the MR. If the reservation succeeds, it simply forwards the newMRreply to the next FMA; otherwise, it sets the QoS_reservation_confirm field to false in the newMRreply to terminate further unnecessary reservations. In the meantime, a failure notification will be sent to the previous intermediate-FMA and all the way back to the root-FMA to cancel previous resource reservations. If the leaf-FMA receives the newMRreply with the QoS_reservation_confirm field set to true, it means all the intermediate nodes in the HiMIP-NEMO backhaul network from the leaf-FMA to the root-FMA are now ready to serve the MR's handovers. For end-to-end QoS guarantees, the root-FMA may need to follow resource reservation protocols on behalf of the MR to reserve resources outside its domain to the CN; however, this procedure is beyond the scope of this paper. The leaf-FMA then sends a HiMIP-NEMO defined message, MRinfo_reply, to the BS (step 4).

After the registration, the MR receives route advertisement from the leaf-FMA (step 6), and broadcasts its prefix information (RA$_{MR}$) in the mobile network. The MH then performs the normal Mobile IPv6 operations (steps 9 and 10).

C. QoS-Handover Protocols

Fig. 3 shows the procedure and the messages exchanged during a proactive handover. Note that on the way of forwarding the MRHOnotify message, the first intermediate FMA that finds both the serving and target BSs are its children, becomes the SWF. If no SWF is found, an expiration function will be executed to release prior QoS reservations (step 3). The expiration function should be carefully calibrated to minimize the *erroneous movements* (e.g., the ping-pong effect).

The SWF creates a routing rule for this handover instance in its routing table to re-direct packets whose prefix is the (old) prefix$_{MR}$ to the target BS (step 4). In step 5, the FMAs on the path from SWF towards target BS will create a new record and routing rule for the MR. When the MRHOnotify reaches the target BS, the latter uses the information of the MR for QoS reservation. Once the process completes, all MHs in the mobile network continue the communication with CNs (step 8). In this process, because of the simultaneous execution of finding an optimal new route and performing resource allocation, the handover delay is minimized.

Afterwards, the MR follows the normal handover procedure to complete the process (steps 11 and 12). In the meantime, messages are sent for the cleanup of routing information and release of the resources at routers on the previous routing path.

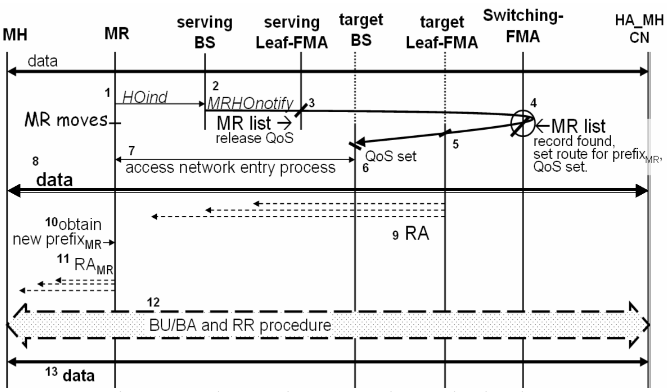

Figure 6. The QoS-incorporated proactive handover

In addition, HiMIP-NEMO supports an efficient reactive handover procedure. If the target BS does not receive an MRHOnotify, it sends an MRinfo. FMAs that do not have any information about the MR follow the same procedure as step 2 in Fig. 2. Eventually, one of the FMAs will find a record of the MR, and it will become an SWF. The SWF stops the forwarding of newMRquery and preforms the following works: *a)* making QoS reservations for the MR; *b)* adding a routing rule to its routing table for the (old) prefix$_{MR}$; and *c)* sending a newMRreply with the newMR field set to "false" and the QoS_reservation_confirm field set to "true" to the leaf-FMA. It then creates a newMRreply message and sends along the path back to leaf-FMA. Each intermediate FMA makes corresponding QoS reservation. Once the new QoS route is established, the communications of the MHs in the mobile network proceed without interruption. In the meantime, messages are sent to release the resources allocated at the routers on the old routing path.

III. Performance Evaluation

In this section, we compare the transmission delay and handover performance of HiMIP-NEMO with MIPv6-NEMO and FMIPv6-NEMO [9]. Table I lists the notations of the parameters used in the following analysis.

A. Analyses

1) Transmission Delay: The difference of packet delay between MIPv6-NEMO (T_{MIPv6}) and HiMIP-NEMO (T_{HiMIP}) is given as follows:

$$T_{MIPv6} - T_{HiMIP} = \left(p_{tunnel} + p_{de-tunnel}\right) + \left[\left(t_{CN-HA\_MR} + t_{HA\_MR-ER}\right) - t_{CN-ER}\right] \quad (1),$$

where ER denotes the edge router of the service domain. This equation shows that the extra delays in MIPv6-NEMO come from *a)* the bi-direction tunnel between the MR and HA_MR and *b)* if the routing path is not optimal. $t_{CN\text{-}HA\_MR} + t_{HA\_MR\text{-}ER}$, will be equal to $t_{CN\text{-}ER}$ only if the HA_MR is on the path between the ER and CN.

In HiMIP-NEMO, routes are all optimal. For FMIP-NEMO, an additional delay incurs due to their use of a temporary tunnel between the serving AR and target AR which may cause significant negative impact on the performance of delay and jitter sensitive VoIP-like applications. In HiMIP-NEMO, the proposed FMA architecture uses geographically meaningful prefixes and switching-FMAs for route redirection which greatly help to reduce latency and packet loss during handovers.

TABLE I. Notations of Performance Parameters

Symbol	Descriptions
$t_{X\text{-}Y}$	The transmission latency of a packet from node X to node Y, plus the routing processing time on node Y.
p_{tunnel} /$p_{de\text{-}tunnel}$	The processing time of (de-)tunneling a packet, including searching a tunnel binding list.
p_m	The processing time of MRinfo, MRHOnotify, newMRquery, or newMRreply messages, including searching the MR list.
p_f	The processing time of FMIPv6 messages, including accessing the data structures of MR, AR1, or AR2.
$h_{X\text{-}Y}$	# of hops from node X to node Y.
d_{L2}	The interval between the time the HOind is sent to the time the MR completes the re-entry process with BS2.

2) Handover Delay: We define the *handover delay* as the time interval between the arrival of the last packet when the MR still maintains the radio link with the serving BS (BS1), and the arrival of the first MR data packet at the target BS (BS2). We assume that the MH receives the last packet from the MR through BS1 at the same time that the MR sends a HOind.

The proactive and reactive handover delays of FMIPv6-NEMO are given as follows:

$$D^{proactive}_{FMIPv6} = t_{BS1-AR1} + p_{tunnel} + t_{AR1-AR2} + P_{de-tunnel} + \left(p_f + t_{MR-BS2} + t_{BS2-AR2}\right) + t_{AR2-BS2} \quad (2)$$

$$D^{reactive}_{FMIPv6} = d_{L2} + p_f + \left(t_{MR-BS2} + t_{BS2-AR2}\right) + p_f + t_{AR2-AR1} + p_f + \left(p_{tunnel} + t_{AR1-AR2} + p_{de-tunnel} + t_{AR2-BS2}\right) \quad (3)$$

We also give the proactive and reactive handover delays of HiMIP-NEMO in the following:

$$D^{proactive}_{HiMIP} = p_m + t_{BS1-AR1} + p_m + t_{AR1-SWF} + h_{AR1-SWF} \times p_m + \left(t_{SWF-AR2} + t_{AR2-BS2}\right) \quad (4)$$

$$D^{reacive}_{HiMIP} = d_{L2} + p_m + t_{BS2-AR2} + p_m + t_{AR2-SWF} + h_{AR2-SWF} \times p_m + \left(t_{SWF-AR2} + t_{AR2-BS2}\right) \quad (5)$$

Equations (6) and (7) give the differences of the proactive and reactive handover delays of HiMIP-NEMO and FMIPv6-NEMO, respectively.

$$D^{proactive}_{FMIPv6} - D^{proactive}_{HiMIP} = \left(p_{tunnel} + p_{de-tunnel} + p_f + t_{MR-AR2}\right) - \left(p_m + h_{AR1-SW} \times p_m + p_m\right) \quad (6)$$

$$D^{reactive}_{FMIPv6} - D^{reative}_{HiMIPv6} = \left[\left(3 \times p_f + p_{tunnel} + p_{de-tunnel}\right) - \left(2 + h_{AR2-SW}\right) \times p_m\right] + \left[t_{MR-BS2} + 2 \times t_{AR1-SW}\right] \quad (7)$$

To further investigate the performance differences between HiMIP-NEMO and FMIPv6-NEMO, we have implemented the HiMIP-NEMO on PCs with Pentium M1400MHz and Fedora Core 1 of 10000 address entries and 500 routing rules. We measure the latency $t_{X\text{-}Y}$ in the core network. It is around 1~3 ms. The values of the other performance parameters such as p_f, p_m, p_{tunnel}, and $p_{de\text{-}tunnel}$, are quite small and negligible compared to $t_{X\text{-}Y}$. In our lab, we have set up an IEEE 802.16d network with Nortel base station. The transmission delay ($t_{MR\text{-}BS2}$), measured is around 20~30 ms. These real number measurements show that both HiMIP-NEMO proactive and reactive handover perform better than that of FMIPv6-NEMO because of the use of the BS and FMAs.

B. Simulation

We also evaluate the HiMIP-NEMO handover performance via Network Simulator 2 (ns-2) patched with Mobile IPv6 and IEEE 802.16e modules. A TCP connection from a CN to an MH in a mobile network is considered. Three scenarios are compared: *a)* handover with Mobile IPv6-NEMO; *b)* reactive handover of HiMIP-NEMO; and *c)* proactive handover of HiMIP-NEMO. Fig. 4 shows the TCP sequence number traces of the three scenarios during the handover. The MH receives the last packet from the serving BS at the 478.8th second. One can see that under the original Mobile IPv6 handoff scheme, the long handover latency causes severe packet losses for TCP connection. Under the proposed HiMIP-NEMO, the performances are greatly improved for both the proactive and reactive handovers. In the figure, for the sake of clarity we vertically shift the sequence numbers of scenarios Mobile IPv6 and HiMIP-NEMO with proactive handover down and up 20 counts, respectively.

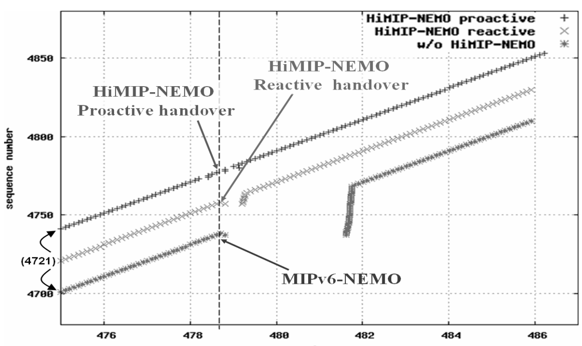

Figure 4. Comparison of TCP packets delivery performance during the handover between HiMIP-NEMO and MIPv6-NEMO

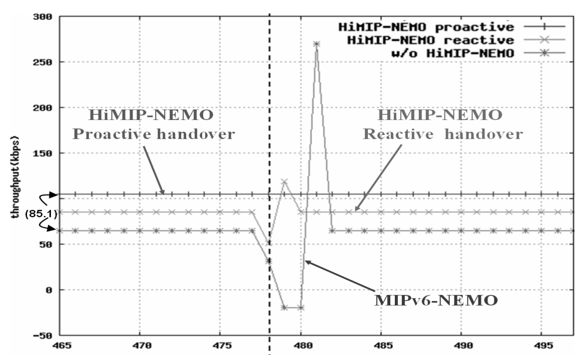

Figure 5. TCP connection receiving rate trace (vertically shifted ± 20)

Fig. 5 shows the corresponding receiving TCP throughput at the MH. One can see that under Mobile IPv6-NEMO, after completing the link layer handover, the MR waits for the old RA to expire so to accept a new one. This waiting time causes a large delay for MH's re-registration. Because of the TCP retransmission and congestion control mechanisms, packets lost during the handover period are recovered afterwards. For real-time UDP-based VoIP-like sessions, such losses can greatly degrade the service performances. In HiMIP-NEMO proactive handover, the handover latency is very small and has almost no effect on TCP congestion control. Therefore, the TCP throughput remains stable during the handover. For the reactive handover, it takes a little bit more processing time to set up the new route, hence we see a throughput drop initially at the handover, but it quickly recovers.

IV. CONCLUSION

In this paper, we present a QoS-integrated cross-layer hierarchical network mobility management architecture and the protocols, HiMIP-NEMO, which demonstrates the advantages of combining optimal route-redirecting, resource allocation with network mobility management to simultaneously achieve QoS handover and reduce latency and packet loss. We present the analyses of HiMIP-NEMO data transmission delay and handover delay, and compare with those of FMIPv6-NEMO, supplemented with some real measurement data from our prototype systems. The results show that HiMIP-NEMO outperforms MIPv6-NEMO. In addition, simulation results of HiMIP-NEMO further show the efficacy of the proposed scheme in the support of QoS-handover.

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