Route Optimization for Roaming Heterogeneous Multi-Homed Mobile Networks

Kumudu S. Munasinghe and Abbas Jamalipour
School of Electrical and Information Engineering
University of Sydney, Australia
kumudu@ee.usyd.edu.au and a.jamalipour@ieee.org

Abstract—**With the provisioning of interworked heterogeneous wireless networks and the growing popularity of smart mobile devices, ubiquitous service and data access is showing a demanding growth. As a result, scenarios of group mobility evolved with the increasing trend where a number of commuters on a transportation carriage would access such services. Making this scenario further complex, there was also the likelihood for some commuters to have Personal Area Networks (PANs) onboard as nested networks. Due to the pinball routing problem encountered by nested mobile networks, macro mobility between heterogeneous networks becomes a challenge. Therefore, when a group of users roam as a single unit, interworked heterogeneous networks must be equipped with efficient route optimization and group mobility management support to overcome these issues. Unfortunately, the current standard for supporting a group of members moving between two networks proposed by the Internet Engineering Task Force's (IETF) NEtwork MObility (NEMO) basic support protocol is limited to homogeneous networks. This paper proposes the integration of NEMO support for enabling group mobility management between multiple heterogeneous networks and route optimization for supporting nested mobility. Results indicate that by integrating NEMO support to an NGMN, handoff, transient packet loss, jitter, and data routing costs are reduced via improved rout optimization.**

*Keywords-**Pinball Routing; Nested Mobility; Network Mobility NEMO; SIP; Mobile IP; MIP-NEMO; SIP-NEMO; IMS***

I. INTRODUCTION

The need for ubiquitous computing and service access has been increasing with the emergence of the Next Generation Mobile Network (NGMN), which is essentially a group of interworked heterogeneous wireless networks and technologies. Consequently, more and more commuters began accessing data and services while travelling on public transportation systems (e.g., buses, trains, ships, and aircraft). Therefore, such a group of commuters travelling in a transportation carriage can be considered as a mobile network thus the emergence of group mobility scenarios. Making this scenario further complex, there is also the likelihood for some of these group members to have Personal Area Networks (PANs) onboard as nested networks. Another possibility is where there may be nested networks is on a multi carriage transport system in which each carriage acts as a nested sub-network [1].

All devices on board the vehicle, irrespective of their capabilities, will be able to achieve global connectivity via one or more special gateway routers installed in the vehicle. In such a scenario, the mobile network is considered to be multi-homed since there are multiple interfaces connected to the Internet through one or more of these mobile routers. As the vehicle (i.e., the mobile network) travels through heterogeneous networks, the mobile router is responsible for provisioning uninterrupted service connectivity for the devices residing with the mobile network, irrespective of the access technology or network that is being used. Therefore, it is essential for efficient group session handoff and route optimization mechanisms to be in place for collectively providing seamless service access for the nodes of a mobile network that is travelling via various heterogeneous networks.

For a group of mobile nodes commuting between homogeneous networks, location transition management was initially addressed by the Internet Engineering Task Force's (IETF) NEtwork MObility (NEMO) basic support protocol by defining an extension to Mobile IP v6 (MIPv6) [2]. However, the main setback of MIPv6-NEMO was that it encountered sub-optimal routing as a result of bi-directional tunneling [3]. There is also the possibility where some commuters may have PANs nested within. For such nested mobility scenarios, as the number of nested levels increase, data routes depart more and more from the optimal. This leads to another multi-angular routing issue called pinball routing, which contributes to latency and increased packet size for each level of nesting [4].

Therefore, in response to the problems of MIP-NEMO, a Session Initiation Protocol (SIP) based version of NEMO is proposed [4]. The main advantage of the latter is that, by shifting network mobility management to the Application Layer it overcomes the route optimization problem and thus reduce the overall latency by efficiently handling nested mobility scenarios. However, the potential of integrating SIP-NEMO for enabling network mobility and route optimization for interworked heterogeneous networks has not been fully exploited as yet. Therefore, this article contributed by proposing a SIP-NEMO based novel architecture for collectively handling seamless session handoffs for the nodes of a mobile network travelling through an NGMN.

The remainder of this paper is organized as follows. Firstly the concepts of SIP-NEMO assisted route optimization are explained. Next, the integration of SIP-NEMO to the NGMN is presented, where three scenarios of network mobility are discussed. Thereafter, the simulation results and validation are presented prior to the concluding remarks.

This work is partly supported by the Australian Research Council under the Discovery Project Scheme (DP1096276).

II. LOCATION TRANSITION AND ROUTE OPTIMIZATION

By and large, the existing approaches for seamless session forwarding and data routing for a multi homed, roaming mobile network can mainly be categorized based on its layer of operation [5]. The initial approach proposed by the IETF was MIPv6-NEMO operating at the Network Layer [2]. Unfortunately, MIP introduced many shortcomings such as sub-optimal routing, increased path lengths, and packet header overheads due to bi-directional tunneling, and hence the solution was not successful [3]. Following the unsuccessfulness of the former, an Application Layer based approach using the SIP protocol was proposed [4].

As illustrated by Fig. 1, by and large, the SIP-NEMO protocol is an extension of the well-known SIP protocol, thus enables SIP clients to easily roam between networks. The route optimization is achieved via appropriate translation of the SIP header. The main element in such a SIP enabled roaming mobile network is the SIP Network Mobility Server (SIP-NMS). A given SIP-NMS has a corresponding SIP Home Server (SIP-HS). As the mobile network roams between networks, the on board SIP-NMS negotiates a new point of attachment/address via the new SIP Foreign Server (SIP-FS). Next, the SIP-NMS recovers all ongoing sessions and informs the SIP-HS about its new location via the new point of attachment/address. In which case, the SIP-NMS acts as the gateway for the roaming mobile network.

As the mobile network changes its point of attachment, the SIP-NMS must ensure that all attached nodes will be reachable and the existing data flows will not be interrupted. This is achieved by translating a SIP-REGISTER request. Another advantage of this is that, the mobile network's changing of the point of attachment or moving from one subnet to another becomes transparent to its onboard clients. Each SIP-NMS has a corresponding SIP-HS, which takes care of the following tasks; accepting the translated REGISTER request from the SIP-NMS, recording the current location/address, and forwarding translated INVITE requests to corresponding SIP-NMSs. The SIP-HS is informed of its new location (point of attachment) as and when a SIP-NMS attaches to a new network. Further, it must be noted that each mobile node onboard the mobile network has a corresponding HS. Therefore, when a new mobile node is attached to a mobile network, it must also update its new point of attachment to the SIP-NMS by sending a SIP-REGISTER request, which is then translated by the SIP-NMS to the corresponding HS of the mobile node. Therefore, when a mobile node attached to a particular roaming mobile network must be contacted; the corresponding SIP-HS is initially queried, which subsequently forwards this request to the relevant SIP-NMS of the targeted mobile network.

Last but not least, the SIP-FS, which is fundamentally a SIP Back-to-Back User Agent (B2BUA), plays an important role by providing a Uniform Resource Identifier (URI)-list service, which reduces signaling cost and handoff delay as a result of optimized routing [6]. As the mobile network roams, its SIP-NMS collects the source and destination addresses of all its ongoing SIP sessions into a SIP-URI list. This SIP-URI list is embedded into the SIP ReINVITE request and forwarded to the

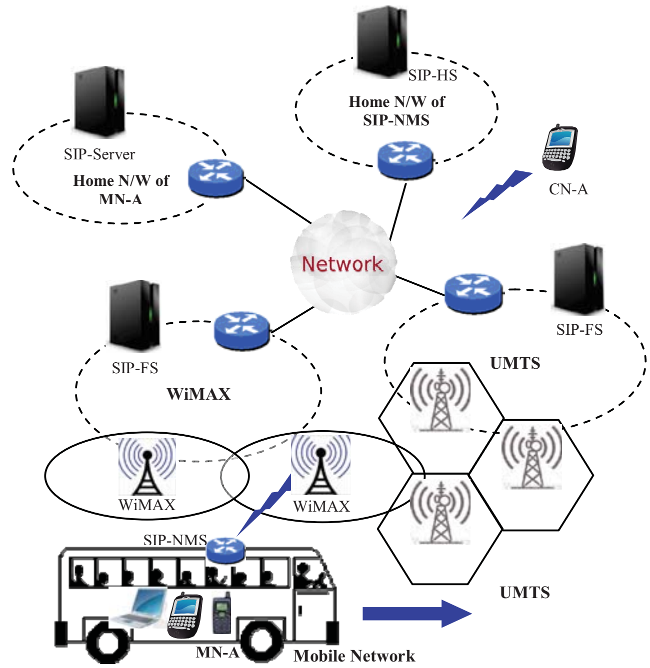

Fig. 1. A simple SIP-NEMO Assisted Route Optimization Scenario.

SIP-FS of the newly attached network. When the SIP-FS receives the SIP ReINVITE request with a URI list, it individually generates SIP ReINVITE requests for all data sessions that need to be handed-off and re-routed to the new network. SIP header translation for route optimization also works best under complex levels of nesting. Furthermore, SIP-NEMO can also provide route optimization when two SIP clients are in the same mobile network even if the mobile network has a complex nested level of routing as described in [4].

III. INTEGRATING SIP-NEMO INTO AN INTERWORKED HETROGENEOUS NETWORK

As previously stated, the aim of this work is to incorporate SIP-NEMO protocol into an interworked heterogeneous networking environment. According to our literature survey, the only noteworthy initiation made towards this is available in [7]. Despites its comprehensive overview on various coupling architectures [7] and their vertical session handoff capabilities, seamless session continuity was not guaranteed [8]. For that reason, we argue that, this article proposes a novel framework capable of collectively handling seamless session handoffs and optimizing data routes for the nodes of a mobile network travelling through interworked heterogeneous wireless networks by using the SIP-NEMO protocol.

In order to implement the proposed solution, a popular NGMN platform has been used [9]. However, it must be noted that this paper is not a test of the interworking capability of [9] but merely uses it for testing SIP-NEMO. Nevertheless, for the

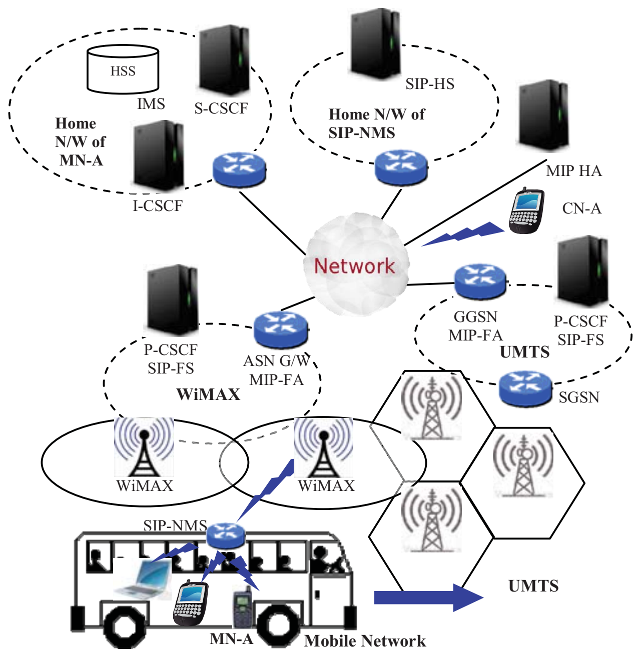

Fig. 2. Proposed SIP-NEMO Integrated Interworking Architecture.

convenience of the reader, we will be giving a brief introduction of [9]'s design. One of the primary design considerations of this architecture is that all networks are loosely coupled for data routing and tightly coupled via the IP Multimedia Subsystem (IMS) for session control signaling [10]. The session mobility management and route optimization are facilitated by using the SIP protocol via the IMS at the Application Layer. Therefore, the session mobility management for a group of users (or a mobile network) can successfully be achieved by introducing SIP-NEMO into the IMS.

We will now explain how SIP-NEMO is integrated into the NGMN architecture. Fig. 2 illustrates the proposed SIP-NEMO integrated NGMN architecture. The integration of SIP-NEMO to the IMS framework is planned in such a way that it complies with the existing 3GPP-IMS and 3GPP2-IMS standards [10]. Therefore, the B2BUAs in each network, which are also Proxy-Call Session Control Functions (P-CSCF) to the IMS, are modified for handling the URI list service. With this modification, the P-CSCF can now function as a SIP-FS to a SIP-NMS that may roam into its network, thus easily being able to handle network mobility. Therefore, the SIP-NMS acts as a Network Address Translator (NAT) for the mobile network's clients trying to connect to the IMS. Then again, the SIP-NMS also appears as a roaming SIP user from the SIP-FS's point of view. Each SIP-NMS also has its corresponding SIP-HS.

We will be firstly looking at the simplest scenario where a node handoff takes place. When a new SIP client joins the mobile network, MN-A first sends a REGISTER request to the SIP-NMS. Next, the SIP-NMS changes the CONTACT field in the SIP header from the MN-A's address to the SIP-NMS's URI address as a part of its NAT mechanism. Followed by this, the SIP-NMS forwards the REGISTER request to the P-CSCF, which is also the SIP-FS in this case. The P-CSCF examines the SIP header to identify the entry point to the MN-A's home domain. Next, the SIP-FS forwards the REGISER request to the MN-A's (IMS) home network. The registration process in the IMS involves the Serving-CSCF (S-CSCF) and the Home Subscriber Server (HSS). A copy of the SIP-NMS's address is stored at the HSS as MN-A's contact address. Finally the S-CSCF of the IMS replies with a 200 OK message to the MN-A via the SIP-NM

As the mobile network, which consists of onboard mobile nodes roams from WiMAX to UMTS a network handoff takes place and the SIP-NMS must first recover its global reachability. Therefore, the SIP-NMS must obtain an IP address for its UMTS interface and ReINVITE all ongoing sessions via the UMTS network. Fig. 3 illustrates the related signaling flow. Similar to the previous explanation, firstly the standard UMTS attach and PDP context activation procedures are performed by the SIP-NMS. In order to guarantee terminal mobility, MIPv4 is implemented at the Network Layer. The actual IP address allocation for the SIP-NMS is initiated by sending the MIP registration request to its MIP-HA via its MIP-FA, which is the Gateway GPRS Support Node (GGSN) in this case [11]. Followed by this is the exchanging of a MIP

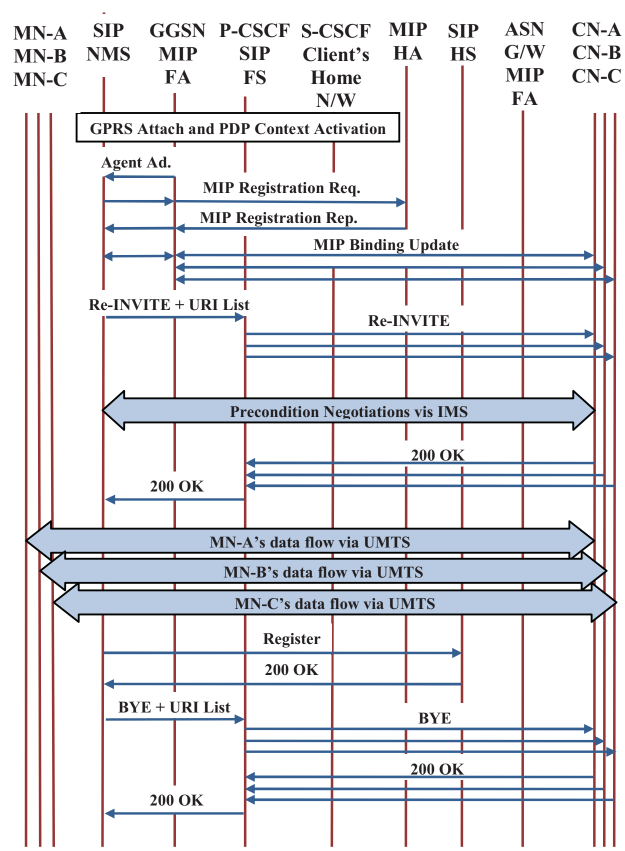

Fig. 3. Signaling Flow for SIP-NEMO associated Network Handoff.

Binding Update message between the SIP-NMS and its existing SIP destination clients for avoiding triangular routing [12].

Next the SIP-NMS sends a ReINVITE request with a URI list to the P-CSCF, which is also the SIP-FS, in order to recall the ongoing SIP sessions. Then the P-CSCF reproduces individual INVITE messages to all CNs. After each SIP CN receives the ReINVITE request according to the URI list, the IMS will initiate the resource/precondition reservations procedures for each of these sessions. Further information on this stage is available from [9]. Now the SIP-NMS is ready for proceeding with the session flow via the new network. The point to note here is that, the SIP-FS combines all responses received by destination clients in the URI list to a single message and forwards it to the SIP-NMS. Hence the session handoff signaling overhead is considerably reduced. After the precondition reservations, each CN will resume the ongoing sessions via the new contact address of the SIP-NMS.

The point to note in this case is that, our proposed solution is based on a make-before-break handoff, which is therefore capable of assuring seamless session handoffs for the SIP-NMS clients, unlike the solution given in [7]. Next, a REGISTER request is sent to the mobile network's SIP-HS by the SIP-NMS. The reason being that, as the SIP-NMS attached mobile network roams into the UMTS network, the new location information (i.e., the IP address) must be updated with its SIP-HS. Note that this does not involve the IMS since it is handled by the NEMO architecture. Once the SIP-HS responds with a 200 OK message, the SIP-NMS attached mobile network will be globally reachable (via the UMTS network). Finally, the breaking of the session via the WiMAX network takes place by using the URI list service.

Finally, we shall now investigate a nested mobility scenario in the case of some commuters having PANs nested within as they travel in a transport network. Assuming that a PAN is also another SIP based mobile network, the SIP-NMS of the PAN will now become a sub-SIP-NMS of the parent-SIP-NMS of the parent mobile network. In this case, the sub-SIP-NMS must first register itself with its parent-SIP-NMS and ReINVITE all ongoing sessions before handoff and setting up the new data routes. As per the illustration in Fig. 4, the nested network handoff takes place in stages and ensures that all sessions and data routes are established with optimized routing paths.

Firstly, the sub-SIP-NMS registers its new point of attachment and IP address with the parent-SIP-NMS. This registration request is responded by a 200 OK message by the parent-SIP-NMS. Next the sub-SIP-NMS sends a ReINVITE request with an embedded URI list through the parent SIP-NMS for re-inviting all its corresponding SIP clients. The parent-SIP-NMS forwards this ReINVITE request to the P-CSCF, which is also the SIP-FS, that will now reproduce individual ReINVITE messages to the URI list and forwards to all corresponding SIP clients. Once these remote SIP CNs receive these ReINVITE requests, ongoing SIP sessions can now be resumed via the new contact address. This is confirmed by a 200 OK response by all remote clients, which is eventually forwarded by the parent-SIP-IMS to the sub-SIP-NMS, thus the sessions are recovered.

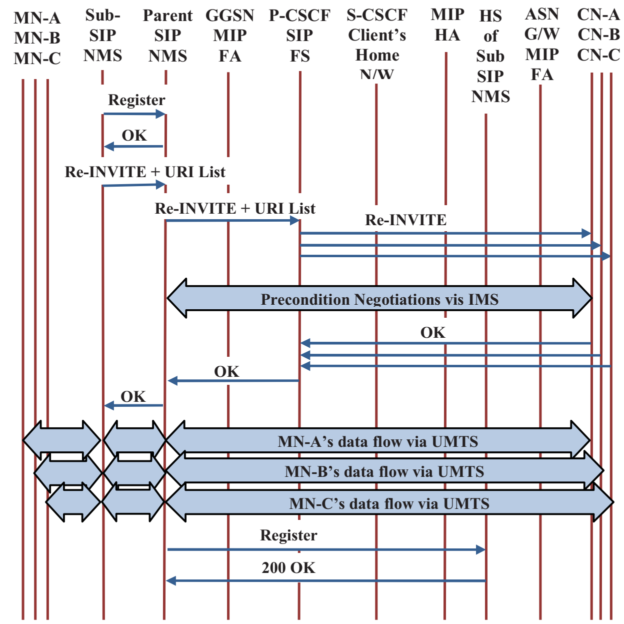

Fig. 4. Signaling Flow for SIP-NEMO associated Nested Network Handoff.

Lastly, an important point to notice is that, the parent-SIP-NMS sends its contact address as the new contact address for the newly attached sub-SIP-NMS via a REGISTER request to the HS of the sub-SIP-NMS. This is feed-backed with a 200 OK response, which now makes the sub-SIP-NMS to be globally reachable. Another important observation is that, unlike in the previous two cases, the IP address acquiring process of the PAN does not employ MIP; thus every time it joins a new mobile network a seamless session handoff may not be guaranteed.

IV. Results and Validation

A. Simulation Platform

The OPNET Modeler 14.0 platform is used for evaluating the performance of the presented architecture. A fully operational SIP-IMS model is designed and integrated to the UMTS Special Module, which is currently available under the contributed models library [13]. Necessary changes are made for SIP Proxy Servers (UASs) to operate as different CSCFs, UAC processes to communicate with modified UASs, IMS-SIP based messaging to flow between CSCFs, introduce global roaming between multiple domains, and necessary process delay controls (i.e. for messages sent between CSCFs and the HSS queries). Thus a UMTS cellular network fully capable of IMS based SIP signaling for session management and route optimization is developed. Furthermore, below the IMS architecture, a MIPv4 framework is also constructed for providing IP mobility and global reachability.

Followed by this, a heterogeneous network is designed with MIP and SIP signaling similar to the illustration of Fig. 2. Since the IMS and the MIP protocol are implemented at the core network of the UMTS cellular network, the exchange of signaling is independent to the underlying Physical and Link Layers. By taking the facts and limitations of OPNET, a fully IP based heterogeneous test bed is designed by interworking a UMTS network with a WiMAX network. Further information regarding this simulation platform is available via [14]. Following this, a group of SIP UACs that roams together are created to give the notion of a mobile network. There also exists a roaming SIP B2BUA within this group, which acts as the SIP-NMS. The SIP-NMS and the P-CSCF/SP-FS jointly handle the SIP URI list services.

When the mobile network roams from WiMAX to UMTS, the SIP-NMS residing in the group combines the source and destination addresses of all its ongoing SIP sessions into a URI list. Next, the SIP-NMS embeds this URI list into a SIP ReINVITE request and sends it to the SIP-FS of the newly attached network. When the SIP-FS receives the SIP ReINVITE request with a URI list, it generates individual SIP ReINVITE requests for all the ongoing sessions that need to be handed-off to the new network (i.e., UMTS). This platform is used for simulating and evaluating the performance of SIP-NEMO assisted vertical handoff and route optimization for a network handoff, and a nested network handoff scenario. The results are compared against a non NEMO based (i.e., MIP-SIP based) method outlined in [9].

B. Simulation Results

The average vertical handoff and route optimization delays for SIP clients roaming from WiMAX-to-UMTS and UMTS-to-WiMAX are illustrated from Fig. 5 and Fig. 6. Irrespective of having SIP-NEMO support or otherwise, the average vertical handoff delay for a single session from WiMAX-to-UMTS is 192 ms and from UMTS-to-WiMAX is 174 ms. In this case, where the SIP-NMS merely works as a SIP proxy, hence the reason for SIM-NEMO and the normal handoff method to incur equal delays as the SIP URI list simply contains a single entry. Also, the reason for WiMAX-to-UMTS handoffs to indicate a relatively higher handoff and route optimization delay is due to the relatively low bandwidth and the complicated structure of the UMTS Terrestrial Radio Access Network (UTRAN).

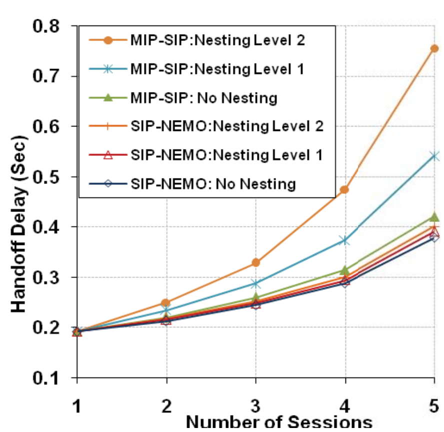

Fig. 5. Delay – WiMAX-to-UMTS SIP-NEMO vs. MIP-SIP Comparison.

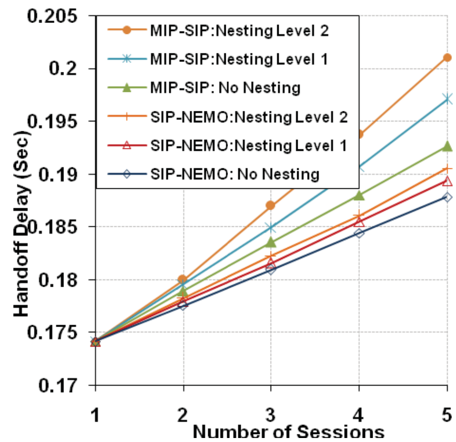

Fig. 6. Delay – UMTS-to-WiMAX SIP-NEMO vs. MIP-SIP Comparison.

As the number of SIP enabled mobile nodes onboard the roaming mobile network increases, benefits of our proposed method become more apparent. For example, as per the no nesting graphs in Fig.5, when two SIP clients are onboard the roaming mobile network, the SIP-NEMO method reduces the handoff delay by approximately 5 ms in comparison to performing individual MIP-SIP assisted handoffs according to [9], which is actually a reduction by 2.5%. Furthermore, as the number of SIP clients onboard the mobile network increases, SIP-NEMO mechanism shows reduced handoff delays. Hence, according to Fig. 5, as the number of SIP clients onboard the roaming mobile network becomes 5, the SIP-NEMO framework is capable of reducing the handoff delay close to 15 %.

Next, the nesting level 1 graphs in Fig. 5 and Fig. 6 shows the behavior in the case of a single level nested mobility scenario (e.g., for a PAN in a mobile network) and nesting level 2 in Fig. 5 and Fig. 6 shows the same in the case of a double nested mobility scenario (e.g., a PAN residing in a VAN in a mobile network). As the level of nesting increases, there seem to be a clear diversion between the non-NEMO and SIP-NEMO graphs. That is, there seem to be a drastic increase in the delay for the non-NEMO graphs in comparison to the SIP-NEMO graphs. This is a direct result of the accumulated message overheads relating to MIP assisted individual route negotiations. These overheads include additional extension headers, effects of pinball routing, and bidirectional tunneling. As the level of nesting increases, as illustrated in the nesting level 2 graphs in Fig. 5 and Fig. 6, the delay caused by MIP route negotiations become more apparent due to the elevated pinball routing activities. Despite the increasing delays of MIP related handoffs and route optimizations, in all these scenarios, all SIP-NEMO scenarios show relatively low delays. As per the comparisons provided by plotting all these graphs together, it can be concluded that SIP-NEMO performs extremely well even under a nested scenario with minimal delay.

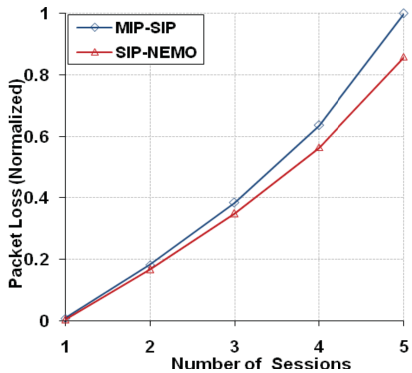

Fig. 7. Packet Loss - WiMAX-to-UMTS Network Handoff (No Nesting).

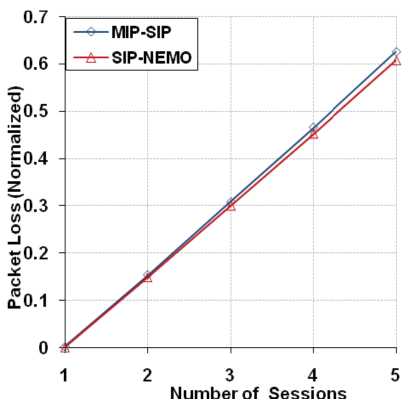

Fig. 8. Packet Loss - UMTS-to-WiMAX Network Handoff (No Nesting).

Figures 7 and 8 illustrate the normalized transient packet loss against the handed-off sessions from WiMAX-to-UMTS and UMTS-to-WiMAX networks respectively (Note: this is in the case of a break-before-make handoff scenario taking place). A relatively higher transient packet loss is observed from the WiMAX-to-UMTS in Fig. 7 in comparison to the UMTS-to-WiMAX in Fig. 8. As the transient packet loss during a vertical handoff is directly proportional to the vertical handoff delay, SIP-NEMO assisted session handoffs incur relatively

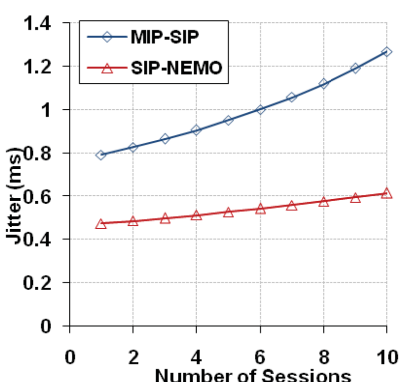

Fig. 9. Jitter Comparison.

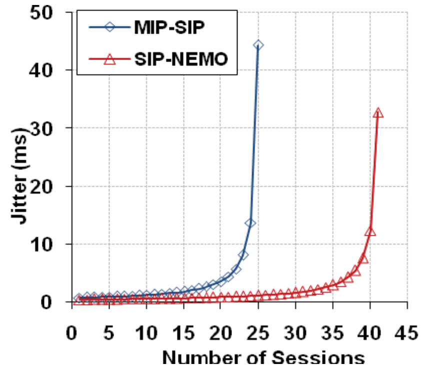

Fig. 10. Extended Jitter Comparison.

lower packet losses in contrast to the comparison graphs obtained from [7]. Next, Fig. 9 and Fig. 10 illustrate the jitter comparison for WiMAX-to-UMTS network handoffs for MIP-SIP and SIP-NEMO mechanisms. In this case, the jitter plot is obtained by calculating the variation of the end-to-end delay over UMTS for sessions that are being handed-off. According these graphs, the jitter rates are within acceptable limits for VoIP applications. Nevertheless, these jitter graphs tend to indicate rather exponential curves as per Fig. 10. Therefore, these graphs confirm that the SIP-NEMO based group session management and route optimization method is capable of successfully supporting a relatively higher number of simultaneous SIP session handoffs, whilst providing acceptable performance.

Finally, we investigate the signaling cost comparison and saving for the proposed SIP-NEMO mechanism. The associated signaling cost calculating method is in accordance to a mechanism proposed in one of our previous works [15]. According to [15], the signaling cost or overhead is defined as

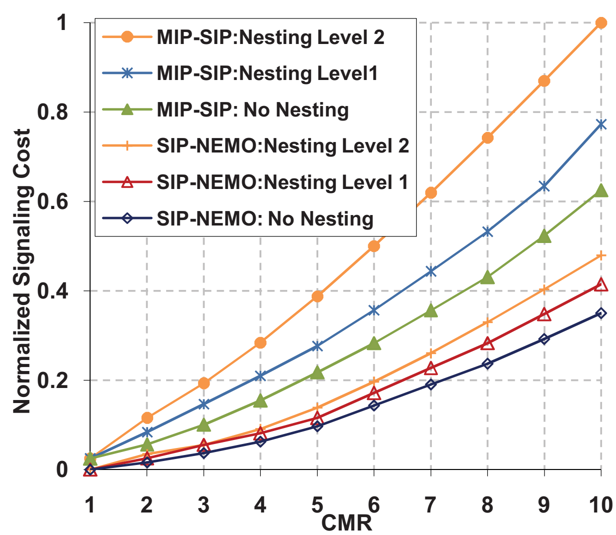

Fig. 11. Normalized Signaling Cost vs. Call-to-Mobility Rate.

the accumulative traffic load on exchanging signaling messages during the mobile host's communication session. Therefore, Fig. 11 illustrates the behavior of the normalized signaling cost against the Call-to-Mobility Rate (CMR) when the session arrival rate varies while the network mobility rate is constant. It can clearly be observed that there is a considerable saving in the associated signaling cost when SIP-NEMO is used. For example, in the case of a no nesting scenario, the proposed SIP-NEMO method is capable of reducing the signaling cost by 60% in contrast to a non-NEMO method when the CMR is 10. Further, in the case of a single level of nesting the saving further increases to a saving of 87 % and for a two level nesting scenario the saving is over 110% when the CMR is 10. Additionally, the trends of these results are also closely in line with the results of Figs. 5 and 6.

V. Conclusions

This paper proposed the integration of SIP-NEMO support for an NGMN architecture for enabling group mobility management between multiple heterogeneous networks with route optimization for supporting nested mobility. The proposed solution introduced SIP-NEMO into the IMS, which was also the coupling mediator of the underlying NGMN architecture. Further, the P-CSCF of the IMS functioned as the SIP-FS of the SIP-NMS, thus easily enabling group mobility and route optimization. Since both the P-CSCF and the SIP-FS are SIP B2BUAs, this was achieved with minimal changes to the existing 3GPP and 3GPP2 standards. The inclusion of SIP-NEMO for facilitating group based session mobility support and route optimization introduced a significant reduction of signaling overhead, hence substantially increased the end user QoS. Results and analysis illustrated that by integrating NEMO support to an NGMN reduced handoff latency, transient packet loss, jitter for both end users and service providers.

Acknowledgment

The simulations in this work were carried out using OPNET Modeler under the OPNET University Program.

References

[1] H. Y. Lach, C. Janneteau, and A. Petrescu, "Network mobility in beyond-3G systems," IEEE Communications Magazine vol. 41, no.7, pp. 52-57, Jul. 2003.

[2] V. Devarapalli, et al., "Network Mobility Basic Support Protocol," IETF RFC 3963, Jan. 2005.

[3] E. Perera, V. Sivaraman, and A. Seneviratne, "A Survey on Network Mobility Support," Mobile Computing and Communications Review, vol. 8, 2004.

[4] C. M. Huang, C. H. Lee, and J. R. Zheng, "A novel SIP based route optimization for network mobility," IEEE Journal in Selected Areas in Communications, vol. 24, no. 9, pp. 1682-1691, Sept. 2006.

[5] C. M. Huang, C. H. Lee, and P. H. Tseng, "Multihomed SIP-based Network Mobility Using IEEE 802.21 Media Independet Handover," in Proceedings of the IEEE Communications Conference, Dresden, Germany, Jun. 2009.

[6] G. Camarillo and A. Roach, "Framework and Security Considerations for Session Initiation Protocol (SIP) Uniform Resource Identifier (URI)-List Services," draft-ietf-sipping-uri-services-07, Nov. 2007.

[7] W. K. Chiang, A. N. Ren, and Y. C. Chung, "Integrating SIP-based Network Mobility into IP Multimedia Subsystem," in Proceedings of the IEEE Wireless Communications and Networking, Budapest, Hungry, Apr. 2009.

[8] V. K. Varma, et al., "Mobility management in integrated UMTS/WLAN networks," in Proceedings of the IEEE International Conference on Communications, Anchorage, Alaska, May 2003.

[9] K. S. Munasinghe and A. Jamalipour, "A Unified Mobility and Session Management Platform for Next Generation Mobile Networks," in Proceedings of the IEEE Globecom, Washington DC, Nov. 2007.

[10] 3GPP, "IP Multimedia Subsystem (IMS)," 3GPP TS 23.228 Version 6.10.0 Release 6, 2005.

[11] 3GPP, "Combined GSM and Mobile IP Mobility Handling in UMTS IP CN," 3GPP TR 23.923 v 3.0.0, 2000.

[12] C. Perkins, "IP Mobility Support for IPv4," IETF RFC 3344, 2002.

[13] A. H. Enrique Vazquez, Jose Ignacio Fernandez, "SIP-IMS Model for OPNET Modeler," OPNET University Program Contributed Models, 2005.

[14] K. S. Munasinghe and A. Jamalipour, "A 3GPP-IMS based Approach for Converging Next Generation Mobile Data Networks," in Proceedings of the IEEE International Conference on Communications, Glasgow, UK, Jun. 2007.

[15] K. S. Munasinghe and A. Jamalipour, Analysis of Signaling Cost for a Roaming User in a Heterogeneous Mobile Data Network, Accepted for publication in Proceedings of the IEEE Global Communications Conference, New Orleans, USA, November 2008.