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Multihoming Support in Mobile IP Networks: Progress, Challenges and Solutions

Mohammad Alreshoodi

Abstract: ***IP network mobility has already emerged as a key domain of wireless IP networking. The network research community has taken great interest and paid considerable attention to advance IP mobility applications. Accordingly, different advanced networking mechanisms have been considered to optimize IP network mobility. One of these mechanisms is network multi-homing which has been the focus of many IP mobility studies within the academic research and IETF communities. The combination of network mobility and multi-homing has turned into a conceivable approach to effectively deal with expanding system availability and improving the performance of mobile IP network. There are many studies proposed during the recent years to realize network multi-homing for the Network Mobility Basic Support (NEMO BS) protocol, a leading IETF IP mobility protocol. This paper studies and reviews up-to-date research works in supporting multi-homing for NEMO-based mobile IP networks. The aim is to investigate the current state of multi-homing support for NEMO networks and outline recent research directions in this regard.***

Keywords **:** ***Networks; IP Mobility; NEMO; Multi-homing.***

I. INTRODUCTION

Typical IP networks allow an IP device to have single IP address configured on one network interface. This enables the establishment of IP network communication over a single network layer connection. Although this would be adequate for some of the network services and applications, it implies having a single point of failure and ending up with limited connectivity. When connection redundancy and network resilience are priorities, it is important maintain sustainable network availability and service.

With the current advancement in technology, it becomes attainable to have multi-interfaced IP devices with the ability to simultaneously connect to multiple access networks. The enhancements provided by the recent version of the IP protocol, IP version 6 (IPv6), enables the configuration of multiple IP addresses in a more managed way. These considerations have accelerated the support of network multihoming by which a network device can establish and utilize multiple network layer connections simultaneously in a seamless manner. The device configures multiple IP addresses on one or multiple network interfaces. Multihomed local network can then establish multiple connections to one or multiple Service Providers (SPs) using one or multiple gateway routers. In the case of mobile IP devices and networks, multi-homing support becomes more critical to provide redundancy and resilience in dynamic environments.

Today, connectivity to wireless access networks can be easily attained not only in urban areas but also in remote environments. Many Internet access options can be exposed to mobile IP devices and networks while being on the move. Wi-Fi hotspots are becoming available in many urban locations and cellular access can be reached in rural areas. The wide availability of these and other access technologies provides mobile IP networks with a number of wireless connectivity alternatives. Multi-interfaced mobile IP devices and multi-gateways mobile IP networks can use all these opportunities to establish more resilience Internet access.

In addition, multihoming paves the way to have support of more effective networking techniques in mobile IP networks. These include seamless handover among homogeneous and heterogeneous access network. Another important aspect is enhancing traffic management and routing path selection. Traffic can be efficiently engineered and Quality of Service can be easily provisioned to meet the requirements of more applications. Load balancing would also be a viable approach by which data traffic can be distributed over many network gateways in a manageable manner. Multihoming can also bring the possibility of having effective failure recovery solutions particularly for dynamic and instable network setups. Multihoming has the potentiality to enhance performance and utilization of mobile IP networks. These considerations signify the importance of multihoming support in mobile IP networks. However, there could be a variety of multihoming scenarios and configurations for the different mobile IP networks. It is possible to have a mobile IP network with a multi-interfaced gateway router or having multiple gateway routers. In other cases, we may have more complex scenarios where a number of gateway router with Internet access are interconnected and their corresponding networks form a nested topology. We can see that these possibilities add to the complexity of the support of multihoming in mobile IP networks. It is important though to understand to what extend multihoming is applied to enhance network mobility and which directions are being taken in this regard. This paper studies and reviews up-to-date research works in supporting multihoming for NEMO-based mobile IP networks. The aim is to investigate the current state of multihoming support for NEMO networks and outline recent research directions in this regard. The rest of this paper starts with Section II providing background information on IP network mobility and the NEMO protocol. In Section III, a brief overview of multihoming in the context of IP mobility is presented.

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* Correspondence Author
Mohammed Alreshoodi*, Applied Science Department, Unizah Community Collage, Qassim University, Qassim, Saudi Arabia
mo.alreshoodi@qu.edu.sa

The review of the relevant literature is presented in Section IV. In Section V, a broad discussion on and a summary of the reviewed papers is given. Section VI concludes this survey paper.

II. NETWORK MOBILITY

A. NEMO

The IETF initially provides host mobility support and introduced the Mobile IPv4 (MIPv4) protocol [1]. MIPv4 enables basic support of mobility for mobile IP hosts moving across the Internet. After the emergence of IPv6, the IETF provides similar protocol known as Mobile IPv6 (MIPv6) [2]. However, MIPv6 comes with improved functionality compared to MIPv4. Moreover, the IETF considered the case of an entire IP network being mobile and roaming across the Internet. For addressing the need of mobility support at the level of mobile IP networks, a basic mobility support solution, referred to as NEMO Basic Support (NEMO BS) [3], has been introduced.

The design of the NEMO BS protocol is based on extending MIPv6 host mobility to provide a set of hosts in a roaming mobile IP network with transparent mobility support. Mobility management of the entire network is the responsibility of the network's Mobile Router (MR). In Figure 1, an example of a NEMO network consisting of different IP hosts, referred to as Mobile Network Nodes (MNNs). While it establishes an Internet connection over its external interface, the MR maintains an IPv6 subnet with a certain Mobile Network Prefix (MNP) being advertised over its internal interface. The MNNs use the advertised MNP to configure their IPv6 addresses.

When it is in the Home Network (HN), the MR connects to the network as a normal IPv6 router and configures its Home of Address (HoA). It also attaches to a NEMO Home Agent (HA). While being at the HN, traffic is routed using conventional IP routing. Once moving away from the HN and connecting to a Foreign Network (FN), the MR configures a Care-of Address (CoA). The MR then starts the registration of the new CoA with the HA by sending a Binding Update (BU) message to indicate its original HoA, current CoA, and advertised MNP. Once received, the request message is processed by the HA to add a binding entry in its Binding Cache (BC). Once that has been successfully accomplished, the HA needs to reply with a Binding Acknowledgement (BA) message. After that, a bi-directional IPv6-IPv6 NEMO tunnel is established between the HA and MR. Then, data packets of the NEMO network are tunneled by the MR via the NEMO tunnel and then forwarded by the HA towards the destination. Traffic coming to the NEMO network is also intercepted and diverted by the HA through the NEMO tunnel. The mobility support provided by the NEMO BS protocol enables a number of applications for mobile IPv6 networks. For example, a mobile Personal Area Network (PAN) can be established and maintained in an emergency situation. An emergency worker can have a NEMO mobile router with a PAN network connecting some IPv6 devices. NEMO can then provide the moving PAN sustainable communication. Another example is mobile vehicular networks which can use the NEMO protocol to ensure sustainable communications while vehicles are on the move. In the case of a moving ambulance, NEMO mobile router would provide continuous communication for real-time medical monitoring. Moreover, public transportation systems including trains and buses can also benefits from mobility support to provide commuters with undisrupted Internet services.

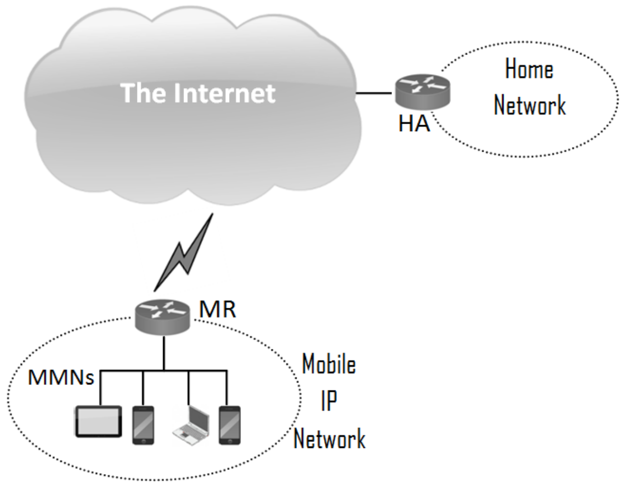

Fig. 1.NEMO Network

B. NEMO Extended Support

In a typical NEMO BS network, the MR connects to an access network on one interface while providing an IP subnet for its MMNs over another interface. It is possible for such a subnet to become the only option for another roaming MR to have external connection and connect to the Internet. The attaching MR in this case carries out binding update and establishes its NEMO tunnel through the existing NEMO tunnel of the MR to which it is connecting. Moreover, traffic of the attaching MR needs to traverse multiple HAs if the MRs belong to different HAs. As a result, indirect communication could happens when the MRs need to communicate with each other. The scenario can be worsened by multiple MRs forming a Nested NEMO topology of chained NEMO networks. It creates a sup-optimal routing model, referred to Pinball Routing [4], which could have adverse impact on network performance in regard to delay and overhead. The more the chained MRs in a nested network, the more the tunneling layers and the worse the problem effect. The NEMO Networking Group of IETF carried out a deep investigation of the limitations of the NEMO BS protocol, as described in RFC 4888 [4]. It provides a motivation for NEMO Route Optimization (RO) with the consideration of the Nested NEMO scenario. Accordingly, many research works has presented different NEMO RO solutions for enabling NEMO Extended Support (NEMO ES) [5] and addressing the inefficiencies of Nested NEMO. An example solution is the use of Reverse Routing Header (RRH) protocol in [6] to address multi-layer tunneling of Nested NEMO. For each packet, routing path information is recorded into the header.

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A similar approach was also proposed in [7] enabling a MR to use a mobility option called the Access Router Option to inform its HA of relevant routing information of its current access network. Other RO solutions are based on enabling direct local communication and addressing sub-optimal routing in nested NEMO networks. Examples are the Extended MIPv6 (EMIPv6) [8] and Optimized NEMO (ONEMO) [9, 10] protocols. In [11], the OLSRMANET routing protocol is adopted for enabling local routing among MRs of a nested network. In [12], the Tree Discovery (TD) [13] protocol is used for the formation of a tree topology among the MRs. For the establishment of local routing, the Network In Node Advertisement (NINA) [14] protocol is adopted. The Top Level MR performs the role of a gateway which is the only entity maintains the NEMO tunnel for the entire nested network. This eliminates the need for NEMO-over-NEMO tunneling and enables optimized local communication. if a MR has a HA different than the one of the gateway, HA inter-cooperation is required to establish a HA-HA tunnel while the gateway's HA start acting as a proxy-HA for the MR traffic. Moreover, a variety of RO solutions for the nested NEMO model is described and compared in [15] and [16].

III. IP MOBILITY AND MULTIHOMING

This Multihoming means that the node must attain the ability to manage various IP addresses at a time [17]. The terms related to multihoming have been assessed and defined in RFC 4885 [5] considering host and network mobility. The multihomed MN or MR is regarded as attaining more than one HoA or CoA which are configured using various prefixes (multi-prefixed node) or on different interfaces (multi-interfaced node). If multiple IP addresses are maintained by their HA, the MN or MR are considered multihomed [18]. Yet, if there is a multihomed MR or various MRs are present in a NEMO network, it is then regarded as a multihomed network [5]. Furthermore, the RFC 4885 also defines how a nested NEMO network can be multihomed by having a multihomed root-MR or attaining multiple root-MRs. Based on that, it is possible to have various multihoming scenarios for a NEMO network. For instance, a multi-interfaced MR could be present within a NEMO network that is connected to the same or various HAs. In another case, several MRs could form a nested NEMO topology while being registered to single or multiple HAs.

A detailed assessment has been made by the IETF Network Working Group within RFC 4980 [19] to understand the potential NEMO network multihoming configurations. Taxonomy has been brought forward to differentiate the various kinds of multihoming configurations while considering three types of approaches. The Configuration-Oriented approach is the initial approach where the classification is based upon three kinds of parameters. These are the number of NEMO MRs, associated HAs, advertised MNPs. Accordingly, a NEMO network has eight potential multihoming configurations. The possible configurations would each attain a triplet (x, y, z), in which x is the MRs number, the HAs number is y and the MNPs number is z. For instance, the configuration (n, 1, 1) refers to the multihomed NEMO network where several MRs are associated with a single HA and would advertise a single MNP. However, there are a number of NEMO multihoming issues that have been highlighted for the configuration-oriented multihoming configurations. For instance, the solutions related to loop avoidance and the ingress filtering were analyzed in [19] along with issues related to fault tolerance like traffic redirection and failure detection. In [20], assessments for each of the eight potential multihoming configurations have been made. On the other hand, [19] also considers the ownership-oriented approach where two models have been defined. The first model is the Internet Service Provider (ISP) model in which a single entity controls the MRs and their HAs whereas the second model is the Subscriber/Provider Model in which the control is managed by different entities. However, the NEMO BS protocol comes with no multihoming support and allows the registration of only a single CoA at a time. This motivated the introduction of the Multiple Care-of Address (MCoA) registration mechanism, specified by RFC 5648 [21]. It provides mobile IP hosts and networks with a multihoming solution allowing the registration of multiple CoA and the establishment of multiple mobility tunnels. As shown in Figure 2, the MR can use the cellular and Wi-Fi connections to maintain multiple registrations with the HA and provide the connecting nodes with more than one communication path. Additional information is needed to enable the HA to install multiple entries for the MR in its registration cache. This information includes a unique Binding Identifier (BID) which is generated for each registered CoA. The MR is required to add a Binding Identifier mobility option containing such information into its BU messages. For each of the Wi-Fi and cellular connections in Figure 2, the MR configures a different CoA on the respective interface and assigns it a unique BID. Over each interface, a BU message containing such information is periodically sent to the HA. Once received, a binding entry is created and a tunnel is established for each of the CoAs. While the MCoA mechanism specifies how a MR can establish multiple communication paths, traffic distribution among the available paths is not specified. RFC 6089 [22] addresses such a limitation to provide a control on how packets should be forwarded over multiple connections of different performance and capabilities. This is based on extending the MCoA protocol with a flow binding mechanism. It provides a solution for binding certain flows to a specific CoA using its BID. This is accomplished by the MR which also generates a unique Flow Identifier (FID) for each binding. A list, referred to as the flow binding list, is maintained to store all the flow bindings. Each entry of the list will then be added to a different Flow Identifier mobility option which is attached to the BU messages being sent to the HA. Once received, the flow binding information indicates to the HA how to distribute the traffic over the available paths consistently with the MR on a per-flow basis. Another example is the MCoA-based mechanism presented in [23]. It provides a solution for translating traffic forwarding policies to a set of filtering rules used by a mobile node or router to distribute traffic among multiple interfaces. It also enables the communication of these rules with the corresponding HAs.

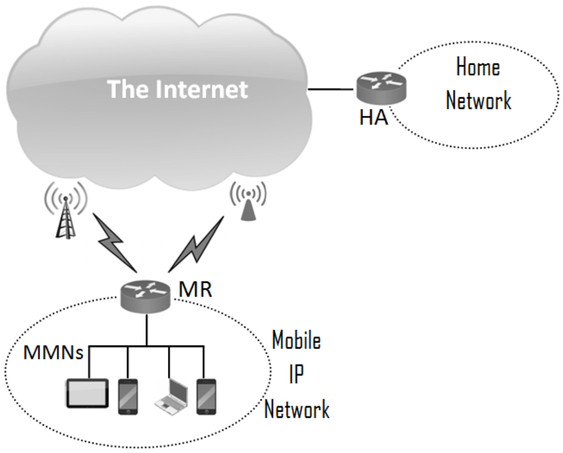

Fig. 2.A Multihomed NEMO MR

IV. REVIEW OF MULTIHOMING SUPPORT FOR NETWORK MOBILITY

Since the past few years, the academic research communities and the IETF have brought forward proposals for various multihoming studies in regards to NEMO networks. There are several multihoming solutions present within these studies considering the various multihoming configurations and issues. Much effort has been made upon addressing multihoming support for a single NEMO network with various a multihomed MR or various MRs. Proposals have also been presented for the Nested NEMO cases with and without RO solutions. These proposals mainly focused on addressing different networking aspects for multihomed NEMO networks. These are optimal interface/gateway selection, seamless handover, load balancing, bandwidth aggregation, and failure recovery. Accordingly, the following subsections present and discuss the relevant multihoming studies.

A. Optimal Interface/Gateway Selection

Selection of optimal network interface and gateway is one of the vital problems in the single multihomed NEMO networks and multihomed nested NEMO scenarios, respectively. It has been the focus of different research works with various considerations on which the selection can be based. Research studies like [24 - 25] have presented interface selection mechanisms based on QoS. In [24], multihomed MR can identify the routes of the required level of QoS using dynamic measurement and then utilize these routes to forward real-time traffic with the help of the Class Based Queuing (CBQ). The simulation results showed improvement on TCP performance. The solution in [25] is based on a per-flow selection algorithm run by the MR to consider the QoS requirements of each type of traffic. It also takes into account user preferences in addition to interface characteristics for the selection process. However, basic analytical assessment is presented to show how dynamic the proposed algorithm is in selecting the optimal interface for certain traffic.Another per-flow selection mechanism is also proposed in [26]. However, it is based on comparing network measurement of each available path over the multiple MRs in a nested NEMO scenario. In this multihoming solution, A Reverse Routing Header (RHH) RO solution together with MCoA protocol was applied. This enables both BU and BACK messages to carry RRH headers which contain a path ID of each path. Using this approach, MRs can perform a per-flow selection of the available paths based on the measurement of the delay of each path and the consideration of TCP load balancing. However, this approach is based on the duplication of periodic BU messages to be sent over the multiple interfaces to facilitate path recording and discovery. This increases the communication and processing overhead particularly for dense deployment. Overhead is also made worse by as each packet carries its own path towards HA in RRH. How the overall performance of the nested network is affected by these techniques has not been evaluated so far.

The researchers in [27] and [28] presented a network performance based selection algorithm with a per-flow traffic control. It addresses a comprehensive multihoming solution to take into consideration various metrics including bandwidth, delay, packet loss, and path cost for understanding the performance of each path in the network. These measures are calculated at each MR to select the best path for each traffic flow accordingly. However, for this mechanism to work, each MNN informs its MR on the selected path of the type of the traffic to be transmitted. Additionally, each MR should add a state corresponding to each session into its routing table. These operations would cause more processing delays extra signaling overhead across the network. This mechanism also does not consider path selection for incoming packets that are originated from other sources external to the nested network.

In [29], another study was proposed in which the Tree Discovery protocol is used by Mobile Routers to create a tree topology. A selection algorithm is then run to select the best available path for Internet connection. This technique involves extensive computations to facilitate the selection of the best internet access based on certain preferences while considering load sharing and failure recovery. Being based on active signaling and establishment of the routing path to the chosen Gateway, very dynamic scenarios can impose some challenges to the proposed route enforcement mechanism.

Another effort that considered network measurement based selections is the Multihomed Mobile Network Architecture (MMNA) in [30] and [31]. It also incorporates enables policy management to provide comprehensive multihoming support and management for nested NEMO networks. It is based on two main processes, namely multihomed mobile tree establishment and gateway discovery and selection. Each process is then based on a number of different protocols and functional components. It extended the NEMO tree structure with the support of MCoA mechanism to enables the establishment of a multihomed tree of multiple gateways. MMNA also facilitates efficient multihoming management framework and optimum usage of the available gateways across the tree topology. Gateway information and performance indicators are disseminated across the network by each gateway, allowing informative and intelligent decisions to be made for efficient use the available gateways. The focus is on ensuring that each communication always traverses the most optimal Gateways in order to ultimately improve network performance and resource utilization. With a real-life testbed experiments, the proposed solution showed improved performance in terms of different networking aspects.

Selection based on policy management has also been the focus in [32]. It proposed frameworks for multihoming management based on an intelligent traffic forwarding mechanism using policies predefined by network operators, end-user applications, and mobile node administrators. It uses the Grey Relational Analysis (GRA) method for better decision making. The proposed solution was tested in both simulation and testbed setups.

The selection process can also be security oriented as proposed in [33]. The researchers proposed a trust management selection mechanism considering the case of having a nested NEMO network. A MR is selected after having its trustworthiness evaluated by the corresponding HA based on a membership-clouds based trust model. They also introduced a secure trust information transmission protocol for securing network communications. The simulation results show that the proposed solutions reflected the trustworthiness in a real-time manner, and prevented compromised MR from being selected.

Another concern being addressed in the context of multihomed nested NEMO is loop-free path selection as proposed in [34]. An optimized nested model in which MRs connect to multiple NEMO networks formed by the Tree Discovery protocol was considered. A multihomed MR attaches to multiple parent MRs using a hierarchical path-selection algorithm. To avoid routing loops, the algorithm only allows the attachment to parent MRs of different trees. The algorithm also allows the MR to attach to others closer to the root MR when within the same tree. A new option is introduced to be attached to RA messages broadcasted by every MR. This option enables a MR to indicate its path ID, level, and clusterhead ID. However, it is not certain in this proposal how a MR interacts with the HA when connecting to more than one network and how the BU operation and tunneling management occurs over different networks. The proposed solution was evaluated analytically and the results showed a reduction in the average nesting level.

B. Seamless Handover Support

Multihomed NEMO networks can facilitate effective support of seamless handover. This has been addressed in several research studies. One example is the proposal in [35] which presents a seamless handover algorithm for a NEMO network with multihomed MR. The proposed algorithm is based on a cross layer approach requiring the reading of signal strength at the link layer in the overlapping area, before making the decision at the network layer. It follows the make-before-break strategy. The experimental testbed results showed that the proposed solution achieved better performance regarding handover delay, Round Trip Time, and throughput as compared to the NEMO BS protocol. The proposed algorithm was compared to a multihomed transport layer-based mobility protocol in [36]. The comparison results showed that transport layer-based mobility performs better than NEMO during the handoff between heterogeneous access networks.

Another seamless handover support with cross layer design is the algorithm proposed in [37]. It is an inter-interfaces handover algorithm that relies on measuring the network signal strength to make the handover decision. The algorithm is based on extending the MCoA protocol with the objective of reducing handover delay. The testing results of the algorithm in an experimental testbed indicated that the solution maintains no packet loss during handover. The algorithm also ensured less Round Trip Time than the standard NEMO BS.

The researchers in [38] used the Proxy Mobile IPv6 (PMIPv6) protocol to provide multi-interfaced MRs with seamless handover support. Additional entities were incorporated into the NEMO architecture at the IP infrastructure. These were utilized by the proposed solution to develop a Multihoming-based Inter-system handoff scheme on PMIPv6 domain in NEMO (MI-PNEMO). The focus is on reducing handoff delay during inter-system handoff. MI-PNEMO is based on MR movement detection and handoff management among the proxy NEMO access routers. It also supports flow-based routing with a dynamic flow redirection mechanism. The performance of MI-PNEMO was tested in a small-scale simulation setup. The results show that handoff delay was reduced while improving packet loss and throughput.

Another solution that incorporated an additional networking technology is proposed in [39]. It uses the IEEE 802.21 technology to provide a vehicular NEMO network of a multi-interfaced MR with a seamless and media independent handover assistance service. This supports making better decisions at MRs to connect to an optimal option among different access network technologies at the appropriate moment. The solution is based on implementing advanced fine-grained handover decision algorithms according to gathered information about the network status, particularly the Received Signal Strength Indicator (RSSI) in the Mobile Router. The Handover Decision Module (HDM) was introduced to control handover procedure at mobile routers, access routers and central ITS stations. The solution was experimented in real-life testbed setups and the results showed a noticeable reduction in the handover delay.

Similar to [38, 39], the proposed study in [40] focused on the case of inter-handoff among heterogeneous access networks. The researchers studied the impact of multihoming support on a specific performance metric, namely the Location Update Costs (LUC) through qualitative analysis. This is important as a long convergence time during inter handoff would increase LUC. The Cell Residence Time (CRT) is also calculated for the MR among different access technologies using the Random Waypoint Model. It is demonstrated that less LUC in the case of NEMO multihoming support as the CRT is increased.

On the other hand, a mathematical model was proposed to analyze network performance during intra-handoff of a single NEMO network with multiple MRs [41]. The handover procedure in this model is managed by a new entity, called an Intelligent Control Entity (ICE). The objective of the proposed model was to understand the performance of traffic delivery when none of mobile routers can transport traffic during the handover period.

Different parameters that would influence the handover performance were considered, such as overlapping coverage distance, vehicle speed, distance between MRs, and scanning frequency. The focus was on the applications of public transportation systems, particularly the bus and train cases. The obtained results indicated that careful network configuration is critically required to achieve seamless handover.

Another research work that considered a certain application is proposed in [42] which provides a handover solution for a train-based NEMO network of two MRs. The MRs have a direct connection and work collaboratively using the knowledge of the movement and route of the train to facilitate a seamless handover. When one MR is handing over, the other MR receives traffic and forwards it to the other MRs via their direct connection. Theses MRs are pre-configured with the expected CoAs along the known train route. This helps in reducing the delay in the CoA configuration. The solution was evaluated using a mathematical analysis and a simulation setup. The evaluation results showed improved handover performance with low delay and packet loss.

Other multihoming solutions provide proactive handover management based on predictive methods. One example is presented in [43] which uses Geographical Positioning System (GPS) data for minimizing handover latency. This is based on using the current GPS position information and previous records of network parameters to predict expected handovers. The benefits of overlapping radio access coverage are exploited by proactively managing multiple tunnels and executing predictive tunnel switching. However, it is assumed that the mobile network follows a predefined path every time it moves which could be the case when considering public transportation vehicles, but not random walking.

The researchers in [44] also used actual location of a MR in addition to previously recorded context data to make handover prediction. They proposed the Secured Efficient Fast Handover Multihoming Based NEMO+ (SEFMNEMO+) framework. It is based on a predictive policy exchange method to enable updating expected handover in advance. The simulation results indicated improved performance in regards to handoff delay and packet loss.

C. Advance Multihoming Management

There have been also considerations for advance multihoming management support with the main focus on load balancing, fault tolerance, aggregated bandwidth. Researchers observe load balancing as a potential mechanism in multihoming environments. In [45], network communications were distributed seamlessly among multiple gateways by extending NDP (Neighbor Discovery Protocol). It is based on a master-slave model by which one MR is assigned the role of traffic management among other MRs. This requires some level of communication and coordination among the available MRs in a multihomed NEMO network. For a large and dynamic network, there could extra overhead that needs to be addressed. However, the practicability of the proposed mechanisms was demonstrated using real-life experimentation.

Another load balancing solution is also proposed in [46] for the case of a multi-MRs NEMO network. It is a priority-based mechanism to enable dynamic traffic distribution among MRs based on their calculated priorities. The calculation is made by the HA for each corresponding MR. It is based on estimating the load level of each MR considering its total number of registered mobile nodes, average traffic delay, packet loss rate, and bandwidth. The relevant mobile nodes are then informed of the priority level of their MRs to support making an optimal decision regarding traffic distribution. Simulations results demonstrated how the proposed solution improved overall network throughput and average delay.

Load balancing support has also been considered in other research efforts. One example is [29] which provide a load balancing support for optimal MR selection in a multihomed nested NEMO network. In [26], a basic load balancing mechanism based on a pre-calculation of the TCP load of each MR was considered. In [34], the Extended Topology Tuning Scheme is presented to minimize the average nested level of a multihomed nested NEMO network. This helped in balancing the connectivity among the nested MRs and optimally distributing their traffic load across the network. In [30, 31], the experimental results demonstrated the efficiency of the proposed multihoming NEMO solution in providing load balancing support.

Moreover, multihomed NEMO networks provide a good potentiality to support failure avoidance and recovery. The availability of many MRs to a NEMO network effectively helps in making fault-tolerant mobility easy to deploy. In [47], a failure recovery mechanism was proposed for the case of multi-MRs NEMO networks. It is based on a proactive approach and incorporating an additional entity, namely the NEMO Gateway (NMG), to the multihomed NEMO architecture. When a failure occurs, NMG manages the redirection of traffic among MRs accordingly. Registration of the MRs should be done with all the different HAs so that multiple tunnels are established among a HA and the different MRs located in the same NEMO network. Fault tolerance support has also been considered in other proposals. Examples are [29, 34] in which a simple fault tolerance approaches were developed for the multihomed nested NEMO scenarios. The evaluation results in [30, 31] indicated that the proposed multihoming architecture solution helped in ensured efficient fault tolerance support.

Another consideration in multihomed NEMO networks is the availability of multiple gateway connections and ability to aggregate their bandwidth to support better and reliable communication. The solution proposed in [48] provides such a capability with the focus on multi-MRs vehicular NEMO scenarios. It enables multiple MRs mounted on different vehicles to ally and make an aggregated Internet connection. This is preserved as long as the MRs are close and perform well enough to maintain good network throughput and connection stability. The experimental testbed results showed that Internet connections among multiple MRs can be aggregated in a dynamic way to achieve better network throughput.

V. RESULTS AND DISCUSSION

This section presents a brief discussion on the surveyed multihomed IP mobility solutions. These are also summarized in Table I.

Multihoming support for mobile IP networks has been addressed with the consideration of different networking aspects. These are optimal interface/gateway selection, seamless handover, load balancing, bandwidth aggregation, and failure recovery. This has been considered for different multihomed NEMO cases. One is the case of a multihomed NEMO network of a single multi-interfaced MR [24-25, 32, 35-40, 43]. The other case is a multihomed NEMO network of multiple MRSs [33, 41-42, 45-48]. Then the more complex scenario of a nested NEMO network of multiple uni- and multi-interfaced MRs [26-31, 34, 44]. In the third column of Table I, A, B, and C denote the first, second, and third cases, respectively.

It is clear that Most of the seamless handover proposals presented in the survey considered the simple case of a single multi-interfaced NEMO MR. For the reviewed path selection solutions; the focus was mostly on the third case considering multiple MRs in complex nested scenarios. On the other hand, the proposals considering advance multihoming management only focused on the second case. It is evident that load balancing and fault tolerance have not been yet addressed for multihomed nested NEMO networks.

Another important consideration is the diversity of the approaches adopted in the reviewed literature. For the path selection solutions, there is a focus on network measurement and performance, policy management, and QoS based selection mechanisms. Other proposal gave limited consideration to different criteria such as security, user preference, and loop avoidance. However, other considerations such as context-based selection have not yet been addressed for multihomed mobile IP networks. For the handover solutions, cross-layer design was adopted in some of them whereas others introduced location-based handover. Other technologies, such as PMIPv6 and IEEE 802.21, were adopted in some of the proposed research works for handover management. Additional entities were also incorporated into the multihoming NEMO architecture to support seamless handover. Although these approaches provided better handover, it is important to keep the complexity level of the solutions to a minimum. This is evident considering the already complex nature of multihomed IP mobility architecture and applications.

While most of the surveyed literatures were practically evaluated, there are a good number of them have only been evaluated analytically. Although it can give some insights, analytical assessment would always require to be followed with a more technical testing for more practical results. This is more evident for the dynamic and mobile scenarios of multihomed NEMO networking. On the other hands, few numbers of the proposals provided a more extensive evaluation considering both simulation and testbed/analytical approaches.

Table 1. Summary of the reviewed multihomed IP mobility solutions

Ref.	Solution	Scenario	Approach	App.	Assessment
[24]	Optimal Path Selection	A	QoS-oriented	General	Simulation
[25]		A	QoS-oriented	General	Analytical
[26]		C	Network Measurement	General	Analytical
[27] [28]		C	Network Measurement	General	Simulation
[29]		C	User preferences	General	Simulation
[30] [31]		C	policy management & Network measurement	General	Testbed
[32]		A	policy management	General	Sim. + Testbed
[33]		B	Security oriented	General	Simulation
[34]		C	Loop Avoidance	General	Analytical
[35] [36]	Seamless Handover	A	Cross-layer design	General	Testbed
[37]		A	Cross-layer design	General	Testbed
[38]		A	PMIPv6 based solution	General	Simulation
[39]		A	IEEE 802.21 based solution	Vehicular	Testbed
[40]		A	Inter-handoff location based handover	Train	Analytical
[41]		B	ICE entity for handover management	Train	Analytical
[42]		B	Collaborative handover management	Vehicular	Sim. + Analyt.
[43]		A	Proactive GPS based handover	General	Testbed
[44]		C	Predictive & location based handover	General	Simulation
[45]	Load Balancing	B	NDP extension	General	Testbed
[46]		B	priority-based mechanism	General	Simulation
[47]	Fault Tolerance	B	proactive approach & the NMG entity	General	Simulation
[48]	Bandwidth Aggregatio n	B	Performance & distance based aggregation control	General	Testbed

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VI. CONCLUSION

The networking research community has been paying considerable attention to advance IP mobility support. As presented in this paper, there has been noticeable interest in introducing multihoming support into the space of IP mobility, following the advancements in wireless networking technologies. This combination has turned into a conceivable approach to effectively deal with expanding system availability and improving the performance of mobile IP networks. However, efficiently incorporating network mobility with multihoming support is challenging. This is evident considering the complexity in possible network mobility scenarios; particularly those involve multiple interconnected heterogeneous mobile routers. Based on the review in this paper, there is still a need for more flexible and practical solutions to address comprehensive multihoming support in the context of complex network mobility. Some important networking aspects such as scalability and elasticity have not yet been effectively addressed. An emphasis can also be placed on examining multihomed mobility support in real-life environments. It would also be viable to consider multihoming support to address more efficient mobility in specific applications such as Intelligent Transportation Systems and Internet of Things.

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AUTHORS PROFILE

Mohammed Alreshoodi, is currently an Assistant Professor at Qassim University. His main research interests include the areas of Computer Network, Wireless sensor networks, Machine Learning.