A Study on the Performance of an Advanced Framework for Prediction-based NEMO Handovers in Multihomed Scenarios

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Abstract — In this paper we provide an extensive performance evaluation of an already introduced advanced handover management solution which aimed at providing ubiquitous IPv6 connection and seamless Internet access for network mobility (NEMO) scenarios. The novel solution makes use of geographic location information and previous records of access network parameters. The method exploits the benefits of multihomed mobility configurations by introducing a special handover execution protocol entirely based on flow bindings. Using actual location information and previously recorded context data, the system is able to predict handovers and proactively prepare itself for the appearance of access networks. We studied the performance of our proposal by implementing the framework and handover execution scheme in a real-life 3G/Wi-Fi multi-access testbed environment, and showed that handover latency is almost totally eliminated. As our solution strongly relies on the prediction accuracy, we have also developed a probabilistic system model and evaluated of the probability of wrong positioning on the prediction raster.

Keywords: IPv6, cross-layer optimization, mobility management, NEMO, MCoA, geographic position information, flow bindings, policy exchange, multihoming, predictive handover, proactive handover, real-life implementation, probabilistic system model

I. INTRODUCTION

Trends in information technology show that heterogeneous, IP-based wireless networks will support mobility for the widest range of single end terminals (e.g., mobile phones, SmartPhones, PDAs, tablets and other handhelds), and even Personal Area Networks (PANs), Vehicle Area Networks (VANs) [1], Intelligent Transportation Systems (ITSs) and Cooperative ITS (C-ITS) architectures [2]–[4], networks of RFID (Radio Frequency Identification) devices and sensors, and various mobile ad hoc networks [5] will have permanent Internet connectivity during movement. Hence, in next generation wireless telecommunication not only single mobile entities have to be taken into account (host

or terminal mobility), but also entire mobile networks moving between different subnets need to be maintained as a whole (i.e., network mobility or NEMO). IPv6 has introduced support for both mobility cases by defining Mobile IPv6 (MIPv6) [6] and Network Mobility Basic Support (NEMO BS) [7]. With these mobility supporting mechanisms all sessions remain active, even when the mobile node/network changes its subnetwork. When a host or a moving network has multiple interfaces and/or several IPv6 addresses, it is regarded multihomed. Multihomed mobile hosts/networks need special protocols to support their mobility management (e.g., MCoA [8], Flow Bindings [9], [10]). Handover at network layer usually takes several seconds due to the large number of L1/L2/L3 processes, the lack of interaction between them, and their complexity. The overall time needed to complete these procedures could go up to several seconds. In order to ensure seamless, continuous communication, this huge outage should be avoided by applying optimized handover solutions in the architecture.

Several improvement proposals exist to overcome the huge delay. All of them aim to speed-up the handover process. Mobile IPv6 Fast Handovers [11] is one example, and there are plenty of other proposals as well [12]–[16]. However, according to our best knowledge, only our previous works [17]–[19] exploit the benefits of overlapping radio access coverages by proactively managing multiple tunnels and executing predictive tunnel switching based on generalized flow binding policy exchange. Our solution extends standard IPv6-based network mobility by forming an advanced and complete framework based on a special, multi-tunnel based, predictive, seamless handover solution. In this paper we further elaborate our previous work and provide an extensive performance analysis of the scheme. In order to do this, we provide a more detailed, broad background on the different handover schemes, show more implementation details, introduce new measurement results and also provide a novel, probabilistic system model for analytical evaluation of the prediction system.

The paper is structured as follows. Section II introduces the scientific background and related work, also summarizing the existing predictive mobility management schemes. Section III recaps our existing solution, and further details the protocol operation. Testbed and measurements results are explained in Section IV. Section V presents the probabilistic system model and our evaluation results on the probability of wrong

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positioning. Finally, we conclude the paper and show some possible future work in Section VI.

II. BACKGROUND AND RELATED WORK

Mobile clients continuously change their position, which could yield access network failures or connection drops. Mobility management in heterogeneous access architectures is aware of handling the mobility related procedures. IPv6 has built-in support for terminal and network mobility, but these basic solutions do not tackle the problem when handovers provide serious communication outages due to the large number of L1/L2/L3 duties. First, the mobile terminal/router has to find and connect to the new network at L1 and L2 (PHY and MAC), and only after the successful L1/L2 connection it could launch the necessary L3 procedures to obtain the new IPv6 address(es) (with stateless [20] or stateful autoconfiguration [21]). After the new IPv6 address is set, the binding procedure starts: it binds (registers) its address(es) in the Home Agent (HA), which provides global accessibility. These procedures could easily result in several seconds of handover delay. Figure 1 introduces how it happens in case of NEMO BS [7].
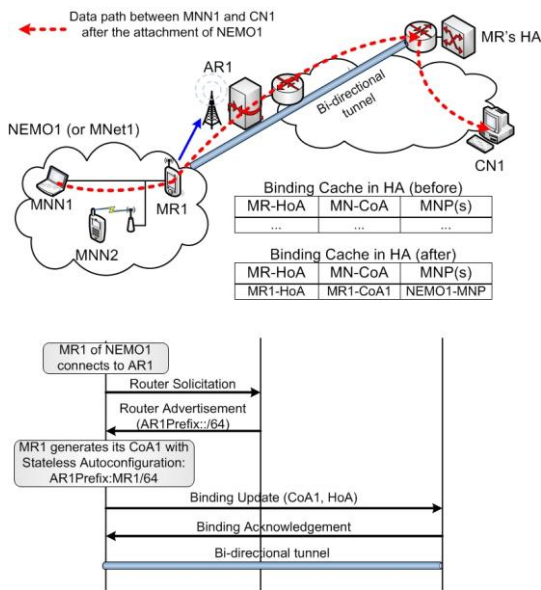

Fig. 1.   NEMO BS handover management

The solution used by NEMO BS is similar to Mobile IPv6 but without routing optimization: when a Mobile Router (MR) leaves its home link, it configures a Care of Address (CoA) in the visited network and registers this CoA with its HA using the binding procedure. However, the Binding Update (BU) message in NEMO BS is quite different from that in MIPv6. While a BU message in MIPv6 contains the Care-of and the Home Address (HoA) of a mobile node, till a BU of an MR contains additional information: the IP subnet prefix or prefixes of the moving network. These so called Mobile Network Prefixes (MNPs) in the Binding Updates instruct the Home Agent to create a binding cache entry linking the MNPs to the MR's Care-of Address. After a successful registration,

the HA intercepts and forwards packets destined not only to the MR, but also to any MNNs that have acquired an address from one of the Mobile Network prefixes of the MR. When the moving network changes its actual network point of attachment, only the MR configures new CoA and sends BU (containing the MNPs) to the HA. Since the Home Addresses of the MNNs inside a moving network are associated with the MNPs registered in the HAs, the HA of the network's MR intercepts all the packets addressed to MNNs and forwards them towards the MR's CoA. The MR decapsulates the packets destined to MNNs and forwards them on its appropriate ingress interfaces. Packets originated from inside the moving network will follow the same routes but in the reverse direction. It is obvious that the big number of encapsulations cause header overhead, and the fact that all the HAs should be involved in the communication path results using traffic routes far from the optimal ones. NEMO BS is not applicable for multi-access or multihoming scenarios as it supports only one interface that has to be configured before starting the NEMO stack. In a heterogeneous environment such as a 3G/Wi-Fi architecture, reconfiguration and restarting of the NEMO BS implementation is required to use a different interface than the configured one. Moreover, the handovers are handled "blind" as no network context information is available during the operation: a strictly reactive behaviour is used.

Multihoming is an advantageous method to provide always-on connectivity in a wireless environment and support multi-access scenarios. In order to exploit such possibilities, Multiple Care-of Addresses Registration (MCoA) [8] was introduced to the Mobile IPv6 protocol family. By utilizing that mobile nodes or routers can connect to multiple access networks simultaneously, it is now possible to enhance handover latency, network redundancy and perform policy based routing even in multi-access environments. Figure 2 depicts a typical scenario, where the MR has two external interfaces, where each interface is connected to an access network with a CoA, and through each CoA a Mobile IPv6 tunnel is created to the Home Agent. While with NEMO BS, identifying a binding was enough using the CoA and the HoA, it is no longer the case with NEMO MCoA as each mobility tunnel endpoint uses the same Home Address on the MR. Using network layer information, the MR can no longer perform an exact routing decision to select an individual tunnel. To solve this issue another identifier, known as Binding Identifier (BID) was introduced to identify the network interface over which the tunnel is established. As the BID is sent to the HA in the BU signalling message, the HA can differentiate between tunnels originating from the same MR. To identify and route packets toward the desired tunnel, policy routing must be used, which allows fine grained diversification among data packets and streams based on network layer and upper layer information. To avoid asymmetric routing where packets belonging to the same packet flow are routed on different tunnels, a flow binding mechanism has to be implemented. Using flow binding control messages, the MR registers flow descriptor and BID pairs at

the Home Agent, so the HA would properly know which tunnel to use when it forwards packets of the data flow back to the mobile node [9], [10].

Using the above introduced multihoming solution, routing of individual media streams can be easily solved, enhancing the experience for not only moving, but stationary mobile nodes as the presence of multiple egress interfaces makes content delivery more reliable and robust.
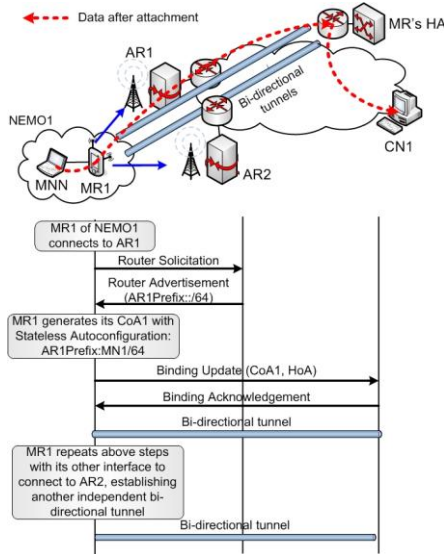

Fig. 2. NEMO multihoming solution with MCoA

Based on MCoA, a special type of handover scheme can be defined (we call it MCoA handover [18]), which relies on overlapping radio access networks (RANs), and in case of an appearing new access network on an unused MR interface, moves every traffic to this new RAN by activating symmetric policy rules for all the MR transmissions (Figure 3).
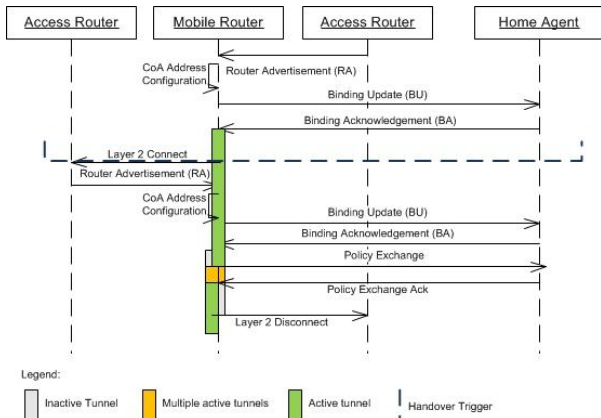

Fig. 3. A possible NEMO MCoA handover solution

This MCoA handover reduces Layer 2 and Layer 3 latencies by connecting to the new network with an MR interface, which does not used for any of the actual communication, and after the initiation of this new connection (i.e., L2 and L3 tasks like physical connection and NEMO tunnel creation), a simple policy exchange executes the NEMO handover. Of course handovers are still handled "blind" (i.e., no context information is available about the new network before the handover). Now it is clear why this idea requires overlapping RANs and creates the possibility for further optimization aiming at shrinking the handover latency.

Various proposals have been published to shrink the delay caused by handovers. In the next section, we recap how to use location information coming from e.g., Global Navigation Satellite System (GNSS), or Geographical Positioning System (GPS) data to speed-up the handover process of multihomed NEMO architectures in heterogeneous access environments. Our proposed method is only usable when the mobile terminal or mobile network moves on nearly the same path every time. Public transportation vehicles (trains, trams, buses, trolleys, etc.), cars and trucks travelling on highways/main roads are examples, when this assumption is valid. Random walks in city centres are beyond applicability, and thus our method cannot be applied there without modification.

Using location information for preparing handovers dates back to 2001. In [15] Wang et al. propose to use location information to improve the performance of inter-cell handovers. Their method is limited to L1/L2 handovers; they did not consider IP connectivity. Dutta et al. [16] extended Wang's work recently, also concentrating on the L1/L2 handovers only. Hee-Dong Park et al. [14] proposed first a NEMO scheme which can be used in vehicles travelling on a predetermined route. They store access network information in a database which is used to predict handovers. They have not considered MCoA scenario, though. Our method makes use of multihoming as we propose to use MCoA with advanced policy exchange mechanisms. The policy exchange mechanism is based on the recommendations of the IETF's Flow Bindings RFC in Mobile IPv6 and NEMO BS [8], [9]. Our solution supports IPv6 only, due to the fact that all related protocols are better implemented in IPv6.

In [22], the authors propose a similar scheme to ours, however this paper lacks the technical description of the system and the handover execution scheme.

Finally, we have published our solution in [17]–[19], where we provided a complete description of our methodology with some preliminary results. This article extends our previous papers with a more complete description also including the details of the applied tunnel management/handover execution scheme, and with a more complete real-life evaluation based on a comparison of our framework with other two different Mobile IPv6 based handover management techniques, i.e., with NEMO BS (Fig. 1) and NEMO MCoA (Fig. 3) handover solutions. We also provide an analysis of prediction accuracy in the proposed solution by studying the limitations of the overall architecture inherited by possible wrong positioning on the prediction raster network. We show that our proposed solution outperforms all existing implementations, and prove that an appropriate prediction raster can keep the probability of wrong positioning below 1%.

III. PREDICTIVE HANDOVER MANAGEMENT FOR NEMO MOBILE ROUTERS IN MULTI-ACCESS ENVIRONMENTS

In this section we recap the main considerations of our already introduced framework including the predictive handover management scheme designed for multihomed NEMO configurations, and also present the details of our multi-tunnel based efficient handover execution scheme which combines the benefits of MCoA with a new prediction-driven cross-layer management entity.

A. General considerations of the proposed solution

There are two levels of handovers which should be considered independently: L1/L2 handovers, and L3 handovers. L1/L2 level handovers are determined by the access technology currently in use. 3G/HSPA, Wi-Fi, etc. handover delays are due to their respective standard and implementation. However, if the mobile terminal or router contain more than one egress interface, it is possible to use one interface for communication and another one for preparation and execution of L1/L2 handovers. In such a handover scenario sessions should be re-directed between interfaces. Since our solution is based on IPv6, native IPv6 support is a must in all access networks.

L3 level handovers are handled by IP mobility solutions (e.g., MIPv6 or NEMO BS). L3 handovers can be speed-up by launching L3 procedures before L1/L2 handover happens. For this reason we use location information. It could be possible to launch the L3 procedure such that it just finishes as the new network appears. If so, the handover latency becomes lower (down to L1/L2 handover delay) and the service becomes almost ubiquitous. Under perfect circumstances (exploiting overlapping coverage areas and benefits of multi-access devices) the latency can be totally eliminated if the L1/L2/L3 preparations are executed in a predictive and timed manner.

In our IPv6-based NEMO BS extension we propose to use location information coming from e.g., Global Navigation Satellite System (GNSS), or Geographical Positioning System (GPS) data to speed-up the handover process of multihomed NEMO architectures in heterogeneous access environments.

The idea behind predictive handover management is very simple: as the node/network moves along a path, it records all access network related data in a database together with the geographical location information. The next time the node/network moves along the same path, based on the geographical information and speed vector, the stored information can be used to predict and prepare handovers before the actual availability of the networks. In the appropriate time, ongoing communication sessions can be seamlessly redirected to some other interface(s) – thus successfully finishing handovers.

The following information should be stored. Network type (WLAN, 3G, WiMAX, etc.), network identifier (e.g., BSSID of WLAN AP, 3G cell identifier, etc.) and IP level information (e.g., network prefix, which can be used to gather the IPv6 address of the node). The first three fields are required: without them it is not possible to prepare handovers in L1/L2/L3 relations. Some additional information, e.g., Signal-to-Noise Ratio (SNR), BandWidth (BW), reliability (how often the network appears at a given geographical location) and Round Trip Time (RTT) are useful for further intelligence and more sophisticated decisions. For instance, the more reliable network should be chosen if several networks are available.
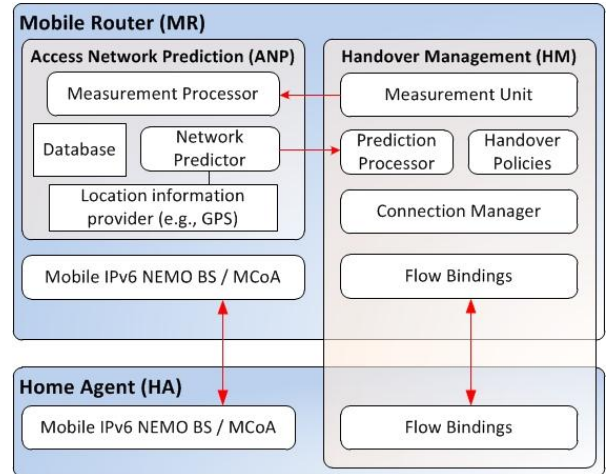

Fig. 4. The proposed predictive handover management framework

When multiple interfaces are available, MCoA [8] and Flow Bindings [9], [10] solutions can be of use. L3 handover preparation consists of the following components. First of all, a BID is created for each egress interface the MR possesses. These BIDs are used as unique identifiers of the interfaces. BIDs are sent in BU messages to the Home Agent in order to identify individual bindings of the MR. The HA that receives the BU messages creates a separate binding for each BID (i.e., for each egress interface of the MR). Therefore the MR owns only one Home Address but the bidirectional NEMO tunnels will be distinguishable based on the BIDs. The sole Home Address of the MR requires the introduction of Flow Bindings which directs packet flows to specific egress interface. In the proposed scheme we use Flow Bindings to direct the whole traffic of the MR through one active egress interface. In this way the solution loses the benefits of redundant interfaces, but gains the possibility to use inactive interfaces for handover preparation, i.e., selecting appropriate access network, performing lower layer connections and acquiring new IPv6 addresses.

Therefore the scheme requires several interfaces for operation. Some of the interfaces are used for normal communication (they will be referred as "active"); the others are used for handover preparation (they are termed as "inactive"). The activation of a new interface must be accurately synchronized with the deactivation of the old one. The activation/deactivation procedure means simultaneous reallocation of NEMO BS tunnels. It is performed by properly scheduled flow binding policy control messages on the HA and the MR. The control messages are called Predictive Policy Exchange Messages.

B. The proposed framework and handover execution/tunnel management protocol

The proposed framework (Fig. 4) has three main components: Access Network Prediction (ANP), Handover Manager on the MR (HM-MR) and on the Home Agent (HM-HA). I do not claim all the functional entities; however the overall framework and the design of the predictive handover execution scheme are my results.

The left most module on Figure 4 running inside the Mobile Router is the ANP. The ANP is responsible for 1) maintaining the access network database; 2) sending prediction messages to HM-MR module; 3) reading GNSS information from the GNSS receiver; and 4) processing the network measurement messages received from the HM-MR module. Tasks 3) and 4) are for the maintenance of the access network database which should be continuously extended/updated during the movements of the MR. Based on up-to-date database records and current, precise position/speed information the ANP is able to provide candidate network parameter prediction. The prediction vector is sent to the HM-MR module in an XML message, and the HM-MR measurement messages are also transmitted in an XML format. In order to avoid the explosion of the access network database size, the received GNSS coordinates are rounded in the following way: the longitude and latitude values are multiplied by 10,000 and rounded to the closest integer. Therefore instead of a continuous space they form a limited set with members called raster points inside a raster net, which plays an important role in the prediction precision (see later).

The Handover Management (HM) module can be divided into two parts depending on which node hosts it. The HM-MR runs on the Mobile Router (Fig. 4) and is responsible for two main tasks. On one hand HM-MR measures the channel state information and other network parameters of the actually available access networks during the movement of the MR. The scale of the measurable parameters is wide and depends on the decision algorithm to be applied. In our proposal the following parameters are measured, collected and sent periodically to the ANP module for further processing and storing in the database:

- Receive Signal Strength Indicator (RSSI) of UMTS
- Signal/Noise Ratio (SNR) and Basic Service Set Identifier (BSSID) of WLAN
- IPv6 prefix information

On the other hand, HM-MR also prepares predictive handovers by handling MCoA tunnels in a timed manner based on the prediction XML messages received from ANP and the indirect interaction with the NEMO MCoA implementation. In order to achieve this, we proposed a special predictive policy exchange scheme which can inform the Home Agent (i.e., the HM-HA module) about the Mobile Router's intents of future handovers. The periodically received candidate access network predictions supply all the necessary information required for handovers to be initiated by the HM-MR. If a handover event is predicted for the near future (e.g., prediction data reveal that the currently used access coverage will disappear soon), the decision algorithm will choose the destination network and initiate the handover mechanisms. In the proposed framework HM-MR follows a simple rule set to select the designated network from multiple candidates:

- an available WLAN network always has higher priority than 3G/UMTS
- the WLAN with the best SNR value has the highest priority among simultaneously available WLAN networks

The HM-HA module is located on the Home Agent (Fig. 4). The HA itself represents the same functional entity as in the case of standard MIPv6/NEMO/MCoA protocols, but in our scheme it also interacts with the HM-MR module through the HM-HA instance for predictive, timed and flow binding based NEMO MCoA handovers using the Predictive Policy Exchange Messages. The HA is informed about the predicted network prefixes and timing information, and thus changes in flow binding policies can be executed and scheduled before the handover event actually happens.

After the decision is made based on the rules defined at the HM-MR module, the designated network will be chosen and passed over to the Flow Bindings submodule at the MR side. This submodule handles the signalling between the MR and the HA for defining which MR-HA tunnel shall the system switch to and when. It is important to note, that before executing these timed and synchronized policy exchange commands for tunnel/routing adjustments on the MR and the HA entities, the designated network (i.e., a new interface) must be chosen and the L1/L2/L3 preparations must be finished for the selected network. Thanks to the prediction based and multihomed NEMO operation, the MR will be able to finish these preparations (including also the L3 NEMO MCoA tunnel build-up using the binding procedure) before the actual handover event occurs. However, it requires that the candidate networks are overlapping in their coverage.

Based on the GNSS aided predictions the policy exchange commands can be executed at exactly the same time both in the HM-MR and HM-HA modules. It means that all the NEMO traffic will be redirected to the new network defined by the new MCoA tunnel without noticeable packet loss or other QoS disruption. This is only possible because we already have a working Mobile IPv6 connectivity through the new network and all L2/L3 configurations are already performed. The Predictive Policy Exchange message would only carry timed commands to switch the packet flow to a functional, but inactive tunnel. Upon disconnect or failure of the active access network, routes and tunnel interfaces are deleted and the next default route with the highest priority is taken to ensure seamless connectivity. Recovering from such failure based on

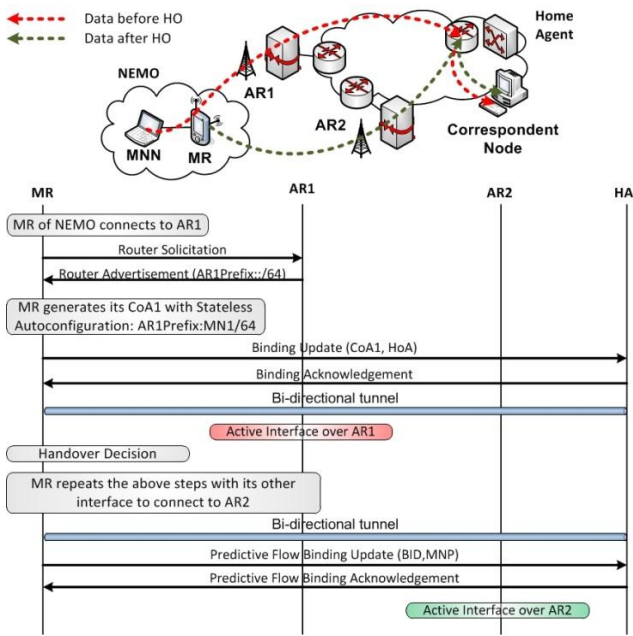the enforcement of handover policies is out of scope of this document.

Fig. 5. Details of the proposed handover execution/tunnel management protocol

The proposed handover execution protocol is detailed in Figure 5. When the HM decides to perform a handover, in order to use the benefits of MCoA, the following steps are executed. Using one of the inactive interfaces the HM connects to the new access network and establishes a new Mobile IPv6 binding. At this stage, the current and new access networks are both connected and Mobility Tunnels are established between the MR and the HA. Handing over to the new access network is entirely based on Flow Bindings, which in this case means that all flows are moved from one interface to another. To avoid asymmetric routing, the MA and HA has to modify their bindings simultaneously, in a timely manner. The schedule is communicated by the Flow Binding modules in predictive Flow Binding Update/Acknowledgement messages (Figure 5). When the changes of flow bindings are executed, the new interface is marked as active, while the rest of the communication interfaces are set to inactive mode. The mobile network nodes (MNNs) inside the NEMO will always and transparently use the communication path spanned by the active interface. Different Handover Policies may have different effects on handover strategies.

IV. IMPLEMENTATION DETAILS

In this section we introduce the most important implementation details, our real-life, loosely-coupled UMTS/Wi-Fi heterogeneous testbed, the scenario created to evaluate our GNSS aided predictive NEMO handover management framework, and the measurement results. We compared our method against two other handover solutions (standard NEMO BS and NEMO MCoA handovers as detailed in Section II) in one networking scenario using four main

handover performance metrics (Handover latency, UDP packet loss, TCP throughput and RTT).

A. Implementation details

This section is devoted to present some additional implementation details of some crucial modules of the overall framework.

1) Access Network Prediction (ANP)

The ANP has two main roles. On one hand it processes the measurements and records the data into the database. On the other hand it sends the periodic prediction messages towards the HM module. Measurement data
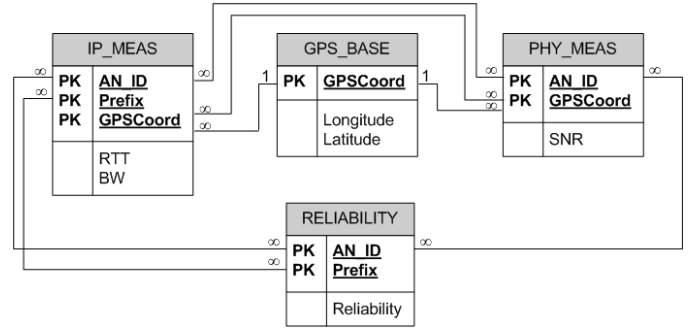

Fig. 6. Database scheme designed for the ANP module

Data from the measurement unit will be processed based on their time stamp <MeasTimeStamp>: GPS coordinates must be paired based on the measurement time, and then an entry should be inserted into the PHY_MEAS table about the followings:

- AN_ID: access network identification
- GPSCoord: the closest GPS coordinate in the raster to the measurement time
- SNR: Signal-to-Noise Ratio [dBm]
- IP_MEAS table is filled only if IP level measurement was also received (bandwidth and round-time-trip values)
- The Prefix entry could be empty or also could contain multiple prefix values
- Reliability table stores the level of reliability of a particular access network: as our vehicle could pass on the same route multiple times, we can summarize the measurement snapshots and using a special rating technique we can classify the stored data according to its appropriateness in a longer session of measurements. E.g., if the BW is low or the Home Agent is not available on a particular link during one measurement snapshot, the system will not immediately remove that access network but will start to degrade the level of reliability for that entry.

In order to create the prediction, first we filter the PHY_MEAS table based on GPS coordinates and SNR values: e.g., if we would like to implement a 10 second prediction window, then we will query AN_IDs with GPS coordinates in the next 10 seconds, and then unusable networks with terrible

SNR values should be left out from the answer. Then we search the IP_MEAS table for prefixes for the given GPS coordinates and AN_ID values. In that way only networks with appropriate physical and IP level parameters will be sent towards the HM module. Based on the prefixes and the AN_ID all the stored values (Reliability, RTT, BW, etc.) can be gathered, which can be used by the HM module to make the handover decisions.
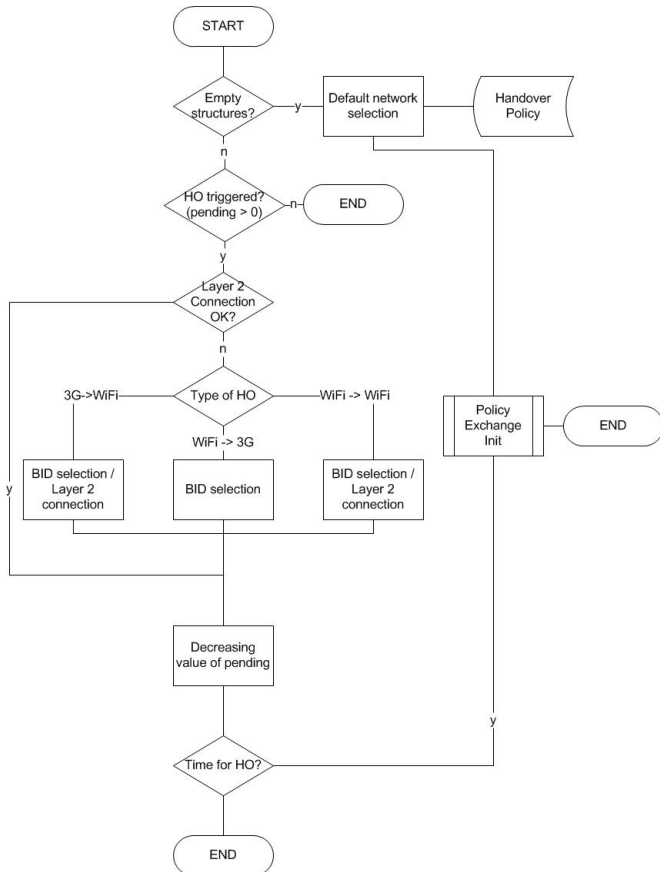

Fig. 7. Detailed operation of the Connection Manager module

2) Connection manager module

This module handles the execution of handovers, deals with the medium-dependent preparation tasks, maintains available interfaces and actual connections, and initiates Policy Exchange operations. As Figure 7 depicts, the Connection Manager loads up a default setting during the startup process. After that it awakes periodically and checks whether there is a need for handover or not. Depending on the decision, it will react according to the type of HO.

− 3G – WiFi: select one Wi-Fi from the list, puts the BID of that network into the Next network structure, then calls the appropriate OS function to perform the L2 connection and finally initiates the MIPv6 MCoA binding procedure.
− WiFi – WiFi: the unused interface must be selected and configured for usage. Then comes the connection initiation similarly to the 3G–WiFi case.

− WiFi – 3G: there is no need to explicitly handle L2 connections as the framework handles it transparently. Other duties are the same as before.

Important task of this module to continuously check the value of the *pending* variable, which is used to manage timely handovers: working with prediction window we can see the future and want to use the appropriate network as long as possible.

B. Testbed architecture

The basis of our evaluation efforts was a heterogeneous, native IPv6 UMTS/Wi-Fi testbed (Fig. 8) built on the existing hardware elements of Mobile Innovation Centre (MIK) [23]. As the figure shows, the 3G part of the access infrastructure is a standard, packet switched UMTS core running an IPv6-compatible GGSN implementation [24] in order to provide native IPv6 UMTS experience to the NEMO. This GGSN is connected to the outside IPv6 network through its Gi interface using native IPv6 transport. The WLAN part of the testbed comprises IEEE 802.11b/g compatible Linksys WRT54GL Access Points (APs) also with native IPv6 backhaul.
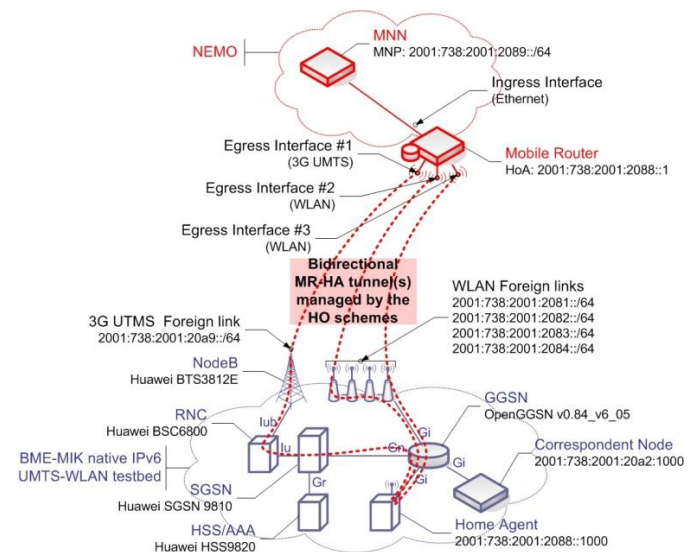

Fig. 8. Real-life testbed architecture

For accessing the above multi-access infrastructure and to provide advanced multihoming features with support for our handover solution, the Mobile Router has been equipped with three egress interfaces; one for UMTS and two for WLAN access, respectively. The MR controlled NEMO in our testbed comprises only one Mobile Network Node (MNN) which connects to the ingress interface of the MR over Ethernet. The Correspondent Node (CN) communicating with the NEMO from the outside network for testing purposes also uses Ethernet connection for IPv6 communication. These two latter nodes (i.e., the MNN and the CN) were running our measurement softwares: synthetic traffic generation was achieved by Netperf [25] while the packet capture and analysis was based on Tshark [26] and some additional shell scripts.

The HA and the MR – besides the NEMO BS and MCoA HA/MR functions implemented by appropriately patched

UMIP 0.4 [27] instances – also can deal with the introduced tasks of our predictive policy exchange scheme (i.e., run the HM/ANP modules if needed).

Since the coverage limitations of this laboratory environment did not allow real, open-air motion of the NEMO, a special solution for movement emulation was introduced in our testbed using pre-recorded GPS traces. The traces were played back by the gpsfake component of gpsd [28] during every measurement run. This component is located on the MR together with the Access Network Prediction and Handover Manager modules of the predictive handover management system, and contains a virtual test track with pre-defined coverage structure along the path (Figure 9). The different coverage areas of this test track were emulated by a prepared database at the ANP, but the access networks were real.

Fig. 9.   Virtual test-track defined for the evaluation

The evaluation scenario we used was implemented based on the above testbed details strongly relying on this virtual motion/coverage information scheme. The yellow, two-lane road represents the left-to-right virtual path of network mobility executed during our measurement runs using the pre-recorded GPS trace. We assume that 3G UMTS coverage is available during the whole route, while WLAN access networks – represented with colored circles – are to appear and disappear according to Figure 9 when the mobile network moves. The green, red and yellow circles represent overlapping WLAN networks with similar range, quality and transmission power, while the blue circle is for an umbrella WLAN coverage with bigger range but worst quality (in means of SNR). On this path consisting of several heterogeneous overlapping access networks, every handover type (3G=>Wi-Fi, Wi-Fi=>Wi-Fi and Wi-Fi=>3G) appears.

V.   MEASUREMENT RESULTS

In order to evaluate the performance of our proposed handover mechanism in the presented testbed, an extensive comparison with existing implementations of different Mobile IPv6 based handover management schemes is necessary.

NEMO BS was chosen as basis to emphasize the drawbacks of using only a single media for horizontal handovers without prediction. Due to the limited functionalities of this mobility protocol the presence of network outage during handovers is expected, causing error-prone transport protocols such as UDP to perform suboptimal.
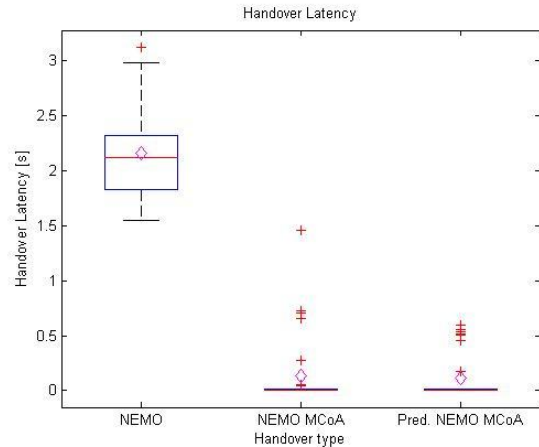

Fig. 10. Handover latency measurement results of multiple runs

To fully take advantage of our heterogeneous test environment NEMO MCoA handovers were used to demonstrate the benefits of inter-media handovers in multihomed networks by manually changing data flows among multiple network interfaces and applying Flow Bindings and Policy Exchange for handover execution. The chance of packet loss and the handover delay is expected to be less compared to the NEMO BS case, as the MCoA protocol extension allows switching data flows on already configured network interfaces. As this method lacks the prediction and automation features our approach has, we simulate handovers by changing to the first new available network blindly, emphasizing the risks what the absence of pre-recorded information can bring.

This second approach however is still expected to be outperformed by our GNSS aided predictive NEMO MCoA handover solution which uses automatic handover decisions based on various likelihood criteria, such as SNR/RSSI and reliability. The overall data throughput is expected to be the highest with our approach, as the amount of time spent on networks with good QoS parameters is maximized and the handover latency is minimized during any mobility cases.

The objective of our evaluation was to compare the above three handover methods and show the power of our framework. Therefore four main parameters were analyzed. In each scenario fifty measurements were executed. Netperf [25] was used for TCP and UDP packet flow generation while Tshark [26] was responsible for packet capture and analysis. The results are presented in box-and-whisker diagrams to display the collected numerical data groups in a compact way. The depicted statistical information are as follows: the lowest sample value (lower line), the lower quartile called Q1 (the lower edge of the box), the median called Q2 (the delimiter of the two distinctive colors of the box), the upper quartile called Q3 (the upper edge of the box), the largest sample value (the upper line), and the mean of the collected data (red lined

rhombus). Red crosses are depicting outliers (i.e., measurement data if they are larger than Q3 + 1.5*(Q3 – Q1) or smaller than Q1 – 1.5*(Q3 – Q1)). The length of boxes (i.e., the interquartile range) represents the middle fifty percent of the measured data. Diamonds show the mean (average) value of the measurements, the solid line in the background depicts the range of measured data.
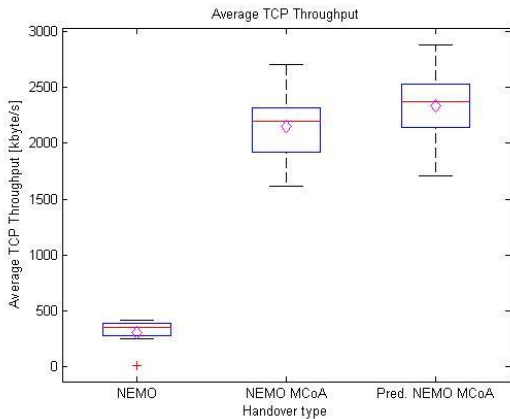

Fig. 11. TCP Throughput measurement results of multiple runs

Figure 10 shows the results of handover latency measurements of multiple runs. Time stamped log messages and kernel events provide the measured latency in seconds passed between the handover decision and the availability of the new Mobile IPv6 tunnel interface on the Mobile Router. As NEMO BS only uses a single interface for handover operations, it showed significant delays while changing between different wireless networks. The gap in dataflow is partly caused by Layer 2 connection delays and Layer 3 operations such as IPv6 address acquiring from the access

router and mobility signalling between the MR and the HA. In both MCoA cases the handovers took place on already configured network interfaces, where the mobility tunnels were already established. The only signalling on the channel was the above introduced policy exchange mechanism between the Mobile Router and the Home Agent. The handover latency in this scenario was measured based on the round-trip-time of the Predictive Policy Exchange Messages. As visible, there is not much improvement between NEMO MCoA and our method. The small improvement of Predictive NEMO MCoA comes from better network QoS parameters as it is capable of selecting the best networks along the path.

Figure 12 depicts our HO latency measurement results focusing on one single run on the virtual test-track. The figure shows that a simple NEMO BS system provides much higher HO delays compared to the advanced MCoA based solutions. It is also highlighted that our prediction based framework adapts to the actual network coverage more precisely while also maximising the time spent on a satisfactory RAN. The prediction based system chooses alternative networks, and follows the handover policy aiming to use 3G network only if Wi-Fi is not available. Our system does not connect to the Wi-Fi with bad SNR (i.e., Blue WLAN) while the MCoA handover is not able to differentiate between such parameters.

Our second test case in our evaluation was the measurement of TCP throughput between a Mobile Network Node and a Correspondent Node. The five-number-representation of TCP throughput is shown on Figure 11. The connection was not lost during the tests due to the error detection and flow control feature of the applied transport protocol.
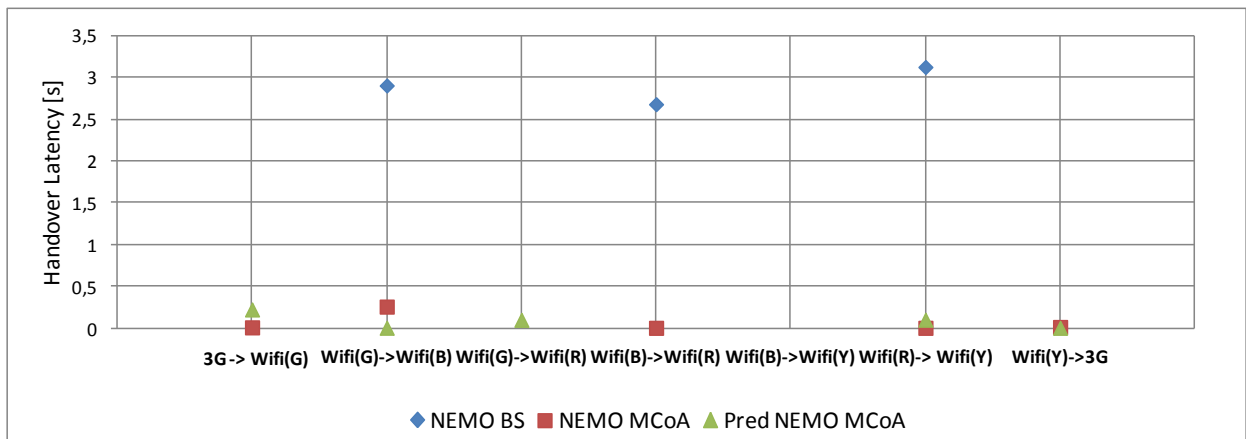

Fig. 12. Handover latency measurement results of one single run (i.e., one virtual path according to Fig. 9)
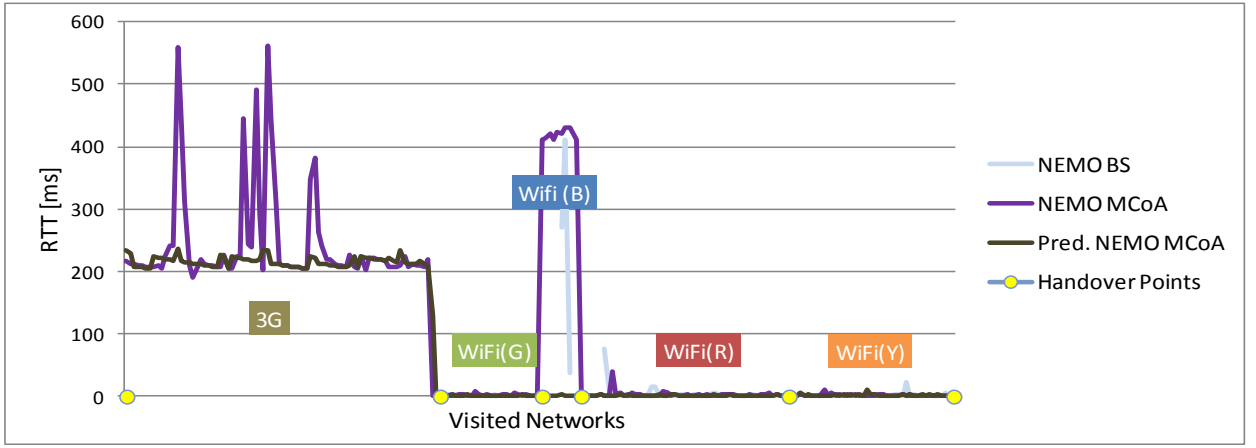
Fig. 13.   RTT measurement results of one single run (i.e., one virtual path according to Fig. 9)

The results justified our assumptions that the gap during the NEMO BS handovers significantly slows down the TCP stream, while during the MCoA handovers it remains stable on a much higher transfer rate. The Predictive NEMO MCoA handover outperformed all the others, thanks to the automated optimal network selection.

Figure 14 shows the boxplot of packet loss when transmitting a unidirectional UDP stream that originated from a MNN towards a CN (our third test scenario). The UDP stream was captured on both the MNN and the CN. After each run the packet loss ratio was calculated by dividing the sum of captured packages on both ends of the communication.

As the single communication medium is not ready during the NEMO BS handover for several seconds, and the transport layer protocol has no error recovery, there is a substantial amount of lost packets in that case. However, in both MCoA scenarios the packet loss remained below the acceptable 5% percent. The usage of Predictive NEMO MCoA handover clearly converges towards the ideal 0% in our evaluation scenario. Note that wireless transmission itself implies some packet loss, so 1% should be regarded really low.

The last test case was focusing on the RTT measurements. Figure 13 depicts our results gathered with one single run of test. The blue coloured Wi-Fi network was artificially degraded with Radio level settings and IP traffic shaping. In case of NEMO BS we can see that there are significant gaps in the connection around the handover points, meaning packet losses caused by managing handovers with only one active interface. In case of NEMO MCoA handovers our MR could also use the 3G access network. The figure clearly shows that without prediction the MR connects to every single Wi-Fi network sensed during the path. The continuity of the graph proves that no significant packet loss occurred, but the MR also used a bad quality Wi-Fi network with 400ms RTT (however, only for a limited amount of time, until the next Wi-Fi network was sensed by the MR on the road).   Our predictive scheme avoids Wi-Fi networks with bad SNR if possible: the Blue Wi-Fi will not be used, the MR chooses the Red network right after the Green one, despite the fact that the Blue appears sooner during the movement. Networks with insufficient performance can be avoided.
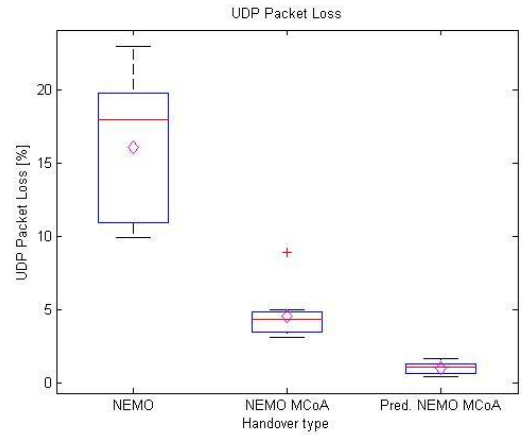

Fig. 14. UDP packet loss measurement results of multiple runs

VI.   ANALYSIS OF PREDICTION ACCURACY

The proposed framework and handover execution protocol strongly relies on the prediction accuracy which depends on the rasterization scheme working inside the ANP module. That is why we have started to analyze the limitations of the overall architecture inherited by possible wrong positioning on the raster net inside the ANP. We have developed a probabilistic system model for the ANP module and proposed an appropriate rasterization scheme where the probability of wrong positioning on the raster remains below 1%.

Assume that we have a set of raster points given as $S = \{x_1, x_2, \dots x_\infty\}$. x_i represents the ith point which is a geographical position with two coordinates: one on the west-east axis and one on the north-south axis. S is an infinite but countable set. The members of the set are constant: they are given by the actual raster size.

Assume that we are at a geographical position x_0 (x_0 can be given by god – no possibility to measure it exactly). We have a GNSS measurement equipment and want to figure out, what x_0 is. We make measurements and we get η as an estimate, which is not exact of course. η is a random number

(Gaussian, due to the large number of independent effects), with expectation of x_0 and covariance matrix C:

$$\mathbb{E}\{\eta\} = x_0 \tag{1}$$

$$Pr\{\eta \leq y | x_0, C\} = \Phi(y, x_0, C) =$$
$$\int_{-\infty}^{y_1} \int_{-\infty}^{y_2} \frac{1}{\sqrt{2\pi}^2 (det C)^{1/2}} e^{(z-x_0)^\top C^{-1}(z-x_0)} dz_2 dz_1 \tag{2}$$

Note that in the last equation we introduced a new notation, Φ. Also note that $\eta \leq y$ means all η points where both coordinates are less than or equal to the ones of y.

The database uses the raster points only. Thus, based on the measured value η we can choose the closest raster point as

$$\xi(t) = \text{argmin}_{x \in \mathcal{S}} \parallel \eta(t) - x \parallel \tag{3}$$

Here, the time dependence have been also added as (t), and $\parallel . \parallel$ measures the absolute distance. With the help of god (knowing $x_0(t)$), we would get the perfect estimate $x(t)$ as

$$x(t) = \text{argmin}_{x \in \mathcal{S}} \parallel x_0(t) - x \parallel \tag{4}$$

The first question is the following. What is the probability of making a wrong estimate?

$$Pr\{\xi(t) \neq x(t)\} = ? \tag{5}$$

Note that both (4) and (5) are non-linear operations, making it difficult to analyse the problem. The following subsection is about evaluating this probability.

Fig. 15 shows the general geographical setup. As the raster net is self similar, we can put it into the centre of the coordinate system. The area of $\mathcal{T}$ is defined as

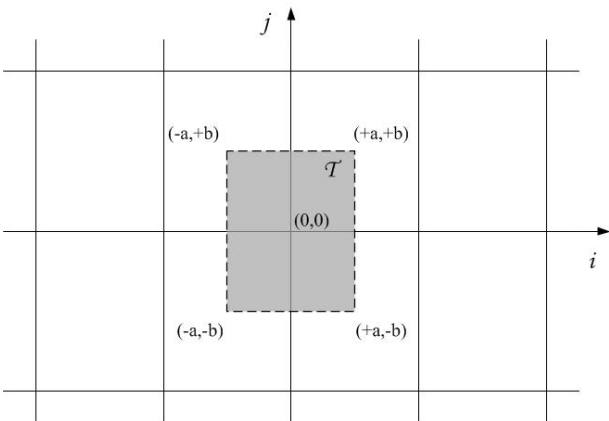$$\mathcal{T} = \{(i, j), \text{ where } -a \leq i \leq +a \text{ and } -b \leq j \leq +b\} \tag{6}$$

Fig. 15. Raster net setup of the probability model

Assuming that the real geographical position (x_0) is equally probable at any position, the probability of making a wrong estimate $(Pr\{\xi(t) \neq x(t)\})$, equals the probability that the real position is inside the grey area $\mathcal{T}$ $(x_0(t) \in \mathcal{T})$, and the measured point is outside of $\mathcal{T}$ $(\eta(t) \notin \mathcal{T})$:

$$Pr\{\xi(t) \neq x(t)\} = Pr\{x_0(t) \in \mathcal{T} \cap \eta(t) \notin \mathcal{T}\} =$$
$$1 - Pr\{x_0(t) \in \mathcal{T} \cap \eta(t) \in \mathcal{T}\} \tag{7}$$

The probability of η falling into $\mathcal{T}$ can be computed as

$$Pr\{\eta \in \mathcal{T} | x_0, C\} = \Phi\left(\binom{+a}{+b}, x_0, C\right) + \Phi\left(\binom{-a}{-b}, x_0, C\right) -$$
$$\Phi\left(\binom{+a}{-b}, x_0, C\right) - \Phi\left(\binom{-a}{+b}, x_0, C\right) \tag{8}$$

Following equation (7), the Bayes' rule and our positioning error constraint, we get

$$0.01 \geq Pr\{\xi(t) \neq x(t)\} = 1 -$$
$$\frac{1}{4ab} \int_{-a}^{+a} \int_{-b}^{+b} Pr\{\eta \in \mathcal{T} | x_0, C\}_{x_0=\binom{i}{j}} dj di \tag{9}$$

Considering a GPS system for our GNSS measurements with a horizontal positioning error of $\sigma = 5m$ (standard deviation), and taking into consideration that the length in one minute of longitude depends on the latitude (which is ~47.5° N for Budapest) our final equation is

$$0.01 \geq 1 - \text{erf}\left(\frac{\frac{x}{2} \cos(47.5°)}{5}\right) \cdot \text{erf}\left(\frac{\frac{x}{2}}{5}\right) \tag{10}$$

Solving (10) where erf is the error function ($\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$) we get that the appropriate raster net to be used in our predictive NEMO handover framework for ANP implementation is larger or equal to $18.2m$ x $27m$.

VII. CONCLUSION

This paper shows that GNSS aided prediction along with other optimization techniques provide the best results in multihomed NEMO configurations. The implemented system with the decision and prediction module outperforms all existing handover solutions in Mobile IPv6 scenarios. Handover latency has been shrunk to L1/L2 handover times or even below. Figure 16 compares the evaluated schemes. Horizontal handover –a basic function − is available for all solutions. However, vertical handover support requires multiple tunnel management, which requires MCoA capability. Automatic layer 2 connection is a function to manage interface connections in a cross-layer manner to provide adaptivity in mobility management. In case of simple NEMO MCoA handover it is only manually achievable. Access Network Prediction is a higher layer intelligence also requiring efficient cross-layer communication. With the help of our probability model based analysis, the details of the crucial ANP module can be wisely selected: we provided analytical method for optimal design of the ANP's raster network.

For the above advanced functions, a well-prepared policy manager is required to handle the rules of handover initiation and execution even in a dynamically changing environment. The system of such rules creates an adaptive order of priority

like in our example, where in case of overlapping 3G/Wi-Fi networks Wi-Fi is preferred, but from multiple Wi-Fi RANs the one with the best SNR should be chosen. To execute the handovers in our proposed scheme, Flow Bindings and Policy Exchange is required, which is also mandatory for the simple MCoA handover solution.

In the future we plan to implement pluggable decision and prediction modules that further optimize network selection on various types of transportation scenarios.

We also plan to extend the solution with possible improvements in the sub modules of the system. For instance, gyroscope could be used to improve localization in places where GNSS systems are not able to work (e.g., in tunnels). Databases could be built quicker if P2P sharing of the database is supported. That is, Mobile Routers could improve their knowledge if they share their database with neighboring routers, or infrastructure based information arrives (e.g., from the road operator). Obviously, security considerations should be addressed first, before opening the databases.

Function/Handover	NEMO BS	NEMO MCoA	Predictive NEMO MCoA
Horizontal handover	☑	☑	☑
Vertical handover	☒	☑	☑
Automatic Layer 2 connection	☒	☒	☑
Access Network Prediction	☒	☒	☑
Handover Policy Manager	☒	☒	☑
Flow Binding / Policy Exchange	☒	☑	☑

☑	Available	☒	Out of scope		Implemented		Not implemented

Fig. 16. Functional comparison of the evaluated schemes

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