Usability and Evaluation of a Deployed 4G Network Prototype

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Abstract: **This article presents a field evaluation of an IP-based architecture for heterogeneous environments that has been developed under the aegis of the Moby Dick project, covering UMTS-like (universal mobile telecommunications system) TD-CDMA (time division-code division multiple access) wireless access technology, wireless and wired LANs. The architecture treats all transmission capabilities as basic physical and data-link layers, and replaces all higher-level tasks by IP-based strategies. The Moby Dick architecture incorporates mobile IPv6, fast handovers, AAA-control (authentication, authorisation, accounting), charging, and quality of service (QoS) in an integrated framework. The architecture further allows for optimised control on the radio link layer resources. It has been implemented and tested by expert users, and evaluated by real users on field trials with multiple services available.**

Index Terms: **4G, AAA, FHO, QoS, tests.**

I. INTRODUCTION

A. Importance of 4G Networks and On-Going Work

The migration from circuit-switched to IP-based technologies and the growing role of mobility pave the way to a next-generation integrated network. The importance of IP-based communications has already been recognised in UMTS (as well as in EDGE/IMT-2000), which provides an IP-packet service using tunnelling mechanisms, but still employing access mechanisms of 2nd generation networks [1]. In this strategy, all the (complex) UMTS access network behaves as "1 hop" at the IP layer, and hides issues such as mobility and QoS from it. However, adding new access network technologies involves then great amount of translation procedures from the specific mechanisms of UMTS to the mechanisms in these other technologies. Because of this, in 4G networks scenarios IP is used to glue all different link-level technologies, deploying technology-unaware protocols for mobility or quality of service (QoS). 4G architectures should be able, thus, to embrace almost any wireless (or even wired) access technology available. Instead of bringing the concept of packet switching into existing connection-oriented cellular network environments—the more traditional evolutionary path, several voices argue that redesigning directly the network to provide 4G capabilities (such as seamless heterogeneous access) may help them to become a reality much sooner than forecasted. This is the reason why research efforts in this area have been promoted (e.g., MIND [2], NOMAD [3], and Moby Dick [4]). This paper presents the field results obtained in the Moby Dick architecture, an IP-based 4-th generation (4G) architecture for heterogeneous environments, covering UMTS-like TD-CDMA wireless access technology, wireless and Ethernet LANs. This is one of the first implemented leader approaches to a 4G network and thus a key contribution to this research effort. This work was developed under the aegis of the EU-funded IST Moby Dick project.

As mentioned, several research efforts were performed in order to design and deploy prototypes of 4G systems or, at least, of several components of what is expected to be found in a future 4G network [5]. Many of these efforts were developed under sponsorship of the European Union IST program, but they often developed different approaches to 4G network systems.

The MIND (mobile IP based network developments) project [2], which is the follow up of the BRAIN (broadband radio access over IP networks) project, was focused in mobility aspects, as well as ad hoc, self-organising, and meshed networks. Concerning the mobility-related work performed within that project, good results [6] were obtained for the wireless LAN (WLAN) horizontal handover scenario, although the network complexity in terms of required infrastructure is high. The IST OverDRIVE project [7] was focused in vehicular environments and worked also in radio resource management issues, thus improving specific access technologies. The LONG project [8] was focused on IPv6 transition and deployment issues, and Moby Dick profited from some of the outcomes of that project. Nevertheless, LONG did not aim at deploying a native IPv6 4G system, as Moby Dick did.

Other European IST projects (like Tequila [9], NOMAD [3], and WINE-GLASS [10]) developed work on some of the areas required for a 4G network (e.g., QoS, mobility, etc.), but none of them implemented the whole picture of a 4G prototype.

Besides the IST initiatives, there are other projects working on 4G related issues. For example, the Cambridge open mobile system (COMS) project [11] at the computer laboratory of the university of Cambridge works on mobile IPv6 and vertical handover performance issues. The main point of this project is that their tests are conducted over test beds using real 2.5G infrastructure (real operator GPRS network). Nevertheless, this project is focused only in mobility, so neither QoS nor AAA is integrated in its test bed.

On the other hand, the Moby Dick project focused precisely in integrating a whole heterogeneous environment and hiding to

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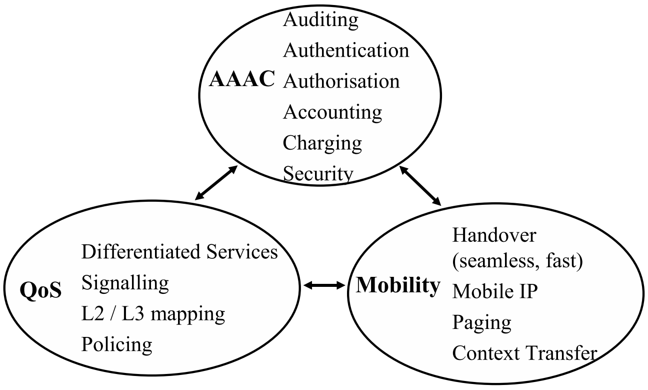

Fig. 1. The Moby Dick 4G functionality.

the user the complexities of the different access technologies. The interaction between multiple network aspects (QoS, mobility, and AAA) was the key difference between the work done in the Moby Dick project and the others.

B. 4G Challenges and Paper Rationale

4G networks will offer all kind of services in a single packet switched network using IPv6 as its network layer. Support for mobility (including paging), AAA (authentication, authorisation, accounting), and QoS (quality of service) must be provided in those networks, each fulfilling an essential functionality (Fig. 1). These aspects have already been addressed individually but integrating all the above functions in a single IPv6-based 4G network is still a hot research topic since it poses additional challenges: a) Some aspects of the different functions may overlap (e.g., both QoS and AAA may need to perform authorisation). b) Some aspects of one function may raise severe burdens to the performance of another (e.g., authorisation must be performed each time the user changes his point of attachment, probably posing serious constraints to a handover procedure).

The originality of Moby Dick is that it dealt with all these 4G aspects in an integrated manner by addressing each of the required functionalities in an optimised and modular way, defining the appropriate interfaces between the different components and deciding the adequate trade offs to obtain better global performance. Moreover, the Moby Dick project [4] did not only covered architectural work, but also implemented a full 4G all-IP network, seamlessly integrating different access networks technologies: TD-CDMA, WLAN based on 802.11b, and wired Ethernet. Thus, Moby Dick is one of the first attempts to design, implement, deploy, and evaluate an integrated 4G system, covering aspects of mobility, QoS, and AAA in a seamless manner across different technologies, using native IPv6 as the common protocol. The work presented in this paper is one of the first presenting a field evaluation of an implemented 4G network prototype. Even if the network developed is clearly of a prototype nature, key lessons on the trade-offs required for optimizing the network behaviour can still be extracted from the field trial.

By evaluating the Moby Dick implemented prototype, it is possible to answer these two fundamental questions:

a) Does the Moby Dick architecture properly confront the required integration challenges and does it perform properly?

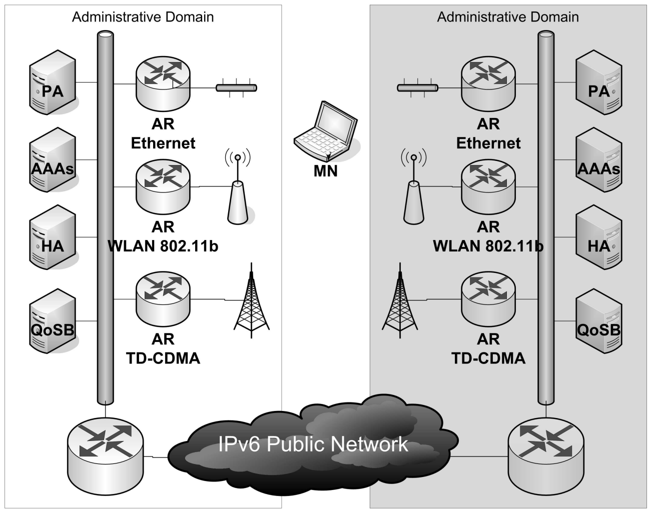

Fig. 2. The Moby Dick "True-IP" architecture.

b) Even in the prototype-graded developed network, do the supplied functions seem usable in a real 4G network?

This paper provides answers to these questions and it is structured as follows: Section II portraits briefly the Moby Dick architecture and how it was implemented in the test beds. The architecture is briefly explained and, for a deeper insight, the reader is encouraged to follow the references mentioned along the paper. Section III describes the key Moby Dick processes, their performance evaluation and, based on these results, provides advices that may be used as hints in the deployment of future 4G networks. In Section IV, an evaluation of the above-mentioned usability of Moby Dick in environments that emulate real situations is provided. Finally, the conclusion gathers the main results of the paper, provides answers to the questions here presented, raises the issues not covered by Moby Dick and presents the challenges for future work.

II. MOBY DICK ARCHITECTURE AND TEST BEDS

Moby Dick architecture treats all transmission capabilities as data-link layers and replaces all higher-level functions by IP-based strategies. The proposed architecture incorporates features from mobile-IPv6 enhanced with fast handover (FHO), from AAA plus auditing and charging (A4C) control and from quality of service (QoS). The Moby Dick "True-IP" architecture (Fig. 2) is composed of different access networks, including Ethernet, wireless LAN, and TD-CDMA technologies, and a core network based on IPv6. The architecture supports terminal mobility (both intra and inter technology) based on mobile IPv6 [12] procedures, QoS based on differentiated services (DiffServ) [13], and A4C based on IRTF and IETF AAA procedures [14]. We consider this new architecture to likely incorporate most features of a future architecture for 4G networks where users, while connected to the same terminal, will roam from one access network to another depending on their preferences (based on cost, availability, or better performance), with no perceptible flow disruption. Over this framework, any kind of services will be provided by using a common infrastructure, like in nowadays Internet.

A. Moby Dick Multiple Access Technologies

Moby Dick uses the following technologies: TD-CDMA (based on the UMTS-TDD band), WLAN 802.11b, and Ethernet 802.3. The processes evaluated in the following sections are technology-unaware, being the same despite the technologies involved (either any of the three considered or even new ones). The three different access technologies were selected in order to demonstrate that the Moby Dick approach provides a great level of flexibility and extensibility, due to the use of IPv6 as unique convergence layer. These technologies were chosen because of the following reasons: TD-CDMA is a wireless network technology which is evolving from circuit switched technologies and conceptually represents the UMTS architecture, naturally with Moby Dick specific modifications. Ethernet is a wired network technology widely used and required in order to cover also wireless/wired network transitions. WLAN is the most promising wireless technology evolving from the Internet mainly because of the important growth on the number of hotspots. By adopting these three technologies, the feasibility of the Moby Dick 4G architecture—where wireless and wired access as well as data and voice communications networks converge—can be evaluated.

B. Implementation

All functionalities have been deployed in the Moby Dick test bed, distributed between two trial sites, located at Stuttgart (Germany) and Madrid (Spain). Besides these sites, other test beds were also installed in Aveiro (Portugal) and Sophia Antipolis (France). Test beds were interconnected via the public IPv6 network (GÉANT network [15]) in order to show the extensibility of the Moby Dick solution in a wider scale.

Users accessed the network using mobiles nodes (MNs) or correspondent nodes (CNs), connected to the network through DiffServ enabled access routers (ARs) developed inside the project.

The key modules located at the MN are AAA registration, paging, and fast handover (FHO) associate with the mobile IPv6 stack (Fig. 3). In the AR, the main functionalities developed are the AAA client, FHO support, QoS manager, and paging (Fig. 4). Inside the core network a QoS broker (QoSB), a home agent (HA), an A4C server, and a paging agent (PA) have been deployed. Application servers, such as DNS, web, and gaming servers, etc. acting as CNs can also be located inside the core network, providing services that were used in the real tests. All Moby Dick physical entities (including the routers) were deployed over general purpose machines (Pentium III and IV PCs) with Red Hat 7.2 and Linux-2.4.16 kernels. For the radio access, WLAN was supported by commercial SMC prism chipset-based WLAN cards with the host AP [16], while TD-CDMA equipment was provided by one of the project partners [17].

Fig. 5 shows a simplified vision of the Moby Dick Stuttgart test bed. Basically, the test bed comprises three different access technologies. There are ARs of each of those technologies (i.e., Ethernet, WLAN IEEE 802.11b, and TD-CDMA), as well a multi-technology capable mobile node (MN), that can seamless roam among the different technologies. Different network nodes are located at the core IPv6 network (i.e., HA, A4C, QoSB, and PA). Last, but not least, there is a CN that hosts several applications (video and MP3 streaming, HTTP server, Tetris and chess servers, Jabber Instant Messaging (IM) server, etc.). The entire test bed had native IPv6 connectivity, which allowed us also to perform tests between the Madrid and Stuttgart sites.The test bed here described, composed of general purposes machines, is just a simplified instantiation (i.e., an experimental prototype) of what a 4G network infrastructure may be, but results obtained can be applied as lessons to real 4G networks, since the Moby Dick architecture considered and deployed in an integrated manner key network processes of future real 4G networks here: QoS, Mobility, and A4C.

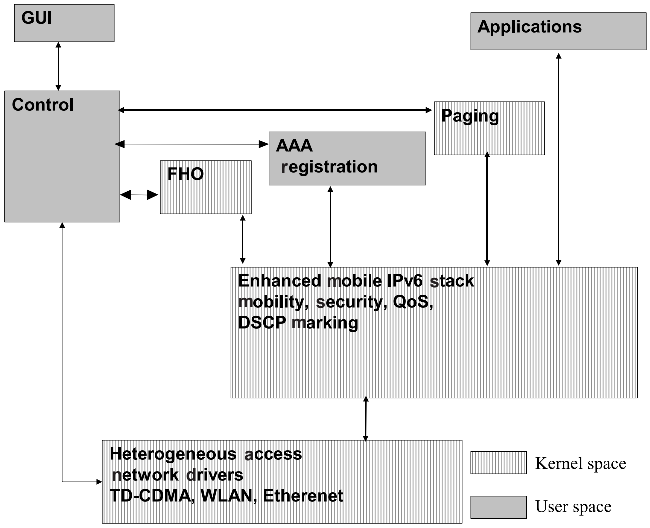

Fig. 3. MN modules.

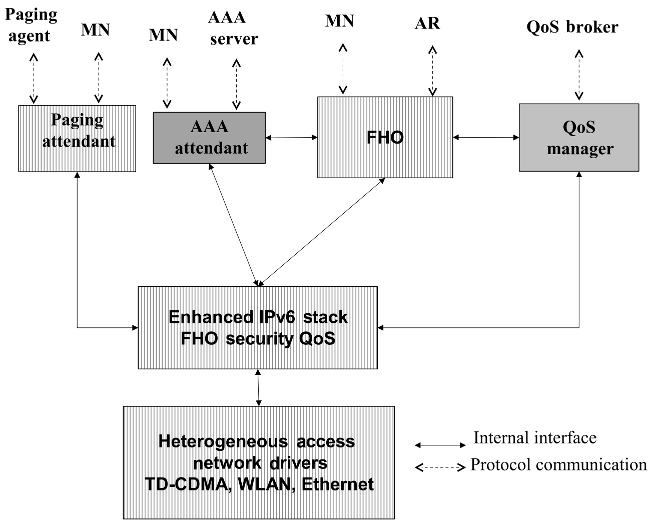

Fig. 4. AR modules.

III. MOBY DICK INTEGRATED PROCESSES EVALUATION AND RECOMMENDATIONS FOR FUTURE 4G NETWORKS DEPLOYMENT

This section deals with the key Moby Dick processes, which are related to QoS, A4C, mobility, and paging. For each process, first a description is given and then, based on the results and the

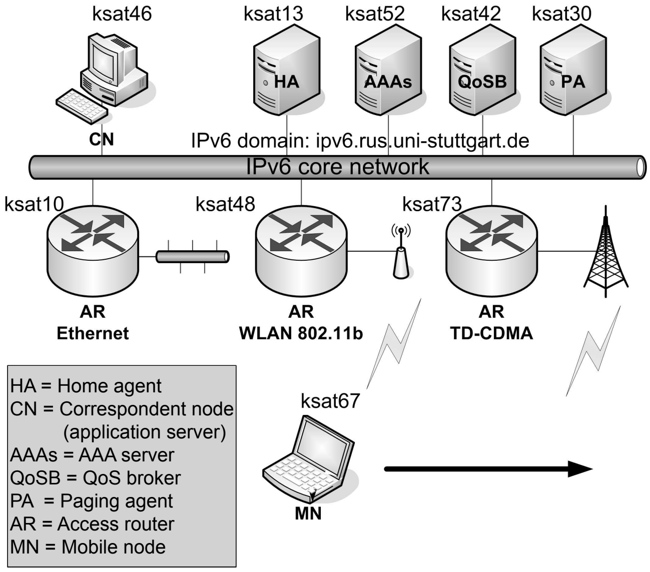

Fig. 5. Moby Dick Stuttgart test bed.

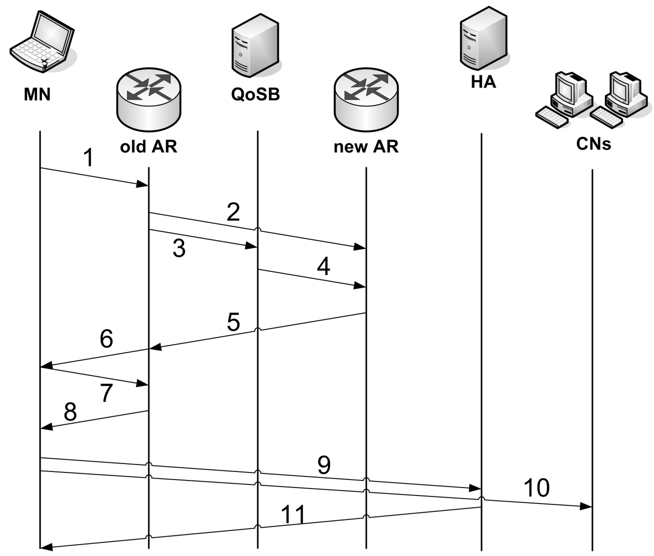

Fig. 6. QoS and AAA enabled FHO.

experience gained from field evaluation, recommendations for 4G networks development are given.

A. QoS and AAA Enabled Inter and Intra Technology Fast Handovers

A.1 Process Description

Seamless terminal mobility is achieved in Moby Dick by using a mobility management implementation based of fast handovers (FHO) for mobile IPv6 (FMIPv6) [18] in combination with message exchanges to and between the QoS broker(s) during the handover, in order to assure a given QoS. The process is only briefly described here (Fig. 6), the interested reader can find more details in [19].

As previously mentioned in Section II-A, this process is completely technology unaware. When the signal level perceived by a MN from its current AR ("old AR", oAR) starts to decrease, it starts a fast handover procedure to a neighbouring AR ("new AR", nAR) from which it receives beacons with better signal quality. The MN indicates to the current AR its willingness to perform a handover and informs it about the destination AR (nAR) and its new care of address—CoA—(Fig. 6, message 1). The oAR then performs two parallel actions: It sends the handover request to the nAR, including AAA context transfer (message 2, with metering session and IPSec tunnel parameters—see Section III-B.1) and, simultaneously, informs its controlling QoSB of the willingness to perform a handover (message 3). The QoS broker accommodates the needed resources and transfers the required user QoS context to the nAR (message 4). Also, when necesary, the QoSB issues the decision for opening TD-CDMA radio bearers in the nAR. Once the new AR receives these two messages, it sends the reply to the oAR (message 5), being negative if the nAR receives from the QoSB an order to abort the handover. The oAR forwards the reply back to the MN (message 6). If the reply is positive, the MN executes the FHO indicating so to the oAR (message 7) who starts then the bicasting process and signals the MN to execute the FHO (message 8). While doing the FHO, the MN receives packets from both the oAR and the nAR thanks to the bicasting process. Finally, once the MN is attached to the nAR, it sends a binding update (BU) to its HA (who replies with a Binding ACK) and CNs (messages 9, 11, and 10, respectively).

A.2 Field Evaluation and Recommendations

In order to evaluate the handover performance, two closely-related parameters were used: Packet loss and handover latency. A flow between the CN and the MN was created, using a small packet size and low interarrival time (high packet injection rate). By detecting packet losses, the handover latency was measured, in terms of that interarrival time. We define handover latency as the time interval in which a MN is not able to send/receive packets to/from a CN. The ping6 tool was used to perform these tests. The tests were also performed using a plain mobile IPv6 implementation (MIPL [20]), that serve as basis for comparison [21].

Handover latencies (HL) for handover between different access technologies, along with the signalling time (ST) needed to prepare the handover procedure (time between messages 1 and 8, Fig. 6) are presented on Table 1, where it is also shown the packet interarrival rate (PI). Results for ST were collected using a protocol analyser (Ethereal). QST (7-th column of Table 1) is defined as the delay required for the communication between the QoS broker and the old and new ARs (messages 3 and 4 of Fig. 6). When no data loss (DL) exists, the HL is between zero and one PI; with n packet losses, the HL is between n PIs and $n+1$ PIs.

These figures remain the same even if delays between the MN and the CN are added (in order to emulate higher round trip times—RTTs—between the MN and the CN), due to the features of the FHO mechanism. On the other hand, the measured handover latencies using a plain MIPv6 implementation were about 600 ms in local scenarios and over 1 second in scenarios where the MN and the CN are in different sites (Madrid and Stuttgart).

Although the WLAN infrastructure mode allows better fre-

Table 1. FHO results pinging from MN to CN.

Origin	Destination	Handover latency			Signalling time (ms)	
		PI (ms)	DL	HL (ms)	Total (ST)	QST
Eth	WLAN	50	0	[0,50)	24,3	22,6
WLAN	Eth	50	0	[0,50)	18,6	14,5
WLAN	WLAN	50	0	[0,50)	17,9	14,5
WLAN	CDMA	300	0	[0,300)	24,8	19
CDMA	WLAN	300	1	[300,600)	301,8	16
Eth	CDMA	300	0	[0,300)	25,9	22,5

Legend : PI: Packet interarrival rate. DL: Number of data packets lost.
HL: Handover latency. QST: QoS signalling time

quency usage, due to the high layer 2 measured latencies (over 150 ms), we decided to use the ad-hoc mode, including modifications to emulate infrastructure mode. Our goal was to show the advantage of a FMIPv6 (integrated with QoS and AAA) approach vs. MIP. It was then essential to minimise the inherent delay introduced by L2 technologies, and thus we employed the ad-hoc mode.

The make-before-break and bicasting paradigms employed in Moby Dick lead to almost no data loss during the fast handover (FHO), provided that the MN has coverage of both the old and new AR during the time needed to prepare the FHO procedure. The less time required, the less the cells need to overlap. With the results -namely ST- given on Table 1, we consider that a time of less than 50 ms is needed to prepare a FHO procedure. For users moving at 240 km/h, if cells overlap more than 3.5 meters no perceptible packet loss would take place, being this a requisite quite straightforward to carry out. Note that the biggest factor in ST time is the context transformation at the QoSB. Because several QoSBs may exist within a domain, each controlling an appropriate number of access routers (and thus of mobile nodes), there are no bottlenecks nor scalability concerns to worry about.

B. Registration of a User and a Terminal in the Network

B.1 Process Description

The Moby Dick AAA system is based on Diameter [22] and its mobile IPv6 application [23]. This was enhanced in the Moby Dick architecture, which extends it to a full A4C system (i.e., AAA plus charging and auditing) and introduces interactions with QoS and mobility (see Section III-A and [24]). The Moby Dick AAA registration process is very similar to Diameter mobile IPv6 process with the AAA client running in the ARs. There are, however, two differences:

1. The AAA.home server does not contact the HA to send it the BU. This approach was adopted for two main reasons: Firstly, some authors claim that this is not very convenient (see [25]) and, further, we could not see any performance gain in doing so; secondly, separating these two processes makes the design clearer as it decouples user AAA registration and MIPv6 terminal registration and thus simplifies overall system implementation.
2. The AAA.foreign server (the AAA.home if the user is not roaming) contacts the QoSB.foreign to send it a NVUP (network view of user profile), which is a part of the user profile containing information related to the transport services that the user is allowed to employ. The primary key of the NVUP is the CoA of the machine (interface) the user is logged in. Note that the home address (HoA) could also have been employed.

As related in [26], ARs in Moby Dick perform QoS policing and shaping following the COPS (common open policy service) outsourcing model [27], with the QoSB as the policy decision point (based on the source address of the packets and on the CoA of the NVUP). That is why the NVUP is sent to the QoSB [28]. The ARs build, upon registration, an IPSec tunnel with the MN, allowing packets (and namely their source address) to be safely associated to a registered user.

The AAA registration process is initiated after a care of address (CoA) is acquired by the MN via stateless autoconfiguration. Once the AAA registration is completed, the user is authorised to consume network resources (being the first thing to do sending a MIPv6 binding update—BU—to the HA).

B.2 Field Evaluation and Recommendations

During the registration, the time to process authorisation requests in the AAA.h server is about 1ms. Meanwhile, ARs generate Diffie Hellman (DH) keys, initiate metering sessions and establish IPSec tunnels with the MNs, a process that takes about 200 ms. The total required time to register a user (with parts of user profile transferred to all the involved entities including the QoSB) is slightly superior to this time. Registering a roaming user may take more time due to the (variable, but possibly high) round trip time between the A4C servers (e.g., not less than 70 ms between Madrid and Stuttgart).

A different test made was the registration of users with zero session life time, thus forcing continuous and immediate re-registration and driving the system to stressing conditions. We simultaneously registered 3 users whose terminals were attached to the same AR, noticing that registration time of one particular user increased with the number of users. On the other hand, with each terminal attached to a different AR, the registration time of the same user had little variation with the number of users. Results are summarized in Table 2. Note that the limited number of ARs available at the tests beds posed limitations at the time of doing these tests but the results are still indicative of the trends to expect.

The AAA.home (AAA.h) server centralises all the AAA processing for the users of a 4G operator, and thus AAA aspects dealt by the AAA.h must not pose scalability concerns. In Moby

Table 2. AAA scalability tests.

Number of other users	Test	Number of registrations of user acuevas	Total time (seg)	Mean time per registration (ms)
0		29	20,29	600
2	All MNs attached to the same AR	20	28,16	1400
	Each MN attached to a different AR	25	13	520

Dick, we decided the AAA.h to be stateless thus doing very few processing for each user and thus avoiding being a bottleneck for AAA aspects. During registration, most of the processing is managed by the AAA client in the access router, including DH key calculation, IPSec tunnel establishment and metering session initiation. And, as we have shown, this is more sensible to massive processing. But, since AAA clients do not centralize all users, this does not represent a scalability problem.

The policing and shaping process when the MN starts to send traffic (i.e., just at the beginning of a flow transmission) was also measured and it took about 20 ms, which is negligible for most applications.

To our knowledge, the Moby Dick AAA Diameter with its mobile IPv6 implementation was the first one available for IPv6 and, besides, it was the first design that could handle AAA plus charging and auditing issues (leading to a A4C system) integrated with mobility (roaming and FHO issues) and QoS. Charging and auditing aspects were also successfully tested both in A4C-only test beds and in global Moby Dick test beds [24]. Results are promising (as explained, scalability problems can be successfully handled) and we believe that the current home location register (HLR) or 3GPP's HSS (home subscriber server) and customer handling systems can be replaced in 4G networks by systems such as the A4C system designed in Moby Dick.

Care must be taken by operators if they plan to do AAA.home servers complex and statefull (in order to provide advanced services in scenarios like the ones described in [29] or in the Daidalos project [30]) due to scalability reasons. As a solution, A4C functions can be split in several machines but sharing user related databases. We may illustrate this with our charging scheme: Charging was done in the AAA.h server and was a resource consuming process so, in order not to affect the performance of the Diameter server, we had to run the charging process in a machine different from the AAA.h Diameter server. Users and charging databases were shared among the charging and the AAA.h server machines.

C. Paging

C.1 Process Description

Like all the processes defined in Moby Dick, paging is independent of the technologies used by the MN. These technologies can change from the moment it is dormant to the moment when it awakes. The process relies on the notion of technology-independent paging areas, managed at IP level. Paging attendants located in the ARs broadcast modified router advertisements in order for the MN to know its paging agent (PA) and the paging area where it is located. When the MN enters the dormant mode, it informs both the PA and the HA: The MN sets

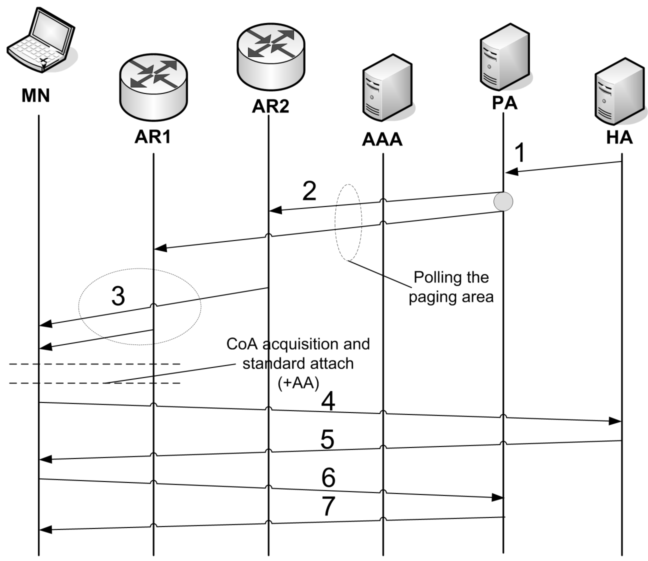

Fig. 7. Paging awaking process.

the PA address as its CoA, and thus the HA will redirect MN packets to the PA. When the MN moves between ARs within a single paging area no signalling is issued. When the MN moves between ARs belonging to different paging areas, the MN only informs the PA of such event. When a CN wants to send packets to the dormant MN, the HA intercepts them, forwards then to the PA (message 1 in Fig. 7) who buffers them until the MN is awaked. To awake the MN, the PA sends a message to all the ARs belonging to the paging area where the MN is located (message 2). These ARs broadcast an awaking message (message 3) and when the MN receives it, it begins the awaking process. An awakened node is like a new node for the network, so the MN first has to do an AAA registration and to send a BU to the HA as explained in Section III-B. Afterwards it notifies its awaken state to the PA (message 6), who will then send to the MN all the buffered packets (message 7) it may have. The MN will then send a BU to the CN. The traffic sent by the MN will be policed and shaped at the AR.

C.2 Field Evaluation and Recommendations

The time needed to awake a dormant node is about 500 ms, including the process of registering and awakening the node (about 200 ms for WLAN interfaces) and the process of establishing the QoS policing and shaping mechanism (about 20 ms).

In order to avoid any loss in the data sent to the MN being awaked, the PA must have properly sized packet buffers for each dormant MN. Provided that the data is sent to the MNs being awaked at a rate of 2 kbps, a 1 kb buffer for each dormant MN is enough to avoid packet losses. This takes place only at the beginning of a communication session, so it is not foreseeable these assumptions to be problematic. In fact, real users have not complained when using the system with common applications (such as instant messaging).

The Moby Dick paging concept is based on the IETF solutions designed within the SEAMOBY WG ([31], [32], and [33]) and, according to the results presented in this section and the experiences of "real" users (Section IV), it is able to serve as basis for future 4G paging architectures.

IV. USABILITY OF THE MOBY DICK SOLUTION

Section III has described quantitative test that indicate the potential good performance of the Moby Dick design and implementation. But we wanted to evaluate also usability issues in "real" 4G environments. To do so, user tests were performed. User tests involved students with no knowledge of Moby Dick and some of the tests were performed jointly between Stuttgart and Madrid test beds.

Users could employ any available IPv6 application (web browsing, online gaming, VoIP, streaming, $\cdots$) over the Moby Dick test beds. Seamless FHO, paging, charging, and user profile dependent QoS under artificial network overload would be experienced by users, which would be unaware of network details. Major user complaints came from users with low priority QoS profiles (as described in some cases below) or were related to the difficulty in configuring the applications. Two of the most relevant user tests are described in this section but many more (in other situations and with several different IPv6 applications) were done.

One test consisted of one user with "gold profile" (i.e., "very good" QoS profile) listening to a streamed MP3 song, using the "xmms" application. Some handovers were done (QoS and AAA enabled) and the song remained playing seamlessly. Charging was checked for that user. The time he was logged into the network, the bytes sent and received (charged also in function of the received quality) and, dependant on the AR the user was attached to (wired, wireless), were charged. The same test was performed with a "bronze profile" (i.e., low QoS profile) user. This user listened to the same song but due to its profile, the BW enjoyed by this user was smaller than required. Thus the quality of the listening was very bad, with frequent glitches. Charges were, of course, lower than the "gold user" as he received less bytes and with a lower priority (and "cheaper" quality). This test showed how the profiles of the users influence the QoS of the services they get, the metering, accounting and charging features and everything integrated with FHO. The components involved were: The ARs with the QoS Manager and AAA clients controlling metering, the QoSB, the A4C.h server, the MN (employed sequentially by the 2 users) the HA, and the CN acting as MP3 streaming server. Although they were not involved in this test, paging attendant (in the ARs) and paging agent were also running. Charging strategies (e.g., by service—listening to a MP3 song—instead of per bytes sent or transmitted) are outside the scope of this work.

We did a very similar test to highlight the power of QoS enabled FHOs. This time, we streamed a movie (using VideoLAN and two unicast streams) and the two users were connected at the same time, each in a different laptop and each laptop attached to a different WLAN AR. The high priority user moved with his laptop closer to the other user and an automatic FHO was performed. The QoS system accommodated resources for this high priority user in the nAR, having to grab resources from the low priority user because we used videos with bit rates that the available WLAN could not accommodate simultaneously. The high priority user experienced a seamless FHO while the other user saw his video stopped. Next, the high priority user did another FHO but this time to a wired Ethernet AR. This FHO was also seamless, and, having freed the resources in the WLAN cell, the video in the computer of the other user began to be correctly displayed again. Finally, the low priority user performed a FHO to the same wired Ethernet AR. The higher available BW of wired Ethernet can accommodate the two videos and this FHO was also seamless. Potential negotiation between the users and the video stream provider to agree on the QoS of a specific stream was out of the scope of this test.

V. CONCLUSIONS AND FUTURE WORK

In this paper we have presented field evaluation results of an IP-based architecture for a 4G "True-IP" network developed under the Moby Dick project. Moby Dick demonstrated the seamless integration of three disciplines, QoS, AAA, and IP Mobility, over a heterogeneous network infrastructure focussing on three access technologies (WLAN, Ethernet, and TD-CDMA). Roaming and enabling a user to maintain any session while seamlessly changing his location or access technology are key aspects for the market. Moby Dick considers as well multi-provider scenarios and user mobility by decoupling a user from an end-system and thus allowing customisation via a centrally managed profile. Moby Dick supports roaming agreements between operators of different technologies. Field trials were connected through the public IPv6 network, showing the possibility to extend the system to a world-wide scale.

The field tests here described provide indications on critical trade-offs for future 4G networks and not only show that Moby Dick successfully confronted its design challenges, but they also demonstrate that the performance obtained is very high. Inexperienced users enjoying popular applications (such as games) over Moby Dick testbed, and under different conditions trying to emulate real scenarios, showed the "usability" of Moby Dick and prove that 4G networks can be a commercial reality. Nevertheless, the prototype developed has several limitations in terms of scope, and provides large margin for improvement. The results presented in this paper may serve as a road map of some of the further work to do. To close our paper we highlight some of the limitations and present planed work.

In Moby Dick QoS was based on DiffServ with QoS brokers and integrated with AAA and mobility aspects. QoS and AAA interaction, briefly described in Section III-B, allowed a fine control on consuming and tarification of network resources. But there was no means so that two users could agree on the QoS (and thus the corresponding price to pay) to be given to the packets sent by each other, neither there were means to charge the users per services (e.g., voice call) instead of per packet. This negotiation and the integration of applications with network elements is being tackled in Daidalos and a first approach is SIP applications interaction with AAA system [29].

As we saw in tests employing voice over IP [34], the percentage of overhead introduced (IPv6 basic, routing, and home address header) was very high, so robust header compression techniques should be employed and evaluated its performance improvement.

As explained in Section III-A.2, the ad-hoc mode was deployed in the Moby Dick project. Nevertheless, this is suboptimal, due to the poor frequency reuse. In Daidalos, infrastructure mode will be deployed, and modifications to the wireless card drivers will be performed to reduce the overall Layer 2 handover, by enabling the MN to scan only in a subset of channels instead of scanning all the 14 channels. In this way, if the MN knows the channels in which other neighbours access points (APs) or ARs operate (this is done in Daidalos using CARD [35]), the Layer 2 handover latency can be low enough to support real-time applications.

In Moby Dick, the AP was collocated with the AR, but this is a non-realistic scenario, as in practice, many APs are attached to the same AR. In Daidalos, more than one AP is connected to an AR and load balancing among APs belonging to the same AR can thus be provided. Furthermore, in Daidalos, the movement of a whole network is also enabled, in order to cope with the increasing demand for ubiquitous Internet access in mobile platforms (such as trains, buses, planes, or cars).

As a final word, it can be stated that the experimental results achieved from the prototype Moby Dick network provide us with indications that this Pure-IP approach may be realizable in future 4G systems. These Moby Dick results are thus instrumental in supporting some of the ongoing trends on next generation architecture. Furthermore, these results, and the physical deployment of the trial sites, provided a clear view of the limitations of the system and highlighted relevant issues for future research in this field.

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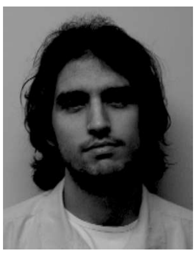

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