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Steuer, Frank; Geithner, Thomas; Kaschwig, Thomas; Bür, Kaan; Albayrak, Sahin

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Total number of authors:
5

A Connectivity Management System for Vehicular Telemedicine Applications in Heterogeneous Networks

Frank Steuer
Technische Universität Berlin
DAI-Labor
Berlin 10587, Germany
frank.steuer@dai-labor.de

Thomas Geithner
Technische Universität Berlin
DAI-Labor
Berlin 10587, Germany
thomas.geithner@dai-labor.de

Thomas Kaschwig
Technische Universität Berlin
DAI-Labor
Berlin 10587, Germany
thomas.kaschwig@dai-labor.de

Kaan Bür
Technische Universität Berlin
DAI-Labor
Berlin 10587, Germany
kaan.bur@dai-labor.de

Sahin Albayrak
Technische Universität Berlin
DAI-Labor
Berlin 10587, Germany
sahin.albayrak@dai-labor.de

ABSTRACT

New wireless access technologies such as UMTS with HSPA extensions, WiMAX, and Flash-OFDM and the convergence towards next generation heterogeneous networks enable the realization of always best connected scenarios. As the resulting heterogeneous networks become easier to access and more reliable to depend on, novel telemedicine services such as vehicular emergency applications emerge. Due to their life-critical characteristics, these applications require connectivity throughout the heterogeneous network. On the other hand, they also have high resource demands. In this study, we propose MIPGATE, our mobile connectivity gateway, as a step towards seamless mobility support for next generation heterogeneous networks. MIPGATE contains modules for the access technologies currently available and a decision mechanism to switch intelligently to the connection offering the most suitable conditions. Link layer triggers and additional context information are used to optimize the handover decision process. MIPGATE is customized according to the requirements of StrokeNet, a mobile telemedicine project for the remote diagnosis of stroke patients using real-time audio and videoconferencing. The MIPGATE system is validated through measurements on throughput, delay, packet loss, and handover latencies using public wireless network infrastructures with the UMTS/HSDPA technology and a Beyond-3G testbed featuring a Flash-OFDM test network. For the payload packets, mean handover latencies of 118 ms in case of handovers to UMTS/HSDPA and 23 ms in case of handovers to Flash-OFDM have been achieved in a real-world network setup. The overall payload packet loss rate is 0.71% and equally distributed over the duration of the measurements. The results show that MIPGATE supports network connectivity under mobility as required by novel telemedicine applications and demanding real-time services.

Categories and Subject Descriptors

D.2.2 [**Computer-Communication Networks**]: Network Protocols

General Terms

Performance, measurement

Keywords

Heterogeneous networks, testbed, vehicular networks, mobile telemedicine, mobility management, seamless handover

1. INTRODUCTION

Within the last decade, the evolution of wireless data communication technologies has been particularly accelerated by both the developments in microelectronics as well as the demand of the user for ubiquitous access. As a practical result of this trend, several types of wireless networks have emerged and become publicly available. In the wide area domain, the Global System for Mobile Communications (GSM), deployed initially for voice only, was enhanced by technologies such as the General Packet Radio Service (GPRS) and the Universal Mobile Telecommunications System (UMTS) as a successor to enable data services.

The next step towards ubiquitous access to data services was the integration of the UMTS infrastructure with locally deployed technologies such as Wireless Local Area Networks (WLAN). The 3rd Generation Partnership Project (3GPP) and the 3rd Generation Partnership Project 2 (3GPP2) established standards for GSM/UMTS [1] and cdmaOne/CDMA2000 [2], respectively, to integrate 3G networks with IEEE 802.11 networks. Different network coupling approaches have been discussed with the goal to provide the user with an experience of seamless connectivity over a heterogeneous network. Ubiquitous access to services and applications is achieved by introducing networks and devices which implement the "always best connected" [3] approach.

The standardization efforts towards the seamless integration of heterogeneous networks also contribute to the continuity and reliability of the network, which will enable mission-critical and emergency applications to be deployed safely on these networks. Today, sophisticated applications such as location-aware services and multimedia streaming are already available and becoming increasingly popular among mobile network users. As the capacity of the heterogeneous network infrastructure increases, service developers introduce even more resource-demanding applications such as real-time data transmission and high-quality videoconferencing.

Telemedicine services are one of the many application categories which will benefit from these developments in mobile communication and information technologies. It is well-known that early and specialized pre-hospital diagnosis and treatment contributes to emergency case survival and aftercare of patients [4]. Since it is practically not possible to have a specialist in every ambulance, telemedicine services introduce accurate diagnosis possibilities, where a limited number of specialists can supervise a large number of emergency staff remotely without leaving their workplaces.

Telemedicine has to adapt to the developments in personal mobile communications in order to use the new possibilities offered by cutting edge technologies to always deliver sophisticated services with added value. In this regard, emerging technologies which are candidates for large-scale deployment in the near future, such as High-Speed Packet Access (HSPA), Worldwide Interoperability for Microwave Access (WiMAX), and Fast Low-latency Access with Seamless Handoff Orthogonal Frequency Division Multiplexing (Flash-OFDM) have to be taken into account to develop a future-proof system.

We developed MIPGATE to provide groups of users and devices with secure and seamless Internet connectivity in moving vehicles such as high speed trains or cars with the additional considerations for future development as mentioned above. MIPGATE consists of several autonomous communication units to maintain connections to available access technologies, a decision mechanism to evaluate network conditions as well as to decide on vertical handovers, and a Mobile IP stack to support seamless connectivity at the network layer. MIPGATE is optimized for real-world deployments using currently available network technologies and standardized protocols. Link layer triggers and additional context information are used for the optimization of the handover decision process. MIPGATE provides support for seamless mobility in heterogeneous wireless networks with close to zero packet loss and low enough handover latencies for smooth migrations of ongoing real-time sessions between different access technologies.

We customized MIPGATE to fulfill the requirements of a mobile telemedicine scenario as defined by the StrokeNet project [5], which aims to start the treatment of stroke patients in ambulances and thereby to reduce consequential damages. The customization included the assembly and configuration of small-sized, lightweight, robust hardware with low energy consumption and the adaptation of MIPGATE to this hardware as an embedded system to meet the additional challenges of vehicular applications. We deployed our architecture in our Beyond-3G testbed for evaluation and performed stationary tests in our laboratory as well as test drives in the city traffic. The results show that MIPGATE provides the telemedicine applications for stroke patients in moving ambulances with seamless connectivity. We also equipped three ambulances with MIPGATE for a real-life medical study to be carried out in the next phase of the project.

The rest of this article is organized as follows. Section II presents previous research efforts and projects related to mobile telemedicine. Section III describes StrokeNet, our telemedicine project with focus on stroke patients. We define our design principles in Section IV and propose the MIPGATE architecture as a solution to the seamless connectivity problem. Section V introduces our experimental testbed and describes the implementation of MIPGATE within the StrokeNet scenario. Section VI provides an evaluation of the performance of the overall system under real-life conditions. Finally, Section VII concludes the article and gives some future research directions.

2. RELATED WORK ON MOBILE TELEMEDICINE

Various systems have been designed in the past years as stationary, portable and mobile telemedicine solutions. The chronological order of the projects developed also reflects the evolution of the communication technologies available from GSM to GPRS and UMTS. A selection of these projects is summarized below.

In the AMBULANCE project [6], the authors develop a portable medical device to transmit diagnostically important physiological signals such as electrocardiogram (ECG), blood pressure, oxygen saturation and heart rate as well as images of the patient from an emergency site to a telemedicine center. The system utilizes a GSM network and communicates using the Transmission Control Protocol over IP (TCP/IP). The system is controlled remotely by the expert, who can switch from physiological signal monitoring to image displaying mode and process the images in both modes for examination.

The MobiHealth project [7] aims at developing new services in the area of mobile healthcare. It builds on the results of various past projects by introducing the body area network (BAN) concept to organize the elements of mobile health systems. The MobiHealth BAN is a patient monitoring system equipped with a basic set of sensors/actuators as well as a mobile base unit (MBU) that serves as a wireless communication gateway to GPRS and UMTS networks.

More recently, a mobile teletrauma system using 3G networks, which is comprised of a trauma-patient unit (TPU) and a hospital unit, is proposed in [8]. The system uses off-the-shelf hardware and commercially available 3G services. TPU transmits patient's information over a 3G wireless link to the hospital unit. Since multiple multimedia streams such as ECG, medical images and real-time video are transmitted at the same time during this process, TPU reduces the amount of data by transcoding it prior to transmission. To minimize the effect of congestion, the media streams are also prioritized according to their real-time requirements and relative importance. ECG and medical images are transmitted via TCP to ensure reliable delivery, whereas the User Datagram Protocol (UDP) is used to meet the real-time requirements when transmitting video. The performance of the system is evaluated using end-to-end delay, jitter, delivery ratio and interframe interval as metrics. The results show that the transcoding and prioritization of the streams improve the system performance.

Due to the bandwidth restrictions of GSM/GPRS systems, UMTS is seen as a better solution for medical data transmission for mobile emergency cases [9]. UMTS supports a variety of service classes such as conversational, streaming, interactive and background, each with different quality of service (QoS) requirements. To work with the UMTS system and get QoS guarantees, however, the air interface has to multiplex different data streams on a single connection. In this context, the authors propose an adaptive rate multiplexing scheme to reduce resource requirements during the joint transmission of voice, ECG, video and medical scans in a telemedicine service scenario with an ambulance or mobile care unit.

The authors of [10] present mobile tele-echography using an ultra-light robot (OTELO), which comprises a portable tele-operated robot allowing a specialist sonographer to perform a real-time ultrasonography to remote patients. The system transmits robotic control data, still images and streaming ultrasound data over a 3G network. The unidirectional transmission of the ultrasound stream represents the bottleneck of an uplink communication channel at the patient station. The components of the OTELO traffic are mapped to the QoS classes of UMTS. An experimental setup is designed to evaluate the system performance over a 3G network in terms of end-to-end delay, jitter and average throughput. The test results validate the successful transmission of ultrasound streams in 3G environments with acceptable delay jitter to maintain real-time interaction with the robot system.

Although the projects summarized above demonstrate the progress made in mobile telemedicine clearly, they suffer from some common deficiencies when the current developments in mobile communications are taken into consideration. First, the vision of network heterogeneity with multiple access networks is missing. Thus, mobility management is not addressed within the context of heterogeneous networks. Secondly, the services implemented mostly require a unidirectional connection and do not have high demands in terms of QoS. Finally, the level of mobility is typically low. We believe that these assumptions are somewhat oversimplified for next generation networks and the mobile telemedicine services that will be running on them. The StrokeNet project represents a collection of the challenges mentioned above and MIPGATE is our solution to address these. In the following sections, we present the details of our study.

3. STROKENET

The goal of the StrokeNet project is to develop technologies and organizational workflows for telemedicine applications in emergency situations to improve the emergency care for stroke patients and to reduce the consequential costs. In this scenario, the ambulance is equipped with a videoconferencing system which allows stroke specialists in a telemedicine center to make first diagnoses, e.g. if it is a stroke case and which kind of stroke. This allows a better medical care for the patients because the ambulance can be directed to the most suitable hospital and the resources in this clinic (staff, diagnostic equipment, rooms) can be prepared in advance. Due to the temporal and qualitative advantages, a significant improvement for the convalescence can be expected. So, the probability for permanent injuries to health is reduced and the average cost per patient is decreased.

The developed technologies and workflows are not limited to this stroke scenario. In the future, medical data can be transmitted over the mobile network, e.g. ECG data and blood parameters. Also, other specialists can be consulted during the patient transport. These physicians are located at a telemedicine center which is able to support a large fleet of ambulances.

One of the most important requirements of StrokeNet is a dependable audio and video connection between the ambulance and the hospital. Due to the mobility of the ambulance, quickly changing conditions of the wireless network must be expected (e.g. radio signal quality, network/cell utilization and network availability). For telemedicine applications in heterogeneous wireless network environments, stable connectivity and mobility management is of high importance. The network connection must be as interruption-free as possible and offer specified minimum quality parameters, e.g. throughput, delay and packet loss.

Because the StrokeNet project is based on public infrastructure, currently mainly UMTS/HSDPA, the network behavior is unpredictable and changing quality of the wireless networks is inherent. To use the best available connection at any time, our solution combines several access networks, e.g. two UMTS links of different providers, WiMAX or Flash-OFDM. To allow a permanent, interruption-free usage, the switching between the networks must be close to seamless and the system has to support migrations between different access network technologies without significant interruptions.

The transmission of video and audio data requires a high transmission quality in real time. In view of the available network capacity (max. 384 kbit/s uplink speed on UMTS/HSDPA) and based on the feedback gained during tests and discussions with health professionals with regard to the required audio and video quality, a codec rate of 192 kbit/s (audio and video together) was chosen. This bit rate offers good video quality and leaves enough bandwidth reserves on the wireless link. Together with packet overhead (including Mobile IP and IPSec headers and depending on the packet size), a bandwidth of about 210 kbit/s is required. In addition, a low to medium network latency (150ms - 400ms [11]), jitter and packet loss (max. 3-5%) are also required.

In medical environments, confidentially and security are very important and regulated by law. Hence, closed network architectures are mandatory in this field. So, the clinic network is securely extended to the ambulance based on an IPSec Virtual Private Network (VPN).

4. MIPGATE

The above detailed application-level requirements which are set by the StrokeNet scenario are now mapped to a technical solution. In this section, we first present these technical requirements and design principles. Then, the proposed MIPGATE architecture and the implementation are described in detail.

4.1 Technical Requirements and Design Principles

The technical requirements for the MIPGATE architecture can be derived as follows. The system should provide seamless broadband Internet connectivity for vehicular applications and systems. It has to act as a mobile router and extend the clinic network to the ambulance by establishing secure connectivity for the devices attached to it. The overall solution should be developed with focus on a potential deployment and therefore scalability, reliability, and maintenance aspects have to be taken into account as well.

A modular design guarantees flexibility and easy extensibility. Different access network technologies have to be supported to enable the "always best connected" scenario [3]. It has to be possible to integrate new access technologies in an efficient manner to cope with the evolution of network access technologies.

Mobility management and seamless handover support is required to support the migration between different access networks during service usage without noticeable interruptions. For a smooth migration of ongoing connections between different access networks, *make before break* scenarios in environments which are characterized by overlapping cells should be supported. Therefore, the use of multiple modems and network adapters in parallel is mandatory for such a scenario. In case of *make before break* scenarios, network connection establishment to the new access network and IP address configuration are completed before the connection is smoothly migrated to the new access network.

The availability of a network and the quality of the radio signal do not provide enough information about an access network to be able to rate the actual quality of the connection itself, the available resources, etc. Therefore, the handover decisions should not only be based on such a rather limited amount of information but more detailed information and additional parameters (e.g. L3 connectivity, network delay, cell size, etc.) have to be taken into account to base the handover decisions on a more substantiated state of context awareness.

To secure the connection between the ambulance and the telemedicine center, an appropriate solution is required. Different potential solutions for VPNs are available (L2TP, PPTP, IPsec). It is important that the chosen solution can be integrated with the selected mobility management protocol.

The system will be integrated with other systems and components. This leads to the requirement that an interface has to be provided which can be used to retrieve status information. As the solution is developed with focus on future deployments, remote monitoring and remote control of the system has to be possible as well. For the evaluation of the system status, a detailed logging mechanism should be available.

4.2 System Architecture and Implementation

The above detailed requirements and design principles have been taken into account and the resulting MIPGATE system architecture is depicted in Figure 1. The system is characterized by a central component called *Decision Engine* (DE). The DE is responsible for the aggregation of all available information about the different access networks. Based on this information and the configuration of the system, the DE takes the handover decisions. The DE is integrated via a so-called *Mobility Abstraction Layer* (MA) with the component which is responsible for the mobility management. This abstraction layer enables the integration of different mobility management solutions without altering the code for the

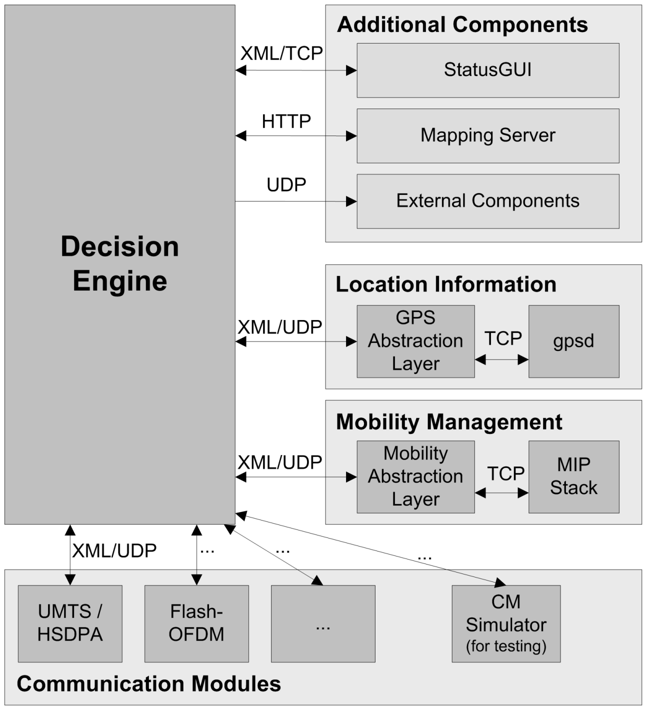

Figure 1: The MIPGATE System Architecture

DE.

The network selection decisions which are taken by the DE are based on the following parameters and conditions:

- Link availability
- Signal strength, signal quality, and historical values of these parameters (change over time)
- Theoretical available bandwidth
- Layer 3 connectivity and quality of this connection (e.g. round trip times (RTT), thresholds for maximum allowed loss of control packets)

Several mobility management protocols can be implemented to support seamless migration between different access networks during service usage (e.g. MIPv4 [12], MIPv6 [13], SIP [14], HIP [15]). Here, a Mobile IPv4 stack which supports NAT traversal [13] has been implemented and integrated. The mobile network for the devices attached to MIPGATE is routed over the Mobile IPv4 tunnel. Mobile IPv4 has been chosen as protocol for the mobility management for different reasons. The main aspects are:

- Support for seamless handovers between different access technologies
- Support for the integration of public networks
- Support for UDP and TCP based applications
- Possibility to integrate VPNs (IPSec, PPTP, etc.)
- Deployment constraints (e.g existence of NAT in some of the access networks, IPv4-only access networks, deployment specifications of the cellular operator, etc.)

In theory, Mobile IPv6 would have been a better approach because of it's more sophisticated mobility features such as route optimization. Here, the deployment constraints are set by the specific telemedicine application scenario. Therefore, the presented solution has to be integrated with today's commercial wireless networks which currently only provide support for IPv4 but not IPv6.

The *Communication Modules* (CMs) are implemented as separate and independent components - one CM per access network technology. These CMs are responsible for autonomous establishment and termination of the network connections (e.g. setup of the PPP context in case of a CM for a UMTS modem card) and the monitoring of these connections. The CMs provide the DE with a homogenized set of information about the parameters of the corresponding network connection (availability, connection status, signal strength and quality, network latency, etc.).

Each CM acts as an abstraction layer to hide technology specific complexities and provide the DE with a generalized interface. Similar solutions have been proposed as Media Independent Handover (IEEE802.21 [16]) and Unified L2 Abstractions for L3-Driven Fast Handover [17]. Both proposed solutions are still in draft status. For the MIPGATE system an own message format and protocol have been developed because the current status of the IEEE802.21 standard would have introduced too high complexity due to the large number of message types and their corresponding formats. In addition, not all required data are included (e.g. details about the current condition of the link). The Unified L2 Abstractions did not cover all required aspects in terms of parameters and information to be exchanged between the CMs and the DE and the message format has not been defined yet.

Inter-process communication between the system components (DE, CMs) is based on an XML-based protocol, where information is exchanged via UDP. This enables a distributed setup of the CMs, even based on dedicated hardware solutions.

A simplified example of the protocol is shown in Figure 2. The update messages are sent periodically from every CM to the DE and consist of two major blocks:

The **main** element contains all necessary information to describe the message itself: The source and destination host name and UDP port, the type of the module this message is sent from and an unique module id and name.

The **interface** element includes the current state of the abstracted network interface: The interface type, the logical interface name given by the operating system and the IPv4 care-of-address. It also contains the measured signal quality and signal strength, the RTT between the MIPGATE mobile router and a predefined test host, the current downlink and uplink throughput and a normalized quality indication of this interface for comparison of different types of access technologies. The connected element specifies whether this module has established an usable connection to the Internet, whereas the *active* element indicates if this interface is used at the present time. The **raw** element describes interface specific attributes, such as network registration status, name of the operator, network and cell type, availability of HSDPA, the area and cell id in case of an UMTS/HSDPA connectivity module.

Besides the update message format, several other message types are defined for inter-process communication between

```
<message id="42" version="0.1.2" type="update">
  <main version="0.1.2">
    <source>localhost</source>
    <sport>16387</sport>
    <destination>localhost</destination>
    <dport>16384</dport>
    <module-type>cm</module-type>
    <module-name>cm_option_umts</module-name>
    <module-id>3</module-id>
    <timestamp>2007-11-08T16:09:02.998+0100</timestamp>
  </main>

  <interface version="0.1.2">
    <type>umts</type>
    <name>ppp0</name>
    <signal-normalized>82</signal-normalized>
    <signal-strength>17</signal-strength>
    <signal-quality>27</signal-quality>
    <ip>10.0.4.13</ip>
    <rtt>133.04201</rtt>
    <throughput-ul>200.093</throughput-ul>
    <throughput-dl>208.456</throughput-dl>
    <active>1</active>
    <connected>2</connected>
    <raw>
      <registration-status>1</registration-status>
      <operator>T-Mobile D</operator>
      <network>UMTS</network>
      <cell-type>unknown</cell-type>
      <hsdpa>1</hsdpa>
      <area-code>3032</area-code>
      <cell-id>0644</cell-id>
      ...
    </raw>
  </interface>
</message>
```

Figure 2: MIPGATE XML Protocol Example

the different MIPGATE modules:

- Status messages sent from the MA to the DE and handover requests sent vice versa.
- Request messages and their corresponding replies to receive the aggregated overall state of the MIPGATE system from the DE.
- Control messages to manage the decision engine by external components, such as a GUI or network assisted mobility management.

For the integration with external components or systems and to provide applications with detailed information, MIPGATE provides a status update interface. Based on this interface, information like the currently used network and detailed information about the network conditions can be accessed. Future applications need to support heterogeneous network environments and adapt to the actual network conditions.

Figure 3 shows a simplified schema of the MIPGATE interface selection process, which is based on two sub processes:

1. Every CM monitors it's corresponding network interface continuously and sends the current state to the DE. In order to decide whether an interface is available, the CM checks if the network link is up, if the connection (e.g. PPP) is established and if data transmission is possible over this interface. For the latter, the CM regularly sends L3 cntrol packets (ICMP ping)

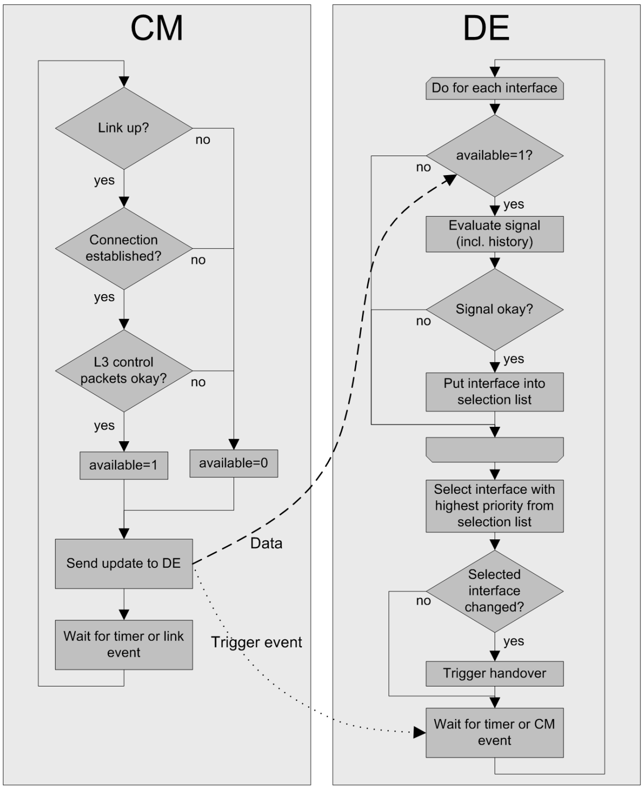

Figure 3: The MIPGATE Decision Process

to a predefined test host and counts the number of successful replies within an adjustable scope. Only if the interface passes all tests, it is marked as available.

2. The DE permanently receives the information about all network interfaces and updates it's internal network interface list. To filter interfaces which didn't satisfy the quality criteria, the DE iterates over the list of all available interfaces and checks if the normalized signal quality matches a preset threshold for this interface type. All interfaces which pass this test are put into the selection list. Depending on the pre-defined priority of each interface, the DE selects the best interface concerning it's policy. If the selected interface doesn't comply with the currently active interface, the DE triggers the MA to handover to the selected interface.

For development and testing purposes, a *Communication Module Simulator* has been implemented. Prerecorded logfiles can be loaded and used for the simulation of previous driving tests. Recorded location information and all details about the different available access networks at any given time are provided to the DE.

Location information (GPS coordinates) is provided by a GPS receiver. The GPS module is integrated by a GPS Abstraction Layer which either connects directly to a GPS receiver or to a gpsd [18].

Several optional components can be integrated to MIPGATE. With a *StatusGUI* which connects to the DE via TCP the user can monitor the current status of the system and also force handovers. This interface enables remote control in terms of network selection and can also be used to

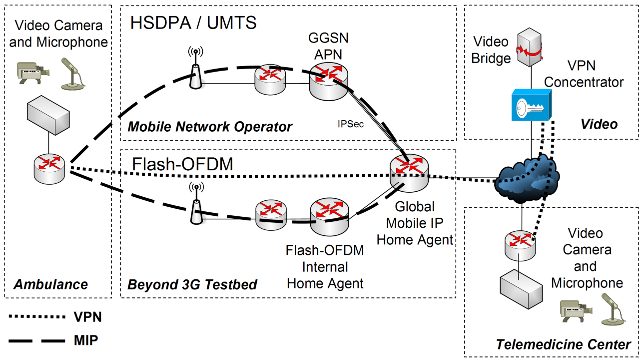

Figure 4: StrokeNet Testbed Setup

trigger handovers from an external application e.g. from the network side.

An optional geographical mapping service can be fed with actual data using HTTP. This additional service can for example be used to optimize the dispatching of different cases of emergency to ambulances.

5. TESTBED SETUP

The architecture described above has been implemented as a prototype. A realistic environment is required for the experimental evaluation of the solution. Figure 4 gives a simplified overview of the overall testbed setup. For the videoconferencing application, a Car-PC with video camera and microphone is connected to MIPGATE. The MIPGATE mobile connectivity gateway establishes the connection via UMTS/HSDPA or Flash-OFDM. The access networks and the mobility management infrastructure are provided by a Beyond-3G testbed [19]. The central VPN concentrator secures the connections between the ambulance, the video bridge, and the telemedicine center in the hospital.

MIPGATE for StrokeNet is based on PC104+ modules (CPU module, PCMCIA adapter modules). Linux has been chosen as operating system and a stripped down version of Debian GNU/Linux 4.0 is used. Flash-OFDM and UMTS/HSDPA access is supported by PC Card adapters.

The access networks and the mobility management infrastructure are part of the Beyond-3G testbed (for details see [19]). For the quantitative evaluation of the solution presented in this paper, a subset of the overall testbed was used. The UMTS network is integrated with the testbed infrastructure using a separated Access Point Name (APN) on the Gateway GPRS Support Node (GGSN) of the cellular network operator. GGSN and the testbed infrastructure are interconnected via an IPSec-based VPN connection. For the operation of the Flash-OFDM cell (Flarion RadioRouter software version 1.1), a testing license in the UMTS frequency band for 1950-1959.9 MHz and 2140-2149.9 MHz has been granted by the German regulator. The Flash-OFDM RadioRouter forwards the traffic to the Flarion internal Mobile IPv4 home agent which routes the traffic towards the testbed. A global Mobile IPv4 home agent based on Cisco IOS 12.3(8)T is deployed as basic mobility management infrastructure. Co-located Care-of Addresses (CoAs) are used for the MIPGATE system and reverse tunneling is configured as tunneling method for the Mobile IP setup. No foreign agents are deployed as these changes were not (yet)

Table 1: Comparison UMTS/FLASH-OFDM

Access Network	Downlink Speed in MBit/s	Uplink Speen in kBit/s	RTT in ms	Cell radius in m
UMTS / HSDPA	1.8 (2006)	384 (2006)	70 – 150	250 – 500 (Berlin city)
Flash-OFDM FRR1.1	1.8 2.7 (peak)	0.6 0.7 (peak)	< 50	ca. 3000 (testbed)

possible in the mobile operator's network. Based on a static configuration, the home agent is aware of the different mobile networks associated with the deployed MIPGATE systems. The MIPGATE system itself serves as the first-hop router for the devices in the corresponding mobile network. For the traffic which is originating on such a mobile network, the MIPGATE system uses the reverse-tunnel to forward the packets to the home agent.

For this preliminary setup, the HA is located in the Beyond 3G testbed. VPN concentrator and video bridge are placed in another location. The setup for the final deployment of the system will differ and all these core components will be located in one central network management center taking also into account redundancy and load balancing requirements.

Internet connectivity for the testbed is provided by the Technische Universität Berlin's campus-wide network, which is served by Deutsches Forschungsnetz (DFN).

Table 1 details the characteristics of the two access network technologies as we experienced the currently deployed versions. We have chosen these two technologies for the experimental validation of the system because they reflect best a potential future deployment of the overall solution.

A video bridge serves as central unit for the videoconference system and the setup of audio and video streams between the paramedic and the expert in the telemedicine center. An H.323 based video conferencing application is used which is not part of the described performance evaluation. H.264/MPEG-4 AVC with dynamically adjusted codecs (quality, frame rate) is configured for video and G.722.1 is used for audio.

All connections between the ambulance, the video bridge, and the telemedicine center are secured by a VPN (IPSec ESP).

6. EXPERIMENTAL RESULTS

To evaluate the capabilities of the MIPGATE solution, different tests in three environments have been performed. At first, the tests and measurements in the laboratory environment are described, which were used to analyze isolated performance effects. Afterwards, the results from the test drives are discussed, which allowed tests of the MIPGATE system under more realistic conditions. At the end of this section, the first experiences in the complete StrokeNet environment are presented. These three environments and tests are described below.

6.1 Laboratory Environment

The laboratory environment was used to evaluate the system behavior and minimize the influence of external factors. This way, the handover performance could be analyzed without effects resulting from mobility (varying signal quality etc.). To simulate the audio/video connection, a UDP traffic generator [20] has been used with data rates of 200 kbit/s for both directions. This constant bitrate emulates the behavior of the video transmission system used in StrokeNet. In this case, the packet generator uses a payload size of 1000 bytes. Together with the UDP and both IP headers (in the case of IPIP tunneling), this leads to a packet size of 1048 bytes. Because the complete StrokeNet environment uses VPN tunnelling, additional IPSec headers are required. The used packet size influences the packet sending rate (on given data rate). But the evaluated effects are comparable to other packet sizes. To minimize the effects of external network components, the remote communication endpoint was located in the same LAN as the home agent. Thus, only the mobility management infrastructure and access networks of the StrokeNet setup were evaluated. Because of the stationary terminal conditions, the remote-control interface of the DE was used for handover performance tests with periodically forced vertical handovers (every 15 s over a duration of 25 min) between UMTS and Flash-OFDM. In case the DE is in the remote-controlled mode, the autonomous handover decisions are disabled and changing network quality conditions are ignored. The data capture was done with *tcpdump* [21] on the MIPGATE mobile connectivity gateway for the evaluation of the packets on the wireless interfaces.

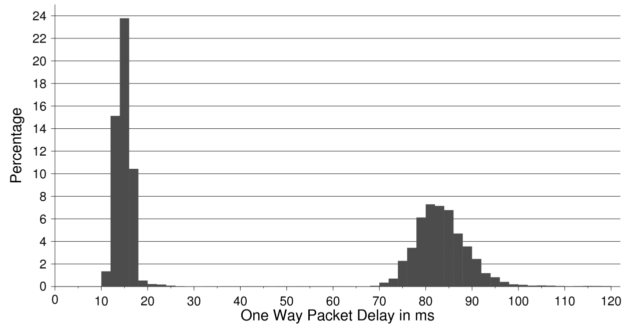

Figure 5: One Way Packet Delay Distribution

From the view of the application layer, three quality attributes - bandwidth, delay, and packet loss rate - are important. According to the performed tests, the required bandwidth is generally available. Figure 5 shows the one way packet delay distribution between a test host in the same LAN as the home agent and the MIPGATE mobile connectivity gateway. It was measured on the application layer using the traffic generator. Because the information of the used network interface is not available on this layer, it can't be distinguished between the access networks. The diagram shows two clearly seperated clusters. With the knowledge of the different network characteristics, these clusters can be assigned to the used access technologies. The first cluster with around 15 ms correspondes to Flash-OFDM whereas the second cluster around 82 ms is related to UMTS/HSDPA.

It is important to determine that 99.5% of all packets are received within 102 ms. During this measurement, the overall packet loss rate on application layer was only 0.21%. The missing packets were evenly distributed without bursts.

Real-time applications, such as videoconferencing and VoIP, are sensitive to the network delay variation, also called

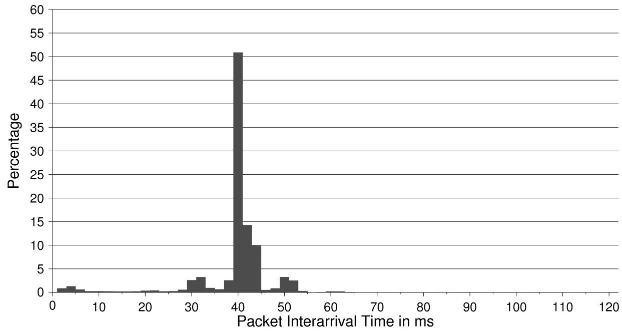

Figure 6: Packet Interarrival Time Distribution (overall)

Table 2: Packet Interarrival Time, Payload Downlink (in ms)

Traffic	Mean	Std.-Dev.	Min	Max
Overall	40	15	0	366
Handover to UMTS/HSDPA	118	37	100	334
Handover to Flash-OFDM	23	31	4	252

jitter. To measure the network jitter, the packet interarrival time was used. The packets are generated with a constant rate such that a constant network delay would lead to a constant interarrival time on the receiver. Therefore, the variation of the interarrival time of received packets shows the network delay jitter.

Figure 6 shows the packet interarrival time distribution of the payload packets. Table 2 contains the statistic values. Additional packet interarrival delays caused by the handover process increase the jitter. To allow an equable data flow on the application layer, a jitter buffer should be used. Hence, many applications use adaptive jitter buffers with variable buffer sizes to adapt to different network conditions.

In this test scenario, the required buffer size can be estimated based on the measured data. In Figure 6, 99.5% of all packets are received within 61 ms after the previous packet. Within this range, the maximum deviation from the mean value is 40 ms (between the minimum value and the mean value). This value is the maximum jitter (with a tolerated loss rate up to 0.5%). With a jitter buffer that equalizes this jitter, the overall loss rate would be 0.71% (including the above mentioned packet loss rate).

An important point for the MIPGATE concept is the seamless handover between different access networks. Additional delays in the user traffic caused by the handover process could affect the application. To evaluate the influence of the handover process, the average interarrival time (Figure 6) was compared with the interarrival times during the handover process (Figure 7). In the first case, the mean value of 40 ms shows the average reception interval. This is equal to the packet sending interval on the remote node and it depends directly on data rate and packet size. The deviation from mean value on the receiver is caused by the network.

Figure 7 shows the packet interarrival time of the downlink traffic during the handover process. This is the time between the last payload packet on the old link and the first one on the new link. The diagram distinguishes between the access technologies for the new link (UMTS/HSDPA or Flash OFDM). Table 2 also contains the statistic parameters from this diagram.

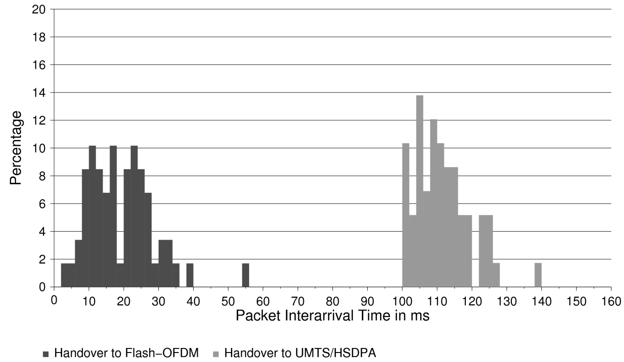

Figure 7: Packet Interarrival Time Distribution (during handover)

The value distribution in Figure 7 shows an interesting effect. It is clearly visible that the average interarrival time has a completely different distribution than the normal downlink traffic. During a handover to UMTS/HSDPA, the mean interarrival time rises to 118 ms while a handover to Flash-OFDM reduces this time to 23 ms. The reason for this is the difference in the network delay of the used access networks.

To summarize the evaluation, the presented setup fulfills the requirements for real-time audio and video transmissions. The required bandwidth is available, the packet loss rate of 0.71% is below the limit of 3-5% and the network delay of maximal 102 ms allows a good audio and video quality. The most important result of these tests is that the handover process is seamless and has no negative effect on the audio and video transmission.

6.2 Street Environment

The street environment was used to test the MIPGATE solution under realistic conditions. The focus here was on the changing radio conditions and the handover decisions. In addition, the results were used for the fine-tuning of the decision mechanism (threshold values, timing parameters).

For the driving tests, the same setup as in the lab was used. The only difference was that the Decision Engine worked autonomously. A circuit track of about 8.5 km in the center of Berlin was used. The test was performed in the normal city traffic with speeds up to 60 km/h. The Flash-OFDM was configured with an overall higher priority so that UMTS was only chosen if the Flash-OFDM was not available or in bad condition. This setup was chosen because Flash-OFDM offers a higher uplink bandwidth and a lower network delay than the currently available UMTS/HSDPA networks. So, Flash-OFDM is the better access network in this StrokeNet scenario and UMTS/HSDPA is used as a fallback solution. About the half course was covered by the Flash-OFDM network. UMTS/HSDPA was available in nearly the whole test area.

Figure 8 shows the throughput (up- and downlink) during the test drive. The color of the horizontal bar on the bottom

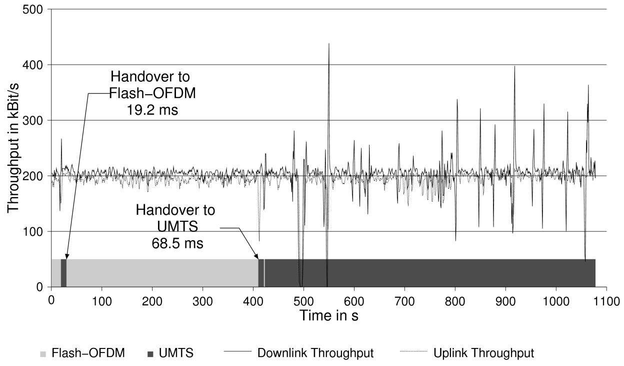

Figure 8: Throughput (during test drive)

displays the used access technology. Exemplarialy, two handovers are shown in the diagram with handover times. The main result of this test is the validation of the MIPGATE solution in application environments. But it also demonstrates the weaknesses of the currently available wireless network infrastructure. Even if a good 3G infrastructure is available, there is no guarantee for a complete coverage. One short interruption can be recognized in the throughput graph at about 500 s. This was short phase of about 9 s where neither Flash-OFDM nor UMTS/HSDPA could provide the required bandwidth.

This test would support the argumentation for the proposed mobility solution. The MIPGATE solution offers the ability to use different public access networks to improve the availability or to expand existing networks (public or private) to provide a better network coverage.

6.3 Complete Application Scenario

In the current development stage, the first prototypes are used in the complete StrokeNet scenario shown in Figure 4. This includes the external components like VPN gateways and video bridge. They are installed in ambulances together with the videoconference system. First technical trials have been performed together with medical staff, paramedics in the ambulance and stroke specialists in the clinic. Technical aspects of these trials were the subjective transmission quality and usability issues. From the medical point of view, the video quality is suitable for stroke diagnosis. These are the first estimations.

Currently, three ambulances are equipped with the StrokeNet solution and another two are in preparation. A medical study over a period of 15 months will follow. The goal is to verify the medical benefits of this solution. During this medical study the MIPGATE solution can be optimized further and new access technologies can be integrated as soon as they become available.

7. CONCLUSIONS AND FUTURE WORK

The adaptation of vehicular telemedicine applications to the evolution of wireless communications depends basically on the development of cost-effective, reliable networking solutions that offer availability, coverage, security, QoS, mobility and application integrity. Our mobile connectivity gateway, MIPGATE, is an attempt towards this direction. It envisions a heterogeneous wireless network as the next generation communication platform to build itself upon and exploits the availability of the multiple access technologies to provide the user with seamless mobility. It is designed as a gateway that enables various user devices in a moving vehicle to build a mobile network and connects them securely to wireless communication infrastructures.

StrokeNet is the case study that shows the applicability of our solution to mobile telemedicine. In its current version, the project aims at supporting the wireless connectivity of a videoconferencing application in a moving ambulance, which is a high priority service for stroke experts that assists them by diagnosing the patient remotely and giving directions to the emergency personnel accordingly. The performance of MIPGATE is evaluated through the StrokeNet scenario under realistic conditions. The test environment consists of the public UMTS/HSDPA network and our Beyond-3G testbed which offers Flash-OFDM as an additional access network technology. Our results validate that MIPGATE can support seamless connectivity with an acceptable connection quality for videoconferencing, which is a high-demanding application in terms of bandwidth, loss and delay, in a moving ambulance.

Following the medical studies to evaluate the potential of StrokeNet, we intend to extend the application set to include the transfer of physiological data such as ECG, blood pressure and oxygen saturation as well as still images. This way, a wider selection of emergency cases, e.g. heart attacks, poisonings or car accidents, can benefit from telemedical support. The system architecture of MIPGATE can easily be adapted to more general application areas such as broadband Internet access for vehicular systems and mobile networks.

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