

On SCTP Multihoming Performance in Native IPv6 UMTS–WLAN Environments

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Abstract—Multihoming is one of the most attractive features of SCTP (Stream Control Transmission Protocol) aiming to make this prosperous transport scheme competitive in mobile environments when the mobile hosts are equipped with multiple interfaces. The complementary characteristic of the 3G UMTS (Universal Mobile Telecommunications System) and WLAN (Wireless Local Area Network) architectures motivates operators to integrate these two successful technologies. Recently spreading wireless devices are increasingly provided with multiple networking interfaces such enabling end-users to access Internet services using e.g. the WLAN's higher bandwidth wherever available, and connecting to the UMTS network in other cases. This paper investigates the performance of multihomed SCTP hosts through extensive experimental studies in such an integrated heterogeneous environment. In order to do this we designed and implemented a real native IPv6 UMTS–WLAN testbed equipped with novel IPv6-based mobile technologies, such providing ideal conditions for SCTP multihoming performance analysis. In this testbed architecture we analyzed numerous settings to measure the handover behavior of the protocol in terms of handover effectiveness, link changeover characteristics, throughput and transmission delay. As our results show, accurate SCTP parameter setup can significantly decrease the handover delay and eliminate the data transmission interrupts.

Keywords - SCTP, multihoming, performance evaluation, IPv6, UMTS, WLAN, testbed, vertical handover, heterogeneous environment, transport layer mobility

I. INTRODUCTION

Mobility is becoming increasingly popular feature for the Internet users; however the developers of the early network protocols did not take into consideration this possibility. The Internet was a static network, where the hosts were connected through one specific link and identified with a unique IP address. The new mobile access technologies have totally changed this attitude. For the next-generation Internet, one of the most essential requirements is to make the roaming possible without losing the connection. Demand for anywhere, anytime communications has been increasing recently. Moreover, with the extensive growth of the Internet and mobile/wireless systems, the user demand for continuous data access caused the introduction of many different kinds of access technologies. Therefore future telecommunication architectures could easily appear as an integration of multiple wireless access technologies (e.g. Bluetooth, UMTS, WLAN, WiMAX, etc.). By enabling multi-access in mobile systems, redundancy and fault tolerance can be achieved. Hosts equipped with multiple network interfaces can be

connected to the Internet via different ISPs, such failures in one network cannot easily break ongoing communication sessions: hosts are capable of switching over to another connection. Moreover, if both connections are active at once, but higher packet loss and delay is experienced on one path, multihoming capabilities can be used to hand over current sessions to the connection offering better values of Quality of Service (QoS) parameters.

The applied Internet protocols and network architectural structure have to be modified and extended to support all requirements of the above advanced networking features. The key problem is how to manage the frequent IP address changes, i.e. how to hand over ongoing communication processes from one interface (or path) to another active interface with the minimal disruption. Mobility and multihoming supporting schemes were designed to handle this question.

Mobility and multihoming support can be provided in different layers of the ISO/OSI architecture [1][2]. Mobile IP [3] with Multiple Care-of Addresses (MCoA) [4] extension is a layer 3 solution, while several proposals exist also in the transport [5] and even in the application layer [6]. A good example for a novel solution between the latter two traditional layers is the HIP (Host Identity Protocol) [7]. To introduce all of the possible solutions and their own advantages and disadvantages is out of scope of this paper. However, a good survey with an extensive analysis can be found in [8] anticipating a multi-layered approach for advanced mobility support and suggesting the transport layer as the main candidate for Internet mobility and multihoming support.

In this paper we focus on SCTP and its multihoming and multistreaming performance over heterogeneous IP networks, more precisely over native IPv6 UMTS–WLAN environments. The importance of building our SCTP experiments on a native IPv6 architecture resides in the fact that IP is considered as the best solution to integrate heterogeneous wireless access networks, and IPv6 will actually be the main networking protocol of the next generation Internet. Nowadays, the most widespread IP version (IPv4) is based on a scheme where the devices are identified by 32-bit long addresses. However, due to the continuously growing Internet penetration it is predicted that all currently available IPv4 address blocks will be allocated by the year 2011 [9]. However there are several methods to overcome this problem (like expanding application of NATs or introducing a secondary market for already allocated but currently unused IPv4 address blocks), it is unquestionable that the most future-

proof strategy for the Internet is the deployment of IPv6. The fundamentals are the same in both versions (v4 and v6), but IPv6 introduces a much larger address space (128-bit long addresses are applied) allowing convenient implementation of Internet applications requiring point-to-point connections between hosts. In addition, IPv6 also provides integrated security (IPSec), QoS, elaborated autoconfiguration and multicasting, and extensions supporting Layer 3 mobility and multihoming. Generally speaking IPv6 supports “always on” paradigm and peer-to-peer type communication in a lot more improved way than IPv4; such providing more seamless and rich communication of users in future heterogeneous, all-IP mobile and wireless architectures.

In order to study multihoming in an integrated, all-IP heterogeneous mobile environment, we realized a native IPv6 UMTS–WLAN testbed and examined the main performance measures of a SCTP-based Layer 4 mobility/multihoming architecture.

The rest of the paper is organized as follows. Section 2 presents related works giving an overview of initial and ongoing research efforts on SCTP multihoming. In Section 3 theoretical background of our work is introduced including the basics of multi-access and multihoming, SCTP, and UMTS–WLAN interworking. Section 4 is devoted to introduce our native IPv6 UMTS–WLAN testbed architecture designed to perform practical SCTP multihoming evaluation, while Section 5 shows and explains the experimental results. Finally, Section 6 concludes the paper and sketches our future work.

II. RELATED WORK

In this paper the behavior of SCTP and the effect of the protocol’s main parameters (*HB.Interval*, *RTO.Min*, *RTO.Max*, etc.) on SCTP multihoming performance is evaluated in a real-life native IPv6 UMTS–WLAN heterogeneous architecture.

Previous works examining SCTP mobility and multihoming performance are mainly based on simulations [10][11][12] or using emulator tools to imitate the behavior of different type of networks [13][14][15]. Some new ideas and SCTP extensions were also proposed. A new method was investigated in [16], in order to facilitate seamless vertical handover between wide area cellular data networks such as UMTS and WLANs using SCTP, but the evaluation was performed also using simulations. In [17] the authors presented and analytically evaluated a novel error recovery scheme to improve SCTP’s mobility supporting capabilities in heterogeneous wireless networks. Shaojian Fu et al. [18] also provided an analytical model for studying the performance of SCTP multihoming. Their proposed model has been validated against simulations. Authors of [19] presented analytical calculations as well in order to have more accurate estimation of the failover time in SCTP multihoming scenarios.

The SCTP standard does not allow using multiple path simultaneously, however, this possibility can gain significant improvement in overall data transmission bitrate. Numerous proposals are available to overcome this issue. Ye et al. [20] introduced an independent per path congestion control principle for standard SCTP, while in [21] a similar solution is presented with load sharing techniques.

There are also attempts to analyze the behaviour of multi-homed SCTP associations and stalls [22], and also to look at other issues related specifically to SCTP multihoming [23][24][25] or to special use-cases of SCTP [26].

Some of the first previous works dealing with SCTP mobility and multihoming performance evaluation in real life testbeds were [27][28] and [29], where authors mainly confined their work to study how SCTP deals with packet loss and throughput in quite simple multihoming experiments. Jinyang Shi et al. [30] investigated the key scenarios for multi-access and multihoming based on an analytical model, and also performed some SCTP/TCP comparison measurements in a GPRS–WLAN architecture. An interesting SCTP testbed was created by Sang Tae Kim et al. [31]. The authors developed a novel IPTV service exploiting the multistreaming feature of SCTP, and compared their method with TCP- and UDP-based schemes for a variety of network conditions. Practical evaluation of SCTP multihoming was performed by F. Siddiqui et al. in [32]. The authors discussed the design and performance issues related to SCTP multihoming operation in a real Ethernet–WLAN multi-network architecture. S. Fallon et al. [33] examined SCTP switchover performance in a pure WLAN environment and showed that with the default parameters, SCTP implementations behave in a counterintuitive manner allowing more time for switchover when network conditions degrade. Also a pure WLAN testbed was used by R. Wakikawa et al. [34] in order to present a smooth handover scheme for Mobile IPv6 based on SCTP failover mechanism. D. Emma et al. [35] and A. Dainotti et al. [36] introduced experimental studies on SCTP in wired (Ethernet), wireless (WLAN) and heterogeneous (wired/wireless) scenarios in terms of throughput and jitter, and also compared SCTP with UDP and TCP considering different packet rates.

However the above efforts focus on measuring SCTP multihoming performance issues, examining specific protocol extensions and studying handover mechanisms, rather than providing extensive practical evaluation of SCTP in an integrated heterogeneous testbed architecture, with support of the next generation IP protocol (IPv6) for enabling unlimited peer-to-peer communication in the future “Internet of Things” world.

III. BACKGROUND

As the background of our work we first briefly overview the main advantages of multi-access and multihoming followed by the basics of SCTP including some tools for providing efficient multihoming support. Finally, some relevant UMTS–WLAN interworking scenarios will be discussed in order to show the different levels of complexity.

A. Benefits of Multi-access and Multihoming

New equipments integrate several access technologies in order to increase bandwidth availability or to select the most appropriate access technology according to the type of flow or choices of the user. A multi-access endpoint determinates a host with several network interfaces, however, to manage these interfaces a novel feature called multihoming support must be introduced to efficiently control these interfaces for improved connectivity.

Multihoming is an advantageous technique to increase the reliability of the end-to-end connection, because it makes possible to reach the multihomed host on more than one IP address. If the communicating endpoints and the IP network are configured in such a way that traffic from one node to another travels on physically different paths (different subnetworks and thus different destination IP addresses are used), associations become tolerant against physical network failures. When one of the interfaces/paths becomes unavailable, the other paths are still ready to deliver data. Besides, multi-access provides ubiquitous access to offer an extended coverage area for the mobile hosts. It is also a good opportunity to spread network traffic load among several routes. This is achieved when traffic load is distributed simultaneously among different connections.

In order to efficiently manage the traffic load on the host interfaces, the corresponding paths must be monitored. When the condition of the actual interface/path is getting worse or fail, a new interface should be assigned for the connection. One of the most important issues is to change the primary path seamlessly. The endpoint must recognize the link failures as soon as possible and change the active IP address, but the handover delays or temporal channel errors should not cause the change of the primary path. The IP change trigger may depend on several protocol settings. It must be defined when should a path considered broken. The number of retransmission attempts, the packet loss ratio and different time constraints may affect the performance of the interface/path changes.

B. SCTP

SCTP (Stream Control Transmission Protocol) is a general purpose transport protocol for the Internet, described in RFC 4960 [5]. Similarly to TCP (Transmission Control Protocol), SCTP also provides connection oriented, reliable and ordered delivery of data between two endpoints. The developers of SCTP aimed to create a new transport protocol that would overcome the limitations of TCP and UDP (User Datagram Protocol). It offers acknowledged error-free non-duplicated transfer of datagrams. Detection of data corruption, loss of data and duplication of data is achieved by using checksums and sequence numbers. In order to provide reliability, a selective retransmission mechanism is applied. SCTP can also be used for applications where monitoring and detection of loss is required. For such applications the SCTP failure detection mechanisms will actively monitor the session. These mechanisms are also used to manage the SCTP handover process in case of multihomed hosts.

SCTP uses an end-to-end window based flow- and congestion control mechanism similar to the one that is used in TCP. The congestion control mechanism of SCTP has been modified and adapted for multihoming. SCTP uses an Additive Increase, Multiplicative Decrease (AIMD) algorithm, similarly to TCP. SCTP endpoints may be reachable by more than one transport address through different data paths. For each possible path a discrete set of flow- and congestion control parameters is kept.

The major features that SCTP provides are multihoming and multistreaming. The multihoming feature enables to be used for mobility support, without any special router agents or anchor points in the network, while multistreaming supports multiple

independent streams within an association. The detailed introduction of multihoming and multistreaming are presented in the following subsections.

1) SCTP Multistreaming

SCTP distinguishes different streams of messages within one SCTP association. All the streams (chunks) within an association are independent but related to the association. Each stream has a stream number that is included inside SCTP packets chunk headers. This delivery scheme reduces unnecessary head-of-line blocking between independent streams of messages. In other words a blocked stream does not affect the other streams in an association. SCTP streams are unidirectional channels, within the data messages are usually transported in sequence. The application may also request a message to be delivered unordered, which can reduce blocking effects in case of message loss, since the reordering mechanism of one stream is not affected by that of another stream that may have to wait for a retransmission of a previously lost data chunk. SCTP multistreaming is particularly effective in cases, when independent control and data channels are considered in the communication. In TCP, control and data typically share the same connection, which can be problematic because control packets can be delayed behind data packets. If control and data messages are delivered within independent streams, control data could be dealt with in a timelier manner, resulting better utilization.

2) SCTP Multihoming

One of the most important enhancements in SCTP over traditional transport layer protocols is the multihoming capability. A multi-homed host is one that can be reached using more than one IP addresses, usually through more than one network interfaces. This feature allows an endpoint of a SCTP association to be mapped to multiple IP addresses. Among the possible IP addresses, one is selected as Primary Address, while the Primary Path is considered as the network path that leads to the Primary Address. Unless specified otherwise by the SCTP user, an endpoint should always transmit on the Primary Path. The sender may change the Primary Address if the number of failures on the Primary Path exceeds a certain threshold. In this case the SCTP implementation notifies its upper layer process that the link has become inactive. Retransmissions should be done on different paths as well, so when one link is overloaded, retransmissions do not affect it.

SCTP packets consist of a common header, followed by a variable number of information units, which are named chunks. There are two types of chunks: control and data chunks. Data chunks contain the actual user messages, while control chunks are used to support the peer-to-peer protocol.

If a client is multihomed, it informs the server about all its IP addresses with the INIT chunk's address parameters. Hence, the client is only required to know only one IP address of the server because the server provides all its IP addresses to the client in the INIT-ACK chunk. SCTP is able to handle both IPv4 and IPv6 addresses.

Another important feature of the SCTP regarding multihoming, is the heartbeat mechanism. This mechanism detects failures in idle paths and endpoints. The aim of this mechanism is to detect whether a destination address is active or passive. HEARTBEAT chunks are sent periodically to all idle

destinations, and the number of sent HEARTBEAT messages without receipt of a corresponding HEARTBEAT-ACK is maintained. The timing of the HEARTBEAT chunks for destination i is determined by the $HB.Interval$ and RTO (Retransmission Timeout) protocol parameters according to the following equation [5]:

$$H_i = RTO_i + HB.Interval(1 + \delta), \quad (1)$$

where δ is a random value between -0.5 and 0.5 and RTO is the Retransmission Timeout for path i .

An address is considered active if acknowledgement is received from its peer within a defined time period (RTO). In this way RTO is a prediction of the upper limit of RTT (Round Trip Time). Separate RTO is maintained for each path which is calculated using the smoothed average of the periodically measured RTT ($SRTT$) and the RTT variation ($RTTVAR$). From these, RTO is computed as [5]:

$$RTO = SRTT + 4RTTVAR \quad (2)$$

If the number of consecutive transmission timeouts exceeds the Path Maximum Retransmission (PMR) protocol parameter, it means the address is inactive. Every time when timeout occurs, the PMR counter is incremented and the value of the RTO is doubled for that path. If the new RTO is less than $RTO.Min$, it will be set to $RTO.Min$, if it is greater than $RTO.Max$, it will be set to $RTO.Max$. According to the previously presented procedure the delay of the path failure recovery and the handover process can be calculated as follows:

$$\Delta = \sum_{i=0}^{PMR-1} 2^i \cdot RTO \quad (3)$$

Generally the failover time using default SCTP settings is likely to be unacceptable to users. Shortening this time can be achieved by setting the relevant protocol parameters (e.g. $RTO.Min$, $RTO.Max$, PMR) to smaller values.

When the Primary Address becomes unreachable or the link conditions are not acceptable, alternative IP address should be used if the endpoint is multihomed. With the heartbeat mechanism the SCTP knows which other addresses are active or not and thus, can avoid using another path that has a failure.

Using SCTP the mobility means the ability to change the endpoints and IP addresses while keeping the end-to-end connection. The change of communication link should be done with minimal disruption to the data transmission in progress. The multiple interface concept can be utilized in dynamic mobile networks where e.g. the host terminal has only one interface but the connection is frequently changed. If the possible IP addresses are known they can be bound even at connection setup. Using the early IP address bindings, the handovers can be handled in such way.

Mobile SCTP (mSCTP) [37] is an extension of the SCTP in order to support mobility more efficiently. The mSCTP protocol utilizes the functions to dynamically add or delete IP addresses for an existing connection in order to support mobility.

C. UMTS–WLAN architecture basics

One of the main features of next generation communication architectures evolving toward 4G and beyond is the inter-operation of multiple radio access technologies such creating heterogeneous networks. In general, today's heterogeneous systems tend to apply a core layer which deals with all network functionality and operates a single network to the upper-layer protocols. Therefore different radio access technologies implement only the physical and link layer functions where each function is specialized to the appropriate technology, and a common language (the Internet Protocol) provides integration.

Access technologies differ in their physical layer, medium access control and link-layer protocols, because different methods are needed to meet different requirements of the physical medium (i.e. local- or wide-area coverages). Consequently, user experience in a 3G UMTS cellular network is quite different from 802.11a/b/g/n WLANs. These differences constitute the complementary characteristics of 3G UMTS and WLAN technologies in the means of service coverage, available bandwidth, RTT, modulation, roaming, FEC, deployment and service costs, etc., such making the integration of these coping architectures very promising (see Table 1 for details).

TABLE I. COMPLEMENTARY CHARACTERISTICS OF UMTS AND WLAN

Parameter	Access technology	
	3G UMTS	802.11a/b/g/n
Coverage	wide-area (15 - 20 km)	local-area (50 – 800 m)
Data rates	low (up to 2 Mbit/sec)	high (5 – 500 Mbit/sec)
RTTs	high (150 – 500 ms)	low (5 – 50 ms)
Security	strong (e.g. AKA)	relatively weak (e.g. WPA-PSK)
Mobility	Link-layer	Layer 3
Cost	high	low

UMTS provides always-on wide-area radio access scheme with high user-mobility support, relatively low offerable data rates and high deployment and service cost, while WLAN networks cover only small, local-areas and present much higher data rates with lower user-mobility support, lower deployment and service cost.

3GPP TSG SA1 workgroup defined six different levels for the UMTS–WLAN interworking [38]. Each level describes the next step on the integration path of open/loose/tight coupling the different access technologies while setting up a flexible and scalable framework to realize full cooperation. The complexity of the inter-working scheme increases from level one to level six. In level one the cooperation between the two systems does not effect the two systems too much as only billing and customer care have been united. The second level provides 3GPP system-based access control and charging while the third level introduces the IP level cooperation between the WLAN and UMTS system, thus Packet Switched services in UMTS are available from the WLAN network as well. However, this third level does not prevent discontinuity of services when performing a handover. Thus level four grants the continuity of services while level five assures seamless operation. In case of the sixth level of cooperation even the Circuit Switched services are made available and handovers cannot be identified any more.

IV. TESTBED ARCHITECTURE

In order to provide an IPv6-capable heterogeneous testbed for analyzing SCTP multihoming in next generation multi-access communication systems, we designed and implemented a native IPv6 UMTS–WLAN architecture based on the existing hardware elements of Mobile Innovation Center (MIK) located in Budapest, Hungary. However almost all the relating hardware and software components were presented in MIK, one important item was missing: the laboratory did not possess any dedicated Gateway GPRS Support Node (GGSN) device for supporting native IPv6 UMTS access. Thus one of our main tasks during the implementation of our native IPv6 UMTS–WLAN testbed aiming to perform extensive SCTP multihoming performance measurements was to design and develop a GGSN, prepared to be integratable with the other UMTS elements and adequate to handle IPv6 type PDP (Packet Data Protocol) contexts as well. In order to achieve this, we used a software GGSN implementation called OpenGGSN [39] as a basis of our work.

OpenGGSN was originally developed to provide a full GTP (GPRS Tunnelling Protocol) [40] implementation for the open source community of Unix systems. The last version was released under GNU GPL in 2004 with version number 0.84 written in standard C programming language. The main part of OpenGGSN 0.84 is the GTP library, the GGSN implementation using the GTP library and an SGSN (Service GPRS Support Node) emulator for testing purposes. The GTP library implements both of GTPv0 and GTPv1 specifications. The GGSN module handles IPv4 PDP contexts with two different address allocation schemes (static and dynamic) and uses virtual TUN interfaces for delivering user data. QoS management is totally missing from the original version. The SGSN emulator handles also only IPv4 type PDP contexts.

Our GPL licensed and publicly available OpenGGSN modification is based on the above software components: OpenGGSN 0.84_v6_03 [41] uses the same GTP library and the main architecture as version 0.84, but extends the original edition with the missing IPv6 routines, some other related components and also with functions making the software to be able to cooperate with HUAWEI SGSN 9810 Serving GPRS Support Node for setting up, maintain and tear down contexts of native IPv6 UMTS communication. All the organic procedures required for the basic standard operations of an IPv6 UMTS system were implemented in our GGSN version. However, due to time constraints and lack of resources we had to take advantages of some simplification possibilities during the design of our IPv6-capable GGSN software in order to reduce the development time and other requested expedients. These simplifications are mainly connected to the address allocation procedures and the QoS-related functions. Despite the fact that the recommendation of [42] says that GGSN should be able to allocate different IPv6 prefix(es) to different UEs thus making possible to link more the one prefix to one PDP context (i.e. single-access multihoming support over 3G), OpenGGSN 0.84_v6_03 does not support this kind of behaviour. The management of different address pools and the QoS provisioning functions are also missing: pre-set link-local address, prefix and resources can only be assigned to the UE sending an Activate PDP Context Request message. All of these

limitations and known issues (together with our main adjustments and fixes) are precisely detailed in [41]. Despite the fact of the currently existing limitations, our work-in-progress, open source IPv6-capable software GGSN platform provides a highly configurable 3G testing environment making possible to observe, measure and even modify every kind of GGSN function, traffic or operation.

The integration of our IPv6-compatible GGSN software into a compact, loosely-coupled IPv6 UMTS–WLAN testbed architecture was a six-step procedure. First, we had to create a new, IPv6-compatible APN in the SGSN, then we had to enable IPv6 PDP contexts for the SIM cards of our devices in the Home Subscriber Server (HUAWEI HSS 9820). After that we compiled, configured and started all the required OpenGGSN 0.84_v6_03 components on a SunFire X4200 running Ubuntu 7.04 (Feisty Fawn) with kernel 2.6.23. As the 4th step we deployed an UMTS–WLAN integrated authentication system managed by a Radius server applying EAP-TLS in order to provide 3GPP system-based access control. Step No. 5 was the configuration of end terminals, while the last step was setting up the appropriate IPv6 routing entries in the routers of the testbed in order to provide GEANT connection to the mobiles. Figure 1. shows all the details of the integrated, native IPv6 UMTS–WLAN architecture we used for our SCTP multihoming experiences.

In this testbed, the UMTS infrastructure consists of one Node B and one RNC linked to the SGSN which is connected to the GGSN and the HSS using standard interfaces. As Figure 1. shows, the SGSN and the GGSN are still communicating over IPv4 (i.e. the GTP tunnels are set up on IPv4), but this fact has no effect on the UE's native IPv6 UMTS connection: the mode of communication between the GSN nodes does not have any impact on the fact that the 3G users are gaining native IPv6 UMTS experience. The GGSN is connected to the Radius server, to the WLAN access component and to the outside network through its Gi interface using native IPv6 transport. The UMTS component enables IPv6 services at maximum 2 Mbit/sec download and 384Kbit/sec upload speeds with RTTs around 180ms. The WLAN connectivity comprises IEEE 802.11b/g compatible Linksys WRT54GL Access Points. This exclusive, local wireless access enables UE to maintain native IPv6 connection with data rates up to 28Mbit/sec and RTTs around 10ms.

For accessing this native IPv6 UMTS–WLAN architecture, UE has been equipped with two separate interfaces for WLAN and UMTS access respectively. UE's hardware is based on Fujitsu-Siemens Lifebook C1110D with a 3Com 3CRPAG175 PCCARD WLAN adapter featuring Atheros^R chipset, and a Nokia N93i SmartPhone as an IPv6-compatible 3G modem for UMTS connectivity.

The SCTP Media Server is a standard PC with a 4GHz Pentium 4 processor and 1024 MB RAM, running a C implementation of our SCTP-based media server application supporting multihoming/multistreaming features and also measurement functions.

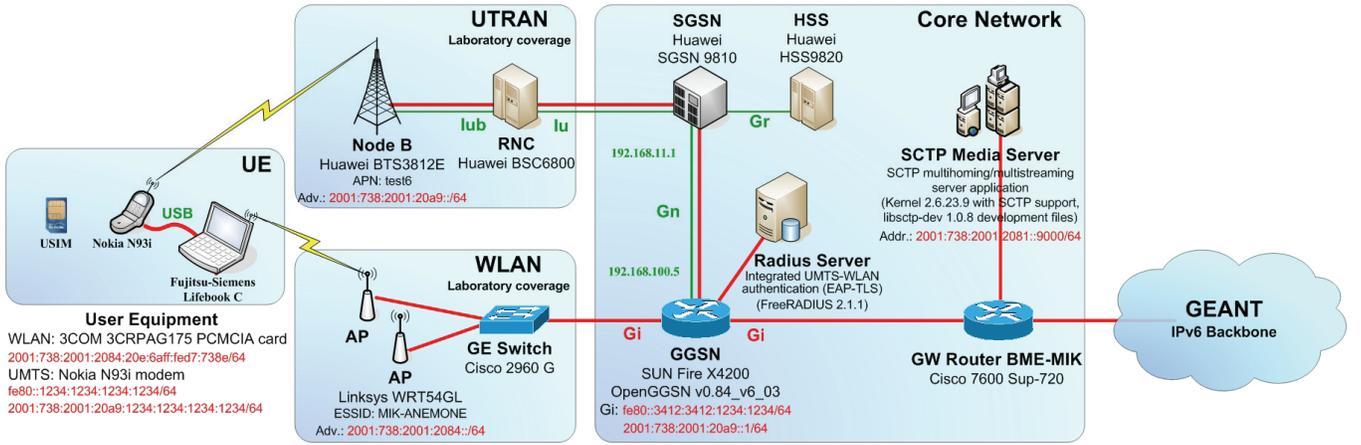


Figure 1. SCTP multihoming testbed in a loosely-coupled, native IPv6 UMS-WLAN architecture

V. EXPERIMENTAL RESULTS

In this section the measurement results of different test scenarios are introduced. SCTP has a large number of adjustable association and path parameters that can be modified using `setsockopt()` kernel function. Applications use `setsockopt()` and `getsockopt()` to set and retrieve socket options respectively. These socket calls are used to change different socket options.

We have focused our measurements on SCTP handover behavior. Our goal was to analyze the effect of different protocol parameter settings on the handover process. However, the handover also depends on the network environment. The tests were made in the native IPv6 UMS-WLAN environment introduced in the previous section.

In the first scenario the multihoming feature of the SCTP protocol was investigated. We have examined the SCTP multihoming performance in a considered situation where the user has WLAN and 3G UMS connections simultaneously. The default and primary connection is the WLAN because it provides higher bandwidth, lower latency and not at least it is cheaper than the communication over UMS network. Therefore the primary address was always belonging to the WLAN interface. The considered scenario was that the user is using its UMS connection only if WLAN is not available. As the WLAN is accessible again, the communication path is to be changed back to the WLAN interface. In order to effectively introduce the considered scenario we have illustrated the Transmission Sequence Number (*TSN*) versus time on Figure 2. Each DATA chunk corresponds to one plot. The DATA chunks that were transmitted through the WLAN interface are depicted in blue, while the DATA chunks delivered in the UMS network is red.

WLAN networks have more transmission capacity, which is also visible in Figure 2. The slope of the blue curve (WLAN) is higher than the red one (UMTS). It is noticeable when the handover occurs from WLAN to UMS the data communication is not continuous. The SCTP stack needs time to recognize that the primary path is not available any more. It also needs time to retransmit the lost packets and reach the available UMS bandwidth. The other direction (UMTS→WLAN handover) is faster because neither link failure detection nor data retransmission is needed.

The most important protocol parameters from the handover point of view are *RTO.Min*, *RTO.Max* and *Path.Max.Retransmission (PMR)*. These parameters, and the continuously calculated *RTO* value determinate the speed of the handover. We have set *RTO.Min = RTO.Max* therefore the *RTO* was kept on a constant value disabling to redouble it every time when timeout occurs, see equation (3). In such way the handover process can be speed up. The delay of the path failure recovery and the handover process in this case can be calculated as follows:

$$\Delta = PMR \cdot RTO \quad (4)$$

The negative effect of this solution is that the *RTO* must be set manually by adjusting *RTO.Min* and *RTO.Max* parameters, therefore the SCTP will loose its adaptability to the link changes.

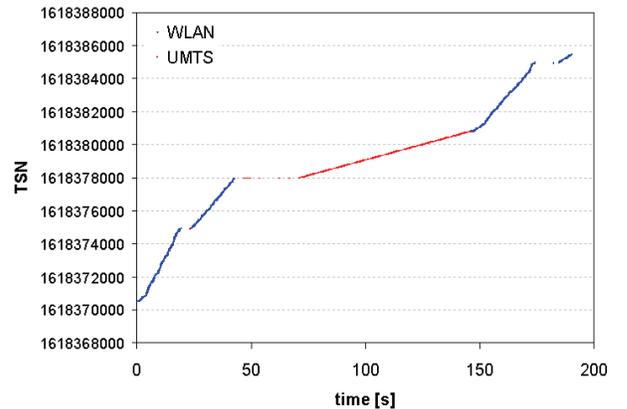


Figure 2. Transmission Sequence Number (*TSN*) versus time (*HB.Interval*=10s, *RTO*=4000ms, *Path.Max.Retrans*=5)

In order to analyze the effect of *RTO* on the handover process we have measured DATA transmission interrupt that is considered as the elapsed time between the last DATA chunk sent on the failing primary (WLAN) interface and the first DATA chunk arrived at the continuously available secondary (UMTS) interface (Figure 3.). The level of seamlessness depends on this delay. We have made more measurements to eliminate to variance of the measured values (the min, max and average values are illustrated in the figures).

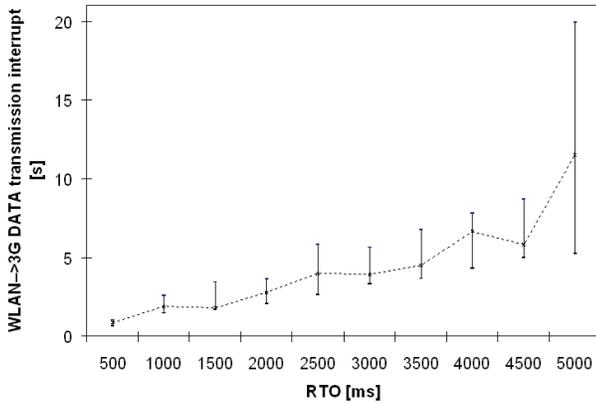


Figure 3. The impact of the RTO on the DATA transmission interrupt (WLAN to 3G UMTS handover)

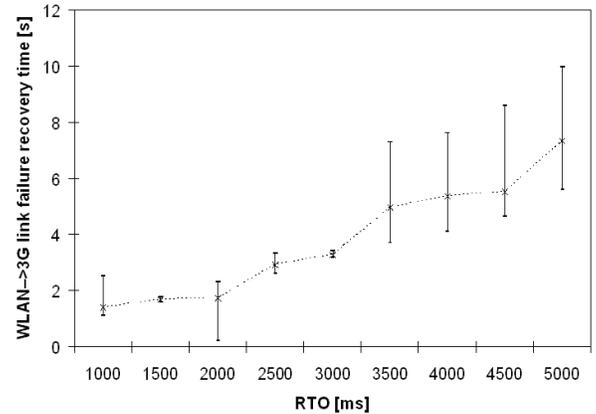


Figure 4. The impact of the RTO on the link failure recovery time (WLAN to 3G UMTS handover)

The other important parameters from the handover point of view were set as follows: $HB.Interval = 10s$, $PMR = 5$. The results fulfill our expectations because the delay is rising linearly when the RTO is incremented. Using the default SCTP parameters ($RTO.Min = 1s$, $RTO.Max = 60s$) the delay would rise exponentially due to RTO redoubling. We have also measured the DATA transmission interrupt with default SCTP parameters. The average handover delay was $227s$, which is not acceptable for the users.

The link failure recovery time and the previously presented DATA chunk transmission delay measurements are very similar. In means of link failure recovery time we have analyzed how fast the path failures can be recovered. The recovery time is considered as the time difference of the first DATA chunk on the new path and the old link failure. As Figure 4. shows as high the RTO value is as long time is needed from the link failure till DATA chunk appears on the secondary link. Notice that $RTO.Min = RTO.Max$ therefore the RTO was kept constant.

We have also analyzed the backward direction, when the primary link (WLAN) becomes available again. The results in Figure 5. shows link availability recognition time needed to recognize that the WLAN is available again is independent from

the RTO . The link availability recognition time is considered as the time elapsed from the link appearance till the first DATA chunk on it. The RTO variable has impact only on the link failure recovery time, because RTO time is needed without acknowledging the packet to consider a datagram as a lost one.

Besides RTO , the PMR (Path Max. Retransmission) is the other key parameter of the SCTP handover. PMR contains the maximum number of retransmissions before this address shall be considered unreachable. Using the default parameters of the protocol the link failure recovery time is rising exponentially according to (3). We have fixed the RTO parameter by setting $RTO.Min = RTO.Max$ so the link failure recovery time is rising linearly as (4) defines. In our measurement we have set the RTO value to 5 seconds (Figure 6.).

The SCTP heartbeat mechanism is responsible for detecting when the primary path has recovered. HEARTBEAT chunks are sent periodically as defined by the $HB.Interval$ and the corresponding equation, see (1). To discover that the primary path becomes available (link availability recognition time), it is desirable to keep the interval between HEARTBEATs relatively small. The obtained measurement results confirm this theory as Figure 7. shows.

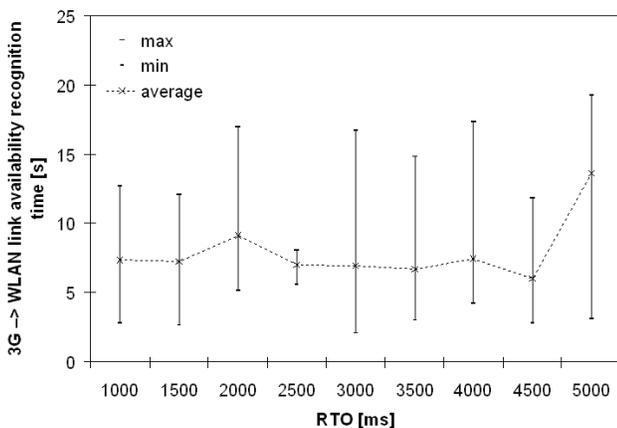


Figure 5. The impact of the RTO on the link availability recognition time (3G UMTS to WLAN handover)

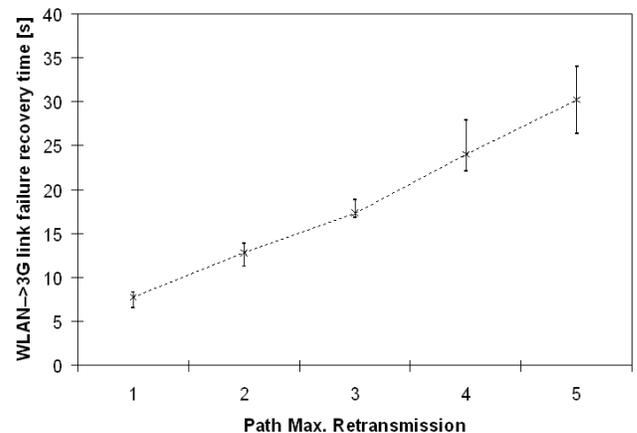


Figure 6. The impact of the PMR on the link failure recovery time (WLAN to 3G UMTS handover)

When changing the communication path back to the primary path, the first packet on the primary link is always a HEARTBEAT chunk. The DATA chunk can be delivered only if HEARTBEAT-ACK is received. The link failure detection is independent from the *HB.Interval* parameter.

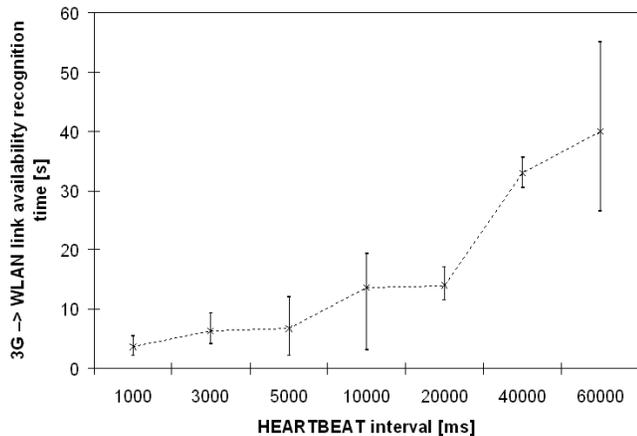


Figure 7. The impact of the HEARTBEAT interval on the link availability recognition time (3G UMTS→WLAN handover)

We have analyzed the performance of SCTP with respect to delay, jitter and throughput with different traffic loads (Figure 8.) Comparative analysis were made between SCTP and both TCP and UDP. The traffic between the two SCTP hosts was delivered as one stream. We used D-ITG [43] packet-level traffic generator to produce traffic flows and to perform measurements. D-ITG can be used to analyze throughput and jitter at the packet level, and also to measure the round trip time delay and the one-way delay. In order to correctly measure the delay of the transmission precisely synchronized endpoints are needed. We have used NTP (Network Time Protocol) for this purpose. The offset of the two endpoints' system clock was acceptable for the delay measurements in both WLAN and UMTS transmissions. In our testbed the average RTT in WLAN was 1.019ms, while the standard deviation was 0.66ms according to the *ping6* tool. Using the UMTS interface the measured RTT was 207.94ms with 119.929ms standard deviation. When the requested bitrate becomes higher than the available bitrate of the used access

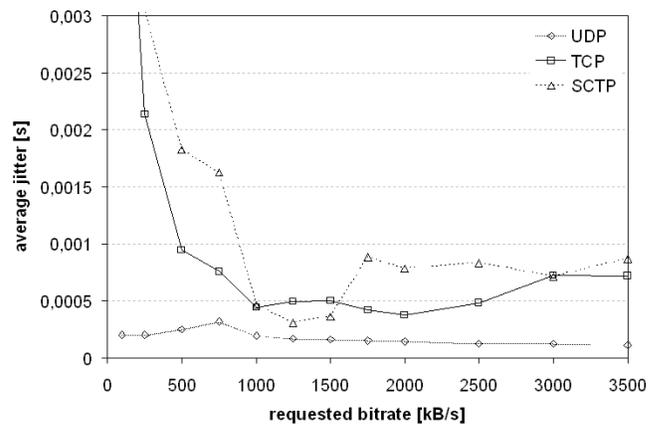
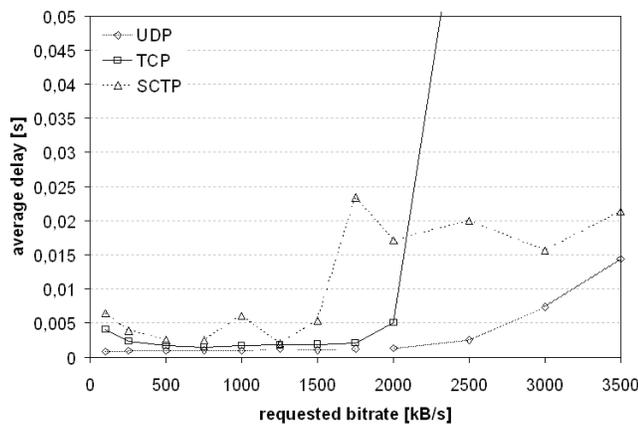
technology, the delay of packet delivery is increasing. The highest delay belongs to TCP due to its congestion control mechanism and the retransmissions of the lost packets. UDP is the protocol that presents the lowest delay and jitter in all cases, while SCTP presents intermediate delay and jitter values. SCTP congestion control provides lower bitrate but lower delay as well. The sudden increase of the delay appears when the network becomes congested.

We have also compared the transport protocols in native IPv6 WLAN and UMTS networks from the throughput point of view (Figure 9.) According to the protocol RFCs we have expected similar behavior because SCTP and TCP adopt the same congestion and flow-control scheme, with the exception of the fast recovery mechanism used by TCP. The current specification of SCTP's congestion control causes performance degradation when there are multiple packet losses in a single window. Our measurements confirm this degradation.

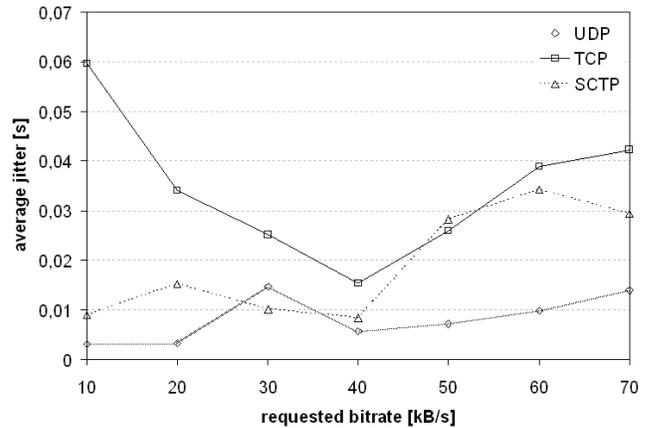
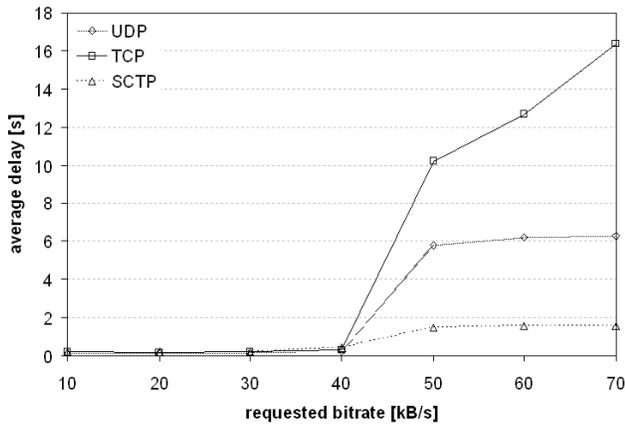
In order to measure the throughput effectiveness of the protocols we have injected synthetic traffic into our testbed with the D-ITG tool and measured the throughputs. The highest bitrate was reached by the UDP because it does not use congestion controlling and retransmissions. On the other hand, UDP suffers from significant packet loss rates. In the competition of the congestion controlled and reliable protocols the TCP seems to have a better control of congestion and it can serve higher bitrate. From the throughput point of view the SCTP has the worst performance. It could not even reach the available capacity of the WLAN links. In our measurements the TCP throughput was about 20–30% higher than the SCTP throughput above 1500kB/s offered bitrate. The breakpoint of the throughput curve was 1500kB/s in case of SCTP, while 2500kB/s in case of TCP.

At lower bitrates the difference of operation of the congestion control algorithms of TCP and SCTP is not significant. As Figure 9. b shows all protocols were performing similarly. Using UDP, the first packet loss appeared at 50kB/s requested bitrate, while at 70kB/s the packet loss rate was 33.82%.

In our testbed the performance of SCTP was comparable to the other protocols only under low packet rate conditions. According to the delay measurements, when the packet rate increases TCP reaches congestion later than SCTP.

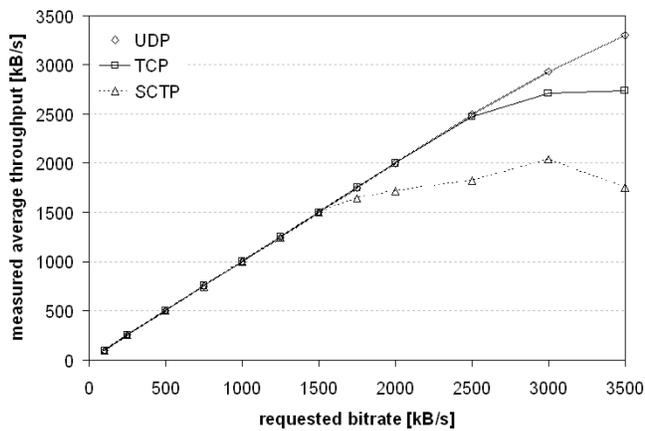


a.) Delay and jitter in WLAN

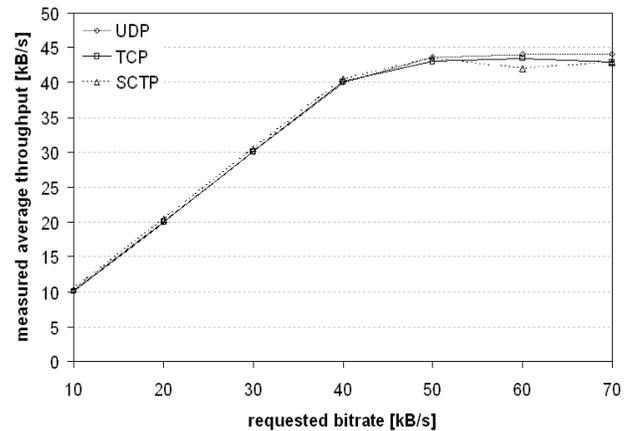


b.) Delay and jitter in UMTS

Figure 8. The average transmission delay and jitter of UDP, TCP and SCTP in our native IPv6 UMTS–WLAN environment



a) Throughput in WLAN



b) Throughput in UMTS

Figure 9. The average throughput of UDP, TCP and SCTP in our native IPv6 UMTS–WLAN environment

VI. CONCLUSION

In this paper we presented an experimental analysis of SCTP in wireless environment in terms of handover effectiveness, throughput and transmission delay. The measurements were done in a loosely-coupled UMTS–WLAN heterogeneous network supporting native IPv6. The multihoming behavior of SCTP is an advantageous feature of the protocol, however, its performance highly depends on the parameter settings. In our measurements we have analyzed numerous settings to justify the analytical correlations of the protocol parameters and the different transmission characteristics. Using accurate SCTP parameter setup, the handover delay and the data transmission interrupt can be significantly decreased. We also compared SCTP with TCP and UDP in terms of throughput in native IPv6 WLAN and 3G UMTS networks. The obtained results showed that the SCTP throughput in UMTS network was similar to other transport protocols, while in WLAN, which offers higher throughput capacity, the performance of SCTP was lower than the other examined protocols. Our future plan is to make recommendations on suitable SCTP parameter configurations in order to minimize

the handover delay and maximize the throughput in heterogeneous IPv6 networks. We also would like to analyze the effect of different link characteristics (network delay, loss rate, etc.) on the performance of SCTP.

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