QoS-enabled Internet-on-train network architecture: inter-working by MMP-SCTP versus MIP

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***Abstract*— Internet-on-the-train is a rising concept in the last few years. Several trials in different countries have proved the feasibility of offering Internet access to train commuters, but none of them combines broadband access, scalability, seamless handover and quality of service guarantees in one solution. In this paper, we propose a new architecture to satisfy these needs. Using real handover measurement data of several common broadband wireless technologies, we compare two possible inter-working mobility solutions: Mobile Multi-Path SCTP (MMP-SCTP) and Mobile IP (MIP).**

I. Introduction

Several wireless technologies can be used for offering broadband Internet access on trains. If we look at GPRS (considered to be the first cellular mobile data service), lots of countries do not even have a full national coverage. When envisaging UMTS or WiMAX cells, they are currently only arising mainly in dense urban areas. Satellites on the other hand are at almost every geographic location available, because of their large footprints (large covered areas). However, they need line-of-sight conditions in order to maintain a broadband connection. This makes satellite connections in dense urban areas, tunnels, mountainous terrain... difficult or impossible.

These findings substantiate the fact that the railway network of a train operating company is rarely fully covered by solely one (broadband) wireless backhaul technology. Hence, when envisaging an Internet connection on the train [1], one will need to combine different technologies. This involves switching from one technology to another when leaving the coverage area of the former. This is called inter-technology handover or "vertical handover".

Bundling several broadband wireless technologies into one data "pipe" should be done in a transparent way: passengers on the train should not be aware of the handovers and should enjoy an uninterrupted seamless multimedia network experience. The IP network architecture that we present in this paper, can use several wireless access technologies in order to provide such an uninterrupted Internet connectivity.

On-board provisions for Quality of Service (QoS) enable the network to differentiate the data traffic: crew versus passengers, delay critical versus high bandwidth applications and fast inter system handovers provide seamless business and infotainment Internet services to train passengers and crew with the necessary QoS.

The remainder of the paper is organized as follows. Section II presents throughput, delay and (vertical) handover measurements of some current wireless technologies. In Section III the architecture of the network is explained. A comparison between the two mobility solutions for our Internet-on-train network system is shown in Section IV. Finally, conclusions and future work are formulated in the last section Section V.

II. Data throughput, packet delay and handover measurements

Using existing public mobile communication networks for backhauling seems to be at first sight an attractive alternative for providing a backhaul connection between the moving trains and the ground, however there are a number of drawbacks.

- In most cases a nationwide coverage for broadband wireless access is not available, and will not be so in the next years to come, depending on the country.
- The use of a public mobile data-communication network in international roaming conditions can raise the backhaul connectivity costs to an unacceptable level
- The networks which have a good coverage (like GPRS or EDGE) have other disadvantages, which are shown in the test results below

The performance of the already available technologies which provide a nation wide coverage, have been tested in Belgium during the month December in 2006. The tests were performed by using two different public mobile network operators. The tests were carried out in a car, equipped with test equipment, that went from Antwerp to Brussels at a maximum speed of 120 km/h.

We opted performing these measurements by car instead of by train, as tests on a real train have some serious disadvantages. This is because the antennas has to be mounted outside the train and requires cooperation of a train operator. As the maximum allowed height of the antennas is often very limited,

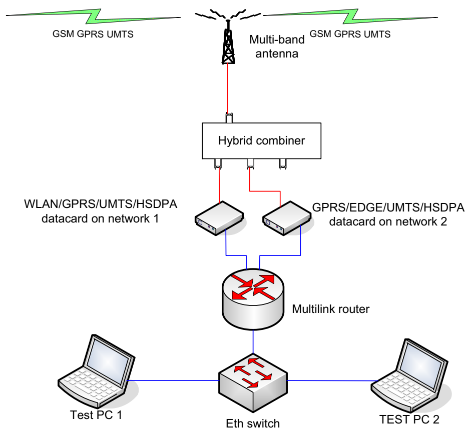

Fig. 1. Setup of the measurement

special antennas would be required. This would make it very expensive, administratively intensive and time-consuming for these measurements.

The main objectives of our tests were:

1) Test the data throughput per type of connection
2) Measure the data packet delay variation of different connection technologies
3) Get information on handover delays between base-stations and between technologies
4) Study the influence of the speed of the mobile user on the above values

Based upon these measurements, we are able to deduce useful parameters (e.g. concerning the overlap and dimensioning) that constitute to intelligent decisions in the PDF (see Section III) for making transparent handovers.

The test setup is shown in Fig. 1. Two universal datacards, capable of connecting to GPRS, EDGE, UMTS and HSDPA data-networks are connected via a hybrid antenna combiner to a rooftop mounted wideband antenna. Each of them has a SIM card of a different network provider. The multilink router is used for setting up and monitoring the connections. One PC is used for measuring data throughput, data delays and handover delays using common tools like DU-meter and Iperf [2]. The second PC is used for administrative purposes like changing the configurations of data cards and router. In all coverage areas of the different access technologies, a static test has been performed. The results of these tests are shown in Table I. In the following paragraphs we discuss our observations.

A. Tests on GPRS networks.

During base-station handovers we notice interruptions of 5 to 10 seconds. From earlier tests done on a network in Germany (Fig. 2), we notice even longer interruptions.

The interpretation of the picture is as follows: A terminal is connected to a cell using 3 timeslots and the CS-2 code-scheme resulting in a bitrate of about 35 kbit/s. Then, a fast handover is performed to a cell where the conditions are less favorable, the link is re-negotiated to use CS-1 and only one

TABLE I

COMPARISON OF THE TEST RESULTS BETWEEN GPRS, EDGE, UMTS AND HSDPA

	speed [km/h]	Throughput [kbit/s]	RTT [ms] Min - Avg. - Max	handover delay [s]
GPRS	0	41,6	484 - 648 - 2337	5 - 10
	120	29,6	484 - 648 - 2337	5 - 10
EDGE	0	170	290 - 683 - 2993	5 - 10
	120	28	290 - 683 - 2993	5 - 10
UMTS	0	360	NA - 160 - NA	< 2
	120	324 - 360	NA - 160 - NA	< 2
HSDPA	0	1000 peak	NA - 140 - NA	NA
	120	1000 peak	NA - 140 - NA	NA

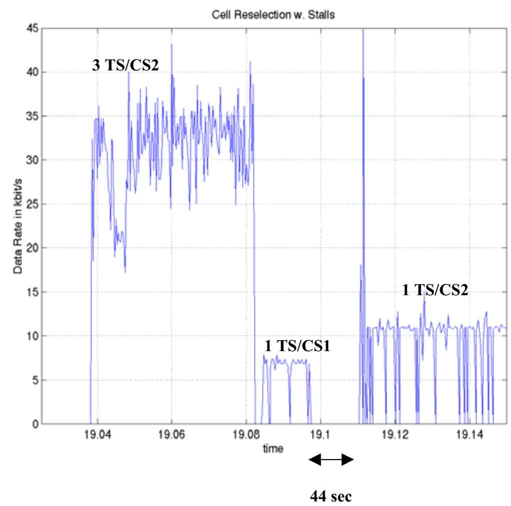

Fig. 2. Data rate measurement during two GPRS handovers

timeslot is assigned by the base-station, resulting in a bitrate of slightly less than 9 kbit/s. The handover results in an interruption of about 5 - 10 s. The terminal stays connected in this cell for about 180 s, and then a handover to the next cell is initiated. This handover causes an interruption of the IP traffic for about 45 seconds, after which the terminal is connected to the next cell, which has a better signal/noise ratio, allowing CS-2 to be used on one timeslot. The randomness in the time that a handover needs is most likely related to the network configuration and planning. A handover between cells on base-stations of the same BSC (base station controller) needs less network resources than a handover to another BSC, where possibly a different SGSN is involved. Furthermore traffic delays caused by the radio network, the available bandwidth in the BS backhaul, and the load of the network, caused by simultaneous voice traffic, can be reasons for the high variations in handover delays.

B. Test on an UMTS network

The UTRAN network supports a feature called "handover advance" which makes it possible to signal an approaching handover in advance between base stations. Due to this feature, the handovers had a very smooth transition. Only a few of the handovers resulted in interruptions of a few seconds.

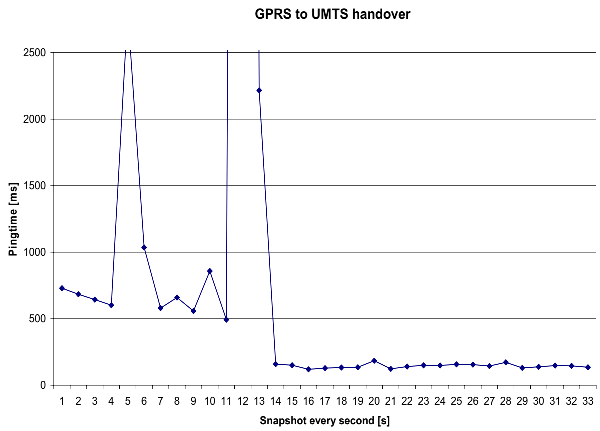

Fig. 3. GPRS to UMTS handover

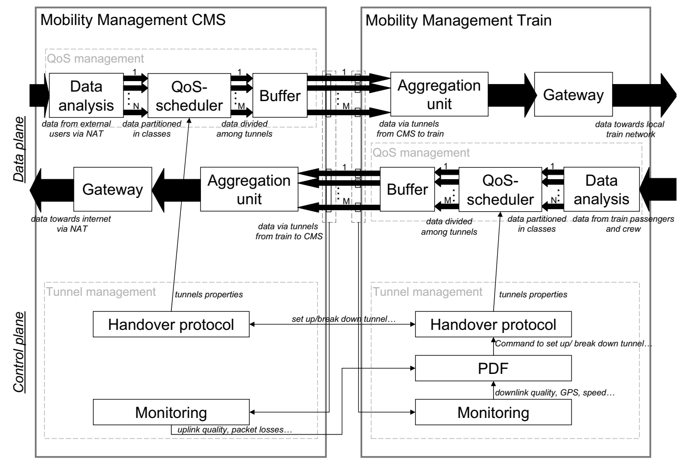

Fig. 4. Architecture: the gateway on the central and on the train

C. Tests on GPRS-UMTS handover

In Fig. 3 can we see the results of a test performing an inter-system handover from the GPRS network to the UMTS network. In the beginning is the terminal connected to the GPRS network (delays < 600 ms), with e.g. on the fifth second a packet that is lost. On the 11th second starts the handover, on the 12th second a packet is lost, the 13th second shows a significant packet delay, and on the 14th second the handover to UMTS is complete, showing the low and stable UMTS packet delay of about 160 ms.

D. Tests on a HSDPA network

Due to an incomplete coverage by HSDPA (at that time in December 2006 only a small part of the UMTS Node-B's were upgraded to HSDPA) it was not possible to do a continuous test on HSDPA, but the general impression is:

1) During the throughput tests peaks of 900 to 1000 kbit/s were measured
2) Round-trip packet delays were even slightly better than UMTS: the average value for HSDPA was 140 ms.
3) Since not enough adjacent base stations along the motorway were upgraded to HSDPA, we were not able to test an HSDPA handover.

E. Discussion

GPRS and EDGE are certainly not the technologies that are usable as a stable backhaul between a fast moving train and the ground. Although the coverage is generally good, the former is too limited in bandwidth, and the latter is not supporting fast mobility of terminals. Both suffer from high and varying packet delays, causing problems with fast handovers. The higher channel modulation rates specified by EDGE, which require a better signal to noise ratio, do cause a fast decay in bandwidth versus terminal speed.

UMTS and certainly HSDPA show a far better behavior, compared to GPRS and EDGE. Backhauling the Internet traffic of a whole train via UMTS still requires several channels to be bundled, to reach an acceptable bandwidth. However, packet delay and base station handovers are very acceptable and stable. Specifically for HSDPA the short TTI (transmission time interval) of 2 ms on the radio links allows fast link adaptations, which is useful when the radio conditions change when communicating with a fast moving train. Also the fast hybrid automatic repeat request (ARQ) mechanism helps keeping the packet delays low.

The results prove that the handover between systems can introduce packet loss and delay, which has an impact on the QoS of the passengers applications. Therefore we need a seamless mobility protocol which is able to hide handover delay and loss at the IP level.

III. Architecture

Previous sections shows us that passengers trying to maintain their own connection would either need to handle multiple technologies to preserve their broadband access, either satisfy with the connection they achieve by using a single technology. Furthermore, if each passenger would maintain an Internet connection by himself (e.g. by a UMTS/GPRS PCMCIA card), the base stations would have to deal with a large number of co-located users and therefore lots of simultaneous handovers. Current broadband network technologies cannot provide the necessary QoS under such conditions. Besides, in order to deal with the signal degradation inside the carriages, repeaters would have to be installed on the trains.

Therefore, we propose a solution where the passengers connect to the Internet using on-board WiFi access points that are connected to the local train network. An intelligent gateway system, also connected to the on-board train backbone, aggregates all available backhaul wireless connections towards the central management system, which is connected to the mainland. This way the train can switch from one access network to an other. This switch should be done in a transparent way, the passenger should not suffer from link breaks or what so ever. The components of the gateways on the train and in the central management system are shown in Fig. 4 and will be discussed in-depth in the following paragraphs.

A. The Policy Decision Function

The PDF is a very important component of the architecture. Its task is to decide which interface(s) should be used to provide a connection between the train and the corresponding access network(s). The PDF can make this decision based on information from a monitoring unit (based upon results from Section II), which provides data concerning link quality, location and speed of the train, position of the train, possibly obstruction of line of sight towards the satellite. Additionally, other parameters such as cost or load balancing can be taken into account. This component has knowledge of the different network technologies and acts as an abstraction layer to the other components of the Internet-on-train network architecture.

The Mobility Management protocols will get input from this PDF in order to exchange messages at the appropriate moments for making a vertical handover.

B. Mobility Management

The Mobility Management modules reside partly on the train and partly on the central management system. It performs all mobility specific actions, in order to make the handover as smooth as possible. We investigate two alternatives for the mobility management handover protocol: Mobile IP (MIP) [3] and MMP-SCTP. Both protocols consider the train as a mobile router and the passengers as a mobile network. Some extensions and optimizations to MMP-SCTP and MIP were implemented in order to adapt these protocols for the train environment and to act as encapsulation mechanisms. We would like to emphasize that in both cases the user will not need a MMP-SCTP or MIP-aware device to access the network: these handover protocols will encapsulate the IP traffic from all users on the train.

MIP enables nodes to change their point of attachment to the Internet without changing their IP address. The mobile node will always be identified by its home address, regardless of its location. The Home Agent, which resides in the home network, accepts all packets destined for the node and forwards them in an IP tunnel towards the mobile node at his foreign destination. By means of registrations is the Home Agent always aware of the location of the mobile node. The packets transmitted by the passenger will be captured by the trains access router and encapsulated in an IP header towards the Home Agent which resides in the central management system. As already mentioned before, the mobile node is for instance not the endpoint of the connection. Instead, the mobile node is considered to be a router with a mobile network of passengers. This prevents the need for the users to maintain their own mobile IP connection. Further, router advertisements are eliminated in this architecture, since the PDF provides the mobility management with the required information concerning the access networks.

We focus on minimizing the actual handover delay by performing a MIP pre-registration as soon as the Mobility Management component is aware of the fact that a handover is imminent. As soon as the PDF informs that the handover is actually going to happen, the Mobility Management component sends a MIP registration request to the central management system after which the actual switch is complete.

TABLE II
COMPARISON BETWEEN MMP-SCTP AND MIP

	MMP-SCTP	MIP
RFC status	Internet Draft	Standards Track
OSI-layer	3.5-4	3-3.5
Data bundling	yes, by nature	no
Multihoming	yes, by nature	only in MIPv6
Reliability	yes, by nature	no
IP-address change	yes	yes, by nature
Load balancing	yes	no

The second mobility protocol that we are studying is SCTP (Stream Control Transport Protocol) [4], which is a reliable transport protocol on top of a potentially unreliable connectionless packet service such as IP. Selective acknowledgments (SACKs) are used to confirm the correct reception and for the retransmission of SCTP chunks on packet loss detection, e.g. during handover. The SCTP endpoints support multihoming, which provides them with multiple links within the same connection, in contrast to MIP. The ADDIP extension [5] is developed to support dynamic address reconfiguration. It enables a mobile host to add, delete, and change new IP paths during an active connection by means of the Address Configuration Change Chunk message (ASCONF). This extension is known as mSCTP (mobile SCTP). Mobile Multi-path SCTP (MMP-SCTP) [6] extends mSCTP by effectively using multiple links simultaneously for data transfer. It can provide a seamless handover for mobile hosts that are roaming between IP networks. We define one primary and a number of secondary paths. As soon as the PDF informs that the handover is actually going to happen, the Mobility Management component sends an “ASCONF change primary path message” to the central management system after which MMP-SCTP will use the best secondary path as primary path. Any outstanding packets will be retransmitted over this new path.

A general feature comparison between both protocols is made in Table II.

IV. COMPARISON OF MIP VS MMP-SCTP

A. Overhead

Both mobility protocols involve some overhead in order to ensure transparent mobility to the user. We provide both theoretical and experimental results concerning the overhead. The data that the passenger sends is packed in a TCP (20 bytes) or UDP (8 bytes) header, plus an IP header (20 bytes). Those packets are captured by the train gateway. We will not take these header into consideration for our overhead calculations.

At the train gateway, MIP will encapsulate this packet in an IP header with as destination address the Home Agent. MMP-SCTP on the other hand, adds a chunk header (16 bytes) to this packet. And multiple chunks are then packed into a

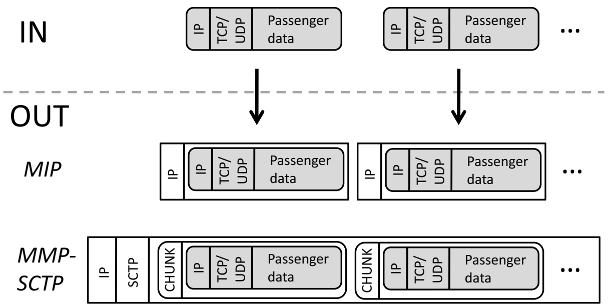

Fig. 5. MIP vs MMP-SCTP Encapsulation

TABLE III
THEORETICAL COMPARISON FOR MIP VS MMP-SCTP: OVERHEAD FOR TCP AND UDP DATA TRAFFIC

Passenger UDP or TCP payload	% Overhead			
	UDP		TCP	
	MIP	MMP-SCTP	MIP	MMP-SCTP
50	25,64	27,18	22,22	27,62
100	15,63	16,67	14,29	16,97
500	3,79	6,72	3,7	6,72
1000	1,95	5,30	1,92	5,30
1400	1,4	3.85	1,39	3.85

SCTP packet by adding a SCTP header (12 bytes) and an IP header (Fig. 5). As many chunks as possible are piggybacked in one packet without exceeding the MTU of 1500. MMP-SCTP has the advantage of providing reliability between the train gateway and the central gateway, but therefore has the drawback that it requires sending a SACK chunk (16 bytes) in the opposite direction, after every two SCTP packets. This is taken into account in the overhead calculation. We assume however bidirectional traffic so that the SACK will be bundled in a larger packet and therefore will not need a SCTP header and a IP header of its own. TCP acks are ignored since the theoretical calculation only considers the overhead produced by one way traffic.

When calculating the overhead percentages, we consider the ratio of the extra bits sent (the MIP or MMP-SCTP headers) to the total of bits sent without a mobility protocol (excluding data link header and initial MIP or MMP-SCTP set-up messages). The theoretical results are presented in Table III.

We compare MIP with MMP-SCTP by means of the testbed in Fig. 6. The passenger (C) is connected with a train gateway (T) and a server (S) is connected to the central gateway (CMS). The T and CMS are connected by two different links. The nodes are ethernet-wired, but in order to emulate the satellite and HSDPA link, we put an impairment node (I) between CMS and T. For HSPDA emulation, we use a delay of 70 ms and an uplink and downlink bandwidth of 320 kbit/s and 768 kbit/s respectively. For the satellite connection, we emulate a delay of 160 ms and an uplink and downlink bandwidth of 512 kbit/s and 2 Mbit/s respectively. We set the (Internet) RTT between the server and the CMS to 200 msec. The protocols are implemented with the Click Modular Router [7].

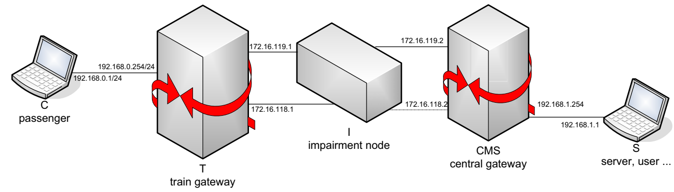

Fig. 6. The testbed architecture

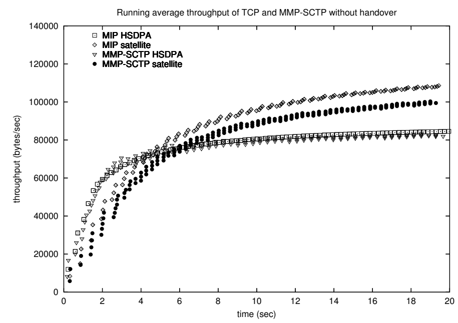

Fig. 7. Throughput without handover for MIP and MMP-SCTP

B. Testbed results

1) TCP performance without handover: By means of our testbed we performed tests with Iperf [2] to investigate the throughput of both protocols in case of TCP traffic. The tests represent the downloading of some data by the passenger from a server during 20 seconds, without any handovers occurring. After the slow start MMP-SCTP reaches a stable throughput of 661 kbit/s for HSDPA and 822 kbit/s for satellite, MIP reaches 625 kbit/s for HSDPA and 900 kbit/s for satellite (Fig. 7).

2) UDP performance with handover: In order to see how MMP-SCTP and MIP handle a predicted handover, we have performed tests on our testbed with Iperf, configured to generate UDP traffic in downlink direction towards the passenger, at a bitrate of 192 kbit/s and a payload size of 1300 bytes. The Iperf client is positioned at the S node (the server) while the Iperf server is positioned at the C node (the passenger).

For MIP, our PDF decides to make a handover between the

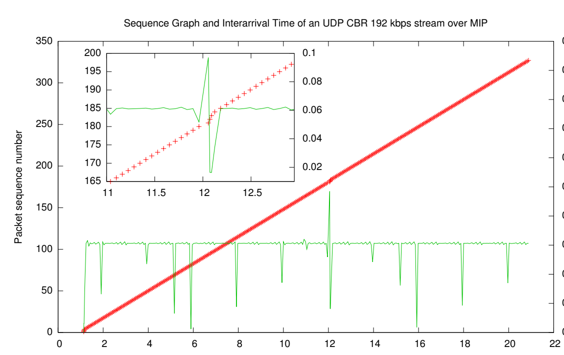

Fig. 8. Sequence graph of UDP with handover for MIP

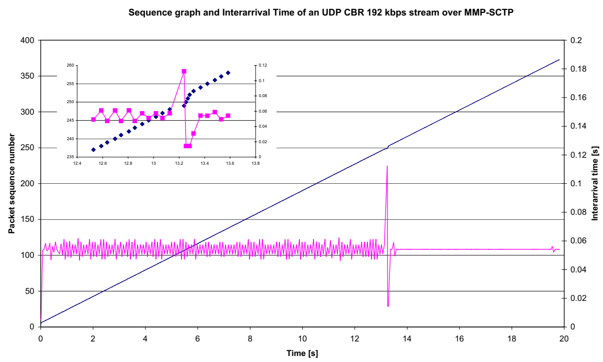

Fig. 9. Sequence graph of UDP with handover for MMP-SCTP

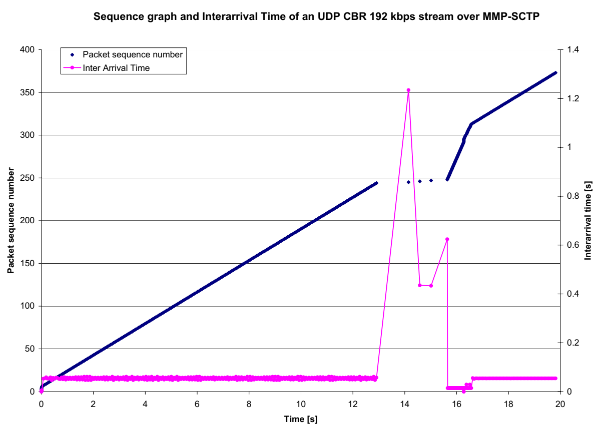

Fig. 10. Sequence graph of UDP with hard handover for MMP-SCTP

satellite and the HSDPA system at $t = 12s$. We see in Fig. 8 that there were no retransmissions necessary and that all UDP packets arrive in order. However, due to the handover and the difference in end-to-end delay between both systems, the inter-arrival-time of the UDP packets peaks and then stabilizes again.

We performed the same test for MMP-SCTP with a handover between the satellite and the HSDPA system ($t = 13s$) (Fig. 9). The results are comparable with the MIP results: there is no packet loss or packets arriving out of order and only a small fluctuation of the inter-arrival time at the moment of the handover.

In Fig. 10 we show how MMP-SCTP handles an unpredicted handover. On $t = 13s$ the primary path goes down. After it has detected the satellite link failure, we can see how MMP-SCTP starts retransmitting the packets on the secondanoticeablery path when the retransmit timer is scheduled. After three retransmits the path is considered to be down and the secondary path (HSDPA) is chosen as the new primary path. The non-acknowledged outstanding packets are retransmitted immediately on the new link. After these retransmissions the inter-arrival-time stabilizes. No packets are lost.

V. Conclusions and Future Work

In general we can conclude that due to reasons of coverage and availability, backhauling a train requires a multitude of technologies and networks. Satellite, GPRS, UMTS, HSDPA, WLAN etc are available but certainly a higher level protocol is needed to bundle the backhaul links to ensure that inter system handovers are seamless for the passengers, i.e. without packet loss or noticeable delay.

We have presented the building blocks of a IP train mobility network architecture, which is able to guarantee these requirements.

For the actual handover protocol, we have compared two IP mobility management solutions: MMP-SCTP and MIP using UDP and TCP throughput tests. These results show us that both protocols are able to handle the handovers seamlessly when handover can be predicted. Although MMP-SCTP has a higher overhead than MIP, it also has built-in packet delivery reliability due to the automatic retransmissions, which is beneficial when handovers are abrupt. However, we can notice that there is still room to optimize both protocols and to improve the "goodput".

In our future work, we shall focus our attention on the functionality of the PDF component to determine the optimal time when a handover should take place in order to be able to minimize handover delay, packet loss and network load.

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