TELEOPERATION OF A MOBILE ROBOT VIA UMTS LINK

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Abstract: Nowadays available broadband wireless communication technologies offer a broad spectrum of applications and the todays availability of UMTS technology has a great potential in the area of networked robotics. This work investigates teleoperation of mobile robots via UMTS communication links. First, several scenarios with artificially generated command traffic between mobile robot and operator are analyzed in order to gain knowledge of the link behavior. In a next step real mobile robot hardware is remote controlled via UMTS. Thereby, the robot transmits sensor data and a video stream of its onboard camera while receiving commands from the operator. The focus of this work is set on the measurement and analysis of the round trip time and the packet inter-arrival time of data in different scenarios like the connection of two UMTS nodes, the connection of an Internet PC and an UMTS node, or the behavior of several UMTS nodes generating a large amount of data. The results clearly show how applications for mobile robot teleoperation can efficiently use UMTS communication in order to allow seamless teleoperation between operator and hardware in distant locations.

1 INTRODUCTION

Communication is a very important issue in the area of mobile robotics. This is especially the case in networked multi-robot systems or joint human-robot teams. Although many advances in autonomy have been made in several applications like e.g. search and rescue still direct teleoperation might be needed. For direct teleoperation (Fong and Thorpe, 2001) the communication link characteristics are even more important than for other applications where data might not be as time-critical. From the human factors point of view situational awareness (Endsley, 2000) is a very critical aspect for robot teleoperation and can be significantly influenced by communication parameters e.g. available bandwidth, delays, packet inter-arrival time, and jitter for the payload data. For direct teleoperation, often the camera image from the robot is one of the major feedback elements for the human operator from the remote environment. Therefore, a relative high communication bandwidth, low delays and a small jitter is desirable for these connections in order to support maintaining situational awareness. Nowadays, in robotics research either wireless LAN according to 802.11 (Ollero et al., 2003) (Zeiger et al., 2008a) or proprietary communication systems are used (Musial et al., 2001) (Pezeshkian et al., 2007). The upcoming high-bandwidth networks for mobile phones or mobile Internet like UMTS offer a new widely used and commercially available technology with high potential for the application in mobile robot teleoperation. Up to now, the coverage of these networks has increased in a way that at least all bigger cities have access to broadband networks. This everywhere availability in large areas is a major advantage for any telematic application compared to a solution where infrastructure initially has to be built up and maintenance effort is necessary. In particular, the application area of service robotics can largely benefit from these characteristics. However , the mobile phone networks like UMTS are designed for different purposes and under different constraints. Therefore, it is important to investigate the critical parameters of a communication technology like UMTS in order to adjust the possible communication parameters on the application layer in a way to realize the optimum usage of this technology.

The remainder of this work is structured as follows. Section 2 gives a brief introduction to the UMTS technology. In Section 3, the test setup is de-

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scribed. In Sections 4 and 5 the evaluations of the tests are given. Also the results of the real mobile robot hardware teleoperation test is presented. This work concludes with a discussion of the results and an outlook in Section 6.

2 UMTS BASICS

The Universal Mobile Telecommunications System (UMTS) is a European standard for third generation mobile telephony (3G). It is based on W-CDMA technology, standardized by the 3GPP, and implemts European specifications of IMT-2000 ITU for third generation cellular radio systems. Although it is not a worldwide standard, UMTS will probably become the most popular one among its competitors. UMTS rigorously divides its infrastructure into two parts (cf. Fig. 1). The UMTS Terrestrial Radio Access Network (UTRAN) handles all tasks related to radio and wireless networking and the Core Network (CN) provides all user services running via UMTS.

The UTRAN maintains the radio connection to mobile operators for circuit and packet switched links. A key to UMTS radio technology is the use of the Wideband Code Division Multiple Access (W-CDMA) user multiplexing procedure. W-CDMA is responsible for ensuring that several participants can communicate simultaneously using the same frequency channel without interfering each other. The UTRAN radio provides two different modes of operation: using UTRA-FDD mode, up- and downlink of data run on separate frequencies. This mode supports data rates up to 384 kbit/s. In UTRA-TDD mode, up- and downlink take place at the same frequency, but are separated by time slots. UTRA-TDD supports data rates up to 2 Mbit/s but is quite uncommon compared to UTRA-FDD. Since demand for higher data rates emerged, UTRAN was enhanced by High Speed Downlink Packet Access (HSDPA) as well as High Speed Uplink Packet Access (HSUPA) to support data rates up to 14.4 Mbit/s on downlink and 5.76 Mbit/s on uplink. The UTRAN is composed of two basic architectural components. Base stations (Node Bs) provide the radio signaling. In addition, there are Radio Network Controllers (RNCs). Managing all radio resources, these RNCs administrate a group of Node Bs. The area covered by all Node Bs connected to one RNC form a Radio Network Subsystem (RNS). These RNSs are linked by cross connections of the RNCs. sThe RNC finally makes the connection to the Core Network (CN), too. Inside the CN, there are several nodes providing various high level services needed for mobile telecommunication. The Mobile Switching Center (MSC) serves as a switching node and gateway for circuit switched connections (phone calls). In case of packet switched data (IP data), these functionality is provided by the Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN). For more details on UMTS please refer to (Holma and Toskala, 2007).

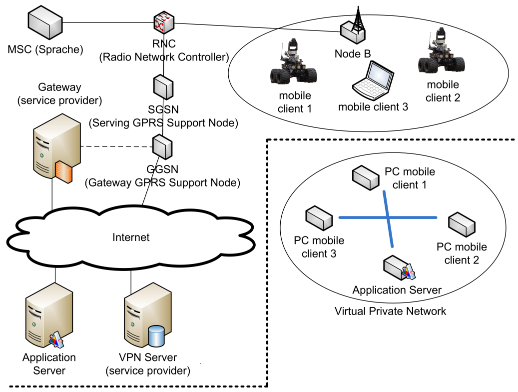


Figure 1: UMTS architecture.

3 SCENARIO SETUP

The focus of this work is set on teleoperation of a mobile robot via UMTS communication link and the characterization of the communication link in order to allow for a seamless teleoperation of the robot. Therefore, three different test setups are analyzed:

- The connection between one robot connected to UMTS and a PC connected to the Internet via DSL (16 MBit/s) (Mode 1).
- The connection of two mobile robots via UMTS (Mode 2). In this case, only the two robots generate traffic.
- The connection of two mobile robots via UMTS while a third UMTS node in the same cell is transmitting a large amount of data to the Internet (Mode 3).

The mobile clients are represented by mini PCs which are connected to the Internet via a USB UMTS device (Huawei 3G modem). This device supports HSDPA and HSUPA broadband data transmission besides the normal UMTS mode. This broadband communication is used for all tests presented in this work. Currently, all UMTS access providers do not provide public IP addresses or in case they do, only a small set of services is supported. Therefore, each UMTS node joins a virtual private network using openvpn (cf. Figure 1). Thus, a physical and hardware component is present, and a logical overlay is set on top of this (cf.

Fig. 1) which enables easy addressing of each mobile node. Also the provided data services can be defined according to the corresponding test. Usually, the UMTS specification promises a reliable packet transmission every 20 milliseconds. To get an idea of the link behavior, for each of the three above mentioned modes, data streams of different sizes are generated. As measurement categories, the packet inter-arrival time is analyzed as this is an important criterion for video and sensor data transmission and the round trip time (rtt) is investigated as this two-way delay is also very important in case the mobile robot is teleoperated directly by a human operator. For the packet inter-arrival time analysis, data is transmitted only one-way and the packet inter-arrival time is plotted at the destination node. Therefore, data is generated with a packet size of 2048 bytes and a packet inter-departure time of 10, 20, 50, and 100 milliseconds which results in packet streams of 20, 40, 100, and 200 kb/s. The round trip time measurements use ICMP ping packets with the size manually set to 2040 bytes of payload and 8 bytes ICMP header. Here, the send intervals for ping packets are also set to 10, 20, 50, and 100 ms which generates data streams comparable to the above described tests for the packet inter-arrival time. Of course, the data stream for the round trip time tests are transmitted in both directions.

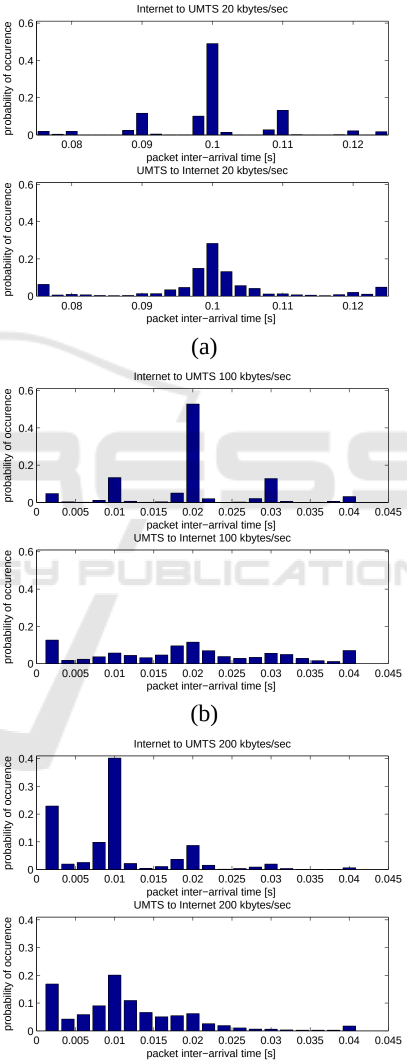
4 EVALUATION

4.1 Packet Inter-arrival Time

For this analysis, the packet inter-arrival time at the destination node is measured. Also the number of packets is counted. The results are displayed in histograms with a bin size of 2 milliseconds. The smallest bin holds all values between 0 and its own value, and the bin with the highest value holds also all larger values up to infinity. The x-axis shows the packet inter-arrival time in seconds and the y-axis shows the relative frequency of occurrence. As the data set of the measurements contains enough data to prove that the resulting distribution is stable, the relative frequency of occurrence can be considered as equal to the probability of occurrence of the corresponding packet inter-arrival time.

4.1.1 Connection between Internet PC and UMTS Node

For this setup, the packet inter-arrival time is measured in both directions for packet streams of 20, 100, and 200 kb/s. Figure 2a shows the results for the 20 kb/s stream. The packet inter-departure time for this stream is 100 milliseconds. The upper subplot of Figure 2a shows, that more than 50% of the packets arrive with an inter-arrival time of 100 ms. Approximately, another 10% arrive with an inter-arrival time of 90 ms and 110 ms respectively. For the opposite direction – from UMTS node to Internet PC (cf. lower subplot of Figure 2a)– the result is completely different. Here, the packet inter-arrival time is closely distributed around the expected packet value of 100 milliseconds.



(a)

(b)

(c)

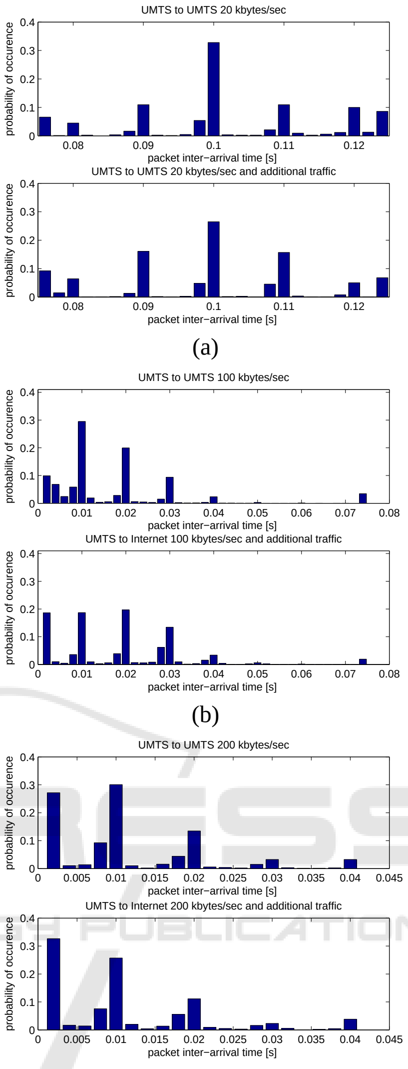
Figure 2: Packet inter-arrival time between Internet PC and UMTS node and a data bandwidth of 20 kb/s (Fig. 2a) , 100 kb/s (Fig. 2b) and 200 kb/s (Fig. 2c).

For the stream with a bit rate of 100 kb/s, the results between the both investigated transmission directions vary significantly (see Figure 2b). At the

UMTS node, more than 50% of the transmitted packets arrive with an inter-arrival-time of 20 ms and two other peaks with 10% each are visible at about 10 ms and 30 ms. For the packet inter-arrival time for the transmission direction from UMTS node to Internet PC, only about 13% of the packets have an inter-arrival time of 20 ms. Here, also small peaks at 10ms and 30 ms ($>$ 6% each), as well as a high amount of packets with 5 ms or less ($>$ 13%) and with 40 ms or more ($>$ 7%) are present. Also for the 200 kb/s stream, the results for both directions are quite different (cf. Figure 2c). For the transmission from Internet PC to UMTS node more than 40% of the packets have an inter-arrival time of 10 ms which corresponds to the packet inter-departure time. More than 20% of the packets have an inter-arrival time of 4ms and less. For the other transmission direction – from UMTS to internet PC – only about 20% of the packets arrive with the expected inter-arrival time of 10 ms. A second peak of about 18% is present for an inter-arrival time of 4 ms and less. Most of the other packets are distributed to inter-arrival times between 4 and 36 ms.

4.1.2 UMTS to UMTS Connection

This section shows the results of transmissions between two UMTS nodes. Each upper subplot of Figures 3a, 3b, and 3c show the packet inter-arrival times when traffic is transmitted only between the two involved nodes. The lower subplots of these Figures show the inter-arrival time of the packets while a third UMTS node transmits a large file to an Internet PC. Thus, this data stream must share the UMTS cell capacity with the measured data stream. Figure 3a shows the results for the 20 kb/s stream. Here, both setups show similar results. The majority of the packets has an inter-arrival time of 100 ms (33% without additional traffic and 28% with additional traffic) and almost all other inter-arrival times are distributed in 10 ms intervals at 80 ms, 90 ms, 110 ms, and 120 ms. For this stream, the additionally generated traffic reduces the amount of the packets with an inter-arrival time of 100 ms for approximately 5%. In Figure 3b the results are displayed for the 100 kb/s stream with a packet inter-departure time of 20 ms. In both situations, almost 20% of the packets have an inter-arrival time of 20 ms. In case of no additionally generated traffic, more than 55% of the packets arrive with an inter-arrival time of less than 10 ms. In case additional traffic is generated, only about 42% of the packets have an inter-arrival time of 10 ms or less. The remaining packet inter-arrival times are distributed at peaks around 30 ms and 40 ms. The results of the 200 kb/s stream displayed in Figure 3c are similar to the above described observations for the 100 kb/s stream.



(a)

(b)

(c)

Figure 3: Packet inter-arrival time between UMTS nodes and a data bandwidth of 20 kb/s (Fig. 3a), 100 kb/s (Fig. 3b), and 200 kb/s (Fig. 3c).

The additionally generated traffic reduces the amount of packets at the expected inter-arrival time of 10 ms for about 5% and the remaining packets are again located at the bins with 10 ms inter-bin distance and inter-arrival times of less than 4 ms, 20 ms, 30 ms, and 40 ms.

Finally, the effective receiving bit rates of the payload data is shown in Tables 1a and 1b. Table 1a shows the results of the test runs between UMTS node and Internet PC and Table 1b shows the results of the test between two UMTS nodes without additionally generated traffic (Mode 2) and between two UMTS nodes with additionally generated traffic (Mode 3). These two tables give an idea of the present packet

Table 1: Resulting effective payload bit rates at the receiving node between UMTS node and Internet PC (Table 1a) and for Mode 2 and Mode 3 (Table 1b).

sending data rate	receiving at UMTS node	receiving at Internet PC
20 kbytes/s	19.20 kbytes/s	19.58 kbytes/s
100 kbytes/s	98.09 kbytes/s	92.62 kbytes/s
200 kbytes/s	194.33 kbytes/s	162.82 kbytes/s

(a)

sending data rate	receiving Mode 2	receiving Mode 3
20 kbytes/s	16.19 kbytes/s	19.31 kbytes/s
100 kbytes/s	94.03 kbytes/s	92.53 kbytes/s
200 kbytes/s	141.80 kbytes/s	125.61 kbytes/s

(b)

loss during the test runs. Surprisingly good results are achieved for all data streams during the transmission from Internet PC to UMTS node. In the opposite direction, an increased packet loss is observed for the 200 kb/s stream. For Mode 2 and Mode 3, where two UMTS nodes communicated with each other, the packet loss was significantly higher.

4.2 Round Trip Times

Figure 4 shows the measured rtts for the generated packet streams. Mode 1 corresponds to the Internet-UMTS node scenario, Mode 2 is the transmission between two UMTS nodes without additionally generated traffic and for Mode 3, the data exchange of two UMTS nodes is measured while a third node transmits additional data to an Internet PC. These boxplots show the median of the measured values (horizontal line) and the box shows 50% of the values bounded by the lower 25% quartile and the upper 75% quartile. Furthermore, lines indicate the most extreme values within 1.5 times the interquartile range from the ends of the box and extreme values lying outside this borders are marked with crosses. For the three streams with 20 kbyte/s, 50% of the measured rtt values are distributed very close to the corresponding median. A similar observation can be made for the 40 kbyte/s stream in Mode 1 and Mode 3, and for the 100 kbyte/s stream in the Mode 1 scenario. As expected, the largest variations appear for the high bandwidth streams with 200 kbyte/s and the 100 kbyte stream in Mode 3 with the additionally generated traffic. In general, 50% of the measured rtt values of each test run are located close to the corresponding median. Only few extreme values are measured below the lower 25% quartile border and sometimes, very high rtt values are measured above the upper border of the 75% quartile (e.g. for 100 kb/s in Mode 3). Thus, the later used application to mobile robotics must consider these high round trip times which occur sometimes and must be able to handle this large variability.

5 REAL HARDWARE TEST

To analyze the UMTS link under real conditions for mobile robot teleoperation, a Pioneer 3-AT is teleoperated from a Laptop via UMTS. The robot platform is equipped with a mini PC and a network video camera AXIS 221 and transmits a motion JPEG video stream with a resolution of 320x240 and a frame rate of 15 frames per second. The Player version 2.0.4 software is used to interface the hardware and for providing communication between the client and the hardware. The client is a Java program which provides a video image of the mobile robot's onboard camera and displays sensor data. During the test runs, the mobile robot generates a sensor data stream and sends it to the Laptop. Additionally, video data is sent each 66.66 ms. The Client program is sending control commands with a bit rate of 1.2 kb/s. In Figure 5, the behavior of the video data which arrives at the operator's PC is shown. The video source generates relatively large packets which must be fragmented. Thus, the send buffers are continuously filled and packets are sent as often as possible. On the receiver's side, the already above observed peaks of the packet inter-arrival times each 10 ms is also visible.

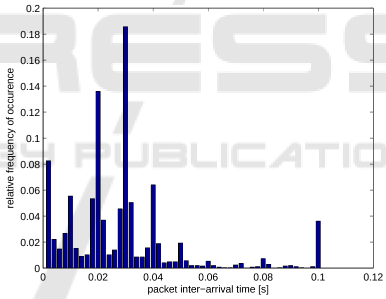


Figure 5: Packet inter-arrival of the video data coming from the mobile robot.

6 DISCUSSION OF THE RESULTS

The above presented results show clearly that UMTS is a well suited communication technology for the teleoperation of mobile robots. The results obtained in the initial test runs with the artificially generated command traffic give a detailed overview of the channel behavior. When data is transmitted from the UMTS node via the UMTS infrastructure and the Internet, the arriving packets at the PC have a higher variance in the packet inter arrival time as typically, the Internet data transfer induces such a variance. In the opposite direction, the packets arrive at the UMTS infrastructure via the Internet. Then the UMTS infrastructure is responsible for further data transmission

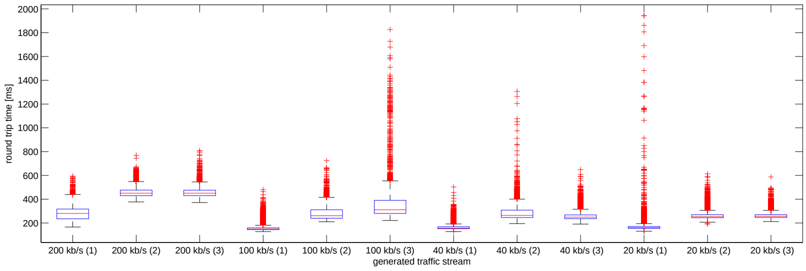


Figure 4: Round trip times in milliseconds (Mode (1): Internet-UMTS; Mode (2): UMTS-UMTS; Mode (3): UMTS-UMTS and additional traffic).

and takes care that packets are transmitted with defined packet inter-departure times. These packet inter-departure times are depending on the used bandwidth and the used HSDPA/HSUPA mode and some other aspects depending on the provider. Nevertheless, the measured packet inter-arrival times are now bound to fixed times which reduces the variance. In general, it can be seen that as soon as the broadband communication mode is entered, data is delivered at the mobile robot and at the operator's PC constantly. Noticeable outcomes are the frequent packet inter-arrival times at 10 ms and multiple of 10 ms with a relatively high peak at the 20 ms inter-arrival times. Also, the received effective payload data rates give a clear view of the present packet loss during the tests. Finally, the measured round trip times and their distribution lead to the following hints for implementing mobile robot teleoperation. The ”just plug and try” setup which is described in Section 5 shows to be already usable. Nevertheless, a defined traffic shaping might be a suitable approach to use the characteristics of the UMTS link more efficient and to increase the quality of teleoperation (e.g. better video quality or less packet loss). Approaches for this idea are already published in another context (Zeiger et al., 2008c)(Zeiger et al., 2008b) and shows to be a useful technique. Nevertheless, UMTS is a promising technology to allow broadband communication for hardware teleoperation and will be in the research focus of networked robotics in near future. Future work will be set on analyzing more details of the UMTS link in combination with mobile robot teleoperation. Open issues are how to use the behavior of the communication channel in order to allow for high quality onboard video transmission together with reliable control data transmission in both directions.

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