VIDEO TRANSMISSION WITH ADAPTIVE QUALITY BASED ON NETWORK FEEDBACK FOR MOBILE ROBOT TELEOPERATION IN WIRELESS MULTI-HOP NETWORKS

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Keywords: Networked robots, mobile robot teleoperation, mobile robot ad-hoc networks, wireless network, ad-hoc network, wireless teleoperation, wireless remote control.

Abstract: A video stream is still one of the most important data sources for the user while remote-operating a mobile robot. Human operators have comprehensive capabilities to interpret the displayed image information, but therefore, some constraints must be fulfilled. Constant frame rates and delays below a certain threshold are a minimum requirement to use video for teleoperation. Modern multi-hop networks often use WLAN to set up ad-hoc networks of mobile nodes with each node acting as traffic source, sink, or router. Considering these networks, routes between sources and destinations might be established via several relay nodes. Thus, the utilization of intermediate nodes which are part of a route influences the overall route performance, whereas sender and receiver have no direct feedback of the overall route status. In case video is transmitted via wireless ad-hoc networks in a teleoperation scenario, the displayed video-stream for the operator might have variable frame rates, very high packet loss, and packet inter-arrival times which are not appropriate for mobile robot teleoperation. This work presents an approach using a feedback generated by the network to adapt the image quality to present communication constraints. Thus, according to the current network status, the best possible video image is provided to the operator while keeping constant frame rates and low packet loss.

1 INTRODUCTION

In the meantime, mobile robots are planned to be used or even already used in many civil applications like surveillance or search and rescue to support and relieve the humans in place. Often, wireless communication is chosen to distribute and share information between the humans and robots in the team. This includes the transmissions of sensor data from the robots, observations from the humans, commands, and plans to the different team entities from the human coordinators. In many cases IEEE 802.11 wireless LAN is used as underlying technology for the wireless network interconnecting the team. Nowadays modern telecommunication equipment with small power consumption and interfaces for easy integration is available. This even allows an affordable system of wireless ad-hoc networks of mobile robots and human team members. These wireless ad-hoc networks offer a lot of advantages in contrast to static wireless network configurations, but also raise a lot of new challenges in the system design. In (Hu and Johnson, 2002) a live audio and video data transmission via a multi-hop wireless network is demonstrated. In addition, several systems of rovers with autonomous functionalities (Parker, 1994), groups of unmanned aerial vehicles (Ollero et al., 2004), as well as heterogeneous multi robot systems were proposed. Rooker and Birk presented multi-robot exploration with robots using wireless networks (Rooker and Birk, 2007). For ground based systems Chung (Chung et al., 2002) presented a test bed for a network of mobile robots. In the field of rescue robotics (Rooker and Birk, 2005) or for integrating UAVs into IP based ground networks (Zeiger et al., 2007) the use of wireless networks is quite common nowadays. With respect to unmanned aerial vehicles (UAVs), (Ollero et al., 2003) presented a system using an access point running in WLAN infrastructure mode onboard the UAV. (Vidal et al., 2002) presented a system for communication between a ground station and a UAV using WLAN in combination with a high-gain antenna and radio modem. The University of Pennsylvania presented a mobile robot team connected via wireless network which performed localization and control tasks (Das et al.,

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2002). Currently, wireless ad-hoc networks for mobile robots are a challenging and interesting scientific topic and scenarios connecting several mobile robots, humans in place (e.g. search and rescue applications), and stationary network nodes (e.g. communication relay nodes) are evaluated and analyzed (cf. Figure 1).

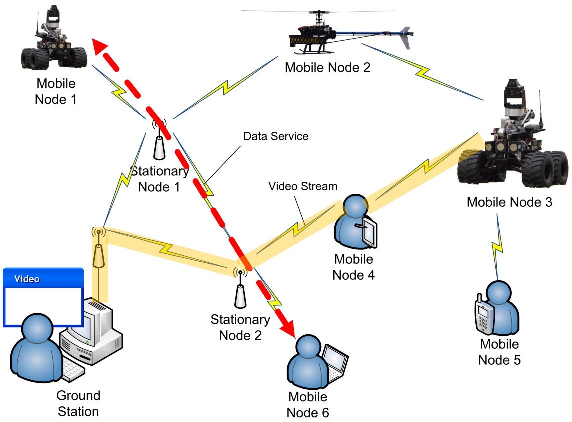

Figure 1: Future scenario of a heterogeneous network of mobile robots and human personnel.

Special ad-hoc routing protocols like AODV (Das et al., 2003)(Chakeres and Belding-Royer, 2004), DSR (Johnson and Maltz, 1996), or OLSR (Clausen, 2003) allow communication also in a highly dynamic network topology which increases the capabilities and the ease of use of mobile robots. These networks allow any-to-any communication between all nodes inside the network on a logical layer. Nevertheless, the radio link always implies the potential danger of a complete communication drop-out and the unpredictable loss of packets with a variable packet loss probability. Also the delay of packets delivered via the same route by hop-by-hop fashion can be variable. The same also applies for the bandwidth – e.g. IEEE 802.11 WLAN usually reduces its bandwidth as the link quality decreases.

The dynamic characteristics of WLAN and especially if it is used together with ad-hoc routing protocols has special drawbacks if direct teleoperation should be implemented over these communication links. Although there was a lot of progress in the area of autonomy for mobile robots, still many applications need the direct teleoperation of mobile robots, which requires in many cases reliable and high bandwidth links for video streams from the robots. For low-bandwidth conditions and very defined environments, e.g. in tele-education, also virtual representations can be used to provide the necessary information for direct teleoperation (Sauer et al., 2005). For the more dynamic scenarios, (e.g. in search and rescue) where the application of wireless ad-hoc networks is very desirable, direct teleoperation with high bandwidths is mostly required. These needs for high bandwidth result from the fact, that the video feedback still delivers the most and richest information from the remote environment to the operator. This detailed information from the remote site is needed to increase and maintain the situation awareness and common ground between robot and human operator as basis for any future decisions and commands done by the human operator. (Murphy and Burke, 2005) showed that this situation awareness is even more important than any autonomy or assistance function implemented in the robot. Dependent on the human teleoperation task different characteristics of the video stream are important. If a navigation task is considered, the most important parameters are a high frame rate, low number of frame losses, and a constant inter-arrival time between to frames. Compared to these parameters the quality and resolution of the video stream is less important for navigation. On the other hand if the human has a search task (e.g. identify objects in a delivered video stream), the quality and resolution has a higher importance than the frame rate. Here, the proposed mechanism for the video-stream adaptation according to the load status of the route is designed for navigating a mobile robot with direct teleoperation.

The presented mechanism allows a variable image quality of the video stream for the operator. The quality is adjusted automatically to the current state of the wireless multi-hop network and respectively the available bandwidth of the used route by using a feedback of the network status. As above mentioned, the state of each single node of a route has a strong influence on the quality of the used link in terms of bandwidth, delay, and packet loss. To increase the performance of mobile robot teleoperation, the available frame rate at the operator PC should be almost constant. In order to adjust the image quality according to the link, an active feedback mechanism is implemented at the application layer of each node. Thus, a feedback of the network is available for the video stream source which can be used to adapt the image quality. The proposed mechanism requires only little resources, is portable and easy to implement, and provides the operator the highest possible video quality for mobile robot teleoperation which can be guaranteed for the current network state. As it supports no traffic classes as it is known from wired IP networks, it should not be considered as a quality of service (QoS) mechanism. Anyway, available quality of service (QoS) mechanisms – e.g. integrated services (IntServ) or differentiated services (DiffServ) – are currently not applicable in ad-hoc networks of mobile robots due to very specific hardware requirements and the special solutions which are currently available for network service providers.

The remainder of this work is structured as follows. In Section 2, the investigated scenario is described and a short definition of the problem is given. Section 4 presents the implementation of the network feedback mechanism and the adaptation of the video stream in detail. The next Section gives an overview of the mobile robot, the communication, and video hardware which is used in the test scenarios. Section 5 defines the test scenarios of real hardware tests and gives the results. Finally, a conclusion is given in Section 6.

2 PROBLEM DEFINITION AND SCENARIO

2.1 Problem Definition

In the above mentioned scenarios, the available throughput of a route via a wireless multi-hop network is a highly dynamic parameter which depends on many environmental influences and affects the quality of the application significantly. The throughput of a wireless node can be decreased due to different reasons. In case intermediate nodes of a route are also part of a route which has to transport other bandwidth intensive flows, the available bandwidth must be shared between all present routes via this node, which will reduce the available bandwidth for the video link. Furthermore, also a decreasing link quality will reduce the bandwidth and increase the packet loss probability. If the network is not reacting to traffic overload at a specific node, this will lead to unpredictable packet loss at this point and delays at the different receivers. For the teleoperation scenario the effect will be that the video stream will get randomly stuck, because packets get lost. Most probably the operator will get confused and will stop the robot.

2.2 Test Scenario Additional Traffic

To set up the scenario where a node is used for more than one bandwidth intensive traffic flow, four nodes are used (cf. Figure 2). All nodes are located such that they are in direct communication range. During the tests, defined additional UDP traffic will be generated between node 3 and node 4 while the investigated video stream is transmitted via UDP from the mobile robot to the user's PC via node 3. The generated UDP traffic is used to reach certain load levels at intermediate node 3. As in this scenario, node 3 and node 4 are in communication range to all other nodes which will also cause interferences at the physical layer.

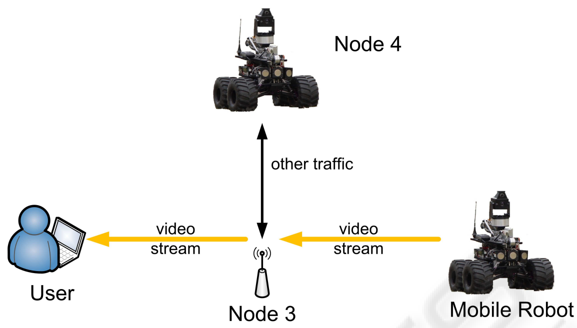

Figure 2: The test setup for additional traffic.

To provide best repeatability of the tests, all nodes are stationary. Only the additional traffic between node 3 and node 4 will be varied according to a defined profile. Measured categories are the packet loss and the packet inter-arrival times. These categories are measured while the amount of additionally generated traffic is increased. As reference test, video transmissions of constant target quality are used and compared to the packet loss of the transmission with adaptive quality.

3 HARDWARE

The proposed mechanism was tested in a real outdoor environment with a wireless ad-hoc network of four nodes. One is the PC of the operator, one is an Outdoor MERLIN (cf. Figure 3) (Eck et al., 2007), and two intermediate nodes are MERLIN robots (indoor version). More details on the scenario are shown in Figure 2 and a detailed description of the test setup is given in Section 2. Figure 4 shows the detailed system setup. All MERLIN robots have a C167 microcontroller for low-level operations and sensor data processing, as well as a PC-104 for more complex and computationally more intensive tasks. The PC-104 uses a Linux operating system and all nodes are equipped with 802.11b standard WLAN equipment (Atheros chip).

To grab the video from an analog camera (approx. 65 degree field of view) an Axis video server is used. It can grab the video from up to four cameras with a resolution of 768x576 pixels. Dependent on the configuration and connected clients, a frame rate of up to 25 images per second can be provided either as MJPEG or MPEG4 over a TCP/IP connection. For the described tests the PC-104 is connected over a cross-link cable to the Ethernet interface of the

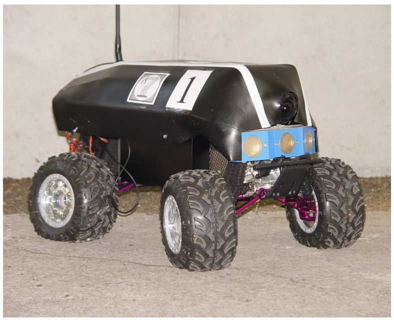

Figure 3: The Teleoperated OutdoorMERLIN Robot.

video server. As nothing else is connected to this Ethernet interface of the PC-104 it can be exclusively used for the video traffic. For the presented tests four MJPEG video streams with full resolution are established with four different compression rates. MJPEG as video compression was selected, as MPEG4 compression takes a significant longer time on the Axis server what causes a significant delay in the video stream. Secondly a loss of a packet during transmission of MPEG4 streams to the robot might lead to longer set of distorted images because compared to MJPEG not all frames of the stream contain the full image information needed. In case of the investigated scenario, the MJPEG frames are transmitted via UDP protocol.

4 NETWORK FEEDBACK AND ADAPTIVE VIDEO QUALITY

The proposed mechanism mainly consists of two parts: the network feedback, and the adaptive adjustment of the video quality. The mechanism is used for a simple admission control of the video source and intends to provide the best possible video image quality considering the current state of the link. The objective is an efficient use of the available bandwidth without overloading the route with video traffic to the operator. Thus, it is not used to increase the link quality directly but uses the available resources most efficient and reliable for the operators' video stream.

4.1 Network Feedback

The network feedback is responsible to transmit the status of a node to the video source. Therefore, nodes of the network host a small client program at the application layer. This client application is listening in promiscuous mode at layer 3 of the ISO/OSI model (IP-layer) and measures the utilization of the wireless link. All kinds of traffic are monitored: incoming and outgoing packets, packets for forwarding, and packets with other nodes in range as destination – basically all traffic causing the radio link of this node to be busy. The network feedback client sends very small UDP packets with an adjustable frequency (in the test setup 10 Hz) and 8 bytes as payload to the video-source if it is a used hop in the video stream route between video-source and receiving node. This payload is used to indicate the status of the corresponding node, either "normal operation" or "overload situation". In the beginning, each node is in the "normal operation" mode. As soon as a certain utilization of the supported bandwidth is exceeded, the status of this node switches to "overload situation". Important parameters for the network feedback clients are the feedback frequency f and the threshold for status determination d. In case f is too high, too much feedback traffic is generated which degrades the performance of the network. Even these packets are very small, too many small packets with a high sending frequency will have a very bad effect on 802.11b WLAN and will significantly decrease the throughput. Thus, the generated feedback traffic should be limited depending on the interpretation rate of the video adjustment mechanism and the selected load window for the wireless nodes. Often it is also not necessary to run a feedback client on each network node. For setting parameter d, it should be considered, that d specifies the percentage of the nominal bandwidth (e.g. for 802.11b this would be 11 Mbit/sec) which can be used without switching to the "overload situation" state. The feedback clients measures packets on layer 3, where the maximum available bandwidth corresponds to the "goodput" of the wireless link which is about 75% of the nominal link bandwidth (e.g. for 802.11b this would be 75% of 11 Mbit/sec).

As the proposed mechanism is used within a network where a link failure can occur at any time, the measurement and signaling mechanism must be active. Thus, link failures and link reestablishing can be monitored reliably. As the mechanism for video quality adaptation performs best with a feedback frequency of $f = 10$ Hz (according to the presented scenario), the generated measurement traffic has a bandwidth of less than 0.003 Mbit/sec per measurement node. To set parameter d, the goodput" of about 7 to 7.5 Mbit/sec (for an 11 Mbit/sec WLAN link) must be considered. In order to allow a reaction on potential overload situations while providing the user a video stream with a bandwidth of 1 to 1.5 Mbit/sec for the best quality, d is set to 50.

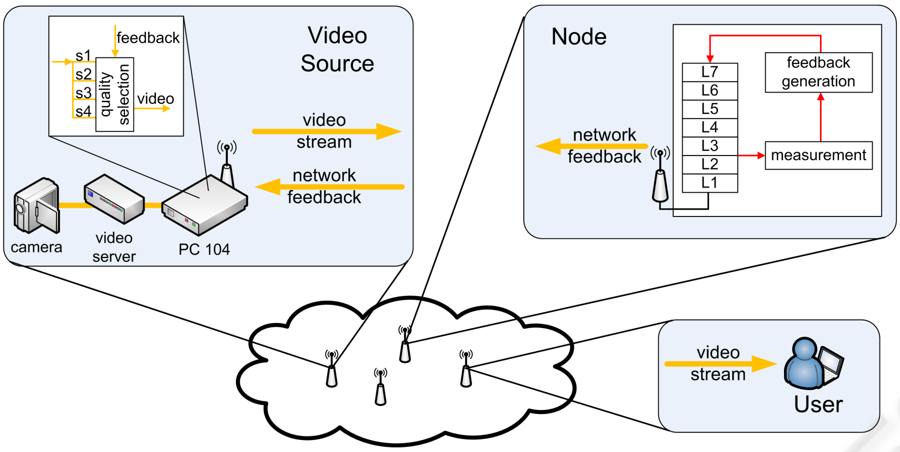

Figure 4: System setup.

4.2 Adaptive Video Quality

The Video Quality in the presented system is adapted according to current state of the ad-hoc route for the video transfer. The adaption mechanism receives all status packages from the nodes between two received frames from the image source, interprets these packages and selects the quality for the next frames with a combination of previous status data and the current state. Do reduce oscillating behavior in quality switching near the selected load limit of the nodes a kind of inertia mechanism for the adaptation process was integrated. The implemented inertia mechanism guarantees not to change the image quality whenever a status of a node changes. It is possible to set a certain number (cf. Algorithm 1, min/max of inertia_counter) of receiving same successive route load states until the quality is changed. Algorithm 1 shows this mechanism how the quality for the next frame is selected according to the received network status messages.

In the current test setup, four different video qualities are used at a frame rate of 11 frames per second each. Table 1 shows the average size of one image for the corresponding image quality level.

A higher number of different quality scales would also be possible. In the current test setup a minimum of -3 and a maximum of 3 are selected for the inertia_counter. With this value the mechanism reacts in the worst case after six frames with subsequent overload states and in average after three frames. This keeps the load caused by the video traffic on the different nodes in a certain defined window around the selected threshold for overload state. In combination with parameter d of the above described feedback mechanism, the quality adjustment intervenes as soon as a node exceeds a radio link utilization of more than approx. 78% (≈ 50% of nominal bandwidth). This prevents the node from reaching a utilization of 100% of the available maximum throughput which would result in a high packet loss rate due to an increasing number of packet collisions.

Algorithm 1: Video quality adaptation.

Input: video streams of different quality;
    load status messages

initialization;
foreach *frame of current selected quality* **do**
  if *one of the nodes overloaded* **then**
    increment inertia_counter by one;
  else
    decrement inertia_counter by one;
  end
  reset node states;
  send video frame;
  if *inertia_counter above max* **then**
    select lower quality if possible;
    set inertia_counter to zero;
  else
    if *inertia_counter below min* **then**
      select higher quality if possible;
      set inertia_counter to zero;
    end
  end
end

Table 1: Average size of one image per quality level.

Quality	minimum	low	medium	high
Size (kbytes)	15	26	34	47

5 TEST AND RESULTS

In a first step, a reference scenario was set up and measured. Therefore, no network feedback mechanism is used and a mobile robot generates a video stream which is sent to the PC of the operator as it is displayed in Figure 2. Between node 4 and node 3, additional traffic is generated during the different test phases according to Table 2 to reach a defined load at intermediate node 3.

Table 2: Generated additional traffic.

Phase	generated additional traffic (Mbit/sec)
1	0
2	3,2
3	4
4	4,8
5	5,6
6	6,4
7	7,2
8	8
9	8,8

The results of this reference test are shown in Figure 5. The x-axis shows the test time in milliseconds. The left y-axis describes the received frame rate in frames per second (fps) and the right y-axis displays the received video data rate in bytes per second (bps) at the receiving node (operator's PC).

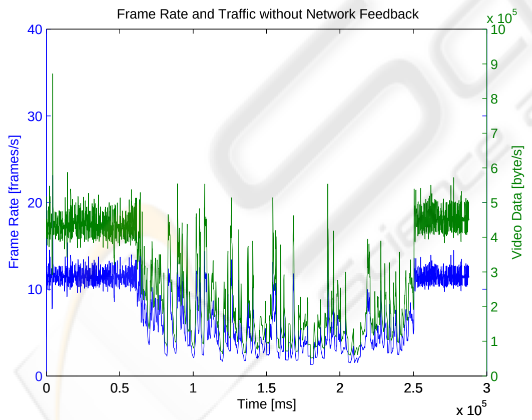

Figure 5: Framerate and Traffic without Network Feedback.

The test started with no additional traffic being generated. Successively, more and more additional traffic is generated by switching to the next phase each 20 seconds according to Table 2. After 200 seconds of test time, the additionally generated traffic is reduced by switching back one phase each 10 seconds. In the beginning of the test – during phase 1 up to the end of phase 3 – the received frame rate is about 11 fps. After switching to phase 4 at about 60 seconds, the received video frame rate decreases significantly. The received frame rate between 100 and 200 seconds drops to $2-3$ fps while node 3 is overloaded. After the additionally generated traffic is reduced, the received frame rate recovered to 11 fps. Increasing the additional traffic forces node 3 to an overload situation. As the bandwidth used by the video stream cannot be adapted to the new situation, a packet loss of the video data is inevitable which is shown in Figure 6. The y-axis shows the number of lost packets vs. the test time on the x-axis.

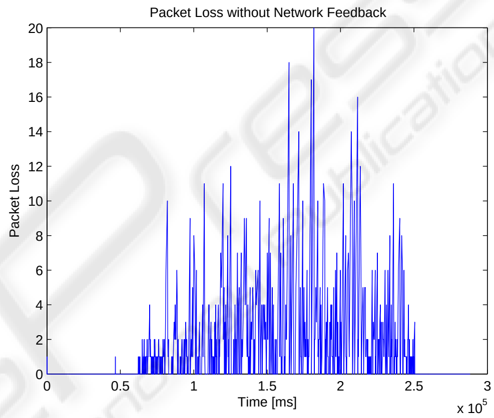

Figure 6: Packet Loss without Network Feedback.

Another measured category is the frame inter-arrival time of the video stream. This is a quite sensitive aspect, as a large jitter (variance of the frame inter-arrival time) is very irritating for the operator due to a very unsteady motion of the video image. Without additional traffic, the frame inter-arrival time is smaller than 100 ms with a variance close to 0 (cf. Figure 7) what corresponds to the average frame rate of 11 fps. After 60 seconds and an additionally generated traffic of 4.8 Mbit/sec, the frame inter arrival time increases to more than 400 ms with a variance of more than 10000 which indicates an unacceptable video for the operator.

The same test setup is used again – now with the network feedback and adaptive quality mechanism (cf. Section 4), which should improve the observed behavior. In Figure 8, the frame rate and the video data rate is shown while using an adaptive video quality together with the network feedback mechanism. In the beginning, without additional traffic, the mobile robot generates a video stream of about 450000 bytes/sec. During the test, the additionally generated traffic is increased similar to the test described above. The implemented mechanism takes care that the video

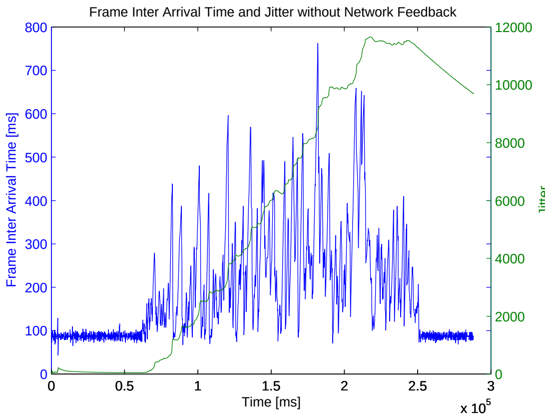

Figure 7: Frame Inter Arrival Time without Network Feedback.

source reduces its generated video traffic to about 300000 as soon as phase 3 (with an additional load of 4 Mbit/sec) is entered. Increasing the additional load at node 3 to more than 4.8 Mbit/sec results again in a reduction of the video traffic (180000 bytes/sec). During the complete test run, the frame rate stays almost constantly at 11 fps as the adaptive video bandwidth reduction avoids the loss of video traffic. Also the frame inter arrival time stays constantly below 100 ms with a jitter of almost 0 (cf. Figure 9).

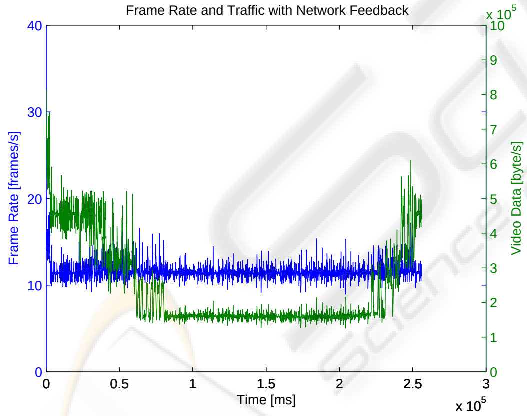

Figure 8: Framerate and Traffic with Network Feedback.

6 CONCLUSIONS

In this work, a mechanism for providing a video stream over a dynamic multi-hop route with an adaptive quality for mobile robot teleoperation is proposed. The mechanism uses a feedback from the network which is generated at dedicated nodes and adjusts the image quality to the current communication

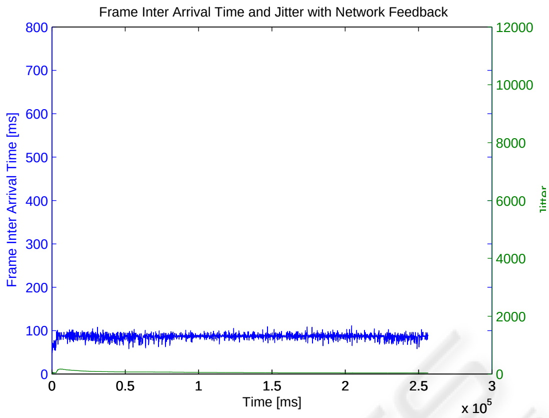

Figure 9: Frame Inter Arrival Time with Network Feedback.

link status. The proper functionality of this adaptive quality mechanism is tested in teleoperation scenarios with real hardware under different network load situations. In situations with a very high link load due to additional other network traffic, usually the packet loss rate and the packet inter-arrival time is affected in a way that reliable and proper teleoperation is not possible anymore. By adjusting the image quality of the video stream it is possible to provide a stable video frame rate for the operator. In fact, the remaining bandwidth for the video stream is used efficiently in terms of providing a video with a stable frame rate suitable for mobile robot teleoperation.

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