Quality-Latency Trade-Off in Bilateral Teleoperation

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***Abstract*—This paper investigates how the latency in a mobile network affect the quality of a highly demanding and sensitive application running on it. The application chosen is a bilateral teleoperation with a haptic input device, meaning a remotely controlled robot with force feedback. The latency of the two a 3G- and 4G Network were measured and simulated in application. To examine how the latency affect the quality of the application, a dexterity test was carried out. The test involved having a user controlling the robot, picking up a few bricks, and then putting them in a box while the time this took was recorded.**

I. Introduction

There is no escaping that we are seeing a tremendous growth in Cloud computing these days. The concept has finally reached the critical mass and everyone have heard about the Cloud, but far from everyone knows how massive its explosion really is. The Cloud Computing industry is growing faster than ever. According to Cisco, two thirds of the workloads will be processed in the Cloud by 2017 [1]. They also predict that we will see a 5-fold increase in the Cloud IP-traffic over the next five years. A research group at UC Berkeley say Cloud computing will be the new utility in the future, comparing it with electricity, gas and the telephone [2].

Along with this we see more and more smart things connecting to the Internet eventually emerging to the Internet of Things. Today we have about 5 billion connected things, by 2020 there will be about 50 billion, and within our life time a trillion, [3]. IDC predicts that, if the major hurdles in the developing the Internet of Things can be overcome, there will be over 200 billion connected devices by 2020, resulting in a trillion dollar industry, [4].

It is natural to see that the Cloud, the IoT and the Network industries are growing in some form of symbiosis, stimulating each other and converging more and more. This is where the amazing will happen. Harbor Research puts it in a very nice way [5]:

> It will bend the traditional linear value chain into a ”feedback loop”.

This paper is based on the Master's thesis, [6], and will focus on how latency effects the quality of an advanced application run over a mobile network. The application of choice is a bilateral teleoperation. If it would be possible to have run a high-quality and reliable bilateral teleoperation over the mobile network the end-result could be amazing. One of the main applications would be in remote surgery. It would allow a surgeon to receive force feedback while performing a remote surgery. This would in turn provide better care at remote areas of the world, as well as at temporary emergency cites. It would allow for one surgeon to operate on three different patients, at three different small cities, on three different continents on the same day!

The outline of the paper is as follows, a quick introduction to bilateral teleoperation and the solution used in this setup. This will be followed by an evaluation section, describing the tests made and its main results. Lastly there will be a conclusion section as well as a short discussion section.

II. Bilateral Teleoperation

The first bilateral teleoperation was built by Goertz in the mid 1940s [7]. Since then a lot of research has been done in order to improve the stability and transparency of the teleoperation link. In a broad sense teleoperation allows an operator to use a joystick, *master device*, in order make a robot, *slave device*, interact with a distant environment. If the slave device has the possibility of sensing forces, these can be reflected back to the master device, giving the operator force feedback. Such link is called a *bilateral teleoperation* link as shown in Fig 1. Transparency is the measure of how easy it is for the operator to interact with the environment. One can say that the higher the transparency, the greater telepresence the operator will feel. Achieving a high transparency generally conflicts with having a high stability of the system.

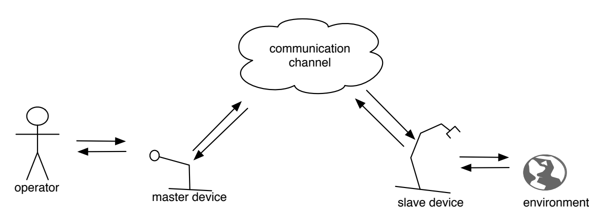

Fig. 1. Overview of a bilateral teleoperation link.

The quality and transparency of a bilateral teleoperation is highly dependent on the communication channel. The reason is that latency may cause more and more energy to be stored in causing it to become unstable. To improve stability a few different methods have been developed over time. A great overview of the history and development of bilateral teleoperation is given in [7].

A. Wave Variable

Inspired by the phenomena of the passive waves, which are stable despite the occurrence of time-delay, the *Wave Variable* was presented in [8]. The idea was that instead of sending velocity in one direction and force in the other, a mixture of these were to be sent in both directions. By choosing these wave variables in a clever manner it is possible to guarantee a passive communications block and thus a stable system. These waves can be modeled according to (1) and (2).

$$u_m = \dot{x}_m - F_m \qquad v_m = \dot{x}_m + F_m \tag{1}$$

$$u_s = \dot{x}_s + F_s \qquad v_s = \dot{x}_s - F_s \tag{2}$$

Since a lossless wave might become a standing wave, some impedance b is added to the system. The new system can be seen in Fig. 2 and expressed according to (3) and (4).

$$u_m = b\dot{x}_m - F_m \qquad v_m = b\dot{x}_m + F_m \tag{3}$$

$$u_s = b\dot{x}_s + F_s \qquad v_s = b\dot{x}_s - F_s \tag{4}$$

The resulting scheme, which is used as the solution in this paper, is described in Fig. 2.

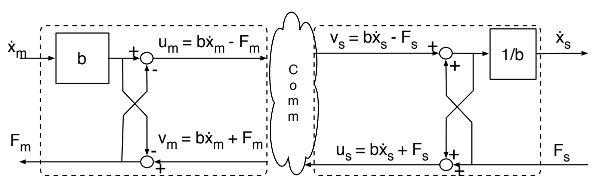

Fig. 2. Bilateral teleoperation using wave variables.

III. Measuring Latency

The approach used to investigate the latency-quality trade-off was to simulate the latency of different networks in order to evaluate their effects in a controlled manner. However, to get accurate results there was a need for accurate models of the different networks. There was four different networks being simulated:

- Wired Network
- 5G Network
- 4G Network
- 3G Network

The approach was to measure the latency occuring over the 3G network and the 4G network. The 5G network was a stepping stone between the Wired Network and the 4G network. The 3G and 4G networks was measured through sending packets between two different dongels once every second and recording the latency.

The results for the latency measurements of the 3G network can be seen in Fig. 3. The figures shows the round-trip latency recorded for each of the packets. The measurement lasted for about 1800 seconds sending one packet every second. The mean latency is about 300 ms.

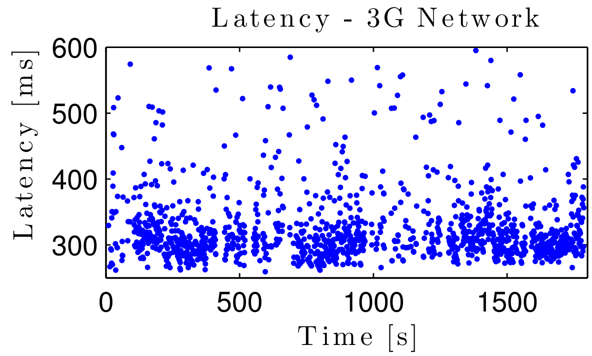

Fig. 3. Latency plot for the 3G network. The y-axis describes the round-trip latency recorded for each of the packet sent. There was one packet sent every second.

The 3G network latency was fitted with a suitable distribution using the Matlab tool *'dfittool'*. The result was a General Extreme Value distribution according to (5), where $\mu = 299.8$ ms, $\sigma = 26$ ms and $k = 0.29$.

$$f_{3G}\left(x \mid k, \mu, \sigma\right) = \frac{1}{\sigma} e^{-\left(1+k\left(\frac{x-\mu}{\sigma}\right)^{\frac{1}{k}}\right)} \left(1 + k\frac{x-\mu}{\sigma}\right)^{\frac{-1}{k}} \tag{5}$$

The results for the latency measurements of the 4G network can be seen in Fig. 4. As in the 3G latency plot the y-axis shows the round-trip delay for the packets. The x-axis shows the packet and there were one sent once every second. The mean latency is concentrated around 60 ms with a maximum value around 65 ms and a minimum value around 50 ms.

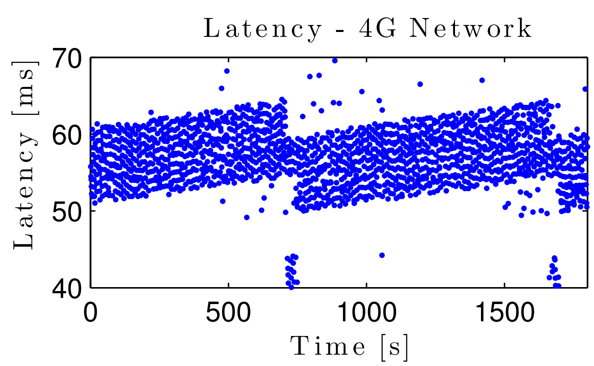

Fig. 4. Latency plot for the 4G network. The y-axis describes the round-trip latency recorded for each of the packet sent. There was a packet sent once every second.

As before, 4G latency data was fitted with a distribution using the Matlab tool *'dfittool'*. The results was a Normal distribution described by (6), where $\mu = 60$ ms and $\sigma = 5$ ms.

$$f_{4G}\left(x, \sigma, \mu\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{6}$$

The latency for the wired network was assumed to have no latency, since it will be negligible in comparison with the one of the 4G and 3G networks. The 5G network is assumed to be somewhere in between that of the 4G and the wired network. Thus the 5G network is chosen to be modeled using (7), with $\mu = 10$ ms and $\sigma = 1$ ms.

$$f_{5G}\left(x, \sigma, \mu\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{7}$$

IV. Test Evaluation

The test setup consisted of a haptic device, an Omega.7, with 7 degrees of freedom - three translational, three rotational and one gripper. It had the capability to actuate forces up to 12 N, but could actuate any moment on the user. The robot used in the setup was an ABB IRB 140 industrial robot. They can both be seen in Fig. 5.

Fig. 5. The test setup used to evaluate the quality of the bilateral teleoperation. The left image show the Omega.7 haptic device and the right image show the ABB IRB 140 industrial robot.

The result of the simulated latency that was used in the setup can be seen in Fig. 6. There the different networks have been simulated in the following order: *Wired Network*, *5G Network*, *4G Network*, and *3G Network*. The wired network had no added latency, the 5G had about 10 ms one-way delay, the 4G had a one-way delay of about 30 ms and the 3G network had a one-way delay of about 150 ms.

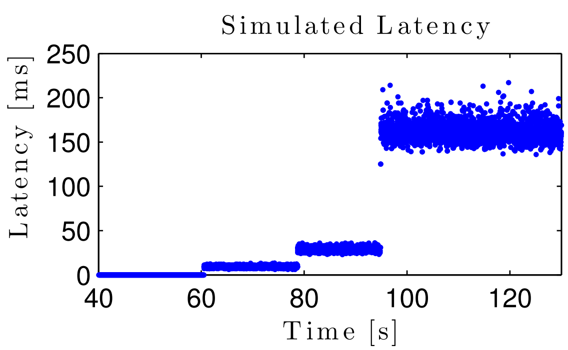

Fig. 6. Network type and simulated latency during the collision test. First the wired network was simulated (no added latency), then the 5G network, the 4G network and last the 3G network was simulated.

A. Collision Test

For the collision test the robot manipulator was set to collide with a hard surface - a hard foam board. The test was meant to investigate if there are any difference in behavior when running on the different network modes. Figure 7 shows the velocity and reaction forces measured at the robot manipulator during a collision, for each on the different network modes. The force and velocity was measured in the direction of the collision. Each collision had a collision force of about 4 N. The upper left image shows the collision for the wired network, the upper right for the 5G network, the lower left for the 4G network, and the lower right image shows the collision for the 3G network.

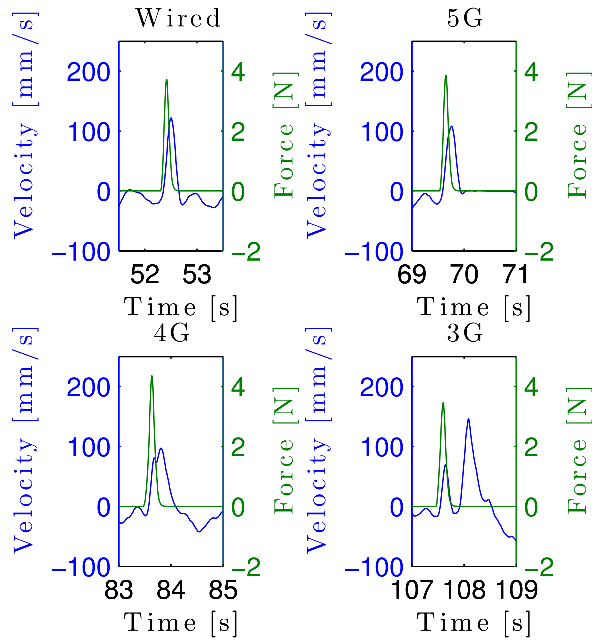

Fig. 7. Collision test for the four network modes Wired network (upper left), 5G network (upper right), 4G network (lower left), and 3G network (lower right). The left y-axis show velocity, the right y-axis show contact force and the x-axis show the time-scale. The velocity and position are in x-direction in TCP frame coordinates.

Looking at the collisions in Fig. 7 one can see that there was a difference in behavior between the four network modes. For the wired network and the 5G network the reaction to the collision occurred in a smooth reaction. Note however that the tip was slightly smoother for the 5G network than for the wired network. For the 4G network there were two distinct peaks during the reaction-phase of the collision. The first peak was due to the local controller at the robot interface and occurred instantly after the collision. The second peak, about 60 ms after the first peak, was due to the reaction made by the operator controlling the haptic interface. The delay between the two peaks happened because the signal had to travel from the robot to the haptic device, interact with the operator, and then travel back to the robot. For the 3G network there were no longer one reaction with two peaks, but rather two distinct reactions - one coming from the the robot controller and one from the operator. The time difference between the two reactions correlates with the round-trip delay of the 3G network, about 300 ms.

B. Dexterity Test

The dexterity test used in this experiment was inspired by the Purdue Pegboard Test, where the test subject is supposed to put different pegs in different holes, and the Minnesota Manual Dexterity Test, where the test subject is supposed to move small pucks into different holes. Both of those tests are timed in order to find if there is a significant difference in the amount of items the test subject can put in place at a specific time, or if the is a difference in the time it takes to complete putting a specific number of items in place. The test subject in our experiment was set to pick up small bricks made out of wood and put them in a rectangular hole, see Fig. 8. There was a total of six bricks and through controlling the robot the test subject should put them in the box as quick as possible. The total time of the test was recorded in order to detect a difference between the different network modes. There was a total of five test runs on each network mode, all made by the same test subject.

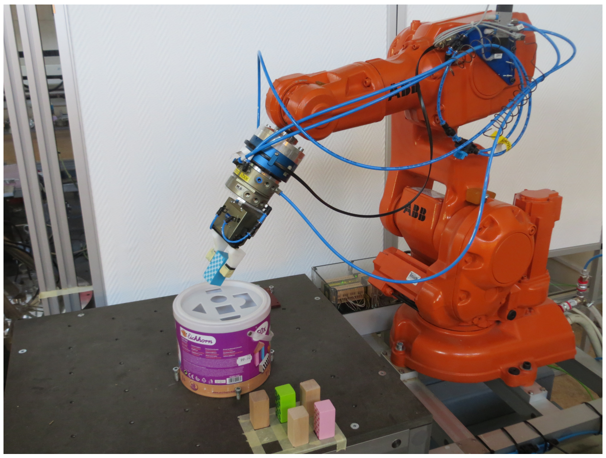

Fig. 8. Test setup used for the dexterity test.

The result of the dexterity test is shown in Fig. 9. The y-axis shows the time it took to complete the test and the x-axis show the different network modes. The plot shows the mean time to complete the test, green circles, along with its standard deviation, the blue bar. Clearly, when performing the test on the wired network or the 5G- and 4G network the test subjects were quicker to finish the test than when running on the 3G network. The wired network was the fastest one with the lowest standard deviation. Interestingly, the 4G network was slightly faster than the 5G network but had a higher standard deviation. The reason for this was that the test subject "got lucky" and was able to find the hole in the box on the first try, thus obtaining a faster test time.

V. Conclusion

The result of the Brick-in-Box experiment, Fig. 9, showed that the system was good enough to complete the experiments regardless of which network was being simulated. It shows that there was indeed a difference between the 3G network and the rest, but no significant difference between the wired network, 5G network, nor the 4G network.

Furthermore if one looks at the results in Fig. 7, there is no change in behavior between the wired network and the 5G network. However, when going from the 5G network to the 4G network there is subtle change in behavior. In the 4G network there is two distinct velocity peaks, seen in Fig. 7. The reason being that the round-trip delay becomes big enough to start playing a role, if just a minor one. When changing from the 4G network to the even slower 3G network the changes seen before becomes exaggerated. Looking at the velocity-force plot there was two distinct velocity curves, rather than just two peaks in one. The first one is due to the local robot controller and the other, about 300 ms after, is due to the reactions of the operator.

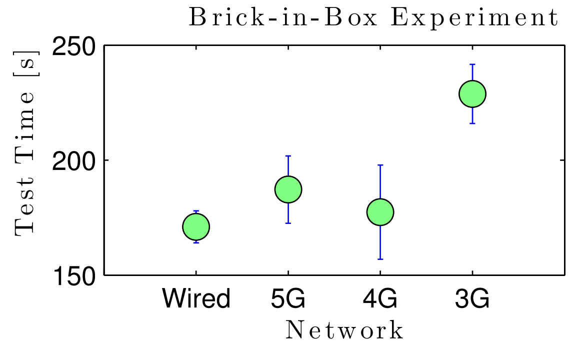

Fig. 9. Results of the dexterity tests showing the average time left, as well the standard deviation, after putting the six bricks into the box.

It is worth noting that the slightly different behavior seen when running on the 4G network did not affect the quality of the bilateral teleoperation to any significant length. The standard deviation of the total test time for 4G was larger than that of the wired- and the 5G network, but the mean time was not significantly different.

Thus it is reasonable to conclude that the latency of the 4G network, a round-trip delay of 60 ms, provides an upper boundary of what is desirable when running this application on a network mode. A goal for the round-trip delay would be that of the 5G network, about 20 ms, simulated in this experiment, the reason being that it shows no difference in behavior, when looking in depth for one, to that of the wired network. These experiments and simulations were done assuming all packages will arrive and in the same order.

References

[1] Cisco, *Cisco Global Cloud Index: Forecast and Methodology, 2012 - 2017*, [Online], 2013

[2] M. Armbrust et al, *Above the Clouds: A Berkeley View of Cloud Computing*, UCB/EECS-2009-28, EECS Department, University of California, Berkeley, 2009

[3] Texas Instruments, *The Evolution of the Internet of Things*, [Online], 2013

[4] L. Dignan, *Internet of Things: $8.9 trillion market in 2020, 212 billion connected things*, [Online], 2013

[5] Harbor Research, *Are You Prepared For Big Changes In The Way We Will Learn, Work and Innovate?*, [Online], 2014

[6] V. Millnert, *Quality-Latency Trade-Off in Bilateral Teleoperation*, ISRN LUTFD2/TFRT--5951--SE, Dep. of Automatic Control, Lund University, 2014

[7] P. F. Hokayem and M. W. Spong, *Bilateral Teleoperation: An Historical Survey*, *Automatica,* vol. 42, no. 12, pp. 2035 - 2057, 2006

[8] G. Niemeyer and J.-J. Slotine, *Stable Adaptive Teleoperation*, *Oceanic Engineering, IEEE Journal of*, vol. 16, no. 1, pp. 152-162, 1991