Performance Analysis of a Compact Robotic Tele-Echography E-Health System over Terrestrial and Mobile Communication Links

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Abstract

In this work, we present a comparative performance analysis of an end-to-end Robotic tele-echography system using two means of communication links; Satellite and mobile (GPRS and UMTS) links. The functional modalities of the system in terms of the Delay, Total Throughput and the Jitter has been investigated, showing the capabilities and limitations of each communication link. The effect of concurrent and asynchronous system data transmission have been studied. The transmission of still and stream of ultrasound images investigated under different network conditions, simulated and on real network. The limitation of the GPRS network with respect to the other communication links options, has been verified and analysed. The outcome of the study is showing that the UMTS network, is a promising communication link for OTELO system.

1 Introduction

OTELO (m**O**bile- **T**ele-**E**chography using an ultra-**L**ight r**O**bot) is a European IST funded project [1] that develops a fully integrated end-to-end mobile tele-echography system for population groups that are not served locally, either temporarily or permanently, by medical ultrasound experts. It comprises a fully portable tele-operated robot allowing a specialist sonographer to perform a real-time robotised tele-echography to remote patients [2]. This Tele-echography system is composed of three main parts:

- An « Expert » site where the medical expert interacts with a dedicated patented pseudo-haptic fictive probe [3] instrumented to control the positioning of the remote robot and emulates an ultrasound probe that medical experts are used to handle, thus providing a better ergonomy.
- The communication media. We developed communication software based upon IP protocol to adapt to different communication means (ISDN, ADSL, LAN, Satellite, mobile…).
- A « Patient » site made up of the 6 Degrees of Freedom (DoF) light weight robotic system and its control unit - Fig 1.

Different communication links can be used to establish Expert / Patient (remotely controlled robotic Ultrasound probe) stations connection. These communication links are terrestrial, satellite, and wireless (GPRS & UMTS) links. While clinical tests have been carried out with satellite demonstrating the feasibility of a remote satellite relayed Ultrasound (US) examination [4], mobile communications widen the possible applications for tele-echography [5] and have been shown as a solution for OTELO [6]. This paper presents a comparative performance analysis between the above links. The functional modalities of the system over these links are presented in the following part. Quality of Service (QoS) over UMTS and GPRS, for medical images, is investigated in the third part so as to compare and evaluate for medical application. Fourth part concerns our evaluation experimental work based on various criterions. Results are discussed in a fifth part.

Figure 1 OTELO Robot with the echograph Unit

2 OTELO functional modalities

OTELO is a mobile multimedia telemedicine application with different data traffic. Robotic control data and stream of ultrasound data have to be transmitted simultaneously. Figure 3 shows the physical settings of the OTELO system and the interface requirements with UMTS/UTRA. The OTELO Expert Station may either link from the IP Multimedia Network or through the ISDN/ADSL.

The data rates for OTELO system are shown in Table 1. As the ultrasound images are mostly transferred from the robot probe to the OTELO Expert Station, the air interface, Uu, between the OTELO Patient Station and the Radio Network Controller (RNC) bearer is asymmetric traffic load. The still ultrasound images, stream ultrasound images, ambient video, sound and robot control data are sent over the uplink channel, while only robot control, ambient video and sound need to be downloaded to the patient side (i.e. Expert station uploading).

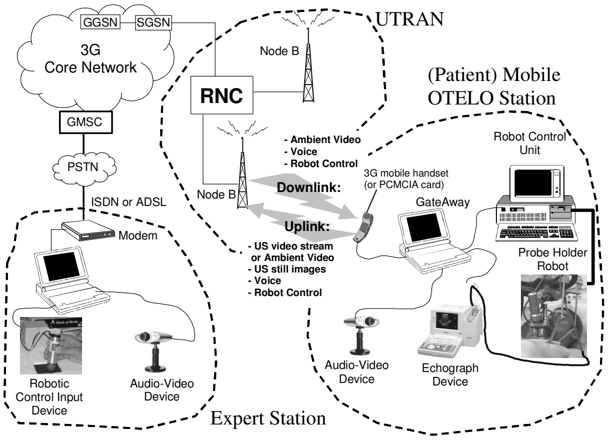

Figure 2 OTELO schedule on UMTS

	Ultrasound video stream	Ultrasound still images	Ambient video stream	Voice	Robot control data
Flow direction	Simplex: Patient to Expert	Simplex: Patient to Expert	duplex	duplex	duplex
Trans-port protocol	RTP/ UDP/IP	TCP/IP	RTP/ UDP/IP	RTP/ UDP/IP	UDP/IP
Speed requirement	Real-time	Non Real-time	Real-time	Real-time	Real-time
Payload data rate requirement over the air-interface	15 frames/s @ 210 kbps Uplink	1 frame/ 10s Uplink	1 to 15 frame/s symmetrically	9.0 kbps symmetrically	2 kbps symmetrically

Table 1 OTELO medical data requirements and corresponding data rates

According to the communication link limitations various scenarios can be identified with respect to the data traffic that should be sent simultaneously so as to enable the performing of the medical examination.

For our experiments we consider the two following options:

1) Real-time robot control and ultrasound video stream feedback to the expert station (no videoconference, no voice, no simultaneous still US images). Data rate for robot control indicated in table 1 is related to a unilateral position control. Thanks to the instrumented fictive probe, the position (3 angles and 3 Cartesian co-ordinates) of the medical expert hand is grabbed and sent periodically to the robot control unit as position set-points that are to be tracked by the robot. No feedback control is provided through the communication link. Although the robot control is unilateral, the robot actual position is monitored by shipped in sensors and sent back to the expert station so as to provide the medical expert with the information of tracking capability of the robot. We're not considering here a robotic control with haptic feedback, which has more drastic requirement [7] but is going to be used for future prototype for OTELO. It shall be also taken into account that the Patient station response time in terms of sending the stream of US image responding to the Expert control should not exceed 300 ms for an ergonomic purpose.

2) Still US images only. During a second phase of examination, when the expert has found satisfactory US slice to study for diagnosis, high-resolution ultrasound still images are needed. According to the available bandwidth on the communication link, a lossy (JPEGLS, JPEG-2000) or lossless reversible compression technique (e.g. Wavelets-LZH) is applied. The size of the medical images varies from 256x256 pixels up to 512x512 pixels and the grey level of each pixel can be saved up to 16 bits.

3 Theoretical link capabilities and Quality of Service for medical images

We focus here on video streaming related to ultrasound scans as it is the critical data for this application.

3.1 UMTS

According to the International Telecommunications Union (ITU) requirements, the data rate that will be available over 3G will depend upon the environment the call is being made in. We focus on the two options that are more likely to be used in the framework of OTELO when considering a mobile patient station within a rescue vehicle:

High Mobility: 144 kbps for rural outdoor mobile use. This data rate is available for environments in which the 3G user is travelling more than 120 kilometres per hour in outdoor environments.

Full Mobility: 384 kbps downlink for pedestrian users travelling less than 120 kilometres per hour in urban outdoor environments.

From the previously defined bandwidth requirements (Table 1) the classification of the OTELO traffic is mapped to the three major traffic classes [6] defined by the 3GPP UMTS QoS Classes [8]. The best-suited UMTS QoS class for video streaming is "Streaming class, streaming RT" which preserve time relation (variation) between information entities of the stream. But for medical image sequence with real-time requirements, the "Conversational RT" class would be necessary. In addition to preserving time relation between entities of the stream, it has conversational pattern (stringent and low delay) which is preferable for a real-time interaction.

3.2 GPRS

Achieving the theoretical maximum GPRS data transmission speed of 171.2 kbps would require a single user taking over all eight timeslots without any error protection. Clearly, it is unlikely that a network operator will allow all timeslots to be used by a single GPRS user. Additionally, the initial GPRS terminals are expected to be limited to one, two or three timeslots for uplink. As such, the theoretical maximum GPRS speeds should be checked against the reality of constraints in the networks and terminals. In reality 40-50 kbps is available. GPRS allows defining QoS profiles using the parameters service "precedence, reliability, delay, and throughput" [9]. Using these QoS classes, QoS profiles can be negotiated between the mobile user and the network for each session, depending on the QoS demand and the current available resources. However, no throughput guaranty can be provided when congestion occur. For ultrasound video streaming each of these parameters should be set at their maximum value so as to give acceptable quality for real-time ultrasound video stream.

4 Experiments

4.1 Experimental settings

For the first scenario described in §2 the study concerns the UMTS with respect to Throughput performance, Delay Jitters and end to end Latency.

The network behaviour has been simulated. The real expert and patient stations were connected through an Emulator running WAN Network (Shunra/Cloud, Licensed software) to simulate the operation of the system on UMTS network. The latency and congestion parameters where obtained by monitoring and capturing different packet sizes transmitted from end-to-end, over operating Vodafone GPRS and UMTS networks.

For UMTS the selected uplink throughput was 64 Kbps which is the most likely to be offered by providers at the present time. Ultrasound scans video was streamed by using commercial program (Netmeeting™ software).

For the second scenario with only still images, Delay and Throughput performance were evaluated for satellite (DSAT, Globalstar) and mobile (GPRS, UMTS) channels.

For GPRS and UMTS uncompressed ultrasound images acquired from ultrasound medical tests were used, after compressing them to JP2 format (JPEG 2000 codec). For UMTS 384 Kbps and GPRS 53.6 Kbps, results are obtained from simulation based on both approximating Vodafone network. Other data are obtained practically with Vodafone network. In every case the ultrasound images are sent from the mobile patient station to the fixed expert station.

4.2 Results

1st Scenario: robot control, US stream

● **Throughput performance:** it indicates how efficiently is used the communication link and correspond to the total number of original packet received by the receiver in a given period of time [10]. We have monitored the throughput performance received at the expert station where the significant data is the ultrasound image sequence which competes with the robotic monitoring data. Figure 3 gives the instantaneous received throughput at the expert station. Two phases are to be identified: phase 1, Netmeeting is connected but not sending any video data while only robotic data are received. In phase 2 both ultrasound and robotic data are received. Figure 4 represents the instantaneous throughput received during phase 2 related only to ultrasound stream packets.

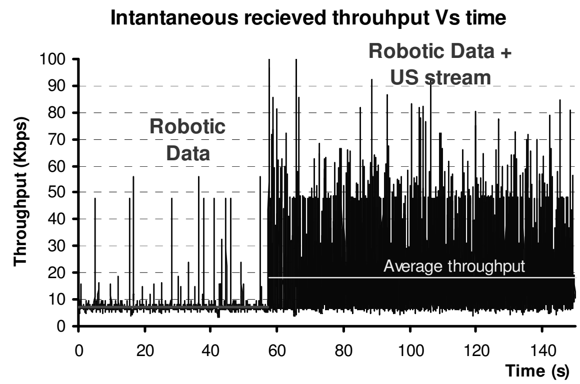

Figure 3 Instantaneous received throughput by the expert station when the mobile patient station is on UMTS-64 Kbps

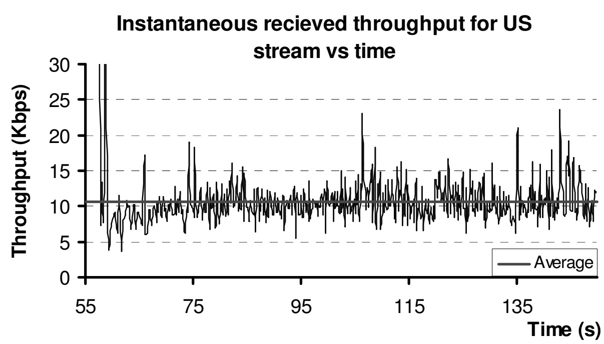

Figure 4 Instantaneous received throughput by the expert station with respect to the ultrasound video stream packet, on UMTS

During phase 1 the average throughput is 6.8 Kbps with a standard deviation of 2.4 Kbps, the range is not significant since the big spikes are mainly due to signalling packets of Netmeeting to keeping its connection alive.

When robotic data are sent simultaneously with US stream (phase 2), the average throughput occupied by the US video stream is 10.6 Kbps (figure 4) while the average throughput occupied by the robotic data is still 6.8 Kbps as when no video is sent. During this period the average total throughput is 18.7 Kbps with a standard deviation of 12.7 Kbps and the range is as high as 158 Kbps. The minimum encountered was 4 Kbps.

● **Delay jitters:** the jitters encountered by the robotic data can easily be estimated as the robotic data packets are sent periodically every 70 ms. Figure 5 shows the time interval between two consecutive robotic data packet and the jitters can be evaluated as the standard deviation of these time intervals. The jitters encountered by video packet can't be driven as easily since the H263 protocol is adaptive to the images changes by providing motion compensation. As shown by figure 6 a baseline removal algorithm is necessary (low pass filtering with a Butterworth fifth order filter)

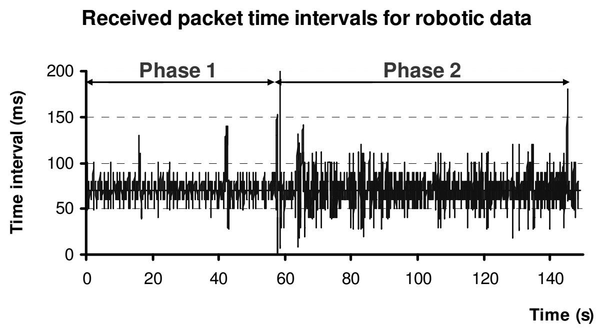

Figure 5 Time intervals between robotic data packet received at the expert station, on UMTS.

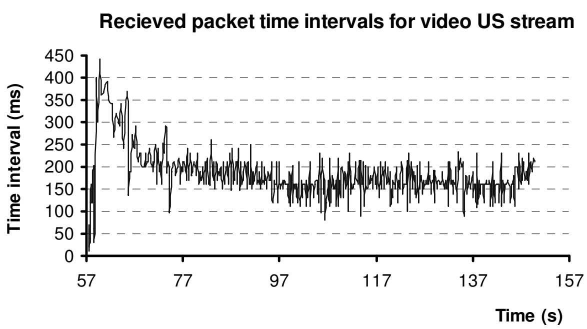

Figure 6 Time intervals between US video data RTP packets received at the expert station, on UMTS

In phase 1 the jitters on robotic data follow precisely a Gaussian distribution with a standard deviation of 9 msec. In the second phase the range has doubled but the standard deviation has only increased to 13 ms.
For ultrasound video data in phase 2, the baseline removal filtering showed us a Gaussian distribution for the delay jitters with a standard deviation of 20 ms.

● **End to End Latency:** we monitored the one way delay of the robotic control data which is the only one to flow from the expert to the patient station in scenario 1. Figure 7 illustrates the latency for each data packet respectively on UMTS.

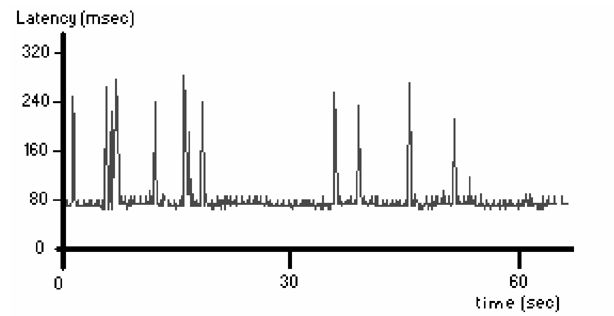

Figure 7 Latency of the robotic control from expert to patient on UMTS.

The average delay is 80 ms and remains very stable along time.

2nd Scenario: still images

Figure 8 is showing the efficiency of the specific communication link with respect to its assigned bandwidth. Although GPRS is a low bandwidth link, as shown in table 2, it is showing reasonable delay. Indeed we could verify that real-time robotic has been achieved on 1 Time Slot (TS) uplink (without sending any other data).

Image size (compressed) 80 KB

Link	Satellite		Wireless		
	DSAT	Globa-lstar	GPRS		UMTS
Theoretical uplink bandwidth (kbps)	2048	128	13.4	53.6	384
Total Tranmission Delay (s)	0.4	5	56	19	2
Average uplink throughput (kbps)	No Data	90	10.4	No Data	280

Table 2 Delay and Throughput performances for satellite and mobile link for scenario 2

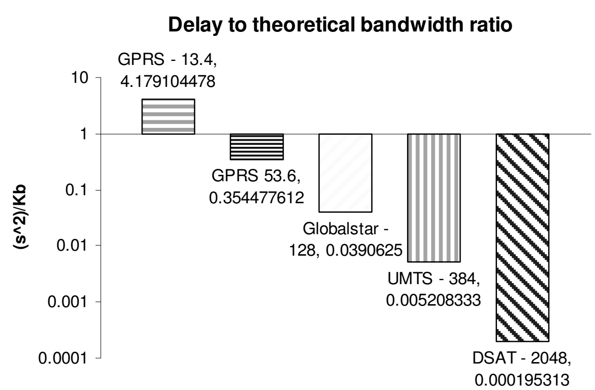

Figure 8 Ratio between the file transmission delay and the theoretical bandwidth for the different communication technology considered

5 Discussion – Conclusion

The use of 3G wireless technology widening the communication links options for this e-health wireless robotic system.

For the interactive scenario 1, UMTS has shown to be able to provide a real-time service with low latency and acceptable jitters compared with those encountered and faced with satellite Inmarsat connection [2] in the order of 40 ms standard deviation. When in phase 2 with simultaneous robotic data and ultrasound video stream, the throughput is severely solicited with high instantaneous variation while the average remains low. That is to say, as there is low jitters, that optimisation could be done in the application layer so as to better exploit the mobile network resources.

For scenario 2, best performance in term of delay is obviously achieved by DSAT higher bandwidth link. However this has to be balanced by the efficiency characterised by the delay to bandwidth ratio (figure 8) which is highly best for GPRS. The throughput efficiency that we can define as the average used throughput to theoretical bandwidth ratio is quite the same for the GPRS, UMTS and Globalstar.

As shown from real clinical experiment [4] the high capacity of the DSAT communications is best suited for an accurate diagnosis during routine examinations. However, our results show that the UMTS link can compete with the satellite link in terms of minimizing the hardware required, ease of mobility and QoS for real-time medical application. The GPRS with its low throughput allows a remote examination with a low ultrasound image quality in non real-time cases, and for still ultrasound images transfer.

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