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BIDIRECTIONALITY IN IP BASED TELEOPERATION

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Abstract

The article proposes a new transport scheme for teleoperation or NCS (Networked Control System) data flows via the Internet. The proposed scheme takes advantage of the bidirectionality of the control loop and the small size of the teleoperation supermedia data, to improve the throughput and efficiency of the transmission; it aims to serve as a network contribution to the stability control efforts of teleoperation systems with variable delays, by increasing the bandwidth availability maintaining TCPFriendness, Fairness and Best Effort requirements in Internet. In this paper we focus on the preliminary presentation of the scheme and simulation studies.

1 Introduction and motivation

Internet is a universal communication channel in a teleoperated or controled system, but it not guarantees the stability of the system because the variable delay property of a public network (Munir and Book, 2001).

A bilateral teleoperation platform has a minimum of two data flows, essentially independent and sending information in opposite directions. The Master device, operated or driven directly by a human, is a joystick or other Human-System Interface (HSI), and the Slave device, usually a mechanical or transport system, is the remote teleoperated system. The data flow from Master to Slave carries information on the operation of the slave actuators, and the reverse flow from Slave to Master carries status information, usually haptic, visual or other, which need the operator to close the control loop. In some works (Cen *et al.*, 2005), teleoperation data are called supermedia data, as distinguished from the multimedia data. In this paper we call supermedia data, all the real time critical data with small size, such as haptic, position, force feedback or status data. Video and audio feedback data are called multimedia data.

The variety of data streams of a teleoperation system is shown in Figure 1, where there are multimedia, supermedia and control data. This figure represents the coordinated SMMS (Single-Master Multi-Slave) Teleoperation from a gantry crane with automatic videocamera tracking, and haptic, status and video data returns (Fernandez Villaverde *et al.*, 2007). Therefore, a teleoperation system can use different protocols and channels for the different data types transmission.

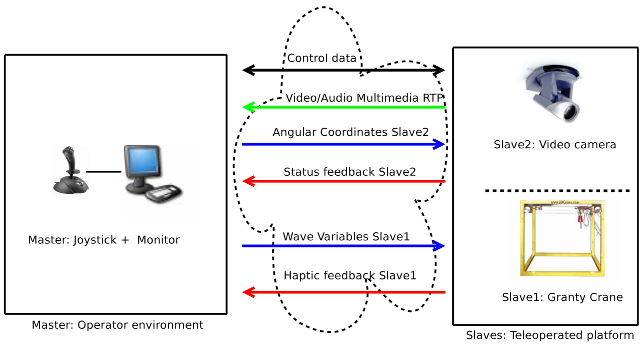

Figure 1. Teleoperation data flows

Assumptions for any teleoperation system with supermedia data can be higlighted by:

- The existence of a reverse data channel, not only network status data (acknowledgement packets or ACK) delivered from normal transport protocols.
- Real-time requirements to maintain system stability. Studies limits the requirements regarding maximum delays and maximum loss rate (García-Rivera and Barreiro, 2007).
- Small packet size, in the same magnitude order as ACK packets of transport protocols. For supermedia data the size are normaly fixed. If Slave to Master data are video, the size increases and the data flow can be treated as multimedia flow, with any well-known protocols such as RTP.

If the teleoperation is performed over a public network like the Internet, TCP (Transmission Control Protocol) is the most used traffic, and the design of new transport protocols must meet TCPFriendly, Fairness and

Best Effort requirements (Floyd and Fall, 1999). A flow is TCPFriendly if its arrival rate is aproximately equal or slower as the rate of a conformant TCP connection under the same network conditions. This tries to keep transport protocols at the same level as the TCP protocol, unless UDP protocol tends to cannibalize the network links. The Fairness means that all data flows that use this protocol will have the same available bandwidth opportunities for their use. Best Effort implies that the flow can use, if necessary, all the bandwidth offered by the network; best effort should be dynamic, that is, it adapts to changes in available bandwidth.

The most commonly used transport protocols, TCP and UDP (User Datagram Protocol) are not conformant with real-time, TCPFriendness, Fairness or Best-Effort assumptions, because TCP is a connection-oriented protocol, reliable, but with a large jitter and delay penalty in the retransmission of losts packets and his flow control algorithm. TCP also has a low payload efficiency for supermedia data, because the payload has a similar size as the protocol header (20 bytes). UDP is a connection-oriented protocol and not reliable, which can meet the real-time requirements and a good payload efficiency, but that does not meet the requirements of Fairness and TCPFriendly. Some of the UDP based multimedia protocols have great difficulty in meeting TCPFriendly and Fairness features, and its massive use can cause a Internet collapse. The control research community has sugested and developed any algorithms and protocols to solve this problem, such as Trinomial algorithm, TFRC or IRTP protocols.

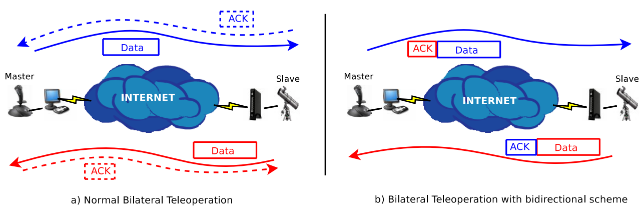

Figure 2. Reverse data and ACK flow

Bilateral teleoperation allows to use the reverse data channel to send ACK packets with network status information, based on time tags and sequence numbers. Basically, the ACK packets serve as a basis for source-based flow control, or to provide reliability and packet recovery using reliable and connection oriented transport protocols. In classical teleoperation protocols, ACK packet flow conforms a completely independent data stream, but in the proposed solution, ACK information is inserted in the reverse data flows, to inform the sender about the network status and to execute the flow control algorithm. Figure 2 shows this idea. The motivation is the availability of more network capacity with the same network use, to send more information having similar traffic consumption.

ACK's sending period depends on the requirements for packet arrival confirmation of the source, that can be one ACK per packet or one ACK every several packets. In the proposed scheme, because ACK information in inserted in the reverse data packet, it is sent back with the same period as the reverse supermedia data flow. This involves an analysis of the proposed scheme and subsequent work on modeling teleoperation data flows.

In this paper we present the motivation of this work, the state of the art in teleoperation protocols, the network bidirectionality of the teleoperation and his theoretical consequences, and finally simulation results of a bidirectional teleoperation protocol with a trinomial flow control algorithm. The paper ends with de conclusions and future work.

2 Related work

There are many open research lines in teleoperation protocols. The authors have identified three basic work lines, classified according to the layer of the OSI/TCP/IP model: link layer protocols, transport layer protocols and application layer protocols. In figure 3 is a brief summary of the state of the art in teleoperation protocols. Some of the solutions presented in the figure are still under definition or do not have enough articles showing their operation and their specific benefits. Other protocols are to generic, such as the protocols associated with the use of certain teleoperation or telerobotic frameworks.

A typical teleoperation network topology implies the Master and Slave local network and the Internet network as seen in figure 3. Internet link technologies are dificult to modify because a high organisational engagement is needed, but the actual base link technologies in Internet such as MPLS, ATM or MetroEthernet have good enough QoS benefits for teleoperation. That makes that Internet link layer technologies are not under study to develop any new teleoperation protocols. Link technologies in local networks are accessible and configurable by users, and can be chosen from among multiple available or even develop their own, such as the link layer RTNP protocol (Uchimura and Yakoh, 2004). The RTNP protocol inserts a tag in the Ethernet header that identifies a high priority packet to the requirements of real-time teleoperation. So, the new link layer can redirect the packet directly to the application layer without waiting in the network and transport layer queues. Real Time Ethernet (RTE) solutions in the local area networks try to identify frames with real-time requirements by inserting identifiers in Ethernet header; intermediate switches priorize frames according to the priority indicators inserted, or by having reserved a direct physical channel to send real-time frames. Interconnectivity for industrial environments, can be a good target for teleoperation and telerobotics, but Link layer industry technologies, based on field buses are an area of interest that exceeds the scope of this work.

Other link layer solutions are used for wireless. In wireless, the packet loss or error probability is much higher as in wired networks, which penalizes the jitter in reliable protocols, or penalizes loss in unreliable protocols. Commercial solutions are noted as ZigBee 802.15.4 for sensor-actuator networks, Bluetooth more focused on the peripherals interconnection to a central system, or Wireless Lan solutions 802.11(a/b/g) where specific solutions are in the transport layer.

Layer			
Link	CAN, Profibus, RTE, RTNP ZigBee, Bluetooth, 802.11	ATM, MPLS,ISDN, FR, MetroEth	CAN, Profibus, RTE, RTNP ZigBee, Bluetooth, 802.11
Network	IPv4, IPv6, VAN, QoS, Multicast, RED-Gateways		
Transport	Trinomial, RAP, TEAR, IRTP, TFRC, DCCP, ETP, SNRTP, RTP		
Aplication	SNRP, FrameWorks, STRON, RON, QRON, OverQoS		

Figure 3. Teleoperation protocols

Possibly the most used transport layer protocol in Internet teleoperation is UDP, but UDP not meets the standards of Internet traffic, such as Fairness and TCP-Friendly requirements. There are several attempts to provide flow control for UDP flows, such as the DCCP (Datagram Congestion Control Protocol) (Kohler *et al.*, 2006). TEAR (TCP Emulation At Receivers) protocol (Rhee *et al.*, 2000) uses a dynamic AIMD (Aditive Increment Multiplicative Decrement) flow control algorithm and makes the assumption that the packet loss probability is independent of transmission speed. Therefore, TEAR no need to recalculate the transmission speed in the sender each time a loss is detected, but instead may be calculated in the receiver each time it knows the network status and the most adequate transmision speed of the sender, and sends the calculated speed back to te sender. TEAR's main features make it suitable for asymmetric connections where available bandwidth is different in both transmision directions, and flows with packet size greater than 1000 bytes. TFRC (TCP Friendly Rate Control) protocol (Floyd *et al.*, 2000), is a flow control mechanism based on TCP, but with less throughput variation, making it more suitable for telephony, multimedia streaming and teleoperation. Like the TEAR, TFRC is a receiver-based flow control algorithm that uses the time between losses for modeling the transmission rate by informing the sender's ACK. Transmission rates are calculated comparing the protocol throughput with a conformant TCP throughput that responds to equation 1 (Padhye *et al.*, 1998). This protocol is common in teleoperation protocols comparisons.

$$T = \frac{s}{RTT\sqrt{\frac{2p}{3}} + t_{RTO}\left(3\sqrt{\frac{3p}{8}}\right)p\left(1+32p^2\right)} \qquad (1)$$

Ecuation 1 models TCP throughput T based on packet losses p, round trip time RTT and retransmission time RTO (Padhye *et al.*, 1998). Packet size s are commonly fixed in teleoperation protocols. Trinomial protocol (Liu *et al.*, 2002), is a Equation-based flow control algorithm with TCPFriendly, Fairness and Best Effort features. Sender distinguish between increment and decrement time intervals, and uses three parameters to determine the IPG (Inter Packet Gap). TCPFriendly feature is obtained comparing the protocol throughput with a conformant TCP throughput that responds to equation 2, based in equation 1 without retransmission, where λ_{TCP} is transmission throughput of the conformant TCP protocol, and λ_{max} is the transmission throughput of the protocol in study. In trinomial algorithm, the main modeled parameter computed at the sender is the Inter Packet Gap (IPG) that basicaly is the inverse of the throughput

$$\lambda_{max} = \lambda_{TCP} = \sqrt{3}/(RTT\sqrt{2p}) \qquad (2)$$

ETP (Efficient Transport Protocol), SNRTP (Simple Network Robot Transport Protocol) and SNRP (Simple Network Robot Protocol), by the same authors (Wirz *et al.*, 2008), seek to establish a protocol architecture covering the transport and application layers, through the development of frameworks for MMMS (Multi-Master Multi-Slave) systems. ETP basically sets a flow control in six states, therefore stabilizes the flow by avoiding large performance fluctuations. These protocols and frameworks are in definition phase. IRTP (Interactive Real-Time Protocol) protocol (Ping *et al.*, 2005) analyzes the transport protocol efficiency for small packets, and reduces the network and transport header size to improve efficiency. Compared with the UDP protocol it maintains a similar header size, but improves its functionality with packet loss recovery and flow control. IRTP is a connection oriented protocol and allows to dynamically distinguish control and supermedia data for teleoperation.

Application layer solutions are usually focused on developing frameworks and working environments for MMMS topologies, specificaly defining data access methods such as Web or Java. An interesting line of overlay networks in application layer are identified, such as the STRON protocol (Supermedia Transport for teleoperation over Overlay Networks) (Cen *et al.*, 2005). An overlay network is a high layer computer network built over a low layer network. The STRON approach is to build a teleoperation specific overlay network, that implements a routing algorithm to minimize loss and delay through logical links.

3 Proposed Scheme

As shown in Figure 1, a teleoperation system can use different protocols and channels for the different data types transmission. Audio and video data transmission have any transport protocols, adequate to the real-time and stability system requirements, but for position, force, speed, haptic returns, sonar data, sensors, actuators or other data types, there is not a good optimized alternative. TCP can meet the control data flow requirements, although it improved enough to consider further studies.

3.1 Bidirectionality

The proposed scheme focuses on the use of bidirectionality in teleoperation supermedia data flows and in the header size of the transport protocol, to optimize the eficiency. Figure 4 may be a basic outline of the proposed transport scheme. Bidirectionality allows the integration of network status data in the reverse supermedia data flow as shown in Figure 2. Quantitatively, this implies a decrease in the total flow required to send the same information, maintaining or improving the stability and passivity characteristics of the remote system by reducing the total network load.

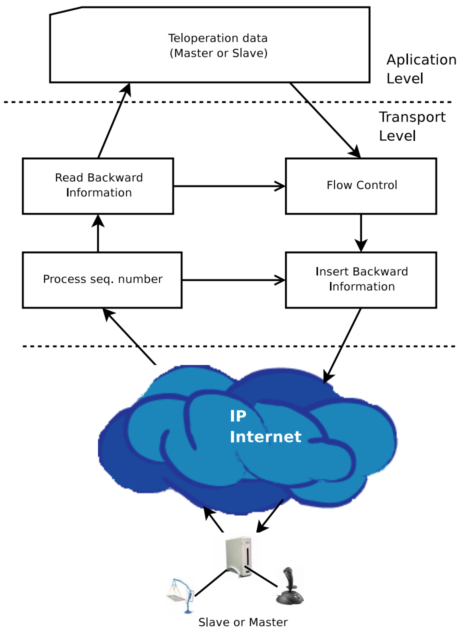

Figure 4. Proposed transport scheme

Naming C_{data} and C_{ack} the flows generated by teleoperation supermedia data and packet acknowlegdement transport data (ACK), that represents network status information, then equation 3 represents in C^{MS} the Master to Slave flow and in C^{SM} the Slave to Mater flow.

$$\begin{aligned} C^{MS} &= C^{MS}_{data} + C^{MS}_{ack} \\ C^{SM} &= C^{SM}_{data} + C^{SM}_{ack} \end{aligned} \tag{3}$$

If the transport protocol implemented to a supermedia flow generates one ACK packet per data packet, then, with no losses

$$C_{data}|_{pqt/seg} = C_{ack}|_{pqt/seg} \tag{4}$$

and

$$C_{ack} = C_{data} * \frac{SA + SH}{SD + SH} \tag{5}$$

where SA, SD and SH, are ACK data field size, teleoperation data field size and header size of the packets respectively. If $C^{\uparrow}$ represents the total teleoperation data flow in one direction and $C^{\downarrow}$ represents the amount of traffic in the oposite direction, the amount of total teleoperation traffic in Internet is

$$\begin{aligned} C_{total} &= C^{\uparrow} + C^{\downarrow} \\ C^{\uparrow} &= C^{MS}_{data} + C^{SM}_{ack} \\ C^{\downarrow} &= C^{SM}_{data} + C^{MS}_{ack} \end{aligned} \tag{6}$$

Assuming that ACK and data packets are of the same size in both teleoperation flows, then

$$C_{total} = (1 + \frac{SA + SH}{SD + SH}) * (C^{MS}_{data} + C^{SM}_{data}) \tag{7}$$

If ACK packets have only transport header, then $SA = 0$, and equation 7 derives in equation 8 for a simetric end-to-end Internet link and same application requirements in both teleoperation directions, Master to Slave and Slave to Master.

$$\begin{aligned} C_{total} &= (1 + \frac{SH}{SD + SH})(C^{MS}_{data} + C^{SM}_{data}) \\ C_{total}|_{NoBidirec} &= (1 + \frac{SH}{SD + SH})C_{total}|_{Bidirec} \end{aligned} \tag{8}$$

Equation 8 reflects the effect of bidirectionality in the amount of traffic comparing with a normal teleoperation transport flow. In supermedia traffic where the data field size is at the same order as the packet transport header, bidirectionality has a important effect as seen in figure 5. These figure compares any transport protocols with different data field sizes. TDTP protocol (Teleoperation Data Transport Protocol) is a proposed bidirectional scheme for teleoperation using trinomial flow control algorithm and a transport header of 5 bytes. Trinomial protocol has the same header size and flow control algorithm but without bidirectionality. IP header is 20 bytes long, TCP header is 20 bytes and UDP header is 8 bytes long. The teleoperation data rate at application level for the comparison in the graph is $400Kbits/sec$ in any of the teleoperation directions. For small data packet size, bandwidth requirements over Internet becomes bigger for the same application. For higher data packet size, bandwidth requirements becomes similar for different packet header sizes. Supermedia data packets size is in the inflexion zone of the graph, that shows the most difference between the transport schemes.

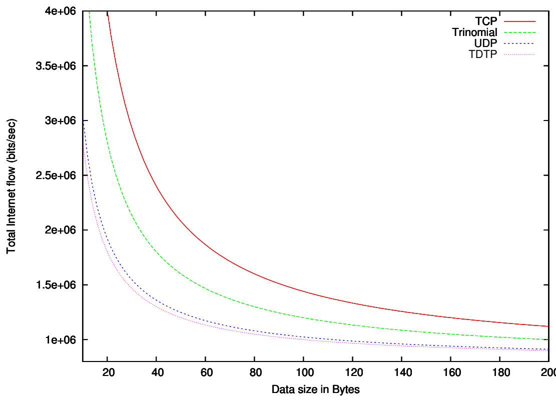

Figure 5. Birectionality TCP,Trinomial,UDP,TDTP

3.2 Flow Control

Flow Control implemented in the proposed scheme are the trinomial algorithm, that calcules the IPG and differentiates increment (equation 9) and decrement (equation 10) transmision rate intervals.

$$IPG_{i+1} = \frac{IPG_i \times W}{IPG_i + W} \tag{9}$$

$$IPG_{i+1} = \frac{IPG_i}{\beta} \tag{10}$$

where $W > 0$ are a variable depending on γ, α and RTT, and $\beta < 1$ are a initial parameter as γ. α is determined at the start of any increment interval.

4 Simulation

Commonly used metrics to evaluate network or protocol performance are throughput, time delay, and amount of lost data. Bandwidth is defined as the amount of information that can be transmitted in a given time period over a communication link. Throughput is the amount of data successfully transferred from one node or system to another in a given time period. If all packets sent are considered as correctly received, bandwidth and throughput results are equal. Time delay is a measure of the round trip travel time between two sites in a network.

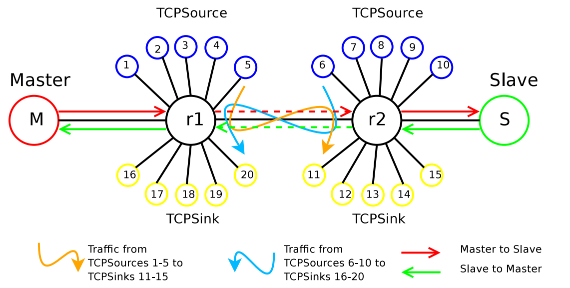

Figure 6. Simulation topology in NS2.

Simulations are processed with Network Simulator 2 (NS2) suite and network topology in figure 6. Network topology uses a bottleneck trunk link between R1 and R2 with 1Mbps capacity, to learn about the scheme benefits in congestion situations. Access links capacity are of 100Mbps. All links are symmetric. R1 and R2 implements a DropTail queue with a queue limit of 15 packets. Simulations were performed over a total of 100 seconds with hard bottleneck congestion due TCP traffic, but no congestion is simulated between 20 and 30 seconds in the Master to Slave direction to show Best Effort characteristics. Data in Master and Slave are sampled at $1000pkts/sec$ with data packet size of 100 bytes, and for trinomial sheme a ACK packet size of 40 bytes is used.

Graphs 7 and 8 shows simulation results for TDTP bidirectional scheme and trinomial not bidirectional scheme, with same flow control parameters. The results shows that TDTP sends aproximately the double of data maintaining TCPFriendnes, fairnes and Best effort charasteristics. The delay are similar for both schemes, and packet loss ratio are similar in TDTP and Trinomial simulation.

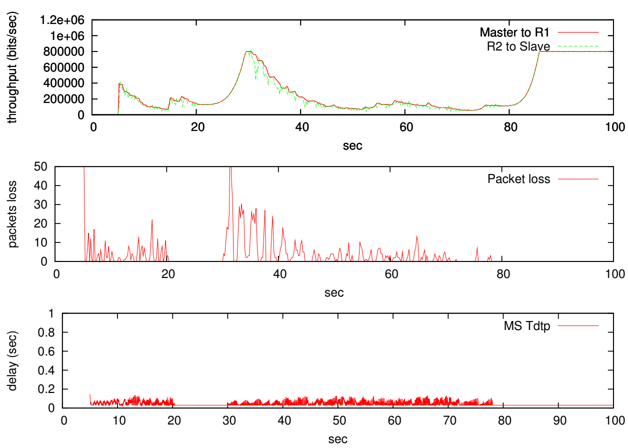

Figure 7. Throughput, packet loss and delay for TDTP protocol

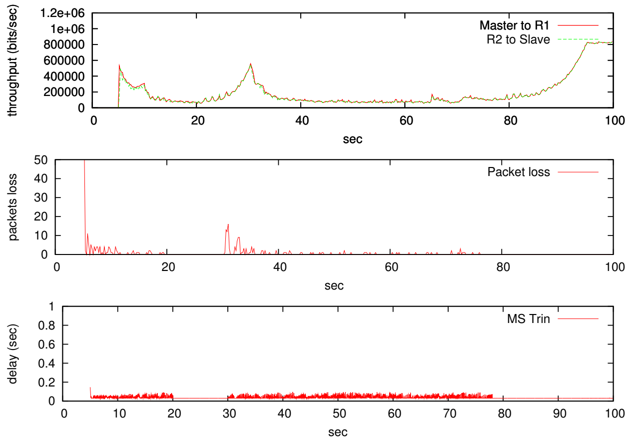

Figure 8. Throughput, packet loss and delay for trinomial protocol

5 Conclusions and Future Work

The bidirectional scheme proposed complies with teleoperation system specifications, such as bidirectionality transmission, real time requirements and data size for haptic or other bilateral teleoperation kinds involving a small data size. The flow control algorithm proposed is the trinomial algorithm, which meets the necessary Fairness and TCPFriendly features of the scheme to be accepted in Internet with similar characteristics as the normal transport protocols. Simulation shows that a bidirectional flow control scheme allows much more bandwidth with similar delays, maintaining TCPFriendly, Fairness and Best Effort requirements for a future reliably Internet.

Future work involves two lines; one side attempting to implement bidirectionality for other flow control schemes, such as TFRC, TEAR or DCCP to better know the improvement of bidirectionality, and at the other side, finding relationships between higher bandwidth by implementing bidirectionality and better throughput for middleware solutions such as Deadband Control (Otanez *et al.*, 2002) or Gain Scheduling (Tipsuwan and Chow, 2004). Deadband control solutions focuses on the relative value of teleoperation data to be transmited, decreasing the amount of data to transmit to improve the network response. Middleware solutions proposes to adapt data and information to the requirements of the teleoperation system before putting it in the network, but it is of interest to converge network and system requirements and select data values and throughput to send to the other side of the communication.

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