Variable delay in scaled port-Hamiltonian telemanipulation

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Abstract

In several applications involving bilateral telemanipulation, master and slave robots act at different power scales (e.g. telesurgery, micro-manipulation). Scaling forces and velocities means scaling the power that is exchanged between master and slave sides through the communication channel. In this paper we show how it is possible to embed power scaling in the scattering based communication channel used in port-Hamiltonian based telemanipulation. Furthermore, a strategy for passively dealing with variable communication delay is proposed in order to allow scaled teleoperation over packet switched networks as Internet.

1 Introduction

Passivity is a very suitable tool to stabilize a telemanipulator; in fact, implementing each part of a telerobotic system as a passive system and interconnecting them in a power preserving way it is possible to achieve an intrinsically passive system which is consequently characterized by a stable behavior.

In the seminal works reported in [1, 2] scattering theory has been exploited to build a communication channel that is passive independently of any constant transmission delay.

Several passivity based strategies have been proposed to control master and slave robots (see [3] for a recent survey). In particular, in [4], the port-Hamiltonian framework ([5]) has been applied to telemanipulation: both master and slave robots, which can be modeled as port-Hamiltonian systems, are controlled by means of intrinsically passive port-Hamiltonian impedance controllers (IPC) which guarantee a stable interaction also with unknown environments. In this way both master and slave sides can be modeled as passive port-Hamiltonian systems that are then interconnected by means of a scattering based communication channel that allows a passive exchange of information independently of any constant transmission delay. The resulting telemanipulation system is intrinsically passive and, therefore, characterized by a stable behavior. In [6] the discrete nature of the controllers is considered and an algorithm to passively discretize port-Hamiltonian systems is proposed. Furthermore, discrete scattering is defined and a communication strategy for passively interconnecting master and slave sides through packet switched communication.
channels characterized by a variable delay and by a possible loss of packets is proposed.

In several tasks involving bilateral telemanipulators, such as telesurgery and telemanipulation of huge robotic arms for extra-vehicular activity in space applications, master and slave act at different power scales and therefore, it is necessary to scale the velocities and the forces that are exchanged in order to take into account for this difference. Ideally, the system should transmit to the human operator a scaled version of the environment impedance such that the dynamic character of the environment remains undistorted. Several researchers addressed this problem. In [7] loop-shaping compensators have been included in a position/force architecture to increase transparency in scaled linear teleoperators and in [8] $H_\infty$ control and $\mu$-synthesis have been exploited to implement power scaling over the Internet for linear telemanipulators. In [9] a control law based on the cancellation of dynamics has been suggested to achieve velocity/force scaling and in [10] the telemanipulator is decomposed in a shape and locked system and a passive feed-forward action is used to implement a scaled coordination between master and slave robots.

Scaling forces and velocities means scaling the power exchanged between master and slave sides. Thus, it is natural to assign the issue of power scaling to the medium through which master and slave sides exchange power, namely the communication channel. In [11] linear telemanipulators characterized by a negligible communication delay are considered and the problem of scaling is tackled from this point of view; it is shown that a scaling of the exchanged power can be performed without affecting the passivity of the overall scheme. Recently, this result has been generalized to the port-Hamiltonian framework. In [12] a novel scattering based communication strategy to achieve power scaling over communication channels characterized by a constant delay while preserving a stable behavior of the overall system is proposed and in [13] these results are further extended and discrete scattering has been used to define power scaling over packet switched networks characterized by a constant delay and by a possible loss of packets.

Another major concern to take into account before using generic packet switched networks (e.g. Internet) as communication channels, is the variability of the transmission delay. The aim of this paper, which is an extension of the work reported in [14], is to provide a strategy to deal with variable delays in scaled port-Hamiltonian telemanipulation. We will show that if a variable delay is not properly handled the system can become unstable and then we will propose a strategy that preserves a stable behavior of the overall scheme independently of the variability of the delay.

The paper is organized as follows: in Sec. 2 some background on port-Hamiltonian based telemanipulation over packet switched networks is given and in Sec. 3 it is shown how to embed power scaling in this scheme. In Sec. 4 we address the problem of variable delay and in Sec. 5 we provide some simulations in order to validate the results obtained. Finally in Sec. 6 some conclusions are drawn and future work is addressed.
2 Background

2.1 Port-Hamiltonian systems

We can consider a port-Hamiltonian system as composed of a state manifold \( \mathcal{X} \), a lower bounded energy function \( H : \mathcal{X} \rightarrow \mathbb{R} \) corresponding to the internal energy, a network structure \( D(x) = -D(x)^T \) whose graph has the mathematical structure of a Dirac structure, which is in general a state dependent power continuous interconnection structure, and a power port represented by a pair of power variables \((e, f) \in \mathcal{V}^* \times \mathcal{V}\) which is geometrically characterized by dual vector elements which are called effort and flow. This port is used to interact energetically with the system and the power supplied through a port is equal to \( e^T f \). Loosely speaking, a port-Hamiltonian systems is made up of a set of energy processing elements (energy storing, energy dissipating and energy injecting) joined, through their power ports, to a power preserving interconnection along which they exchange energy. We can furthermore split the interaction port in more sub-ports, each of which can be used to model different power flows. We will indicate with the subscript \( I \) the power ports by means of which the system interacts with the rest of the world, with the subscript \( C \) the power ports associated with the storage of energy and with the subscript \( R \) the power ports relative to power dissipation. The dissipation in the system can be modeled using as characteristic equations \( e_R = R(x)f_R \) with \( R(x) \) a symmetric and positive semi-definite matrix. If we furthermore set \( \dot{x} = f_C \) and \( e_C = \frac{\partial H}{\partial x} \), we obtain the following power balance due to the skew-symmetry of \( D(x) \):

\[
\dot{H}(t) + f_R^T(t)R(x)f_R(t) = e_I^T(t)f_I(t)
\]

which clearly says that the supplied power \( e_I^T f_I \) is either stored or dissipated and that, therefore, a port-Hamiltonian system is passive.

Loosely speaking, a port-Hamiltonian system is made up of a set of energy processing elements (energy storing, energy dissipating and sources of energy) that exchange energy by means of their power ports through a set of energy paths which form a power preserving interconnection that can be modeled as a Dirac structure.

A very broad class of physical systems, both linear and non linear, can be modeled within the port-Hamiltonian framework which can therefore be used to model telemanipulators endowed also with nonlinear robots. For further information see [5].

2.2 Port-Hamiltonian based telemanipulation

The digital port-Hamiltonian based telemanipulation system over packet switched networks is represented in Fig. 1 using a bond-graph notation; the double band on the bond represents a discrete exchange of energy. We can see that the continuous plant (i.e. a port-Hamiltonian system representing either the master or the slave) is interconnected in a power preserving way (by means of the Sample & Hold device \( SH \) proposed in [6]) to the discrete intrinsically passive controller (represented by a
Figure 1: The Passive Sample Data Telemanipulation Scheme.

passively discretized port-Hamiltonian system). Master and slave sides exchange energy through a packet switched communication channel. The power flowing through each discrete power port (either at the master or at the slave side) of the communication channel is decomposed into an incoming and an outgoing scattering variable in such a way that

$$e^T(k)f(k) = \frac{1}{2} \| s^+(k) \|^2 - \frac{1}{2} \| s^-(k) \|^2$$

where

$$s^+(k) = \frac{1}{\sqrt{2N-1}} \left( e(k) + Zf(k) \right)$$

$$s^-(k) = \frac{1}{\sqrt{2N-1}} \left( e(k) - Zf(k) \right)$$

and $Z = NN > 0$ is the impedance of the scattering transformation. Integrating in a discrete sense the quantities we get that the energy flow during one sample period is

$$E_L(k) = T e^T f = \frac{T}{2} \| s^+ \|^2 - \frac{T}{2} \| s^- \|^2$$

and, therefore, we can interpret $\frac{T}{2} \| s^+ \|^2$ and $\frac{T}{2} \| s^- \|^2$ as an incoming and an outgoing energy packet respectively. The communication strategy usually adopted for non scaled bilateral telemanipulation is given by:

$$\begin{align*}
s^+_m(k) &= s^+_m(k - \delta) \\
s^-_m(k) &= s^-_s(k - \delta)
\end{align*}$$

where the indexes $m$ and $s$ stand for master and slave and $\delta = dT$ is the communication delay. At each sample time the system will read the incoming energy packet $s^+(k)$ and $e(k)$ and will calculate the outgoing energy packet $s^-(k)$ and $f(k)$. The telemanipulation scheme is passive independently of any constant communication delay but it allows only a non scaled exchange of energy between master and slave side.

In packet switched communication channels as the Internet, the communication delay is usually variable. It can happen that at some sampling instants nothing is received at the master (or slave) side because of an increase of the communication delay. In this case the controller has to replace the unreceived information with something else.

The so called Hold the Last Sample (HLS) strategy is quite used in software based application and it consists of replacing the empty sample
with the value of the last received packet. Suppose that the communication delay increases in the communication between master and slave sides and that nothing is received from time $k$ to time $k + m$. Using the HLS strategy we would have that as long as the expected packet $s_m(k - \delta)$ is not received we provide to the slave side the packet $s_m(k - \delta - 1)$. When at time $k + m$ the expected packet is received, we have injected into the telemanipulation system an extra amount of energy equal to

$$\sum_{i=0}^{m-1} \frac{1}{2} \|s_m(k - \delta - 1)\|^2 T$$

Thus, this strategy is not suitable for bilateral telemanipulation since it destroys the passivity of the overall telemanipulation system leading to a potentially unstable behavior.

The strategy that is used in port-Hamiltonian based telemanipulation consists of replacing an empty sample with a null packet and it has been proposed in [6]. Suppose again that the communication delay increases in the communication between master and slave sides and that nothing is receive from time $k$ to time $k + m$. Using this strategy we would have that as long as the expected packet $s_m(k - \delta)$ is not received we provide to the slave side the packet 0. Since the energy content of a null packet is 0, when at time $k + m$ the expected packet is received, we do not have injected any extra energy into the system and, therefore, the intrinsic passivity of the port-Hamiltonian based telemanipulation system is preserved.

On the other hand, it can happen that a decrease of the communication delay changes the flow of packets and that a packet that should be delivered after another one is actually delivered before. In this case the Use the Freshest Sample (UFS) strategy is used: a time stamp is attached to each transmitted packet and if a packet older than the last received packet arrives, it is simply discarded. This technique avoids the introduction of extra delay needed for implementing buffering strategies which would highly degrade the transparency of the overall telemanipulation system, as proven in [15]. In this case, the energetic contribution of the discarded packet is dissipated and this makes the communication channel strictly passive and, therefore, the UFS technique keeps on preserving the passivity of the overall telemanipulation system.

For further details on port-Hamiltonian based telemanipulation and for a more formal treatment of the problem of variable communication delay, the interested reader is addressed to [16, 6].

3 Power scaled telemanipulation

In this section we show how it is possible to embed power scaling in port-Hamiltonian based telemanipulation over digital networks characterized by a constant delay. Consider the telemanipulation scheme reported in Fig. 1. The discrete power ports through which master and slave sides are interconnected to the communication channel are $(e_m(k), f_m(k))$ and $(e_s(k), f_s(k))$ respectively. If the communication delay is negligible, master and slave controllers can be connected directly through power variables
and, in non scaled discrete port-Hamiltonian based telemanipulation, master and slave sides are interconnected through a discrete common effort interconnection which is described by:

\[
\begin{align*}
  e_s(k) &= e_m(k) \\
  f_s(k) &= -f_m(k)
\end{align*}
\] (4)

In this way

\[
\begin{align*}
  P_s(k) &= e_s^T(k)f_s(k) = -e_m^T(k)f_m(k) = -P_m(k)
\end{align*}
\] (5)

that is the power supplied to the slave side is exactly that extracted from the master side, namely no power scaling takes place.

In order to allow a scaling in the interconnection between master and slave side, the following power scaled common effort interconnection can be used [12]:

\[
\begin{align*}
  e_s(k) &= \alpha e_m(k) \\
  f_s(k) &= -\beta f_m(k) \\
  \alpha, \beta &\in \mathbb{R}^+ \\
\end{align*}
\] (6)

where \(\alpha\) and \(\beta\) are the scaling factors. In this case we have that the power variables at the slave side are scaled with respect to those at the master side and that

\[
\begin{align*}
  P_s(k) &= e_s^T(k)f_s(k) = -\alpha\beta e_m^T(k)f_m(k) = -\alpha\beta P_m(k)
\end{align*}
\] (7)

namely the power supplied to the slave is equal to the power extracted from the master side scaled by a factor \(\alpha\beta\). In case of a non negligible communication delay, the interconnection between master and slave sides cannot be implemented using directly power variables since, as it has been proven in [2] for non scaled telemanipulation, in this way the communication channel would become a non passive system and it would destabilize the overall telemanipulator. As it happens in non scaled port-Hamiltonian telemanipulation, it is possible to use discrete scattering to implement the communication strategy reported in Eq.(6) in such a way that the interconnection between master and slave sides is passive and, consequently non destabilizing, independently of any constant communication delay. Using Eq.(2) in Eq.(6) to reformulate the interconnection in terms of scattering variables and considering the transmission delay, the following communication strategy is achieved:

\[
\begin{align*}
  s_s^+(k) &= \frac{2\alpha\beta}{\alpha + \beta} s_m^+(k - \delta) + \frac{\alpha - \beta}{\alpha + \beta} s_s^-(k - \delta) \\
  s_m^+(k) &= \frac{\beta - \alpha}{\alpha + \beta} s_m^-(k - \delta) + \frac{2\alpha\beta}{\alpha + \beta} s_s^-(k - \delta)
\end{align*}
\] (8)

where \(\delta\) is the constant communication delay. Both master and slave incoming scattering variables (i.e. \(s_m^+(k)\) and \(s_s^+(k)\)) are the sum of a term that arrives from the communication channel (i.e. \(s_s^-(k - \delta)\) and \(s_m^-(k - \delta)\)) and of a local term (i.e. \(s_m^-(k - \delta)\) and \(s_s^-(k - \delta)\)). Thus it is necessary to implement both at the master and at the slave side a buffer that stores the outgoing packets that have to be used to build the incoming scattering variables. The following result has been proven in [13]:


**Proposition 1** If the interconnection between master and slave sides in the scheme reported in Fig. 1 is made through the strategy reported in Eq. (8), then the overall telemanipulation system is dissipative.

Using the communication strategy reported in Eq. (8), it is possible to safely scale the power exchanged between master and slave over a delayed communication channel; in this way, when using the telemanipulation system, the human operator perceives the impedance of the master side and a scaled version of the dynamics taking place at the slave side. The communication channel becomes a subsystem characterized by a lossless behavior that, analogously to what happens in non-scaled telemanipulation, is perceived by the human operator as part of the slave side. The scaled interconnection between master and slave prevents from proving passivity of the overall system and allows only proving dissipativity. Nevertheless, this is sufficient for guaranteeing that the overall telemanipulation system is characterized by a stable behavior both in free motion and when interacting with any passive environment; for further details see [12, 13].

### 4 The problem of variable delay

The aim of this section is to propose a strategy to passively deal with variable delay in the power scaled communication strategy reported in Eq. (8). In the following, we will use this notation for discrete derivative and discrete integral:

\[
\frac{dg(k)}{T} = \frac{g(k+1) - g(k)}{T}, \quad \int_k^h g(i)T = \sum_{i=h}^{k-1} g(i)T
\]

where \(g(\cdot)\) is a generic sequence. Furthermore, to lighten the notation, we will not explicitly indicate the dependence of the energy function on the state.

The key point in proving dissipativity of the scaled port-Hamiltonian telemanipulation scheme proposed in [13] is that the communication channel is lossless with respect to the sum of the power extracted at the slave side and the scaled version of the power injected at the master side, namely that the following power balance holds:

\[
P_{\alpha\beta}(k) = dH_{ch}(k)
\]

where

\[
P_{\alpha\beta} = \frac{1}{2} \alpha\beta \|s_m^-(k)\|^2 - \frac{1}{2} \alpha\beta \|s_m^+(k)\|^2 + \frac{1}{2} \|s_s^-(k)\|^2 - \frac{1}{2} \|s_s^+(k)\|^2
\]

and

\[
H_{ch} = \int_k^h \left( \frac{1}{2} \alpha\beta \|s_m^-\|^2 + \frac{1}{2} \|s_s^-\|^2 \right)
\]

is the discrete lower bounded function that represents the energy stored in the communication channel. Thus, in order to keep on guaranteeing a stable behavior in presence of variable communication delay, it is sufficient to develop a strategy that preserves passivity of the communication channel with respect to \(P_{\alpha\beta}\).
As reported in Sec. 2, a strategy for passively dealing with variable delay in non scaled port-Hamiltonian telemanipulation is that of replacing a packet that is not received on time with a null packet, as proposed in [6]. In this section, we will analyze the two possible ways through which this strategy can be extended in case master and slave sides are interconnected through the power scaled communication strategy reported in Eq.(8). Let \( \delta \) be the minimum time necessary for delivering a packet from master to slave and viceversa.

Following the approach reported in [6], when a packet is not received in time because of some network delays, it should be replaced with a null packet. In case a packet is late in the communication between master and slave (slave and master) sides we miss the contribution relative to the term \( s_m^-(k-\delta) \) for building the packet \( s_m^-(k) \) (\( s_m^n(k) \)). Thus, referring to Eq.(8), it is possible either to try to partially build the incoming packet using only the term stored in the local buffer or to replace the incoming packet with a null packet. Summarizing, two possible strategies are possible:

S1 Compute the incoming packet using only the contribution relative to the local term \( s_m^-(k-\delta) \) (\( s_m^n(k-\delta) \)).

S2 Set to zero the incoming packet discarding the contribution relative to the local term \( s_m^-(k-\delta) \) (\( s_m^n(k-\delta) \)).

Suppose that, at time \( k \), the communication delay in the interconnection between master and slave sides increases of \( n \) samples, where \( n(k) \geq 1 \). Since the expected packet is not received at time \( k \), using strategy S1 and Eq.(10), we have that:

\[
P_{\alpha,\beta}(k) = \frac{1}{2} \alpha \beta \| s_m^-(k) \|^2 - \frac{1}{2} \alpha \beta \| s_m^n(k) \|^2 + \frac{1}{2} \| s_m^-(k) \|^2 - \frac{1}{2} \frac{\alpha - \beta}{\alpha + \beta} \| s_m^-(k-\delta) \|^2
\]

we can always write

\[
P_{\alpha,\beta}(k) = \frac{1}{2} \alpha \beta \| s_m^-(k) \|^2 - \frac{1}{2} \alpha \beta \| s_m^n(k) \|^2 + \frac{1}{2} \| s_m^-(k) \|^2 - \frac{1}{2} \frac{\alpha - \beta}{\alpha + \beta} \| s_m^-(k-\delta) \|^2 = dH_{ch}(k) - \frac{1}{2} \frac{4 \alpha \beta}{\alpha + \beta} \| s_m^-(k-\delta) \|^2 s_m^-(k-\delta)
\]

Since the communication delay has increased of \( n(k) \) sample periods we have also that:

\[
P_{\alpha,\beta}(i) = dH_{ch}(i) + \gamma(i) \quad i \in [k, k + n(k) - 1]
\]

The term \( \gamma(i) \) can be negative for some values of the scattering variables and therefore the communication channel can exhibit a non passive behavior in the interval \([k, k + n(k) - 1]\). At the instant \( k + n(k) \) the packet transmitted from the master side at time \( k - \delta \) is delivered to the slave side and thus it is possible to build the packet \( s_m^-(k) \) that, nevertheless, it is not the one expected since at the slave side the packet \( s_m^n(k + n(k) - \delta) \) should be received and used to build \( s_m^+(k + n(k)) \). Thus, at time \( k + n(k) \)
we have that:
\[
P_{\alpha\beta}(k + n(k)) = \frac{1}{2} \alpha \beta \|s_m^-(k + n(k))\|^2 - \frac{1}{2} \alpha \beta \|s_m^+(k + n(k))\|^2 + \frac{1}{2} \|s_m^-(k)\|^2 - \frac{1}{2} \alpha \beta \|s_m^+(k - \delta)\|^2 - \frac{1}{2} \|s_m^-(k - \delta + n(k))\|^2 + \frac{1}{2} \|s_m^-(k - \delta - n(k))\|^2 + \frac{1}{2} \|s_m^+(k)\|^2 - \frac{1}{2} \|s_m^+(k + n(k) - \delta)\|^2 + \frac{1}{2} \|s_m^-(k + n(k) - \delta)\|^2
\]

Thus, making computations similar to those done in Eq.(16), we have that:
\[
P_{\alpha\beta}(i) = dH_{ch}(i) + \frac{1}{2} \|s_m^+(i)\|^2 \quad i \in [k, k + n(k) - 1]
\]

Since when the expected packet is late a null packet is sampled at the slave side, the communication channel is characterized by a strictly passive behavior during the interval \([k, k + n(k) - 1]\). At the instant \(k + n(k)\) the packet transmitted from the master side at time \(k - \delta\) is delivered at the slave side and it is possible to build the packet \(s_m^+(k)\) that, nevertheless, is not the one expected since at the slave side the packet \(s_m^-(k + n(k) - \delta)\) should be received and used to build \(s_m^+(k + n(k))\). Thus, making computations similar to those done in Eq.(16), we have that at time \(k +
Suppose now that the communication delay in the interconnection be-

passivity of the system.

when using the strategy

the behavior of the communication channel keeps on being pas sive. Thus,

\[ k \]

packet transmitted from the master side at time

\[ s \]

corresponding

arrives, it is simply discarded and, since we are using strat egy

transmitted packet and if a packet older than the last receiv ed packet

the F reshest Sample (UFS) technique: a time stamp is attache d to each

tribution master and slave sides decreases. In this case, we adop t the Use

the amount of injected energy has been already dissipated an d, therefore,

ally received packet

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\[ s \]

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packets

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\[ k \]

\[ S \]

since strategy

Thus we have that at the instant

\[ k + n(k) \]

the communication channel dis sipates an amount of energy equal to the content of the expected packet

\[ s^+_{\beta}(k + n(k)) \]

and produces an energy amount equal to that of the actu ally received packet

\[ s^+_{\beta}(k) \]

Nevertheless, as it can be seen in Eq.(18), the amount of injected energy has been already dissipated and, therefore,

the behavior of the communication channel keeps on being passive. Thus,

when using the strategy S2, the effect of an increase of the communica-
tion delay is the introduction of dissipation and this does not alter the

passivity of the system.

Suppose now that the communication delay in the interconnection be-
tween master and slave sides decreases. In this case, we adopt the Use
the Freshest Sample (UFS) technique: a time stamp is attached to each
transmitted packet and if a packet older than the last received packet
arrives, it is simply discarded and, since we are using strategy S2, the corresponding

\[ s^+_{\beta}(k) \]

is replaced with a null packet. Suppose that the packet transmitted from the master side at time

\[ k + 1 - \delta \]

arrives before that transmitted at time

\[ k - \delta \]

and let

\[ k + j \]

with

\[ 0 < j < n(k) \]

be the time instant at which it is delivered. We have that the behavior of
the communication channel is given by:

\[ P_{\alpha\beta}(i) = dH_{\alpha\beta}(i) + \frac{1}{2}\|s^+_{\beta}(i)\|^2 \quad i \in [k, k + j - 1] \]

\[ P_{\alpha\beta}(k + j) = dH_{\alpha\beta}(k + j) + \frac{1}{2}\|s^+_{\beta}(k + j)\|^2 - \frac{1}{2}\|s^+_{\beta}(k + 1)\|^2 \]

\[ P_{\alpha\beta}(i) = dH_{\alpha\beta}(i) + \frac{1}{2}\|s^+_{\beta}(i)\|^2 \quad i \in [k + j + 1, k + n(k) - 1] \]

\[ P_{\alpha\beta}(k + n(k)) = dH_{\alpha\beta}(k + n(k)) + \frac{1}{2}\|s^+_{\beta}(k + n(k))\|^2 \]  

(20)

Before the instant

\[ k + j \]

nothing is received at the slave side and, therefore,

since strategy S2 is used, the communication channel has a dissipative be-
behavior. At time

\[ k + j \]

the slave receives the packet

\[ s^-_{\alpha}(k + 1 - \delta) \]

and

the packets

\[ s^+_{\beta}(k + 1) \]

is built. Since this is not the expected packet, as de-
scribed in Eq.(19), an energy amount equal to that of the expected packet

\[ s^+_{\beta}(k) \]

is produced. Nevertheless, the system keeps on being passive since the en-
ergy amount produced has already been dissipated at time

\[ k + 1 \]

After the time instant

\[ k + j \]

and before

\[ k + n(k) \]

nothing is delivered at the slave side and, therefore, the system dissipates energy. Finally at the instant

\[ k + n(k) \]

since we are using the UFS technique, the contribution relative to the packet

\[ s^-_{\alpha}(k - \delta) \]

is discarded because a younger packet has already been processed and therefore the communication channel exhibits a strictly dissipative behavior. Thus, the effect of a decrease of the commu-
nication delay is again the introduction of dissipation in the dynamics of the communication channel. Thus we have proven the following result:

**Proposition 3** Consider a scaled port-Hamiltonian telemanipulation scheme where the interconnection between master and slave sides is made through

\[ n(k) : \]

\[ P_{\alpha\beta}(k + n(k)) = \frac{1}{2}\alpha^2\|s^-_{\alpha}(k + n(k))\|^2 - \frac{1}{2}\alpha\beta\|s^+_{\beta}(k + n(k))\|^2 \]

\[ + \frac{1}{2}\|s^+_{\beta}(k + n(k))\|^2 - \frac{1}{2}\|s^-_{\alpha}(k + n(k))\|^2 + \frac{1}{2}\|s^+_{\beta}(k + n(k))\|^2 = \]

\[ = dH_{\alpha\beta}(k + n(k)) - \frac{1}{2}\|s^+_{\beta}(k + n(k))\|^2 + \frac{1}{2}\|s^+_{\beta}(k + n(k))\|^2 \]  

(19)

Thus we have that at the instant

\[ k + n(k) \]

the communication channel dis sipates an amount of energy equal to the content of the expected packet

\[ s^+_{\beta}(k + n(k)) \]

and produces an energy amount equal to that of the actu ally received packet

\[ s^+_{\beta}(k) \]

Nevertheless, as it can be seen in Eq.(18), the amount of injected energy has been already dissipated and, therefore,
Eq. (8). If the strategy S2 is adopted, the variability of the communication delay makes the communication channel a strictly dissipative system.■

Summarizing, strategy S1 should not be adopted to handle variable delays since it transforms the communication channel into an active system which destabilizes the overall telemanipulation system. Thus, somehow counterintuitively, the partial construction of a packet does NOT improve performances. On the other hand, strategy S2 can be safely adopted since in this way the effect of variable delay is the introduction of dissipation and this does not alter the dissipativity of the overall telemanipulation system. In this case a variable delay causes a decrease of performances since part of the energy required to perform a certain task is not delivered on time (or it can even be discarded) but the overall system is still characterized by a stable behavior.

5 Simulations

In this section we provide some simulations in order to validate the obtained results.

Consider a simple 1-DOF telemanipulation system. Master and slave robots are simple masses of 1 kg and the digital controllers are obtained by discretizing through the technique proposed in [6] a port-Hamiltonian system that is physically equivalent to the parallel of a spring and a damper and the sample time is $T = 0.01$ s. Master and slave sides are interconnected through a packet switching transmission line over which the discrete scattering based communication strategy proposed in Eq.(8) is implemented with scaling factors $\alpha = 2$ and $\beta = 2$. The communication delay is variable with a mean of 0.3 s and the strategy S2 described in Sec. 4 has been adopted. The operator applies an impulsive force to the master and the results are reported in Fig. 2. Since the scaling factors for the exchanged flows is $\beta = 2$ the position of the slave should be twice bigger than that of the master but, because of the use of strategy S2, the dissipation introduced by the variability of the communication delay allows to achieve the scaling only partially as it can be seen in Fig. 2(a).

In Fig. 2(b) the power flows exchanged between master and slave sides are reported. The power extracted from the master side is scaled and then, after some delay, supplied to the slave side. Nevertheless, in several sample periods, 0 power is supplied (and this causes the peaks in the figure) because null packets are sampled to replace late packets and some packets, since the UFS strategy is used, can be discarded; the received packets, as expected, are scaled by a factor $\alpha\beta = 4$. In Fig. 2(c) and Fig. 2(d) the exchanged flows and efforts are reported. Since the adopted communication strategy implements a discrete power scaled common effort interconnection, the signs of the flows are discording. The irregular behavior that characterizes the flows and the efforts is due to the dissipation introduced when using S2 which, again, allows only to partially achieve the desired scalings. Summarizing, variable communication delay decreases the performances of the overall system and allows only to partially achieve the desired scalings; nevertheless, the telemanipulation system keeps on having a stable behavior.
In the next simulation a contact task is implemented. The human operator applies a constant force of 1 N to the master and the slave interacts with a wall, implemented as the parallel of a stiff spring, $K = 1000 \text{ N/m}$, and of a damper, $b = 100 \text{ Ns/m}$, which is set at $x = 0.3 \text{ m}$. The simulation results are reported in Fig. 3. In Fig. 3(a) we can see that the slave stops when it meets the wall and the scaled interaction force is fed back to the master side which stops. The position of the master goes further with respect to what would happen in case of constant delay. This is because, when a packet is late and is replaced with a null packet, no reaction force is implemented at the master side to counteract the operator’s force. In Fig. 3(b) the exchanged power flows are reported. We can see that both power flows are characterized by peaks due to the fact that some expected packets are not received on time or discarded because they’re too late; nevertheless, when the transmission is successful, the power extracted from the master side is scaled by a factor $\alpha\beta = 4$ and supplied to the slave side. In Fig. 3(c) and in Fig. 3(d) the behavior of the exchanged flows and of the exchanged efforts respectively are reported. Notice that, despite of the peaks due to the variability of the delay, at steady state, the $e_s$ is twice bigger than $e_m$, meaning that a scaled version of the interaction force is reported to the operator. Also in the contact case, therefore, the variable communication delay decreases performances but preserves a stable behavior of the overall system.
6 Conclusions and Future Work

In this paper we have proposed a strategy to passively deal with variable communication delays in power scaled port-Hamiltonian telemanipulation. This technique, together with the one developed in [13] to deal with loss of packets, allows to use a generic packet switched network as a communication channel in power scaled port-Hamiltonian based telemanipulation. It can be easily extended to generic passivity based teleoperators, using the passive inputs and outputs for defining the interconnection between the passive master and slave sides. In the future we aim at developing a new communication strategy that replaces a late packet with a non null packet obtained through a passivity preserving interpolation of the received information. In this way part of the energy associated to the late packet is delivered on time and performances should improve.

References


