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On the Robustness of Networked Control Systems with Quality of Service Adaptation Co-design

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Abstract: The current study proposes a control-aware Quality of Service adaptation co-design method for networked control systems. The Quality of Service adapter is based on a Differentiated Services model, and uses information from theoretical stability analysis for its design. The experimental results confirm that such a co-design approach, where the stability margin with respect to a maximum network time delay is taken into account by the Quality of Service adapter, can lead to good control performances even with conventional controllers.

Keywords: networked control systems, time delay, robust stability, Quality of Service model, co-design control method.

1. INTRODUCTION

The communication technology available today makes networked control systems (NCS) a viable solution for distributed control. Hence, the networked control field has gain an increased interest in the scientific community, which is sustained by the large area of the NCS's applicability (e.g. remote surgery (Bergeles and Yang, 2014), automotive (Caruntu and Lazar, 2011), unmanned vehicles (Seiler and Sengupta, 2001), and industrial applications (Wilamowski and Irwin, 2011).

Although they have a lot of advantages like low cost, high availability and redundancy, modularity, ease of maintenance and diagnostics (Zampieri, 2008), NCS also have some shortcomings, induced by the network component, like time varying delays, information loss and limited transfer capacity (Hespanha et al., 2007; Tipsuwan and Chow, 2003), that can affect the performance and stability of the control system.

Consequently, adequate control solutions are needed to overcome this issues before NCS can be largely implemented in practice. In the past few years, multiple control strategies have been proposed for NCS in the specialized literature, that can be divided in two categories: *control of network solutions* (e.g. end-to-end Quality of Service (QoS) (De Moraes and Vasques, 2004) and *control over network solutions* (e.g. model predictive control (Caruntu et al., 2013; Franze and Tedesco, 2014), optimal and robust scheduling (Longo at al., 2013), event based control (Liu et al., 2014), passivity (Kottenstette et al., 2013), optimization through optimistic planning (Busoniu et al., 2013), fuzzy control (Zhang et al., 2013), communication disturbance observer (Natori et al., 2010), Smith predictor (Lai and Hsu, 2010).

For better performance, control strategies from both categories can be combined by using a co-design method (Song, 2009). According to (Aubrun et al., 2010), two types of co-design methods exists. A first method, referred to as an "*implementation-aware control law design*" presumes a real-time continuous adaptation of the control law based on the network QoS (e.g. continuous adaptation of the controller / compensator gains according to the network time varying delay (Stefan et al., 2013), continuous adaptation of the sample rate (Bai et al., 2012). The second method, defined as a "*control-aware QoS adaptation*" presumes a real-time reallocation of network resources based on QoS in order to maintain the quality of control (e.g. network resource reservation for NCS (Stefan and Dragomir, 2015; Diouri et al., 2007).

The current paper analysis the robust stability of a networked control structure with respect to network disturbances, and proposes a control-aware QoS adaptation co-design method, which takes into account the stability results in terms of a maximum delay bound and is based on the Differentiated Services architecture for end-to-end QoS.

The remainder of this paper is organized as follows. Section II formulates the problem. Section III presents the co-design methodology. Section IV analyses the system's robust stability. Section V presents an illustrative example and Section VI states some final conclusions.

2. PROBLEM FORMULATION

Most control over network solutions assures the system's stability and performance as long as the network induced disturbances (time-varying delay, jitter, bandwidth capacity, packet loss rate) remain in some predefined nominal boundaries. When a co-design methodology is adopted, the control of network solution could guarantee these boundaries by imposing certain QoS values through network resource allocation. But, when the network resources are limited, as in the case of a multiservice network environment (e.g. Internet's networks (Tanenbaum and Wetherall, 2010)), in order to maintain the quality of control with minimal impact on network utilization, the system has to dynamically allocate the network resources based on the QoS requirements.

Problem statement: Develop a co-design control structure for the NCS, identify the bounds of the network induced disturbances that the NCS has to impose such that the system is robustly stable, and show that in practice control performances can be met for an intermediate bound.

3. QUALITY OF SERVICE ADAPTATION CO-DESIGN

Consider the NCS from Fig. 1. The local side of the NCS consists of the controlled process, while the remote side is composed of the controller serving the control loop and the QoS adapter which continuously adapts the network parameters by using information obtained from both paths of the network. The adapter manages both transmission channels in order to maintain network transmission disturbances in certain limits imposed by the NCS design. Here, w is the reference signal, u is the control signal, y is the process output, while u_N and y_N are the signals received through the network corresponding to u and y.

3.1 Quality of Service Adapter

The QoS adapter has the role of imposing certain limits in which the network induced disturbances may take values – upper and lower bound – in order to maintain the quality of control. To do this, with minimum resource consumption, the adapter has to dynamically allocate network resources for control, based on the QoS requirements.

The adapter relies on a QoS model to implement and maintain the imposed network requirements. Two types of level three end-to-end QoS models are defined for IP based networks (Dordal, 2015): *signalled* QoS and *provisioned* QoS models. The signalled QoS models use a signal protocol / framework (e.g. Resource Reservation Protocol (RSVP), Next Steps in Signaling (NSIS)) to announce the needs of the end hosts for network resource reservations. The provisioned QoS models setup the network equipment to service multiple classes of traffic with different QoS requirements.

In practice, to facilitate true end-to-end QoS, two QoS models were designed and implemented (Evans and Filsfils, 2007): Integrated Services (IntServ) (signalled QoS) and Differentiated Services (DiffServ) (provisioned QoS). Although both QoS models can be used to implement the QoS adapter, the current paper uses the second approach, because of the extended scalability it offers, making it suitable for large networks with wide area coverage (Dordal, 2015). Fig. 2 presents the proposed DiffServ based NCS.

The ingress node implements a traffic conditioner which classifies incoming packets by their types, meters, marks, shapes and drops them according to predefined conditions.

The DiffServ domain implements several types of per hop behaviors (PHB): a default PHB providing a best effort service for common network applications, an expedited forwarding PHB (EF) assuring minimal time-varying delay, jitter and packet loss rate for hard real-time applications and a variable number of assured forwarding PHB (AF) for soft real-time applications, each one having a certain bandwidth and buffer space assigned.

3.2 Control

Consider the controlled process to be a SISO linear time invariant system of the following form:

$$\begin{aligned}\dot{\mathbf{x}}_p(t) &= \mathbf{A}_p\mathbf{x}_p(t) + \mathbf{B}_p u_N(t) \\ y(t) &= \mathbf{C}_p\mathbf{x}_p(t)\end{aligned}, \qquad (1)$$

with $\mathbf{x}_p \in \Re^r$ as the state vector of the process.

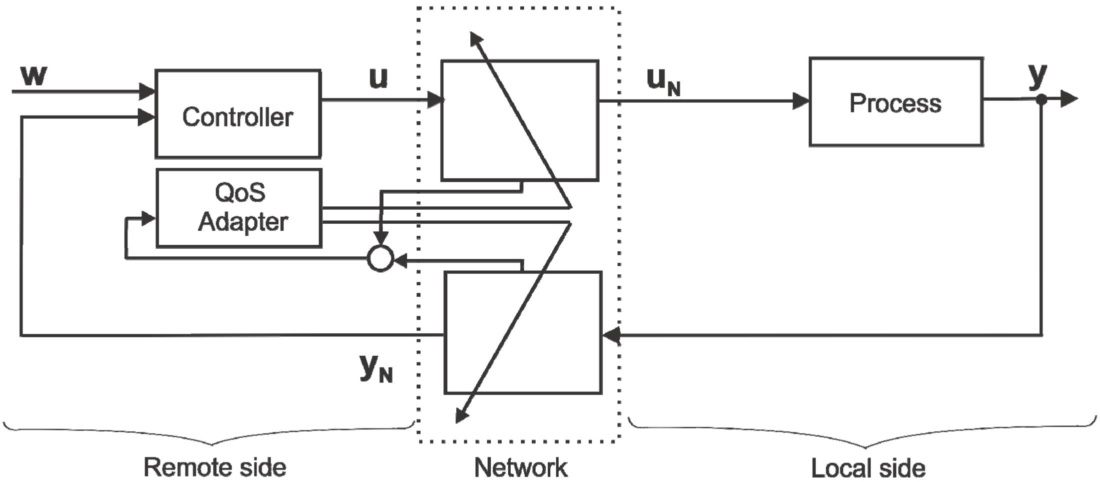

Fig. 1. Co-design based networked control structure (Stefan and Dragomir, 2015).

If the process is remotely controlled through a communication network characterized by the network time delays, τ_d and τ_f, then the remote controller receives the signal:

$$y_N(t) = y(t-\tau_f),$$

and in turn the process receives the signal

$$u_N(t) = u(t-\tau_d).$$

For the design and analysis stages, due to the linearity of the controlled process, the time delay can be considered only on the feedback path, which means that:

$$y_N(t) = y(t-\tau)$$

and

$$u_N(t) = u(t)$$

with

$$\tau = \tau_d + \tau_f.$$

Further on, for the process (1), an output feedback controller of the form:

$$\begin{aligned} \dot{\mathbf{x}}_c(t) &= \mathbf{A}_c\mathbf{x}_c(t) + \mathbf{B}_c(w(t) - y_N(t)) \\ u(t) &= \mathbf{C}_c\mathbf{x}_c(t) + \mathbf{D}_c(w(t) - y_N(t)) \end{aligned} \tag{2}$$

is considered, where $\mathbf{x}_c \in \Re^s$ denotes the states of the controller. The controller is designed to ensure satisfactory tracking performances with respect to the reference w, for a nominal (constant) network delay value τ_n.

4. ROBUST STABILITY ANALISYS

Consider the closed loop network control system:

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{x}(t-\tau) \tag{3}$$

obtained from (1) and (2) and other dependencies from the previous section for w = 0. In (3) $\mathbf{x} = [\mathbf{x}_p^T \; \mathbf{x}_c^T]^T \in \Re^n$ (n = r+s) and

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_p & \mathbf{B}_p\mathbf{C}_c \\ \mathbf{0} & \mathbf{A}_c \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ -\mathbf{B}_c\mathbf{C}_p & \mathbf{0} \end{bmatrix}$$

are constant matrices of dimension n×n.

As a working assumption for the current study, the system (3) free of delay (i.e. $\tau = 0$) is considered asymptotically stable. Moreover, because the control design was done considering a nominal delay value (τ_n), the system (3) is assumed to be asymptotically stable even for this constant delay value. The aim is to find an upper delay bound τ_{max} (first delay interval) for which the system is robustly stable.

In order to derive necessary and sufficient robust stability conditions, we appeal to the method proposed in the paper (Kharitonov and Niculescu, 2003) (the frequency domain approach for constant delay perturbation), particularized for the case when the system free of delay is asymptotically stable. The method starts from the matrix pencil

$$\mathbf{\Lambda}(z) = z\begin{bmatrix} \mathbf{I}_m & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \otimes \mathbf{I}_n \end{bmatrix} + \begin{bmatrix} \mathbf{0} & -\mathbf{I}_m \\ \mathbf{I}_n \otimes \mathbf{B}^T & \mathbf{A} \oplus \mathbf{A}^T \end{bmatrix}, \tag{4}$$

where $\otimes$ and $\oplus$ represent the Kronecker product and sum, and with $m = n^2$. Then the following set can be introduced:

$$\mathbf{\Lambda}_{0,+} = \left\{ (\tau_{k_i}, \alpha_k) : \tau_{k_i} = \frac{\alpha_k}{\omega_{k_i}} > 0 : e^{-j\alpha_k} \in \sigma(\mathbf{\Lambda}), \; j\omega_{k_i} \in \sigma(\mathbf{A} + e^{-j\alpha_k}\mathbf{B}) - \{0\}, \; 1 \le k \le 2m, 1 \le i \le n \right\}, \tag{5}$$

with $\sigma(\cdot)$ as the set of (generalized) eigenvalues.

Next, Theorem 1 from (Kharitonov and Niculescu, 2003) is invoked, particularized for the case when the system free of delay is asymptotically stable (for a formal proof see (Kharitonov and Niculescu, 2003)).

Theorem 1: The system (3) is robustly stable for constant delays up to a

$$\tau_{max} = \min\{\mathbf{h} : (\mathbf{h}, \alpha) \in \mathbf{\Lambda}_{0,+}\}$$

if and only if the system with the nominal delay value τ_n is asymptotically stable.

□

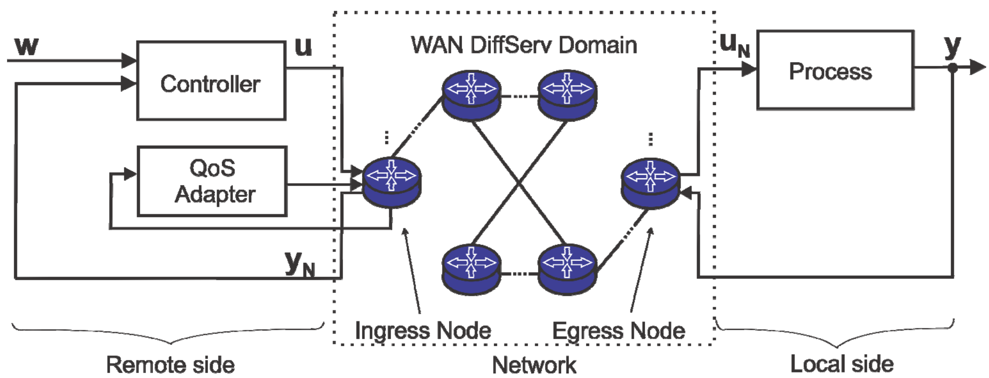

Fig. 2. DiffServ based networked control structure.

Thus, through the application of Theorem 1, the robust stability analysis provides the network delay bound τ_{max} which should be imposed by the QoS adaptor.

5. CASE STUDY

5.1 Control structure components

Consider the networked control structure from Fig. 1, with an electric drive as the controlled process, a TCP/IP network and a conventional PI controller ensuring a speed control objective. The PI controller was chosen because it is widely implemented in practice (Astrom and Hagglund, 1995).

The electric drive is composed of a permanent magnet DC motor, an electronic actuator (PWM) and a tachogenerator.

The model associated with the electric drive has the form (1) with $x_p^T = [x_{p1}\ x_{p2}]$ (x_{p1} is the motor speed, x_{p2} is the armature current) and

$$\mathbf{A}_p = \begin{bmatrix} 0 & T_m^{-1} \\ -T_a^{-1} & -T_a^{-1} \end{bmatrix}, \mathbf{B}_p = \begin{bmatrix} 0 \\ T_a^{-1} \end{bmatrix}, \mathbf{C}_p = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad (6)$$

where T_a and T_m are the electrical, respectively electromechanical time constants of the motor. The parameter values used throughout the entire case study are the ones from Table 1.

The controller (2) is particularized to a PI controller with:

$$A_c = 0,\ B_c = 1,\ C_c = K,\ D_c = KT_i\ . \quad (7)$$

The TCP/IP network taken into account is a 10 Mbps country size wide area network (WAN) characterized by a round trip time (RTT) of 100 ms (mean value) (2 x 50 ms one way delays (OWD)) induced by signal propagation (Tanenbaum and Wetherall, 2010). The network channels are bidirectional and symmetric in terms of both speed and delay. For simplicity, the WAN is considered to connect 7 network nodes (Fig. 3): 4 hosts (H_1, H_2, H_3 and H_4) and 3 routers (R_1, R_2 and R_3).

5.2 Control Co-design

The controller was designed for the system with a constant nominal delay (τ_n = 100 ms). Although for 1st order and 2nd order systems, as well as some benchmark type process models (of low order), one could resort to (quasi-) analytical tuning methods (e.g. Cohen Coon – see Astrom and Hagglund, 1995), in this case study numerical optimization methods are addressed due to the general applicability of such methods (even for higher order systems).

The optimization problem aims in minimizing the error between the reference w and the output y, for a step reference signal. Consider an IPTSE (integral of powered time-weighted square error) type objective function, for which the optimization problem is formulated as:

$$\underbrace{\min}_{\substack{K \in [K^{min},\, K^{max}] \\ T_i \in [T_i^{min},\, T_i^{max}]}} J(K, T_i), \quad \text{with} \quad J(K, T_i) = \int_{t=t_0}^{t=t_m} t^{\chi} \left(w(t) - y(t) \right)^2 dt, \quad (8)$$

where χ>1, t_0 is the initial time moment and t_m is the moment when the steady state regime is practically reached. $[K^{min}, K^{max}]$ and $[T_i^{min}, T_i^{max}]$ are the allowed ranges of K and T_i. The optimization problem (8) can be framed as classical nonlinear least squares problems with constraints, for which several efficient methods exist in the literature (Bjorck, 1996).

For the DC motor controlled process, the PI parameters obtained by minimizing J from (8) – with χ = 2 – are K = 3.7 and T_i = 0.144 sec.

The QoS adapter is implemented using the particular DiffServ domain from Fig. 3 containing two edge routers (R_1 and R_3) and one core router (R_2). Depending on the traffic direction, both edge routers play the roles of ingress and egress routers performing packet classification and marking, policing, shaping and scheduling functions (Pacyna, 2006).

On the edge routers, the packets are divided into different classes based on the source and destination IP addresses and are marked accordingly. The single rate, two colour token bucket traffic policer (Evans and Filsfils, 2007, Pacyna, 2006) is adopted to enforce the predefined profiles on the traffic flows from different classes. Non-conformant traffic is marked with the differentiated services code point (DSCP) of a lower priority class. To maintain the time delay and packet loss values in the limits imposed by the control system design, a finite-state machine logic implemented into the QoS adapter selects the priority class of the exceeding traffic.

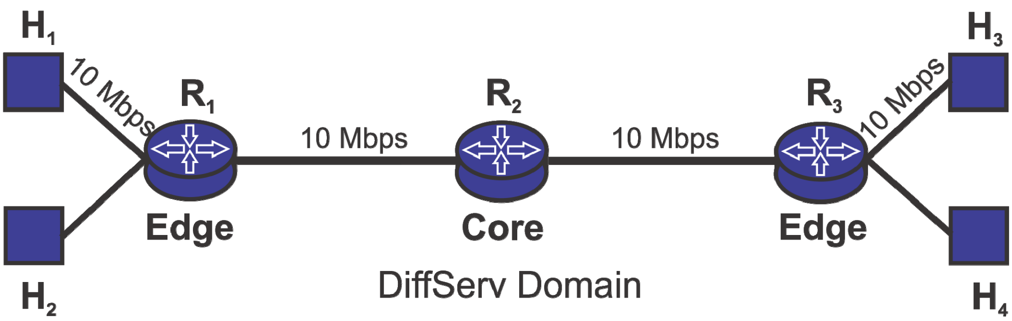

Fig. 3. Considered wide area network setup.

This design has the advantage of ensuring a minimum guaranteed transfer rate for every flow (defined by the committed information rate (CIR)) in case the network resources become scarce.

All the routers implement one EF for the conformant traffic and four AF with different priority levels for the exceeding traffic. To avoid congestion, a random early detection (RED) queuing discipline and a weighted round robin scheduler (WRR) are considered (Evans and Filsfils, 2007; Pacyna, 2006).

5.3 Robust stability

The control system with the nominal delay τ_n is asymptotically stable according to the distribution of the rightmost characteristic roots (λ) of the system – Fig. 4 (all the roots lie in the open left half plane). The characteristics roots were computed using the method from (Wu and Michiels, 2012). Then, using the stability method presented in Section 4, we obtained that the system is actually robustly stable for a time delay up to a τ_{max} = 380 ms.

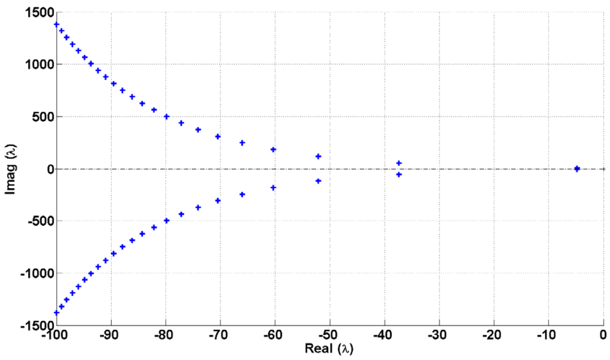

Fig. 4. Rightmost characteristic roots (λ) of the control system for the nominal delay τ_n.

The stability analysis has considered so far fixed time delay values. In practice, the network induces time varying delays. However, the experimental results show that the closed loop control system conserves its stability for certain variations of the network induced time delay (from a phenomenological point of view, the process dynamics is slower than the dynamics of the network (including delay variations), and thus filters out such rapid network disturbances).

5.4 Experimental results

The experimental setup consists of an electrical drive connected to a dSPACE board (Fig. 5). The controller was implemented in the Matlab/Simulink environment and loaded on to the dSPACE board (directly connected to the computer). A sampling period h = 0.001 sec was adopted. The DC motor (power of 20 W) is controlled through an electronic actuator within the voltage domain of ±24 V, has a moment of inertia of $5.18 \cdot 10^{-6}$ kg·m^2 and it can reach a maximum speed of 4000 rpm. The motor speed is measured through a tachogenerator. The parameter T_m and T_a were determined based on experimental identification (see Table 1 for system's parameters). The network system composing the NCS is implemented on the dSPACE board using the Network Emulator described in details in the paper (Stefan et al., 2011). The emulator's algorithm is:

Algorithm for the Network Emulator:

Initialization:
- define maximum allowed delay τ_{max}
- initialize buffer $\mathbf{x}_{NE}$
- initialize $y_{NE,0}$

Repeat at each sample time k:

Step1: read inputs $u_{NE,k}$, τ_k and p_k

Step2: if $\tau_k > \tau_{max}$ or $p_k = 0$ jump at Step5

Step3: rewrite value at position τ_k+1 in buffer $\mathbf{x}_{NE}$ with $u_{NE,k}$

Step4: delete all buffer values from the positions to the right of position τ_k+1

Step5: if the value from the first position of buffer $\mathbf{x}_{NE}$ is non zero write it to output $y_{NE,k}$, else $y_{NE,k}$ becomes $y_{NE,k-1}$

Step6: shift buffer $\mathbf{x}_{NE}$ with one position to the left

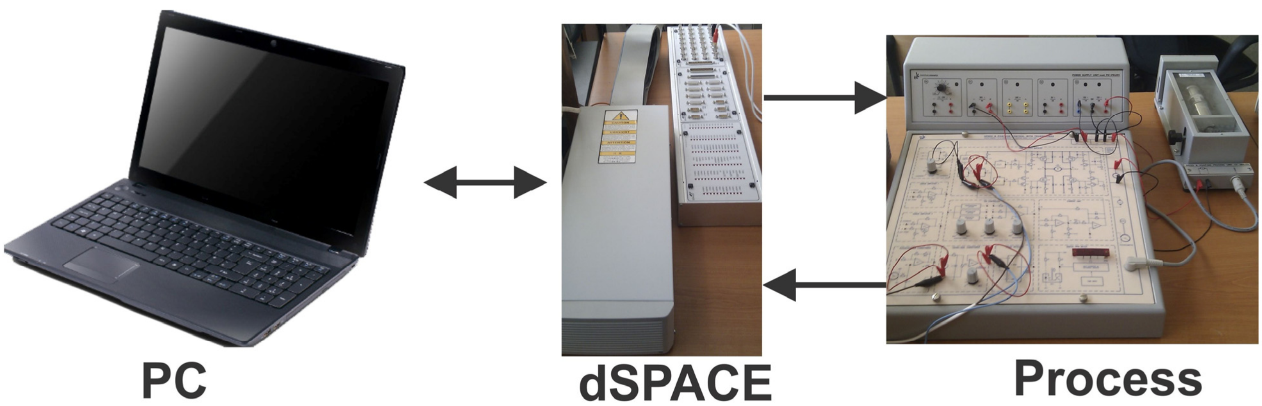

Fig. 5. Experimental setup.

Table 1. Systems's parameters.

Parameter	Value
P	20W
J	$5.18 \cdot 10^{-6}$ kg·m^2
y_{max}	4000 rpm
T_m	0.157 sec
T_a	0.039 sec
K	3.7
T_i	0.144 sec
h	0.001 sec

Here, u_{NE}, τ and p (packet loss flags signal) are the input signals, y_{NE} is the output signal and $\mathbf{x}_{NE}$ is the state vector. The scenarios for the τ and p signals can be obtained through measurements using real networks or a network simulation software.

For better flexibility, the WAN network presented in Fig. 3 was implemented using the Network Simulator 2 (NS2) software (Issariyakul and Hossain, 2012). The simulation considers two user datagram protocol (UDP) data flows passing through the network. The first data flow, DF_1, transfers data packets between the hosts H_1 and H_3 (Fig. 3). The second one, DF_2, is a generic transport layer data flow exchanging information between the hosts H_2 and H_4. DF_1 is generated using a constant bit rate (CBR) source that transmits packets at a constant data rate and simulates multiple NCS control signals transfers. DF_2, considered as a perturbation flow, is obtained from an exponential traffic source, capable of generating random data at a maximum rate of 100 % of the network throughput capacity.

The same simulation results (τ and p signals associated to the DF_1 flow) are selected as inputs for the Network Emulator on both network channels for the direct and the feedback path of the NCS, by considering a symmetric traffic distribution.

Next, two experimental scenarios will be presented: one that tests the limit of stability for the designed NCS, and the other which illustrates that good tracking performances can still be obtained if the network delay disturbances are kept in reasonable bounds.

The first experimental scenario (Fig. 6) considers a constant RTT delay of 380 ms (see Section 5.3) for the control signals flow DF_1. For a step reference signal w (magnitude 1000 rpm) the output signal y presents sustained oscillations and thus validates that the NCS is marginally stable for τ_{max}.

However, in control engineering practice one wants to show not only that the system is stable for network delay values up to τ_{max}, but also that the system ensures certain control performances. In this context, several experiments were conducted in order to determine a performance margin, i.e. a maximum network delay value for which the system exhibits certain reference tracking performances: overshoot below 10% of maximum speed and settling time below 1.5 s. The performance margin, determined experimentally, was two times greater than the nominal delay (upper bound) $\tau_q = 2*\tau_n$.

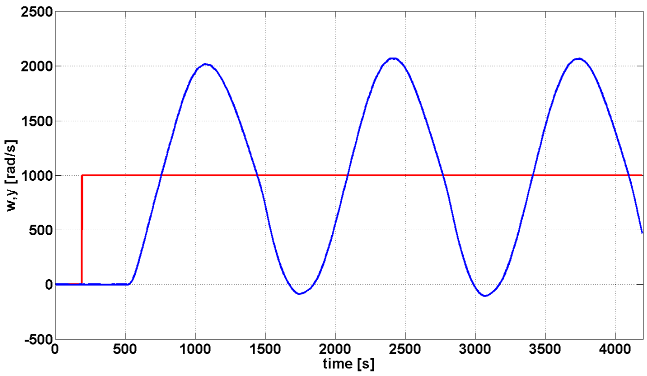

Fig. 6. Experimental results – marginal stability for the network delay $\tau = \tau_{max}$.

The second experimental scenario illustrates that the imposed control performances are met (Fig. 7) even when the network delay varies up to the value τ_q; in other words, that the control systems ensures good tracking performances.

The scenario is specifically tailored so that the QoS adapter would permit a maximum RTT of τ_q for the DF_1 traffic and no packet loss. In Fig. 7 there are two transitory regimes: one between 1 sec and 2.5 sec for which the network delay takes the nominal value of about 100 ms (53 ms on each path – Fig. 8), and the second between 2.6 sec and 4.4 sec in which the network delay increases up to 200 ms (92 ms on each path – Fig. 8).

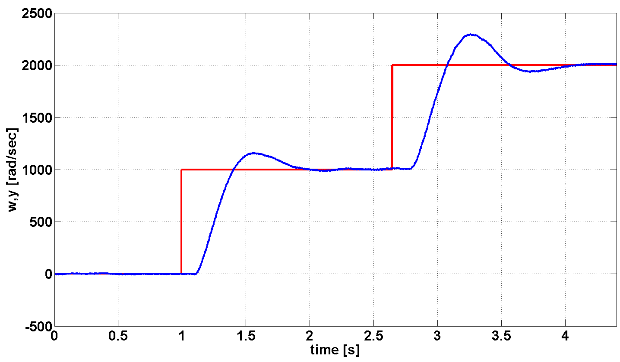

Fig. 7. Experimental results – tracking performance for a network time varying delay with τ_q as upper bound.

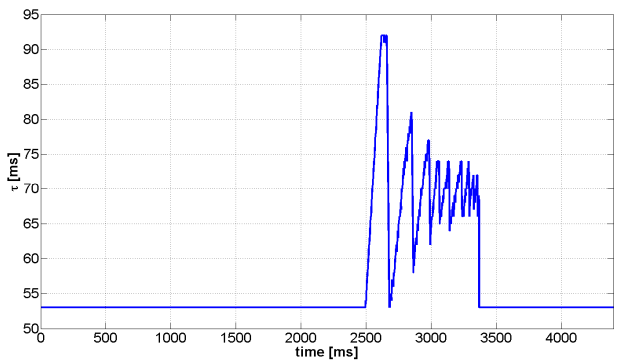

Fig. 8. Experimental results – network time delay variation on each path (direct and feedback).

6. DISCUSSION

6.1 Control aspects

The current study shows that a co-design approach to NCS can reduce the complexity needed for the controller, by using a Quality of Service adaptor which maintains some imposed network parameters. The consequences are of both theoretical and practical nature. From a theoretical point of view, the limits of performances of the NCS can be pushed further by improving also the communication performances. From a practical perspective, as the industry tends to avoid high complexity for the controller, such co-design methods can lead to feasible results.

6.2 Networking aspects

Although the Internet expansion makes it an ideal candidate for the development of telecontrol applications (Yang, 2011), the adoption of such solutions is impeded by the lack of the support needed, at the network level, to impose certain requirements of performance and reliability. This lack of support for network resource reservations originates in the founding principle of the Internet: "Net Neutrality" (Wu, 2003) which states that all traffic should be treated equally regardless of its type. In the last years, with the diversification of network applications using the Internet for data transmissions, more and more scientists and network engineers agree that Internet regulations should be updated to allow Internet providers to divide data traffic into classes with different needs regarding network delay, jitter and bandwidth requirements.

6.3 Conclusions and further perspectives

The focus of the study was to develop a methodology that uses information from theoretical stability (regarding the influence of the transmission time varying delay) in the design approach of a QoS adaptor. The case study illustrates the applicability of the approach. Additionally, depending on the network resources available, if the performances margins can be quantified for a particular class of control systems in terms of a network delay bound τ_q then the QoS adaptor could be designed directly to impose this bound, instead of the stability bound τ_{max}.

The applicability of the co-design approach proposed in this study will be better highlighted by distributed NCS over the Internet (smart buildings, smart/micro grids, SCADA systems, networked mobile agents (e.g. UAVs)), where multiple delays act on multiple control loops.

Furthermore, with the development of the "Internet of things" (Mcewen and Cassimally, 2014), in recent years, co-design methods, like the one presented in this paper, are starting to become a necessity.

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ABBREVIATIONS

AF	Assured forwarding
CBR	Constant bit rate
CIR	Committed information rate
DC:	Direct current
DF:	Data flow
DiffServ:	Differentiated Services
DSCP:	Differentiated services code point
EF	Expedited forwarding
IntServ:	Integrated Services
IP:	Internet Protocol
IPTSE:	Integral of powered time- weighted square error
NCS:	Networked control systems
NS2:	Network Simulator 2
NSIS:	Next Steps in Signaling
OWD:	One way delays
PHB:	Per hop behavior
PI:	Proportional integrator
PWM:	Pulse-width modulation
QoS:	Quality of Service
RED:	Random early detection
RSVP:	Resource reservation protocol
RTT:	Round time trip delay
SCADA:	Supervisory control and data acquisition
SISO:	Single input – single output
TCP:	Transmission control protocol
UAV:	Unmanned Aerial Vehicle
UDP:	User datagram protocol
WAN:	Wide area network
WRR:	Weighted round robin scheduler

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