Proceedings of the
44th IEEE Conference on Decision and Control, and
the European Control Conference 2005
Seville, Spain, December 12-15, 2005

Multi-hopping Induced Gain Scheduling for Wireless Networked Controlled Systems

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Abstract— **A multi–hopping induced gain scheduler for Wireless Networked Controlled Systems (WiNCS) is proposed. The control scheme is based on a client–server architecture. The data packets are assumed to be carried over a network composed of wireless sensor nodes running the 802.11b protocol. The number of hops necessary for packets to reach their destinations is variable and depends on current traffic conditions. Changes in the number of hops induces changes in the latency times introduced by the communication network in the feedback loop. To deal with these changes an LQR–output feedback scheme is introduced, whose parameters are adjusted according to the number of the hops. The weights of the LQR controllers are subsequently tuned using LMIs to ensure a prescribed stability margin despite the variable latency times. The overall scheme resembles a gain scheduled controller with the number of hops playing the role of the scheduling parameter. Simulation results on the NS-2 simulator are provided to highlight the efficacy of the proposed scheme.**

Index Terms— **Networked controlled system, LMI, time delayed systems, wireless sensor networks.**

I. Introduction

The field of Networked Controlled Systems (NCS) has received considerable attention in recent years. The need to exchange information through a wireless communication channel implies time varying delays in the control loop that can affect the performance of the closed loop system and even drive it to instability [1, 2]. The characteristics of the communication channel therefore play an important role in the modeling procedure of the controlled system and in the selection of an appropriate controller.

Among NCS, Wireless NCS (WiNCS), and in particular WiNCS built around wireless sensor networks (WSN) [3, 4] is a rapidly evolving area at the moment. Recent technological advances have resulted in small, integrated sensing devices, capable of running a complete protocol stack. These devices have been optimized for communication with limited resources (transmission power, memory, no support for floating point calculations). The ease of deploying networks comprised of such sensor nodes, due to their low prices and their small size have made such networks very popular. Thus embedded sensor networks have found support from a number of companies and new communication standards have been developed to support them, for example the 802.15.4 [5] and the ZigBee Alliance [6].

From the control point of view, WiNCS in general and sensor networks in particular pose additional problems for the designer, stemming from the mobility of the nodes, which often leads to structural changes in the topology of the network.

In the research effort reported in this paper the main objective is to utilize the technology and the characteristics of a sensor network based on the IEEE 802.11b protocol to construct and study a client–centric control application. In the standard Client–Server WiNCS [7, 8] architecture, shown in Figure 1, the client computes the control command $u(t)$ and transmits it via a wireless link to a server. The server receives the data–packet after a certain delay, transfers it to the plant, samples the plant's output $y(t)$ and transmits the measurement back to the client through the same sensor network. The client receives the output after some delay and repeats the process.

The main difficulty with the design of such a control loop is the presence of the sensing and actuation delays introduced by the communication network. Unlike conventional time delay systems, the delays introduced by the network are time varying [9, 10], since these depend on the traffic currently on the network. For wireless communication channels, the problem is further complicated by the mobility of the nodes, which induces structural changes in the packet routing procedure. Accordingly, the number of hops necessary for a packet to reach from the client to the server (and reverse) varies in a step manner introducing an additional source of varying delays by the network.

In earlier work [7], we studied the design of NCS based on LQR–output feedback for a single, peer–to–peer wireless link. In this case it was possible to use LMIs [11, 12] to select the parameters of the LQR problem to ensure that the poles of the closed loop system maintains a prescribed stability margin despite the variability of the network delays. In this paper we extend this approach to investigate the effect of multi–hopping in the process. Based on the results of the maximum delay that the controlled system can tolerate, obtained for the peer–to–peer system, a gain scheduling controller, which uses the number of hops to select appropriate LQR gains is developed and tested in simulation. In Section II, we review the properties of the sensor network that we consider in this study. In Section III, a theoretical formulation for the calculation of an LQR-output feedback controller based on LMI-theory is presented. In Section IV, the proposed controller is applied to a simulated client–

This work was partially funded by: a) the European Social Fund (ESF), Operational Program for Educational and Vocational Training II (EPEAEK II), and particularly the Program HERAKLEITOS, No. B238.012, b) EU's FP6 Technologies-004536 RUNES research program and (c) Network of Excellence HYCON, contract number FP6-IST-511368.

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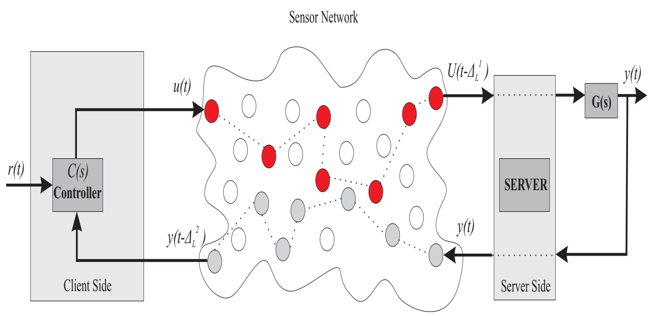

Fig. 1. Client–Server Architecture Based on a WSN

Network Characteristics	Values
Simulation Time (sec)	500
Number of nodes	20
Number of Connections	20
Maximum N_o of Packets Transmitted per Connection	10000
UDP Transmission Interval per Connection(sec)	0.2
Maximum Speed per Node (m/sec)	20
Coverage Area	670x670
Agent Type	UDP
Routing Protocol	DSR

TABLE I
SIMULATION PARAMETERS

server scenario and relevant results are presented. Finally, Section V, presents conclusions and directions for current work.

II. PROPERTIES OF WIRELESS SENSOR NETWORKS

Although WSN maintain several characteristics of conventional networks, they also have key differences [4]. WSNs combine three important components: sensing, data processing and communication [3]. The nodes that comprise a sensor network are spatially distributed, energy–constrained, self configuring and self–aware. WSNs can provide quite effective performance in noisy environments, since they allow sensors to be placed close to signal sources, therefore yielding high signal to noise ratios. Moreover, the scalability of the sensor network permits the monitoring of phenomena widely distributed across space and time, and their versatility makes them an ideal infrastructure for robust, reliable and self–repairing systems.

An important issue related to scalability [13] is the fact that after some point, communication becomes more expensive than computation. The requirements for collaboration and adaptation to "stochastic networking" features (usually due to exogenous factors) impose the need for the development of novel protocols dedicated to sensor networks, such as [14]. Another major concern is energy consumption, which requires a compromise between node collaboration and energy constraints [15] and affects the maximum active communication area. These features that affect the routing of communication packets sent over a WSN which requires multiple hops to complete the origin–destination travel. The dynamic nature of the network further implies that the number of hops may be variable.

In this paper we investigate how these features affect the design of controllers that attempt to close the loop over such a network. Towards this goal, a mobile ad–hoc network (MANET) in a noisy, crowded environment is simulated, as the communication medium that transfers the data packets between a remote controller and the plant.

A. WiNCS simulation

The network scenarios are tested with the NS–2 [16] simulator for the physical, MAC and network layers of each node. Providing a variety of networking protocols, several scenarios can be simulated, based on the cases examined. The parameters that have been utilized for our test case are outlined in Table I. The simulated WSN consists of n–mobile nodes, communicating over a wireless link based on the IEEE 802.11b standard, as shown in Figure 2. For the examined case we assume that all nodes "wake up" at the same instant. While every node in the network may potentially exchange information with other nodes, two nodes are of particular interest: the node attached to the plant (server) and the node attached to the controller (client). The routing protocol assumed is the Dynamic Source Routing Protocol (DSR) [17]. In the transport layer information exchange is based on the User Datagram Protocol (UDP).

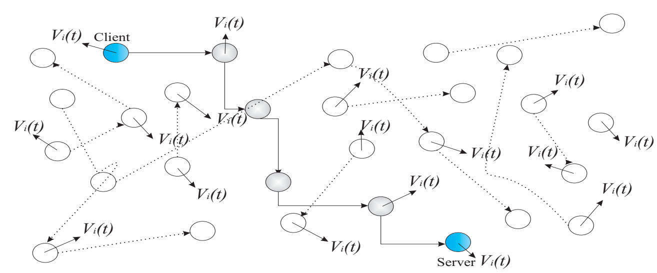

Fig. 2. An instance of the simulated scenario

In this research effort we are interested in a noisy MANET, focusing on the relationship between the transmission delay of a UDP frame that is produced from the multi–hoping mechanisms of the network and the characteristics of the route that the frame follows until it reaches it destination.

Due to node mobility, routing is not fixed [18]. Therefore, the number of hops during the transmission of a packet changes as the node moves from one position to another. Moreover due to the connectionless services provided by the transport layer, other interesting phenomena are also observed. For example a packet that fails to reach its destination or an intermediate node, may be dropped, or sent back to its source node. The retroactivity phenomenon observed, as a consequence of the unreliable services that UDP provides, is becoming even more dominant as a delay factor in heavy network traffic conditions. Some of the observed events are described in the cases that are presented in Figure 3.

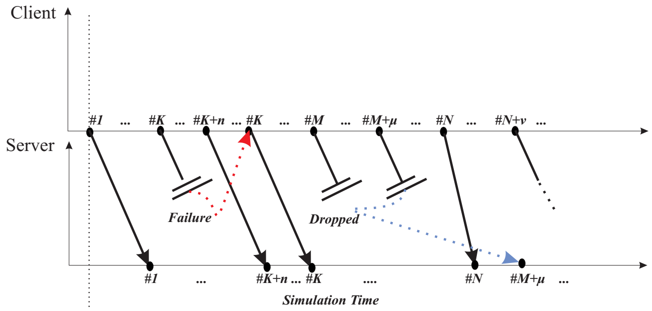

Fig. 3. Phenomena observed during a UDP Data Transmission from Client to Server

III. LQR-Output Feedback gain scheduling controller

Consider a discrete time WiNCS in a zero–latency environment, with linear dynamics given by:

$$\begin{aligned} x(k+1) &= Ax(k)+Bu(k) \\ y(k) &= Cx(k)\ . \end{aligned} \tag{1}$$

A. LQR–Output Feedback for NCS

Let the control objective be the computation of an LQR–output feedback controller, $u(k) = Ky(k)$, that minimizes the following cost [19]:

$$\min_K \sum_{i=0}^{\infty} \left[y^T(i)Ry(i) + u^T(i)Qu(i)\right] e^{\sigma i}\ , \tag{2}$$

with $\sigma \geq 1$. Upon computation of this controller the resulting closed–loop system has its poles (eig$(A + BKC)$ located inside a disk of radius $\frac{1}{\sigma}$.

In an actual WiNCS, as shown in Figure 4, delays are inserted in the loop, that depend on the number of the hops L that the data packets execute. Therefore, instead of the anticipated control command $u(k) = KCx(k)$, the control command applied to the plant is given by:

$$u(k) = KCx(k - r_s(k)). \tag{3}$$

We assume that the overall delay is time varying: $r_s(k)$ is a bounded sequence of integers $r_s(k) \in 0, 1, \ldots, D$ where D is an upper bound of the delay. The closed–loop system is

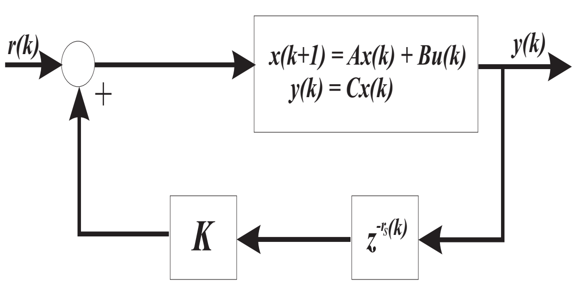

Fig. 4. Model representation of a Time Delayed WiNCS

formed by augmenting the state vector to $\tilde{x}(k)$ to include all the delayed terms, as

$$\tilde{x} = [x(k)^T, x(k-1)^T \ldots, x(k-D)^T]^T\ .$$

The dynamics of the open–loop system, at time k, with the augmented state vector take the following form

$$\begin{aligned} \tilde{x}(k+1) &= \tilde{A}\tilde{x}(k) + \tilde{B}u(k) \\ y(k) &= \tilde{C}_{r_s}(k)\tilde{x}(k)\ , \quad \text{where} \end{aligned}$$

$$\begin{aligned} \tilde{A} &= \begin{bmatrix} A & 0 & \ldots & & 0 \\ I & 0 & \ldots & 0 & 0 \\ 0 & I & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \ldots & I & 0 \end{bmatrix}, \qquad \tilde{B} = \begin{bmatrix} B \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \\ \tilde{C}_{r_s}(k) &= \begin{bmatrix} 0 & \ldots & 0 & C & 0 & \ldots & 0 \end{bmatrix}, \end{aligned} \tag{4}$$

where the vector $\tilde{C}_{r_s}(k)$ has its elements zero, except from the $r_s(k)$–th one. The overall closed loop system is

$$\tilde{x}(k+1) = \left(\tilde{A} + \tilde{B}K\tilde{C}_{r_s}(k)\right)\tilde{x}(k)\ , \tag{5}$$

$$y(k) = \tilde{C}_{r_s}(k)\tilde{x}(k) \tag{6}$$

Notice that the closed loop system is switched [20, 21], since the $r_s(k)$ (and thus the feedback term $K\tilde{C}_{r_s}(k)$) is time varying. The closed loop matrix $\tilde{A} + \tilde{B}\ K\ \tilde{C}_{r_s}(k)$ can switch in any of the $D+1$–vertices $A_i = \tilde{A} + \tilde{B}\ K\ \tilde{C}_i$.

To ensure stability of the closed loop system, conditions are sought for the stabilization of the switched system

$$\tilde{x}(k+1) = A_i\tilde{x}(k),\ i = 0, \ldots, D.$$

Under the assumption that at every time instance k the bounds of the latency time $r_s(k)$ that are produced from the L–hops can be measured, and therefore the index of the switched–state is known, the system can be described as:

$$x(k+1) = \sum_{i=0}^{D} \xi_i(k)A_i x(k)\ , \tag{7}$$

where $\xi_i(k) = [\xi_0(k), \ldots, \xi_D(k)]^T$ and $\xi_i = \{^{1,\text{mode}=A_i}_{0,\text{mode}\neq A_i}$.

It can be shown [11] that the switched system in (7) is stable if $D+1$ positive definite matrices $P_i,\ i = 0, \ldots, D$ can be found that satisfy the following LMI:

$$\begin{bmatrix} P_i & A_i^T P_j \\ P_j A_i & P_j \end{bmatrix} > 0, \forall (i,j) \in I \times I, \tag{8}$$

$$P_i > 0, \forall i \in I = \{0, 1, \ldots, D\}\ . \tag{9}$$

Based on these P_i–matrices, it is feasible to calculate a positive Lyapunov function of the form $V(k, x(k)) = x(k)^T \left(\sum_{i=0}^{D} \xi_i(k)P_i\right) x(k)$ whose difference $\Delta V(k, x(k)) = V(k+1, x(k+1)) - V(k, x(k)))$ decreased along all $x(k)$ solutions of the switched system, thus ensuring the asymptotic stability of the system. It should be noted that the bounds of the corresponding set can be arbitrary as $I = \{D^{min}, D^{max}\}$, D^{min},D^{max} ϵ $\mathbb{Z}^+$.

B. Gain Tuning of Output-Feedback Parameter

The computation of the output feedback controller $u(k) = Ky(k - r_s(k))$, results in a stable system that can tolerate a communication delay of D–samples ($r_s(k) \in \{0, 1, \ldots, D\}$). It should be noted that the controller design procedure was posed in the following manner: a) select the cost–weight matrices R and Q and σ–parameter, b) compute K from the LQR–Output minimization problem, and c) compute the maximum delay D that can be tolerated with this given gain K.

In most cases, the number of hops that produces the communication delay of a typical NCS does not vary rapidly, and remains within certain bounds over large periods of time. In regard to the delay term, we can state that $r_s(k) \in \{D_1(L), \ldots, D_2(L)\}$ over a large time window, where $D_1(L)$ and $D_2(L)$ depend on the number of hops (L). In this case, the control design problem can be restated as: At sample period k, given L select the weight matrices $Q(k), R(k)$, and compute the largest prescribed stability factor $\sigma(k)$ in order to maintain stability despite the communication delays.

Rather than adjusting in an ad–hoc manner the weight matrices, we focus on the $\sigma(k)$–quantity. A closed–loop system derived via the usage of a small radius $\frac{1}{\sigma(k)}$ in the optimization step, has a fast system response, since all of its poles have small magnitude $|\text{eig}(A + BKC)| \leq \frac{1}{\sigma(k)}$. However, this system cannot tolerate large delay variations $D_2(L) - D_1(L)$ and the suggested gain–adjustment relies on this anticipated observation. The $\sigma(k)$–scheduling amounts to computing the largest value, while at the same time justifying the LMIs of (8),(9) for a given index set $I = \{D_1(L), \ldots, D_2(L)\}$. This design philosophy provides the fastest system while tolerating the given delay bounds. The computation of this optimum $\sigma(k)$ is based on the following algorithm:

1) Set $\sigma(L) = 1$.
2) Compute $K(L)$ from (2). Check whether the LMIs of (8),(9) are verified. If no, then there is no solution with the given Q and R and $\sigma(L)$.
3) If yes, then increase σ by $\sigma(L) = \sigma(L) + \Delta\sigma$. Repeat the previous step, unless satisfied with the obtained bound of prescribed stability.

The output of the computation is a pair $(\sigma(L), K(L))$ for each hop number L that ensure stability with margin $\sigma(L)$ for all communication delays in the bounds $[D_1(L), D_2(L)]$.

IV. Simulation Studies

The suggested scheme was applied in a simulated prototype SISO-system with the following transfer function $G(s) = \frac{0.1^3}{(s+0.1)^3}$. Assuming a sampling period of $T_s = 5$ second, the discrete equivalent of the continuous system is (accounting for the ZOH)

$$
\begin{aligned}
x(k+1) &= \begin{bmatrix} 1.82 & -1.104 & 0.2231 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} x(k) + \\
&+ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} u(k) \\
y(k) &= \begin{bmatrix} 0.001439 & 0.003973 & 0.006794 \end{bmatrix} x(k)
\end{aligned}
$$

Assume that a discrete controller $u(k) = K\ y(k - r_s(k))$ is inserted in the loop.

A. Theoretical Results

In Figure 5, we present the amplitude of the maximum eigenvalue of A_{r_s} as a function of the constant time delay $r_s T_s$ using $T_s = 5$ seconds, for three different gain values $K \in \{-1.1927, -1.4439, -1.7225\}$. These gain values were computed from the suggested algorithm minimization of (2), where in $Q = R = 1$ and $\sigma^{\max} = \frac{1}{0.85}$. As an example we should note for $K = -1.7225$ (-1.4439) the system is stable ($|\lambda_{\max}(A_{r_s})| \leq 1$) for $r_s T_s \leq 20(30)$ seconds.

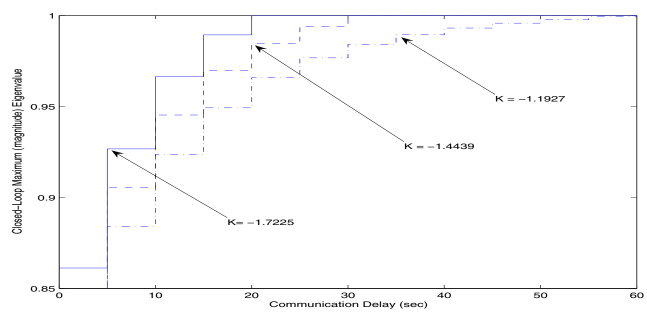

Fig. 5. Stability bounds for discrete controlled TDS (T_s=5sec)

Based on exhaustive simulation of data packets traffic in the utilized sensor network, the dependence among the number of the hops and the bounds in the communication latency times that are introduced is presented in Figure 6 for the MANET-parameters presented in Table I. Based on these worst case bounds on the communication latency times

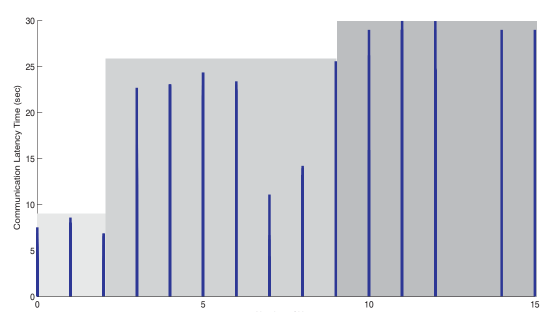

Fig. 6. Communication latency time dependence on the number of hops

with respect to the number of the hops, L, the switched controller's gains are determined as:

$$\begin{array}{lllll} I_1 & = & 0,1,2,3 & K^1 = -1.7225 & 0 \leq L \leq 2 \\ I_2 & = & 1,2,3,4,5 & K^2 = -1.4439 & 3 \leq L \leq 9 \\ I_3 & = & 4,5,6 & K^3 = -1.1927 & 10 \leq L \leq 15 \end{array}$$

It turns out that the LMIs (8) are satisfied with these gains.

Next, we try to maximize the range of delays $I^i = \left[D_i^{\min}, D_i^{\max}\right]$ for which solutions to the LMI problem (8) exist for each gain. In Figure 7 the shaded areas show the ranges I^i sets for which the LMI problem could be solved for each K^i. The corresponding sets were $I_D^1 = [0, 15]$, $I_D^2 = [5, 25]$, and $I_D^3 = [20, 30]$. It is apparent,

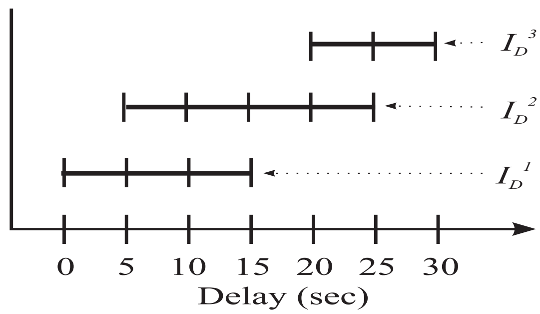

Fig. 7. Stability limits of a Discrete Controlled TDS, T_s=5 sec

that from the LMI problem there exists no controller that can tolerate delays up to 30 seconds. However, if the latency time varies slowly, then from the overlapping property of these sets, the whole region can be covered and stability can be guaranteed by minimum dwell time arguments. The details of this argument are a topic for future research. It should be noted, that from the experimental section the observed latency time exhibited a reasonably slow variation and the provided switching controller proved stable up to a 30–second delay.

B. Simulation Results

The suggested output feedback controller was applied over the WiFi (802.11b) network. The NS-2 was used for simulating the packet transmission process. Typical round-trip communication delays versus the transmitted packet index appear in Figure 8. From the recorded values, packet delays up to 30 seconds (equivalent to 6 delayed samples) are possible. The mean value of the packet round-trip delay was 2.5586 seconds.

Each packet is tagged with the number of hops that were used to complete its travel; the number of hops that corresponds to each packet–travel appear in Figure 9. From the recorded values when the number of hops L was less than 3 $(0 \leq L \leq 3)$ the maximum packet delay was less than 15 seconds $(DT_s \leq 15)$. Similarly $3 \leq L \leq 9$ corresponds to $5+ \leq DT_s \leq 25$ and $9 \leq L \leq 15 \rightarrow 20+ \leq DT_s \leq 30$.

The relationship between the communication latency time and the number of hops appear in Figure 10. Essentially, Figure 10 reflect the mapping between the packet hops and

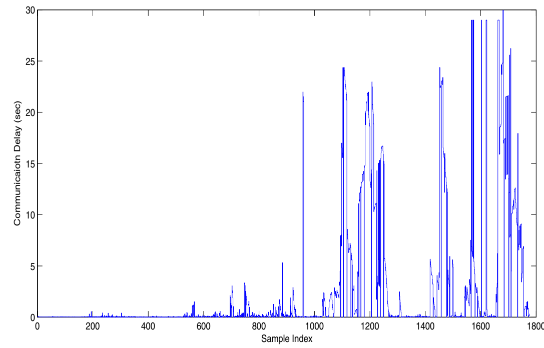

Fig. 8. Round–trip communication delay versus the sample index

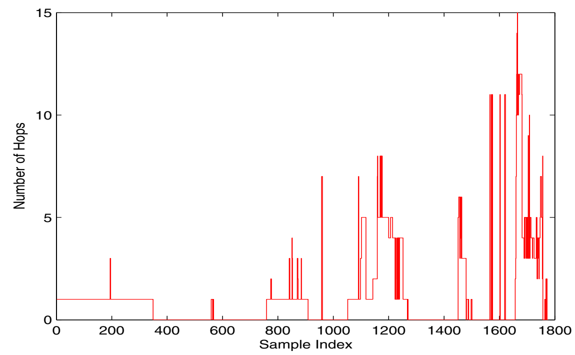

Fig. 9. Number of hops versus the sample index

delay time. It should be noted that the delay–classification into these three distinct packet–hop classes $L \in \{0, \ldots, 3\}$ or $\{3, \ldots, 9\}$ or $\{9, \ldots, 15\}$ is arbitrary and more efficient clustering techniques can be used. In regard to controller design, the parameters used in optimization cost were $Q = R = 1$ while the initial value of the prescribed stability radius σ was selected one $(\sigma = 1)$. For each one of the three classes $I_1 = \{0, \ldots, 3\}$, $I_2 = \{1, \ldots, 5\}$ and $I_3 = \{4, \ldots, 6\}$ the output feedback gain was computed according the aforementioned scheduling procedure. In this scheme, $\Delta\sigma = 0.01$ and this process was terminated when $\sigma \leq 0.95$.

V. Conclusions

In this article a multi–hopping induced gain scheduler for Wireless Networked Controlled Systems (WiNCS) was presented. The control scheme is based on a client–server architecture where the communication link relies on the 802.11b protocol, while the data packets are carried through a number of hops among the utilized communication nodes. The designed controller needs to accommodate the embedded transmission delays due to the varying number of hops that are introduced from the sensor network behavior. The resulting controller relies on a gain-scheduling framework; the controller structure stems from the LQR-output feedback case, where the prescribed stability factor is tuned according

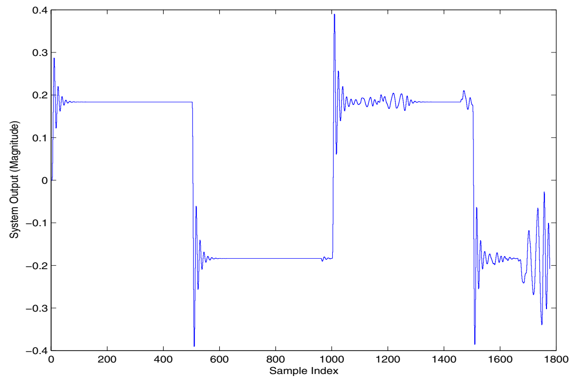

Fig. 10. Networked controlled system response

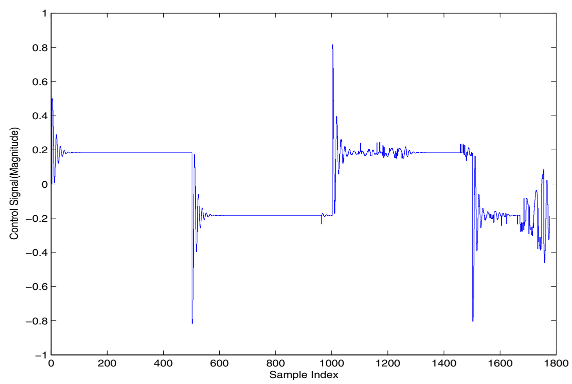

Fig. 11. Control effort

to the measured communication delay. The robustness of the suggested scheme is investigated through the use of LMI–theory. Simulation results are presented to investigate the efficiency of the proposed scheme.

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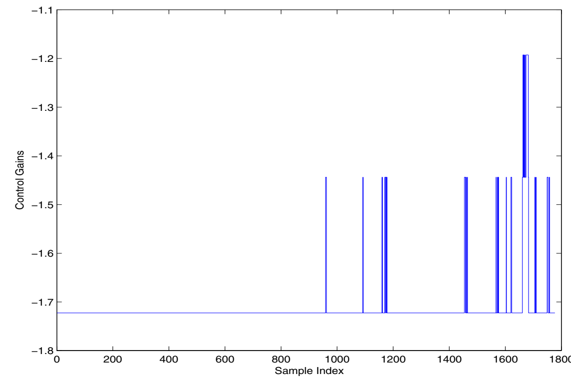

Fig. 12. Mobile NCS Control Signal

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