DEVELOPMENT AND EXPERIMENTAL VERIFICATION OF A MOBILE CLIENT-CENTRIC NETWORKED CONTROLLED SYSTEM

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Abstract

In this paper the development and experimental verification of mobile client-centric networked controlled system is presented. The feedback control loop is closed over a General Purpose Radio Service (GPRS) communication channel, between the plant and the controller. The inserted delays from the communication network, are time-varying, degrade the system dynamic performance, while forcing the system to instabilities. The designed controller has primitive characteristics and ensures the stability of the overall discrete time-delayed system. LMI-theory based theoretical results provide the worst-case scenario of the latency time that this controller can tolerate.

1 Introduction

Remote client-server control architectures are susceptible to various issues [1] stemming from the need to exchange information over a communication link [2], [3]. These problems expand for the case of public communication link, where the end user (client and server side) has no apparent influential and immediate control over the provided quality of service (QoS).

Amongst those communication networks comprising of "public" links: a) the internet, b) conventional industrial networks (Fieldbus, Lonworks, etc.), and c) the wired and wireless sections of a telephone service provider are considered to be typical members of the installed base.

The mobile (wireless) telephony (GSM, CDMA) sector embraces a set of characteristics that are detrimental to the stability of the closed loop remote controlled system. Its narrowband attribute (GSM 14.4Kbps, CDMA 19.2Kbps) along with the communication overhead for data retransmission due to packet losses, when coupled with the time-varying latency times severely affect the performance of the system. These eminent issues are caused due to the voice- rather than data-oriented transmission tuning attributes of the mobile telephony sector. 2G-mobile network infrastructure was designed to primarily carry voice, while its charging policy depends on the duration of each call. Bi-directional GSM-based data transfer is still considered a relative expensive scheme, since charging is time-dependent rather than volume-dependent. HSCSD-enabled GSM-phones can multiplex up to three available channels reaching to a maximum transmission speed of 43.2Kbps; however the time-charging nature prohibits its widespread usage.

In order to overcome the time-dependent pricing structure, 2.5G-mobile phones relying on the GPRS-protocol [4] transmit data at bursty-modes employing a data volume-dependent charging strategy. Although the maximum achievable bandwidth over GPRS is 115.2Kbps (upload & download) (Class-29), most mobile operators offer up to a 43.2-upload (14.4-download) Kbps (Class-4) available bandwidth to their customers. It should be noted that this bandwidth is not guaranteed but can be offered as long as there are available time-slots at a mobile-cell; this occurs when there is no congestion from voice-calls. Since a higher priority is placed in the GSM-based voice-call, the available bandwidth for GPRS-based data transmission can fluctuate significantly over periods of time (0-to-43.2Kbps in increments of 14.4Kbps). Subsequently, this affects the stability and performance of the remote-controlled system. Situations, where the GPRS-service is interrupted for a limited period of time (a maximum interval of 45 seconds was observed over a period of six months in our experimental evaluation) can be proved quite harmful to the control scheme, and proper actions need to be undertaken.

Driven mostly from security reasons, mobile-phone service providers (m-psp) do not offer an extended set of privileges to their customers for data transmission purposes. Classical protocols (i.e. ftp and http) and corresponding actions can be issued from a client with a GPRS-enabled phone to access a remote (server) site with a valid IP-address. However, a server-based initiation of a transmission back to the client (GPRS-phone) is blocked from the firewall of the m-psp. This is necessary to ensure termination of data calls back to the customers of m-psp from untrustworthy sites. Subsequently, there is a need for a "client–centric" remote-control framework, where all actions in the feedback loop (transmitting the command signal $u(k)$ and receiving the system's response $y(k)$) are initiated from the client. Henceforth, the scheme must be "centered" on the client's actions and the supporting software for remote communication should be modified accordingly.

In a mobile Networked Control System (moNCS) [5], shown in Figure 1, the client computes the control command $u(k)$ and transmits it wirelessly to a server-site. The server receives the data after a certain delay, transfers them to the plant, samples

the plant's output $y(k)$ and transmits it back to the client for future processing. The client receives the delayed–output and repeats the aforementioned process. Due to the inherent delays in the formulation and transmission of signals between the client and server sides [6, 7], there is a need to investigate the stability of this Time-Delayed System (TDS). For this reason, recent theoretical results stemming from LMI theory [8] will be used, in this article.
This paper is organized as follows. In Section 2, a detailed description of the client-centric moNCS architecture is presented. Recent theoretical results, based on LMI-theory customized for this architecture and the utilized controller are offered in Section 3. The proposed scheme is applied in theoretical and experimental studies at a prototype system, with the results shown in Section 4. Conclusive remarks are offered in the last Section.

2 Client–centric Mobile NCS architecture

Within the considered moNCS architecture presented in Figure 1, the control law is computed remotely at a client computer with the control/response signals transmitted towards/from a server-computer located near the plant. The assumed plants continuous transfer function is $G(s)$, while the latency intervals from the client site to the server and reverse are Δ_L^1 and Δ_L^2, respectively. Assuming a sampling period T_s and an embedded ZOH-device in transferring the discrete signals to the plant, let the discrete controlled systems transfer function be $G(z^{-1}) = \left(1 - z^{-1}\right) \mathcal{Z}\left\{\frac{G(s)}{s}\right\}$ and $d_i = \lceil\left(\frac{\Delta_L^i}{T_s}, 1\right)\rceil$, $i = 1, 2$. Essentially, d_i correspond to the "inserted" delays from the GPRS–network infrastructure during the data–packet exchange.

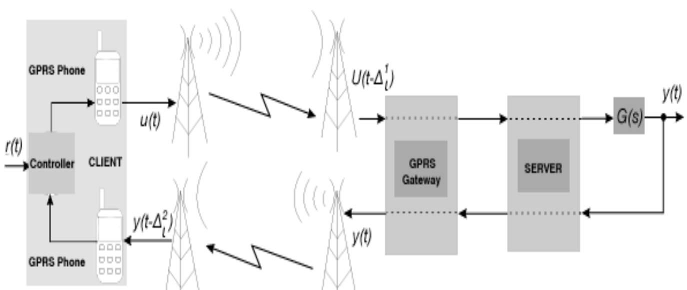

Figure 1: Mobile Networked Control System Architecture

Within this architecture, the wireless segment poses the most complicated problems to the overall development, since appropriate software drivers must be designed to account for the signaling between the mobile-device and the GPRS-network.

2.1 Mobile–Networked Communication Issues

The client-centric nature of the remote control scheme dictates that the client initiates all data transmissions. Accordingly, the client transmits the control command using the UDP-protocol and records the system's output by issuing an "FTP–get" command. For accommodating the client's requests the server must run locally an FTP-server and have its corresponding UDP-port opened.

In Figures 2 and 3 we present the procedures rulin g the data packet exchange between the client and the server. The UDP-latency and FTP-latency times are noted as L^{UDP} and L^{FTP}, respectively.

The highlighted issues in Figures 2 and 3 display a set of six cases covering possible problems that can be encountered in the data exchange procedure.

In Figure 2 the top portion (first case) exhibits ideal characteristics: a) the client uses the UDP protocol and transmits the control signal, b) the server receives this packet and converts the digital format of the signal to an analog (voltage)and applies it to the plant, c) after a certain time, the client initiates the FTP–get command and requests to receive through the server, the digitized value of the system's output, d) the server samples the output and sends it back to the client through the opened FTP-connection. In the ideal case, this four-step sequence is completed within on sampling period T_s. The second case (middle portion) describes the situation where an instantaneous loss of a UDP-based packet transmission fails. In this case the server applies to the experiment the last correctly transmitted signal $u(k)$ from the client. In the third case we describe the packet reordering situation, where the UDP-based transmission is delayed and the FTP-based reception has already been initiated by the client.

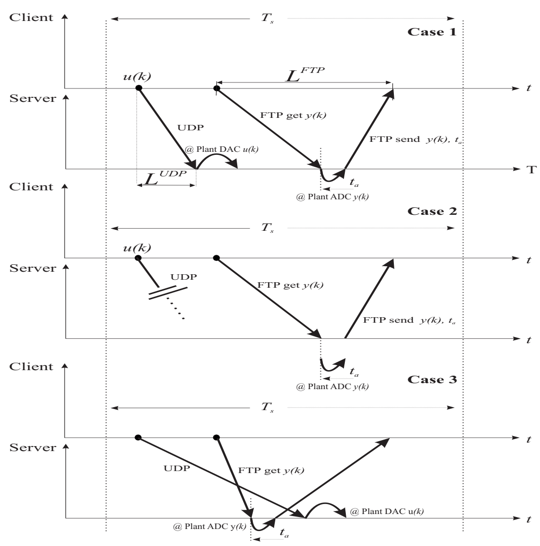

Figure 2: UDP and FTP Data Packet Exchange Flowchart

The fourth case (top portion of Figure 3) corresponds to a situation of an instantaneous lost of FTP-based data acquisition. The UDP transmission is performed correctly, but the client's request for the FTP-get command fails. In this case the client computes the next control signal $u(k + 1)$ based on the previously recorded (and outdated) $y(k - 1)$ output. The fifth case (middle portion) stands for an instantaneous loss of the communication link. During this phase the UDP and FTP data packet are lost. The client computes the next control signal $u(k + 1)$ based on the last correctly received, from the FTP protocol, system output. In the sixth case (bottom portion) we have high latency times due to traffic congestion and the sequence cannot be completed within one sampling period.

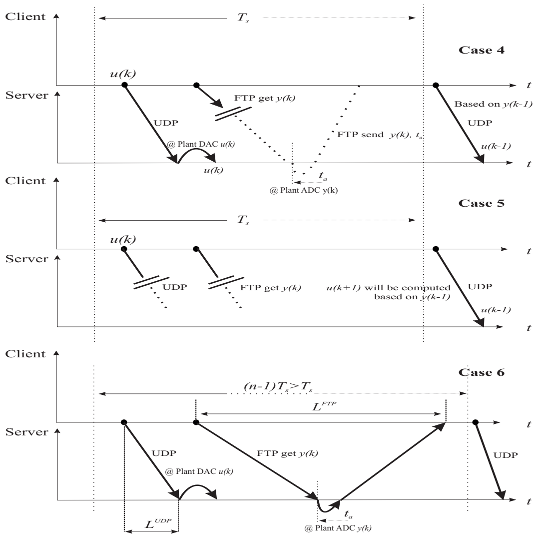

Figure 3: UDP and FTP Data Packet Exchange Flowchart

3 LMI–based stability analysis of moNCS

Assume the plants transfer function representation in the state space be:

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

In a zero–latency environment ($d_1 = d_2 = 0$:immediate transmission conditions), the utilized controller, corresponds to that of a static output feedback [9], or $\tilde{u}(k) = Ke(k) = K\left(r(k) - y(k)\right)$. However, due to the client-to-server transmission delay the applied control signal is $u(k) = \tilde{u}(k - d_1)$. Similarly, due the reverse transmission $e(k) = r(k) - y(k - d_2)$, as shown in Figure 4.

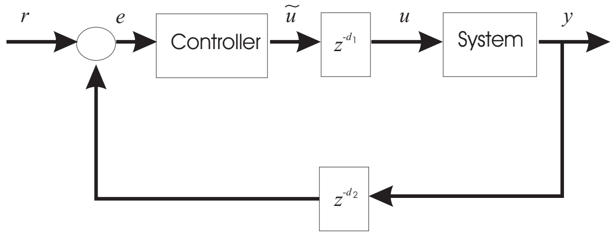

Figure 4: Model representation of a TimeDelayed moNCS

Let $r(k) = 0$ and $r_s(k) = d_1 + d_2$ be the overall delay at time k. If the overall delay is time varying, the resulting control law is given by:

$$
u(k) = K_{r_s}(k)Cx(k - r_s(k)) \,,
$$

where $r_s(k)$ is a random bounded sequence of integers $r_s(k) \in [0, 1, \ldots, D]$, and D is the upper bound of the delay term. The closed–loop system is formed by augmenting the state vector to $\tilde{x}(k)$, in order 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

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

$$
\tilde{A} = \begin{bmatrix} A & 0 & \ldots & & 0 \\ I & 0 & \ldots & 0 & 0 \\ 0 & I & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \ldots & I & 0 \end{bmatrix}, \qquad \hat{B} = \begin{bmatrix} B \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix},
$$

$$
\tilde{C}_{r_s}(k) = \begin{bmatrix} 0 & \ldots & 0 & I & 0 & \ldots & 0 \end{bmatrix}, \qquad (2)
$$

where the vector $\tilde{C}_{r_s}(k)$ has all of its elements zeroed, except from the $r_s(k)$-th one whose value corresponds to the unitary matrix.

The closed–loop system is switched [10], since $r_s(k)$ (and thus the feedback term $K_{r_s}(k)C$) is of time-varying nature. The overall closed loop system is

$$
\begin{aligned}
\tilde{x}(k+1) &= \tilde{A} + \tilde{B}K_{r_s(k)}\tilde{C}_{r_s(k)}\tilde{x}(k) + \tilde{B}r(k) \,, \qquad (3) \\
y(k) &= \tilde{C}_{r_s}(k)\tilde{x}(k) \qquad (4)
\end{aligned}
$$

The closed loop matrix $\tilde{A} + \tilde{B}\ K_{r_s}(k)\ \tilde{C}_{r_s}(k)$ can switch in any of the $D+1$–vertices $A_i = \tilde{A} + \tilde{B}\ K_i\ \tilde{C}_i$, and therefore 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 latency time $r_s(k) = d_1(k) + d_2(k)$ can be measured, and therefore the index of the switched–state is known, the system can be described as:

$$
x(k+1) = \sum_{i=0}^{D} \xi_i(k)A_i x(k) \,, \qquad (5)
$$

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

The stability of the switched system [11], in (5) is ensured if $D+1$ positive definite matrices $P_i,\ i = 0, \ldots, D$ can be found that satisfy the following LMI:

$$
\begin{aligned}
\begin{bmatrix} P_i & A_i^T P_j \\ P_j A_i & P_j \end{bmatrix} &> 0, \forall (i,j) \in I \times I, \qquad (6) \\
P_i &> 0, \forall i \in I = \{0, 1, \ldots, D\} \,. \qquad (7)
\end{aligned}
$$

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 $\Delta V(k, x(k)) = V(k+1, x(k+1)) - V(k, x(k)))$ is a positive function for all the $x(k)$–solutions of the switched system, thus ensuring the asymptotic stability of the system.

In this research effort, the controller design focuses on computing the largest sets $I = \{I_{\min}, I_{\min}+1, \dots, I_{\max}\}$, where $0 \le I_{\min} < I_{\max} \le D$ for which the preset controller gain can stabilize the system against any switching within members of this set.
An upper limit of the maximum (theoretical) limit of D can be obtained from the continuous-time solutions of our inherent TDS. Assume that the transfer function $G(s)$ description of the system can be cast in the state–space format

$$\dot{x}_c(t) = A_c x(t) + B_c u(t),\ \ y(t) = C_c x(t)\ .$$

Given the controllers action $u(t) = Ky(t - \Delta_L^1 - \Delta_L^2)$ the closed-loop system takes the form

$$\dot{x}_c(t) = A_c x(t) + B_c K C_c x(t-\tau) = A_c x(t) + A_d x(t-\tau)\ ,$$

where $\tau = \Delta_L^1 + \Delta_L^2$. The maximum permissible delay $\tau^{\max}$ can be computed from the solution of the following optimization problem (with a set of LMIs):

$$\tau^{\max} = \max \tau, \qquad \text{subject to} \qquad (8)$$

$$\begin{bmatrix} (A_c+A_d)Q_1 + Q_1(A_c+A_d)^T & \tau A_c Q_1^T & \tau A_d Q_1^T \\ +\tau A_d(Q_2+Q_3)A_d^T & & \\ \tau A_c Q_1 & -\tau Q_2 & 0 \\ \tau A_d Q_1 & 0 & -\tau Q_3 \end{bmatrix} < 0$$

$$Q_i > 0,\ i = 1,2,3\ .$$

Given $\tau^{\max}$ the maximum delay D can be computed as $D = \lceil \frac{\tau^{\max}}{T_s}, 1 \rceil$.

4 Simulation and Experimental studies

The suggested scheme is applied in a prototype SISO-system with a transfer function $G(s) = \frac{0.1^3}{(s+0.1)^3}$. Application of a controller $u(t) = Ky(t-\tau)$, yields the following TDS

$$\dot{x}(t) = \begin{bmatrix} -0.3 & -0.03 & -0.001 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} x(t) + \begin{bmatrix} 0 & 0 & 0.001 \times K \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} x(t-\tau)$$

In Figure 5 we present the maximum allowable time delay $\tau^{\max}$ that reserves stability as a function of the controller-gain K for the continuous time case. For example, for the case where $K = 1$ the maximum tolerable constant delay is $\tau^{\max} = 23$ seconds. It should be noted that this value stems from the solution of the optimization problem (8), and by no means is the largest one that can be computed using other relevant theorems (see [12]).

Assuming a sampling period of $T_s = 1$ second, the discrete equivalent of the continuous system is (accounting for the ZOH)

$$\dot{x}(t) = \begin{bmatrix} 3.316 & -3.6640 & 1.35 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} x(t) + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} u(t)$$

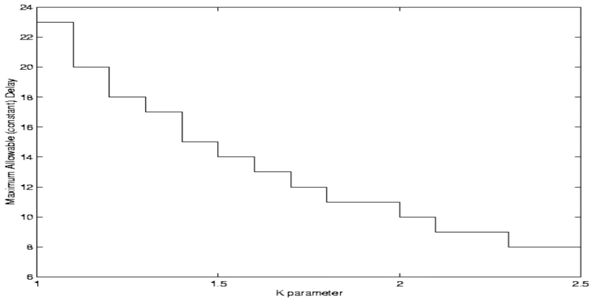

Figure 5: Stability bounds for continuous TDS

$$y(t) = \begin{bmatrix} 0.1797 & 0.7748 & 0.2088 \end{bmatrix} \cdot 10^{-3} x(t)$$

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

In Figure 6, we present the amplitude of the maximum eigenvalue of A_{r_s} as a function of the time delay $r_s T_s$ for three different gain values $K = 1,\ 1.5$ and 2.

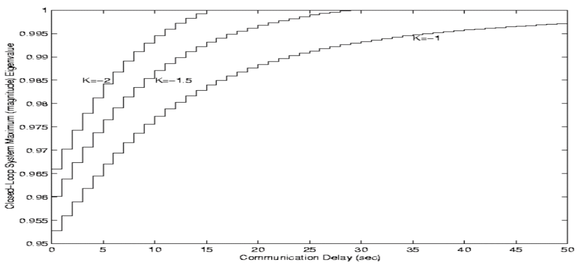

Figure 6: Stability bounds for discrete TDS (T_s=1sec)

We should note that, for example, for $K = 2\ (1.5)$ the system becomes unstable ($|\lambda_{\max} A_{r_s}| \ge 1$) for $r_s T_s \ge 15\ (28)$ seconds, while for $K = 1$ the system remains stable for delays smaller than 50 seconds. A direct comparison with the results from the previous Figure 5 indicates that the results obtained from the discrete domain are not as conservative as the ones from the continuous domain.
A different discretization using $T_s = 5$ seconds and a similar graph appears in Figure 7, where as expected the results are similar to the aforementioned ones with the only difference set in the size (quantization step) of the sample period T_s. Similarly, the system becomes unstable for $r_s T_s \ge 15$ and 30 seconds for $K = 1$ and $K = 5$ respectively.

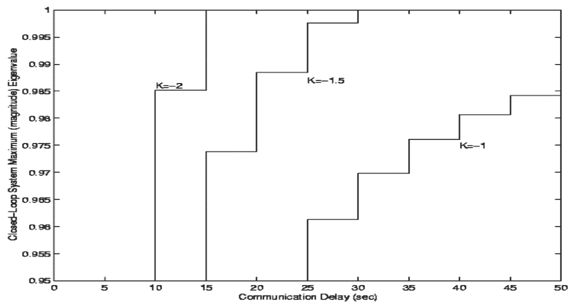

Figure 7: Stability bounds for discrete TDS (T_s=5sec)

For the case of time varying delays (quantized with a T_s step) within subspaces $I_D^i = [D_{\min}^i T_s, D_{\max}^i T_s]$, the problem of computing positive definite matrices in the LMI–related problem in (6) for different I^is is sought, where $I^i = \left[D^i_{\min}, D^i_{\max}\right]$. If the maximum anticipated delay is DT_s (in our case 50 seconds), then in the ideal case if the problem (6) is solved for $I^i = [0, D]$, then the controller can tolerate any delay up to DT_s. In Figure 8 we provide with shaded areas the limits of different I^i sets for which the LMI–related problem could be solved. In the left (right) portion, the sampling period was set at $T_s = 10\ (5)$ seconds. For the largest period, the maximum attainable "timesets were $I^1_D = [0, 40]$ and $I^2_D = [10, 50]$, whilst for $T_s = 5$ seconds, the corresponding sets were $I^1_D = [0, 30]$, $I^2_D = [20, 40]$, $I^3_D = [25, 45]$, and $I^4_D = [40, 50]$.

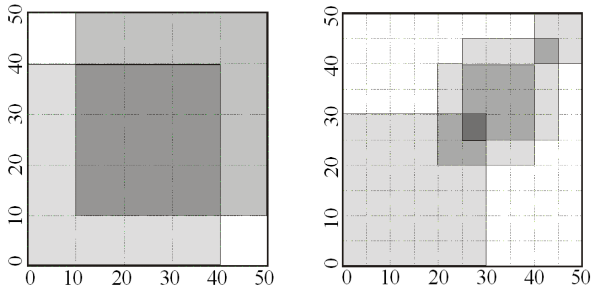

Figure 8: Stability limits of the discrete TDS

It is apparent, that from the LMI–posed problem there exists no controller that can tolerate delays up to 50 seconds. Instead, for $T_s = 10\ (5)$ the maximum tolerable latency time is 40 (30) seconds. However, if the latency time varies slowly, then from the overlapping property of these sets, the whole region can be covered. The definition of this "slow–variation" is a topic for future research within this overlapping decomposition context. It should be noted, that from the experimental section the observed latency time exhibited a reasonably slow variation and the provided controller proved stable up to a 50-second delay.

The suggested controller was applied in experimental studies over a private networks mobile service provider. A GPRS-enabled phone (Motorola TimePort T189) was used for the data transmission, while the necessary interface and drivers were written using as a kernel the NI's Labview environment. The software run at the client and server sides on a Pentium-4 system, equipped with proper software to measure the latency time and the transmission speed (NetPerSec by Ziff Davis) in bps achieved during the experimentation.

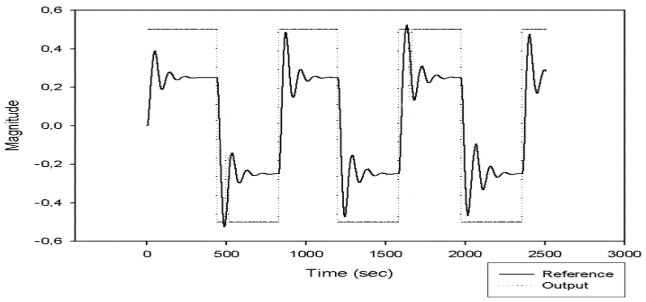

Figure 9: Mobile (GPRS-based) NCS Response

In Figure 9 we present the response of the system when excited with a pulsing reference signal. The control signal is presented in Figure 10 where the effects of the time delays are eminent. For the packet–loss cases, or when there is a temporary malfunction in the communication link and the server does not accept data through the UDP port, the last recorded control command is transmitted to the plant.

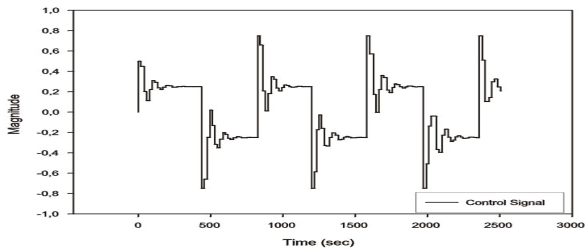

Figure 10: Mobile (GPRS-based) NCS Control Signal

The latency times due to the transmission: a) through the UDP-port from the client to the server, and b) through the FTP-agent from the server to the client are shown in Figures 11 and 12, respectively. From the recorded data the transmission delays have a mean value of 18 seconds with a worst case at 35 seconds.

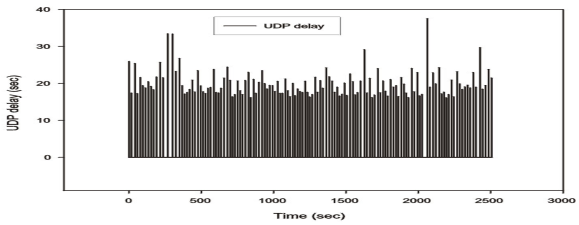

Figure 11: Transmission delay of the mobile UDP–connection

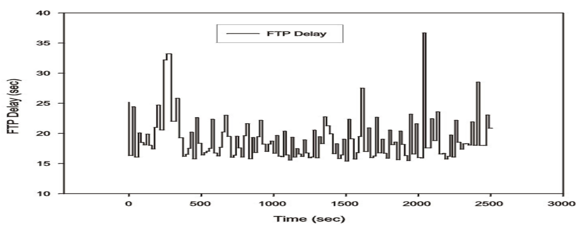

Figure 12: Transmission delay of the mobile FTP–connection

At the client-side based on the attainable bit rate for transmission and reception purposes, the typical raw-data speed had an average of 21 Kbps, while a peak value of 40 Kbps was observed. The actual data-rate (omitting the overhead) exhibited an average of 1.4 KBps for the transmission and 0.9 KBps for the reception activity.

Similar plots appear in Figures 13 and 14 for examining the characteristics of the attainable bit rate for transmission and reception purposes at the server-side. The actual data-rate (omitting the overhead) exhibited an average of 0.3 KBps for the transmission and 0.35 KBps for the reception activity.

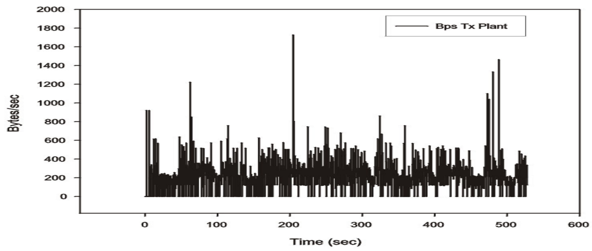

Figure 13: Data Transmission Rate at Server-Side

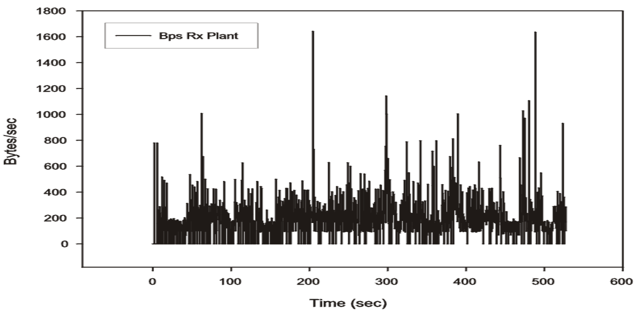

Figure 14: Data Reception Rate at Server-Side

5 Conclusions

In this paper the development and experimental verification of a mobile client-centric networked controlled system was presented. The remote aspects of the communication protocol are carried over a GPRS–network. The designed controller needs to accommodate the embedded transmission delays due to the packet exchange between the two sides (client-server). Theoretical results based on LMI–theory are offered to investigate the stability of the closed–loop system.

6 Acknowledgments

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