Proceedings of the 12th Chinese Automation
& Computing Society Conference in the UK,
Loughborough, England, 16 September 2006

Design Issues and Simulation models of Wireless Networked Control Systems

M S Hasan (PhD Researcher), Hongnian Yu, Alison Griffiths and T C Yang
Faculty of Computing, Engineering and Technology, Staffordshire University
Stafford, UK
{m.s.hasan, h.yu, a.l.griffiths}@staffs.ac.uk, t.c.yang@sussex.ac.uk

***Abstract*—This paper investigates the design issues for the wireless networked control systems. The impacts of the packet delay, packet drop/loss, delay jitter and sampling jitter on the performance of a wireless networked control system are discussed. An inverted pendulum model is used to conduct the simulation study. The extensive simulation results reveal that packet delay and loss have more significant impact than sampling jitter and delay jitter.**

Keywords- Packet drop/loss, delay jitter, sampling jitter, wireless networked control systems, settling time, maximum percent overshoot, steady state error percentage.

I. INTRODUCTION

Networked Control Systems (NCS) [1], [2], [3], [4] implement a closed loop control mechanism over a communication network to exchange information between controller and plant sites. NCS offers many advantages over traditional control systems, for instance, reduced system wiring, ease of system diagnosis and maintenance, increased system robustness, low cost and power requirement, rapid and easy installation and diagnostics [1] etc. The development of high performance portable computers and recent advancement of wireless networks have created a new era of research: Wireless Networked Control Systems (WNCS). WNCS can be very useful in applications where the controller and/or the plant have to be mobile and no infrastructure is possible, for instance, military use, rescue operation, assembling space structures, exploring hazardous environment, executing tele-surgery [5], monitoring, online aircraft monitoring [6] etc. An industrial application of WNCS is shown in Figure 1 where a number of robots are being controlled over wireless network from a controller. However, designing a successful WNCS brings new challenges to the researchers because of wireless network's unpredictable aspects such as topology change, node mobility, delay, jitter etc. Many of these are responsible for performance degradation and even system instability [7], [8].

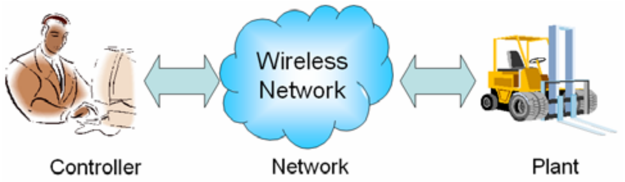


Figure 1. Industrial application of Wireless Networked Control Systems (WNCS)

Much of the research works for wireless networks is based on simulations as it is difficult and costly to launch real world experiments with mobile nodes [9]. Matlab and Simulink are widely used in the research community for control engineering simulation. This paper attempts to investigate various aspects of WNCS, e.g., random packet delay, sampling jitter etc. so that these can be integrated in the Matlab/Simulink model to evaluate the overall system performance. It can be noted that the models can be applied to any NCS in general.

The rest of the paper is organised as follows. Section II discusses the WNCS design issues that are investigated in this paper, section III explains the models of the design issues, section IV includes the results when the models are applied to a WNCS with an inverted pendulum as a plant and a PD plus gravitational type controller. Finally, section V draws some conclusions and points to some future works.

II. DESIGN ISSUES

Overview of network, control and various design issues of networked control systems can be found in [2], [10]. NCS or WNCS needs careful co-design of the three C fields: Control, Computing and Communication as shown in Figure 2. This paper categorises the design issues in these three main areas. Other issues are beyond the scope of the paper.

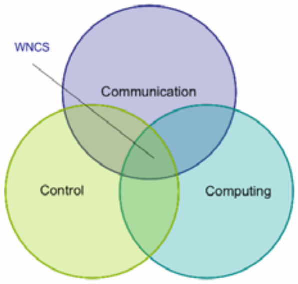


Figure 2. Knowledge requirements for Wireless Networked Control Systems

A. Communication network: Delay

Network delay can degrade the NCS performance significantly and even destabilise the entire system [11], [12], [5], [6]. The total closed loop delay τ can be formulated as $\tau = \tau_{sc} + \tau_c + \tau_{ca}$ where τ_{sc} is sensor-to-

---

This research project is funded by the Faculty of Computing, Engineering and Technology, Staffordshire University, UK

controller, τ_c is controller computation and τ_{ca} is controller-to-actuator delay, respectively. However, for simplicity, the computation delay τ_c is ignored or treated as a part of the controller-to-actuator delay since it is negligible compared to the τ_{sc} and τ_{ca} delays [4], [13], [14]. Therefore the total delay can be obtained as $\tau \approx \tau_{sc} + \tau_{ca}$ [15] as shown in Figure 3.

B. *Communication network: Packet Drop*

Wireless networks can suffer from packet drop/loss that can cause instability of the NCS. Node or link failure, interference, collisions, poor transmission etc. can cause a packet drop. Re-transmission might be considered as a compensating mechanism. However, if it is an obsolete packet it will simply produce more traffic in the network. As NCS carries real-time traffic; it might be beneficial to drop a packet that can not be transmitted immediately; the tolerable packet drop rate must be analysed to maintain guaranteed desired system stability [15]. Modern NCS can tolerate packet drop up to some extent and can still maintain stability [16], [15]. Modelling of NCS with packet drop can be found in [5], [12], [17] etc.

C. *Communication network: Delay Jitter*

Jitter is defined as deviation of an instant in the signal from its actual position in time [2]. This problem can be caused by some or all of the following: clock drift of a transmitter-receiver, congestion, routing algorithm in communication systems, scheduling of real-time tasks in computer systems [2], [18], number of hops on the path etc. Figure 4(a) depicts the cause of delay jitter where packets are arriving at the destination with different time delays [19].

In order to achieve satisfactory system performance with limited computer resources, this must be taken into account at design time since it can lead to significant performance degradation [20]. The motive of delay jitter control is to ensure that the packet delays are kept between predefined maximum and minimum delays and to minimise the difference between packet delays [2], [21]. This problem can be removed by using buffers at the receiver as shown in Figure 4(b) [22]. However, this approach introduces large buffers at receiver and higher overall packet delays. Besides buffers, delay jitter problem can also be minimised or avoided by synchronising the NCS plant and controller nodes periodically. Synchronisation can be achieved by software, hardware or combination of these two [15].

D. *Computing: Sampling Jitter*

The inconsistency of sampling period is called rate/sampling jitter [3]. It can also be defined as the difference between the maximum and minimum sampling latencies in all executing tasks [23]. This can be caused when controller tasks are scheduled based on priority or tasks have non-pre-emptive characteristics as shown in Figure 5 [7] where task T_2 experiences 8 time units before the fourth sampling. Sampling jitter compensation approaches for control applications can be found in [24].

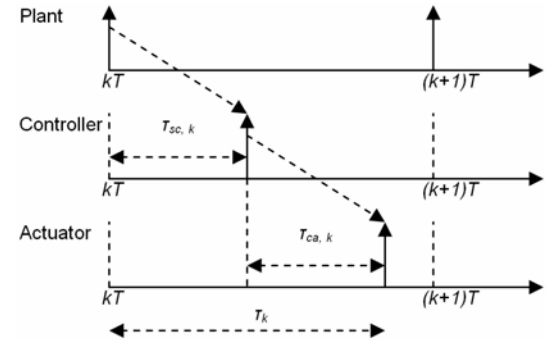
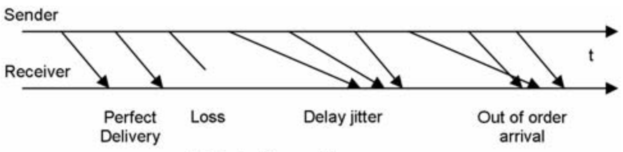
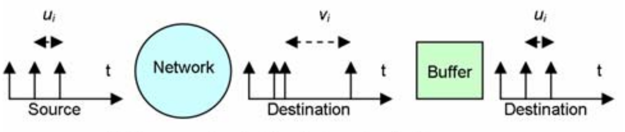


Figure 3. Timing diagram of NCS delays [15]



(a) Delay jitter problem



(b) Compensation/buffer solution of Delay jitter

Figure 4. The Delay Jitter problem and compensation/solution technique using buffers at the receiver [19],[22]

III. DESIGN ISSUE MODELS

Simple models of the fundamental network on design issues of NCS such as network delay packet, drops etc. can be found in [4], [15], [17]. A combined model that incorporates packet delay, packet drop, sampling jitter and delay jitter is shown in Figure 6. This section presents the Matlab/Simulink models for the design issues that have been discussed in section II.

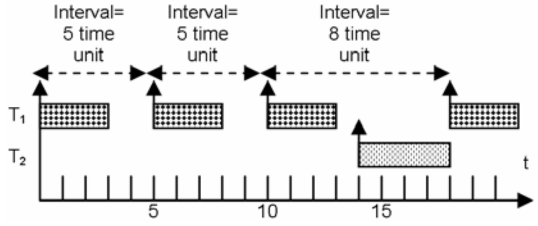


Figure 5. Cause of Sampling Jitter [7]

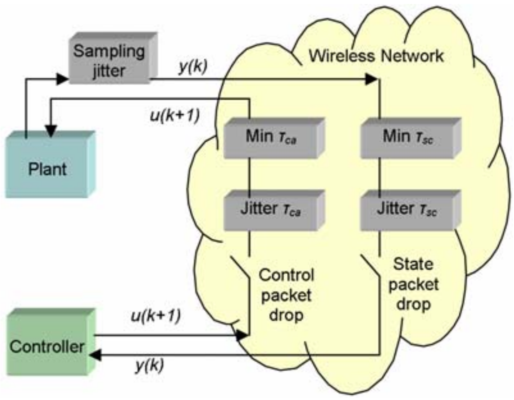


Figure 6. Modelling packet delay, packet drop, sampling jitter and delay jitter

A. *Communication network: Delay and Delay Jitter*

The network delay and delay jitter can be modelled using four Simulink blocks as shown in Figure 7. In this example, the delay jitter ranges between 20 and 50ms. The “Integer Delay” block produces a constant 20ms delay. The “Uniform Random Number” generates value in the range of 0–30 that is used as input to the “Variable Integer Delay” at different sampling instants to produce the variable delay jitter.

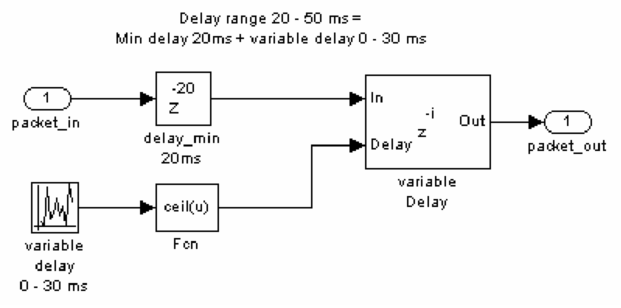


Figure 7. Model for Delay and Delay Jitter

B. *Communication network: Packet Drop*

The packet drop model is depicted in Figure 8. The “Uniform Random Number” generates a number in the range of $-x$ to $(100-x)$ inclusive where x is the percentage of packet drop. This number is used as the switching input of the switch. The switch passes the packet if the number is greater than or equal to zero; otherwise the packet is dropped.

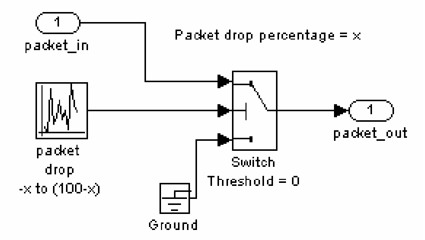


Figure 8. Model for the Packet Drop

C. *Computing: Sampling Jitter*

As the sampling jitter is the variation of delays between consecutive sample instants, it can be modelled using “Uniform Random Number” and “Variable Integer Delay” blocks shown in Figure 9.

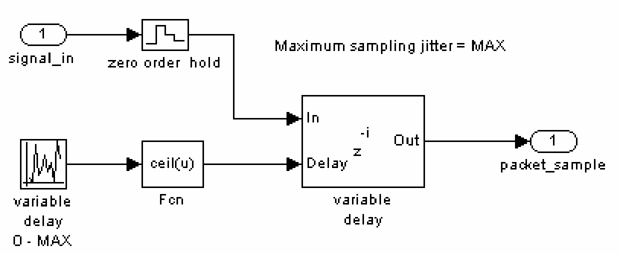


Figure 9. Model for Sampling Jitter.

IV. SYSTEM MODEL AND RESULTS

The design issue models are applied to the control system of an inverted pendulum. The entire system is shown in Figure 10. The second order differential equation of the pendulum is given in (1) where the mass of the pendulum, $M = 2Kg$, length of the pendulum, $L = 0.5m$, friction coefficient, $F = 0.5Nms/rad$ and gravitational acceleration, $g = 10m/s^2$. The q and u are the angle and input torque, respectively.

$$\frac{d^2q}{dt^2} = \frac{1}{ML^2}(u - F\frac{dq}{dt} + MgL\sin q) \ ...(1)$$

The experimenting PD plus gravitational controller is given in (2) where the proportional constant, $K_p = 12$ and the derivative constant, $K_d = 1.5$. The r and $\dot{q}$ are the reference and first derivative of the pendulum angle, respectively.

$$u = K_P(r - q) - K_d\dot{q} - MgL\sin q \ ...(2)$$

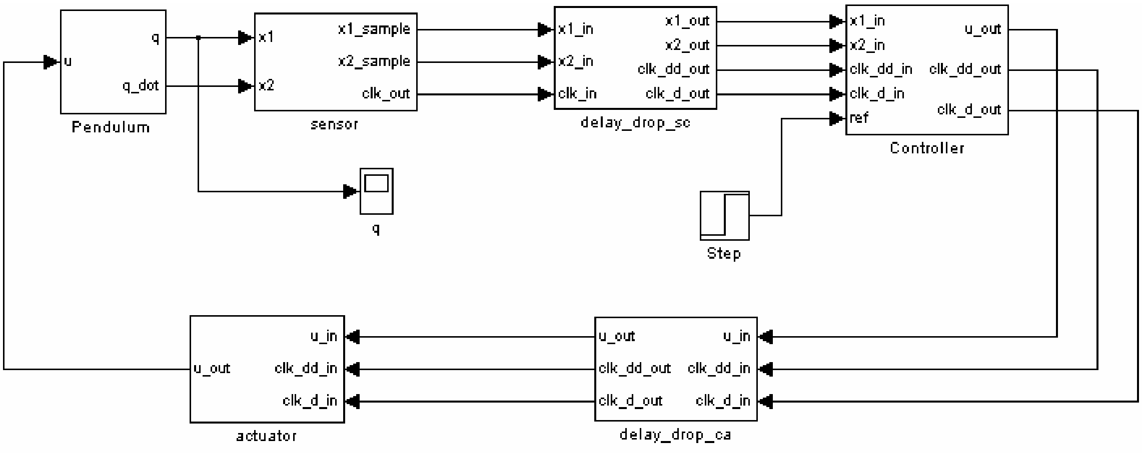


Figure 10. Application of the models to the inverted pendulum Simulink simulation

The WNCS model is based on clock/time driven sampling with sampling period $0.1s$. Control computation and actuation are driven by events. In other words, the sampling task is initiated at predefined time instants; control/actuation tasks are invoked when an event occurs, for instance, when it receives an information packet from another node through the network [3], [23], [12]. Clock driven sensing and event driven control-actuation are found in many applications. This approach has several advantages, for instance, it does not require plant-controller synchronisation and also supports multi-rate sampling [13]. In this model, the sensor subsystem produces a clock signal that is used to detect the arrival of a state packet and a control packet at the controller and plant site, respectively. When a clock signal transition is missing, it is assumed that the packet is lost as shown in Figure 11 and no action is taken. The initial condition of the pendulum is set to a zero angle and a $\frac{\pi}{2}$ rad angle is given as step reference at time zero. The following sections explain the performance of the system in terms of settling time, maximum percent overshoot and steady state error. Settling time T_s is assumed as 5% of the steady state value. The results from packet delay-drop and sampling delay jitter are compared with the ideal case scenario that is given in the following section.

A. *Ideal case: zero sampling jitter, zero delay, zero delay jitter, zero packet loss*

The ideal case response of the inverted pendulum is shown in Figure 12. The settling time, maximum percent overshoot and steady-state error are listed in TABLE I.

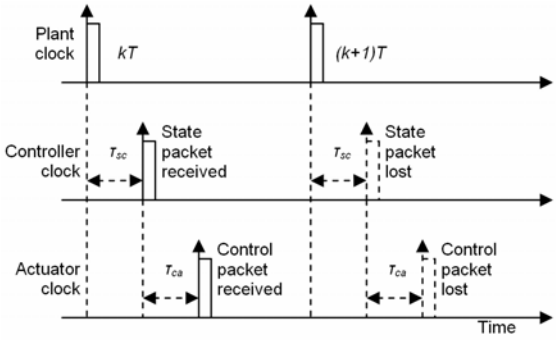


Figure 11. Timing diagram of control/actuation invocation for packet loss

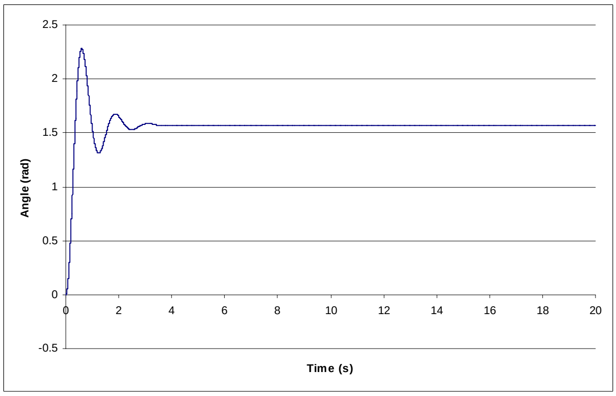


Figure 12. Ideal case response

TABLE I. SYSTEM PERFORMANCE FOR IDEAL CASE RESPONSE.

Performance parameter	**Value**
Settling time	2.013s
Maximum percent overshoot	45.17%
Steady state error	$1.31\times10^{-8}\%$

B. *Effect of packet delay and drop*

This section discusses the results of packet delay and drop with zero delay jitter and zero sampling jitter.

1) *Settling time*

The system model can tolerate a packet drop rate up to 10% for various packet delays as shown in Figure 13. For packet loss rate 15% and 20% the system can stand delays up to 40ms and 20ms, respectively. It can be noticed that the settling time exhibits an exponential increasing trend with the packet delay. However, the graph for 20% packet loss shows some anomalies as it goes down with higher packet delay before the pendulum gets instable.

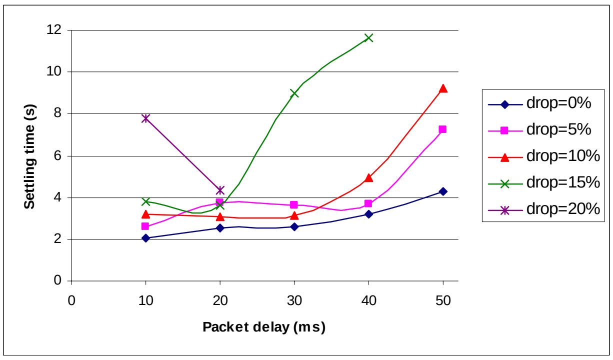


Figure 13. Packet delay vs. settling time for different packet drop rate.

2) *Maximum percent overshoot*

The packet delay and maximum percent overshoot is plotted in Figure 14. From this figure it can be established that the maximum percent overshoot tends to increase exponentially with the packet delay.

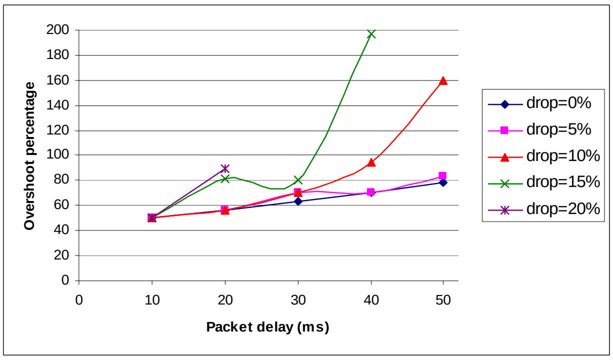


Figure 14. Packet delay vs. maximum percent overshoot for different packet drop rate.

3) *Steady state error percentage*

The steady state error percentage is depicted in Figure 15. The change of steady state error percentage is very insignificant with delays. However, a packet loss rate of 10% significantly shows a jump to nearly 0.95% at delay 50ms.

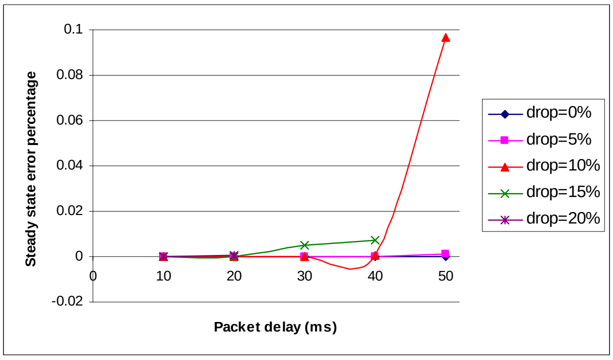


Figure 15. Packet delay vs. steady state error percentage for different packet drop rate.

C. *Effect of delay jitter and sampling jitter*

This section presents the result for delay jitter and sampling jitter. The packet delay and packet drop rate were set to 0ms and 0%, respectively to observe the effect of delay and sampling jitter.

1) *Settling time*

As shown in Figure 16, settling time tends to increase with packet delay jitter in a linear fashion. The system was stable for all values of delay and sampling jitter. The effect of sampling jitter is more significant at higher packet delay jitters (40ms or higher).

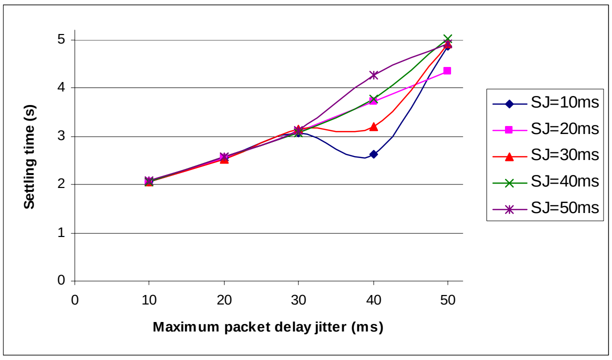


Figure 16. Maximum packet delay jitter vs. settling time for different maximum sampling jitter (SJ)

2) *Maximum percent overshoot*

Figure 17 illustrates the maximum percent overshoot behaviour. Again, the increase of the maximum percent overshoot is almost linear with packet delay jitter.

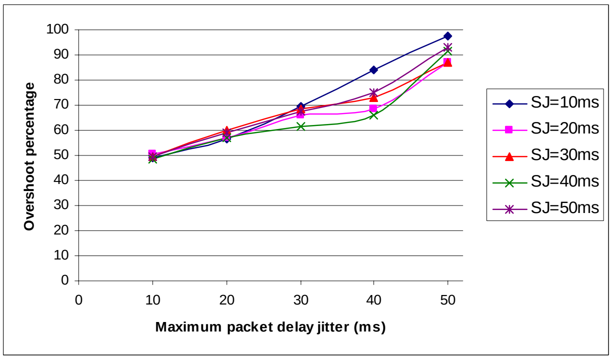


Figure 17. Maximum packet delay jitter vs. maximum percent overshoot for different maximum sampling jitter (SJ)

3) *Steady state error percentage*

Figure 18 depicts the steady state error percentage. It shows that the error percentage is very low for all sampling jitter when the delay jitter is 40ms or lower. For delay jitter 50ms or higher it can become considerable.

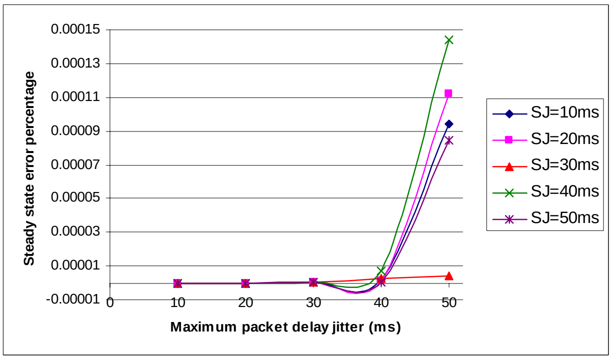


Figure 18. Maximum packet delay jitter vs. steady state error percentage for different maximum sampling jitter (SJ)

V. CONCLUSION AND FUTURE WORK

WNCS is a relatively new research area and is still thriving. Much of the research work relies on simulation models for the systems. This paper presents simple models for design issues such as packet delay, loss, delay jitter and sampling jitter that can exhibit random behaviour. It was found that the random packet delay and loss have more significant impact on system performance than the random sampling jitter and delay jitter. As the maximum packet delay jitter increases, packets might experience longer delays in the network. However, a small τ_{sc} can cancel out the effect of a longer τ_{ca} and vice versa. Therefore, the performance degradation is not severely affected by the delay jitter.

As future work, the performance of PD, PID, adaptive, and predictive types of controllers will be investigated. Another extension can be the use of signal-to-noise ratio to receive or discard a packet at controller or plant site.

REFERENCES

[1] R. M. Murray, K. J. Astrom, P. P. Khargonekar, S. P. Boyd, P. R. Kumar, S. S. Banda, P. S. Krishnaprasad, R. W. Brockett, G. J. McRae, J. A. Burns, J. E. Marsden, M. A. Dahleh, G. Meyer, J. C. Doyle, W. F. Powers, J. Guckenheimer, G. Stein, C. J. Holland, and P. Varaiya, "Control in an Information Rich World, Report of the Panel on Future Directions in Control, Dynamics, and Systems," California Institute of Technology 2002, http://www.cds.caltech.edu/~murray/cdspanel/report/cdspanel-15aug02.pdf, 6 Mar 2006.

[2] T. C. Yang, H. Yu, M. R. Fei, and L. X. Li, "Networked control systems: a historical review and current research topics," *the Journal of the Institute of Measurement and Control*, vol. 38, no. 1, pp. 12-16, 2005.

[3] J. Nilsson, "Real-time Control Systems with Delays," in *Automatic Control*, thesis, Lund Institute of Technology,

Lund, Sweden, 1998, http://www.control.lth.se/documents/1998/nilj98dis.pdf.

[4] T. C. Yang, "Networked Control System: A Brief Survey," *IEE Proceedings - Control Theory and Applications*, vol. 153, no. 4, pp. 403-412, 2006.

[5] S. Mastellone and C. T. Abdallah, "Networked Control Systems and Communication Networks: Integrated Model and Stability Analysis," presented at the 16th IFAC World Congress, Prague, Czech Republic, 2005.

[6] J. Colandairaj, G. W. Irwin, and W. G. Scanlon, "Analysis and Co-Simulation of an IEEE 802.11B Wireless Networked Control System," presented at the 16th IFAC World Congress, Prague, Czech Republic, 2005.

[7] P. Marti, J. M. Fuertes, and G. Fohler, "Minimising Sampling Jitter Degradation in Real-Time Control Systems," presented at IV Jornadas de tiempo real, Zaragoza, Spain, 2001.

[8] D. Henriksson, "Flexible Scheduling Methods and Tools for Real Time Control Systems," in *Automatic Control*, PhD thesis, Lund Institute of Technology, Lund, Sweden, 2003,

[9] D. Kotz, C. Newport, R. S. Gray, J. Liu, Y. Yuan, and C. Elliott, "Experimental Evaluation of Wireless Simulation Assumptions," presented at the ACM/IEEE International Symposium on Modelling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM), pp. 78-82, 2004.

[10] H. Yu, C. Harding, and M. S. Hasan, "Overview of Networks and Control," presented at the International Conference on Instrumentation, Control and Information Technology, Japan, pp. 205-210, 2005.

[11] J. K. C. So, "Delay Modelling and Controller Design for Networked Control Systems," in *Electrical and Computer Engineering*, Master's thesis, University of Toronto, Canada, 2003, http://www.control.toronto.edu/~sojimmy/Thesis.pdf.

[12] Y. Yang, Y. Wang, and S. H. Yang, "A Networked Control System with Stochastically Varying Transmission Delay and Uncertain Process Parameters," presented at the 16th IFAC World Congress, Prague, Czech Republic, 2005.

[13] N. J. Ploplys, "Wireless feedback control of mechanical systems," in *Mechanical Engineering*, MSc thesis, University of Illinois, Champaign, 2003, http://mr-roboto.me.uiuc.edu/ARGWeb/theses/NicksThesis/Ploplys_MS2003.pdf.

[14] Y. Tipsuwan and M. Y. Chow, "Control methodologies in networked control systems," *Control Engineering Practice*, vol. 11, no. 1099–1111, 2003.

[15] W. Zhang, M. S. Branicky, and S. M. Phillips, "Stability of Networked Control Systems," *IEEE Control Systems Magazine*, vol. 21, no. 1, pp. 84-99, 2001.

[16] N. J. Ploplys, P. A. Kawka, and A. G. Alleyne, "Closed-loop Control over Wireless Networks," *IEEE Control Systems Magazine*, vol. 24, no. 3, pp. 58-71, 2004.

[17] M. S. Branicky, V. Liberatore, and S. M. Phillips, "Networked Control System Co-Simulation for Co-Design," presented at the American Control Conference, Denver, 2003.

[18] Y. Zhou and H. Sethu, "A Simulation Study of Relationships between Delay Jitter and Properties of a Switching Network," presented at the Applied Telecommunication Symposium, Washington, D.C., USA, 2000.

[19] K. Jeffay, "Dealing with Delay-Jitter," 1999, http://www.cs.odu.edu/~cs778/jeffay/Lecture10.pdf, 6 Mar 2006.

[20] A. Cervin, D. Henriksson, B. Lincoln, J. Eker, and K. E. Arzen, "Jitterbug and TrueTime: Analysis Tools for Real-Time Control Systems," presented at the 2nd Workshop on Real-Time Tools, Copenhagen, Denmark, 2002.

[21] D. C. Verma, H. Zhang, and D. Ferrari, "Delay Jitter Control for Real-Time Communication in a Packet Switching Network," presented at the Tricomm 1991, North Carolina, pp. 35-43, 1991.

[22] C. A. Fulton and S. Q. Li, "Delay jitter first-order and second-order statistical functions of general traffic on high-speed multimedia networks," *IEEE/ACM Transactions on Networking*, vol. 6, no. 2, pp. 150-163, 1998.

[23] K. E. Årzén and A. Cervin, "Control and Embedded Computing: Survey of Research Directions," presented at the 16th IFAC World Congress, Prague, Czech Republic, 2005.

[24] P. Marti, J. M. Fuertes, and G. Fohler, "Sampling Jitter Compensation in Real-time Control Systems," presented at the 13th Euromicro Conference on Real-Time Systems, Netherlands, 2001.