UK Postgraduate Workshop on Human Adaptive Mechatronics (HAM)
15-16 January 2009, Staffordshire University, UK

Impact of network size on the performance of Wireless Networked Control Systems over Mobile Ad-hoc Network

Mohammad Shahidul Hasan, Hongnian Yu, Alison Carrington and T C Yang

***Abstract*—Wireless Networked Control Systems (WNCS) over Mobile Ad-hoc Network (MANET) is a new area of research and has many potential applications, for instance, military or rescue missions, exploring hazardous environments etc. For performance evaluation, researchers mostly rely on computer simulations as WNCS experiments are expensive to execute. The size of the wireless network i.e. number of nodes plays a vital role on the performance of the WNCS over MANET. This paper explores the effect of the network size on the performance of a WNCS using co-simulation that utilises SIMULINK and OPNET to simulate plant/controller behaviour and the MANET respectively. It investigates the impact of network data rates, node mobility, the packet delay, packet drop on the system stability and performance.**

I. Introduction

NETWORKED Control Systems (NCS) are now being implemented over wireless networks because of the latest development of high speed reliable wireless communication technologies and the need for node mobility in many applications. These systems are known as Wireless Networked Control Systems (WNCS). The simplest WNCS includes a plant and a controller with point-to-point wireless communication between them. An advanced version of WNCS applies the control mechanism over a multi-hop Mobile Ad-hoc Network (MANET) as it offers a dynamic, self-organising wireless network and can be easily deployed without any infrastructure [1]. However, WNCS over MANET has brought many challenges to researchers, such as unpredictable network packet delay and dropouts, random node movements etc.

Research on WNCS mostly relies on simulation studies since launching real experiments is expensive and time consuming [2], [3]. The motive of WNCS co-simulation is to simultaneously simulate both the system dynamics and the network events [4]. Research works e.g. [5], [6], [7], [8] etc. combined two simulation packages to achieve a more efficient co-simulation approach. OPNET and MATLAB have been integrated to evaluate the performance of smart antennas using the MX interface provided by MATLAB, which allows C programs to call functions developed in MATLAB [5]. A co-simulation platform that combines the *NS2 network simulator* [9], [10] with the *Modelica* framework has been presented in [6] where NS2 models the communication network and Modelica simulates the system, sensor, actuator etc. SIMULINK and OPNET co-simulation for WNCS over MANET has been considered in [7], [8]. This paper implements a co-simulation approach that integrates the strengths of SIMULINK and OPNET to produce more realistic simulation results. Both simulators execute in parallel interactively in a synchronised fashion. However, as SIMULINK is time driven and OPNET is event driven, the challenge for the co-simulation approach is to synchronise the time concepts that have been implemented in this research work.

The size of the MANET i.e. number of nodes number of nodes plays a vital role on the performance of the WNCS. This paper explores the effect of the network size on the performance of a WNCS.

Section II explains the overall simulation model including the *double inverted pendulum coupled by a spring plant* model that has been taken as the case study. Section III presents the validation of the co-simulation approach using the results. Finally, section IV draws some conclusions and points to future works.

II. Simulation Model

A. Plant/Controller model

This paper considers a benchmark case plant model: a double inverted pendulum coupled by a spring. A detailed development of the model and design of the linear control law can be found in [11], [12]. In this study, we implement the distributed nature of NCS using four sensors and two actuators as shown in Figure 1. In this model, if any angle of the pendulums exceeds 60 degrees (1.04 radians) from their central positions, the simulation will stop and the system is considered as unstable.

The states of the pendulums are sent to the controller at different sampling rates through two different wireless channels. The control objective of the system is to keep both the pendulums upright or to make them follow a particular reference/trajectory such as a sinusoidal or pulse signal by applying the controls to both actuators separately as depicted in Figure 1. In this paper, the pendulums are required to follow pulse signals and to maintain the stability condition mentioned previously. The challenging issue is to maintain suitable communication network packet delays, packet losses etc. so that the system remains stable.

Mohammad Shahidul Hasan, Hongnian Yu, Alison Carrington are with the Faculty of Computing, Engineering and Technology, Staffordshire University, UK (email: {m.s.hasan, h.yu, a.l.carrington}@staffs.ac.uk).

T C Yang is with Department of Engineering and Design, University of Sussex, UK (email: t.c.yang@sussex.ac.uk).

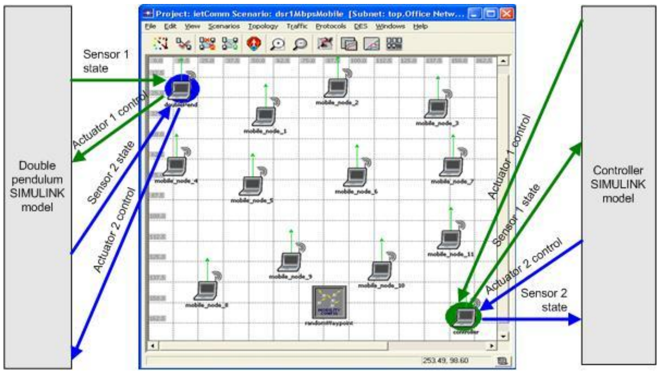

Figure 1. Interactive SIMULINK-OPNET co-simulation.

B. *SIMULINK-OPNET interactive co-simulation*

In the interactive co-simulation environment, OPNET executes as the master simulator and maintains the co-simulation time. The OPNET plant and controller nodes invoke two MATLAB engine servers to execute the plant and the controller SIMULINK models respectively as shown in Figure 1. The state of the particular sensor is read from the SIMULINK model by the OPNET plant model before generating the state packet. When a control packet arrives at the plant, the control information is passed to the corresponding actuator of the SIMULINK model.

The synchronisation mechanism between the SIMULINK and the OPNET models is explained in Figure 2. OPNET begins execution and pauses at simulation time 0. The OPNET node models invoke the corresponding SIMULINK models. After initialisation, the SIMULINK plant model pauses at time 0. OPNET resumes execution and pauses at sampling time *T1*. It passes a command to the SIMULINK plant model to execute until time *T1*. When SIMULINK pauses at time *T1*, the OPNET plant node model reads the plant state from the SIMULINK model and generates a sample packet.

The total closed loop delay is denoted by *t1* which is measured as sensor to controller delay plus controller to actuator delay. Upon receiving a control packet at time *T1+t1*, OPNET issues a command to the SIMULINK plant model to execute until time *T1+t1* with the previous input *u0*. At time *T1+t1*, the SIMULINK plant model pauses and the input is changed to the new control *u1*. When SIMULINK finishes execution, OPNET continues to run the simulation in this fashion. The same synchronisation mechanism has been used for co-simulation of NS2 and Modelica in [6].

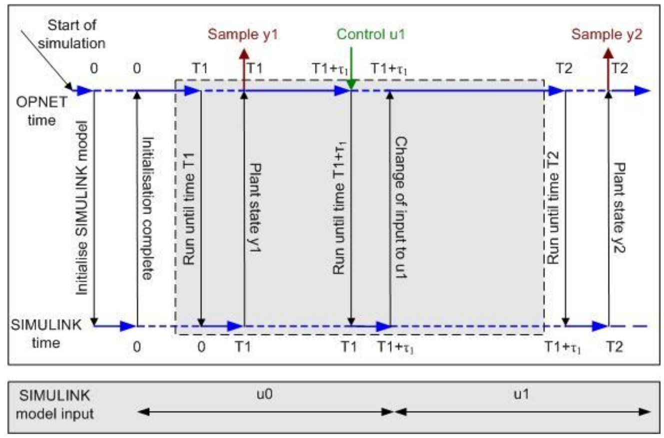

Figure 2. SIMULINK-OPNET synchronisation

C. *MANET model*

Figure 3 shows the comparison of computer simulation models and real world experiments [3], [13], [14]. *Model 1* involves two components: *path loss exponent* and *fading*. *Model 2* is the *two-ray ground-reflection* model that uses only the path loss component. Finally, *model 3* represents the *ideal propagation* model. The comparison revealed that *model 1* exhibits the behaviour closest to the real world experiment [3].

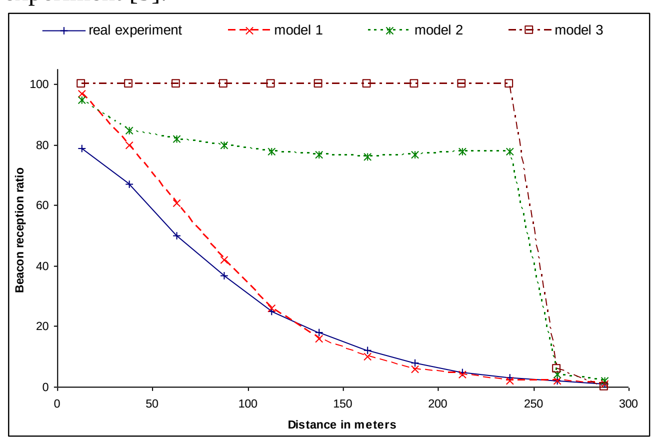

Figure 3. Comparison of three simulation models with real world experiment [3].

The radio channel used in this paper implemented *model 1*. The simulation model implements IEEE802.11b technology using MANET nodes equipped with Lucent Orinoco wireless network cards [13]. Table I gives the transmission ranges obtained from the OPNET simulation based on the Lucent Orinoco card specification [15]. It is noted that as the data rate increases, the receiver needs higher signal power to receive packets properly thus reducing the successful transmission range. Hence, under IEEE802.11 technologies, a multi-hop ad-hoc network exists at two-three hops and ten-twenty nodes [2], [16]. The WNCS area has been chosen as a square open field of size 174m × 174m based on the transmission range of 1Mbps data rate. Thirteen MANET nodes produce the same node density as presented in [3], [13], [14]. To observe the effect of the number of network nodes, five network sizes, i.e., six, ten, thirteen, twenty and twenty six nodes have been considered in section III.

Table I. Lucent Orinoco wireless network card specification and transmission ranges obtained from OPNET simulation.

	1 Mbps	**2 Mbps**	**5.5 Mbps**	**11 Mbps**
Output power (dBm)	15 dBm			
Receiver sensitivity (dBm)	-94	-91	-87	-82
OPNET maximum transmission range (m)	245	195	140	90

For movement, a *random way-point model* has been implemented where nodes move from one point to another random point at a constant speed chosen from a specified range. They wait at the new point for some time and then another random destination point is chosen. This movement model provides continuous node movement so that MANET routing algorithms can be evaluated [13], [14]. In this simulation, node speeds are chosen uniformly between 1 and 10 m/s. Nodes wait for 60s before moving to a new destination point [13].

MANET routing protocols are categorised into two major classes: proactive and reactive (on-demand). A *proactive protocol* attempts to keep an up-to-date routing table by constantly requesting update information and sharing routing tables [17]. In contrast, *reactive routing protocols* establish a route when requested and routes are maintained until the destination becomes unreachable or the route is no longer required. To date, no clear indication was found regarding the best routing policy. The performance depends significantly on the scenario under consideration [2].

Dynamic Source Routing (DSR) [18] and Ad-hoc On-demand Distance Vector (AODV) [19] are widely used reactive routing protocols. The OPNET simulations of WNCS presented in [20], [21] revealed that DSR exhibited better performance than AODV. Moreover, it should be noted that AODV is unable to handle unidirectional links whereas DSR can [22]. Therefore, DSR has been investigated in this paper.

III. Result

A pulse signal of amplitude 5 radians, period 1.5s and 10% pulse width has been applied as the reference signal. The controller has been placed at the south-east corner of the field and the double pendulum plant is located at the opposite (north-west) corner as shown in Figure 1. The DSR policy is used to investigate the WNCS performance in terms of pendulum stability and tracking capability for various sampling periods, network data rates, node movements and network sizes, i.e., number of nodes. First the results with thirteen network nodes have been presented. Then the networks with halved (six), doubled (twenty six) and two intermediate sizes (ten, twenty) nodes are explored.

A. *Effect of sampling periods*

Typical values of sampling periods can range from hundreds of microseconds to hundreds of milliseconds [23]. A higher sampling rate improves the performance of an NCS [24]. But it increases computational overheads and generates excessive traffic into the network [25].

Five sampling periods (0.005s, 0.006s), (0.02s, 0.03s), (0.05s, 0.06s), (0.10s, 0.11s), (0.15s, 0.16s) and the lowest data rate of 1 Mbps have been applied to the thirteen stationary DSR nodes first. The pendulum tracking performance for the sampling periods is shown in Figure 4. The *direct control* that is implemented without the network using only SIMULINK is shown as *matlabPend1* and *matlabPend2*. The SIMULINK-OPNET co-simulation control performance is compared with the direct control. It is noted that for the sampling period of (0.005s, 0.006s), the plant became unstable as defined in section II.A. Again, though the sampling period of (0.15s, 0.16s) kept the plant model within the stable conditions, it showed occasional spikes in the pendulum angles. This is because the sampling period was too large for the double pendulum plant. Therefore, for the rest of the investigation, sampling periods (0.02s, 0.03s), (0.05s, 0.06s), (0.10s, 0.11s) are considered.

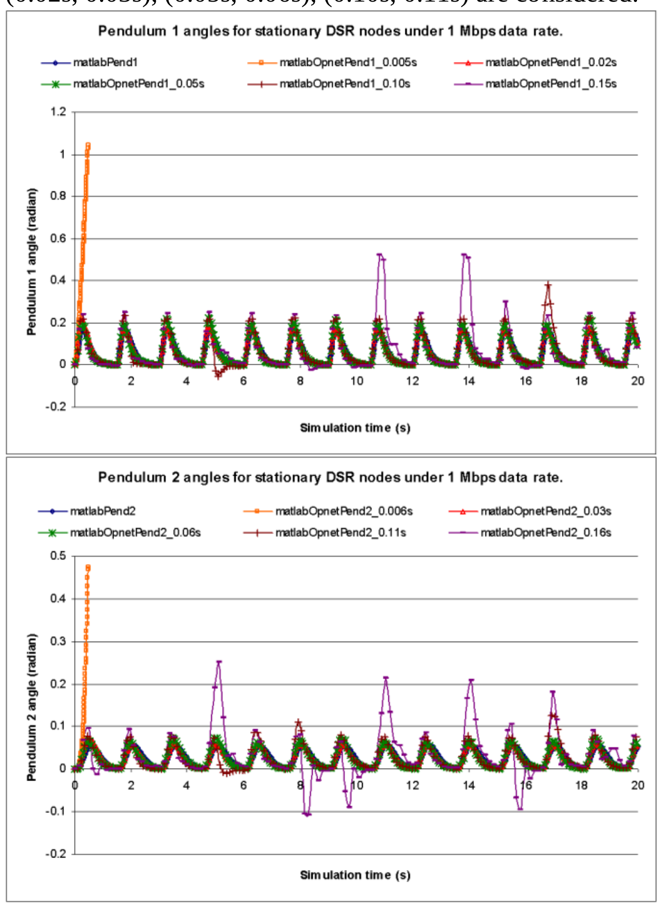

Figure 4. Pendulum tracking performance for thirteen stationary DSR nodes under various sampling periods at 1 Mbps data rate.

The packet routes and delays produced by OPNET were extracted for analysis purposes. According to Table I, the receiver can receive low power signals properly at the data rate of 1 Mbps, so most of the packets can reach the controller or plant directly. Therefore, packet delay and drop probability exhibit low values.

B. Effect of node movement and network size

The total overshoot percentage of pendulum 1 and 2 and for stationary and mobile six, ten, thirteen, twenty and twenty six DSR nodes is given in Figure 5 and Figure 6 respectively. Figure 5 and Figure 6 also present the summary of plant stability. When the plant is unstable the overshoot percentage is shown as zero.

It is noted that the data rates of 1 and 2 Mbps kept the plant stable for all five network sizes under both stationary and mobile conditions. This is because the plant and controller could communicate with each other directly or via a maximum of one intermediate node at these data rates. The overshoot percentages were low for sampling periods (0.02s, 0.03s), (0.05s, 0.06s).

For stationary networks it is clear that the six node network did not support data rates of 5.5 and 11 Mbps at all. This is because the small network could not establish an intermediate node that is required between the plant and the controller to cover 174m × 174m according to Table I. For the data rate of 5.5 Mbps, the ten, thirteen, twenty node networks showed similar performances. However, extra nodes in the twenty six node network did not produce any better routes than the ten, thirteen and twenty node networks. For the data rate of 11 Mbps, only the sampling periods (0.10s, 0.11s) was supported with high overshoot.

All mobile networks except the thirteen node scenario supported the data rates of 1, 2 and 5.5 Mbps for all sampling periods. It might be that the random node movements established such routes that supported the delay constraint of the WNCS properly. For the stationary node scenario, the data rate of 5.5 Mbps did not support the plant stability under any sampling period in the case of the six node network and the plant remained stable for only one sampling period, i.e., (0.10s, 0.11s) in the case of the twenty six node network. As the node movement is introduced, the plant stayed stable for the networks with six and twenty six nodes under all three sampling periods at the data rate of 5.5 Mbps. However, the stability window became narrower for thirteen nodes as node movement was introduced. For instance, under a sampling period of (0.10s, 0.11s), the plant is stable at all data rates in the case of stationary nodes. But, plant stability is supported only for data rates of 1 and 2 Mbps for mobile nodes.

In general, the sampling period of (0.02s, 0.03s) is not supported by the data rate of 11 Mbps at all. This is because the packets needed to travel through multiple intermediate nodes before reaching their destination, which produced longer delays and higher drop probability. The stability performance was not significantly improved by increasing the number of nodes above ten and hence ten is the optimal network size for this particular scenario.

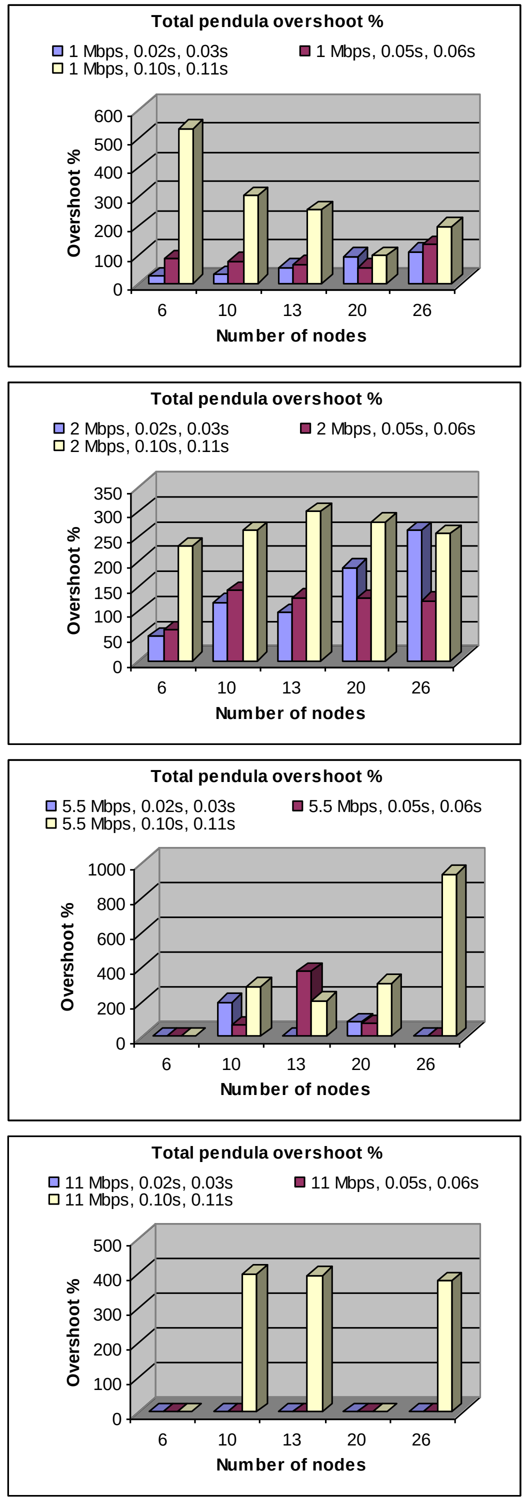

Figure 5. Total overshoot percentage for stationary nodes.

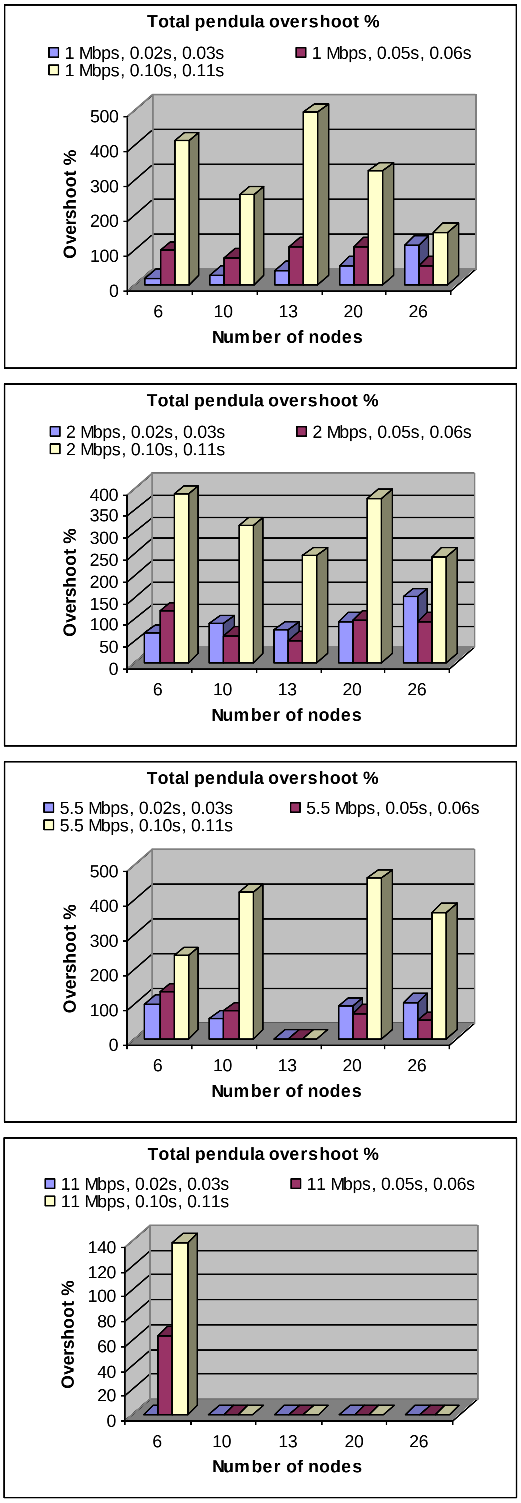

Figure 6. Total overshoot percentage for mobile nodes.

IV. CONCLUSIONS

It was found that the main challenges of WNCS over MANET are to maintain acceptable packet delays and drops. An increased network data rate makes the transmission range smaller. Therefore, packets need to travel via more intermediate nodes to reach their destinations. Both smaller transmission range and route re-establishment could cause higher packet delay and drop probability. Increased number of network nodes does not always guarantee reliable route establishment, i.e. overall system stability. Though, in general, the mobile node scenario showed better stability performance than the stationary scenario, random node movement might make the system stability region narrower as the MANET needs to establish new routes.

ACKNOWLEDGMENT

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

REFERENCES

[1] E. M. Royer and C. K. Toh, "A Review of Current Routing Protocols for Ad Hoc Mobile Wireless Networks," *IEEE Personal Communications*, vol. 6, pp. 46-55, 1999.

[2] M. Conti and S. Giordano, "Multihop Ad Hoc Networking: The Theory," *IEEE Communications Magazine*, vol. 45, pp. 76-86, 2007.

[3] 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), 2004.

[4] J. R. Hartman, "Networked Control System Co-simulation for co-design: Theory and experiments," in *Electrical Engineering and Computer Science*, vol. Master of Science. Cleveland, Ohio, USA: Case Western Reserve University, 2004.

[5] V. Dham, "Link Establishment in Ad Hoc Networks Using Smart Antennas," in *Electrical and Computer Engineering*, vol. Master's: Virginia Polytechnic Institute and State University, 2003.

[6] A. Al-Hammouri, V. Liberatore, H. Al-Omari, Z. Al-Qudah, M. S. Branicky, and D. Agrawal, "A co-simulation platform for actuator networks," presented at the 5th international conference on Embedded networked sensor systems, Sydney, Australia, 2007.

[7] M. S. Hasan, H. Yu, A. Griffiths, and T. C. Yang, "Interactive co-simulation of MATLAB and OPNET for Networked Control Systems," presented at the 13th International Conference on Automation and Computing, Stafford, UK, 2007.

[8] M. S. Hasan, H. Yu, A. Griffiths, and T. C. Yang, "Co-simulation framework for Networked Control Systems over multi-hop mobile ad-hoc networks," presented at the 17th IFAC World Congress, the International Federation of Automatic Control, Seoul, Korea, 2008.

[9] L. Breslau, D. Estrin, K. Fall, S. Floyd, J. Heidemann, A. Helmy, P. Huang, S. McCanne, K. Varadhan, Y. Xu, and H. Yu, "Advances in network simulation," *Computer*, vol. 33, pp. 59-67, 2000.

[10] K. Fall and K. Varadhan, "The Ns Manual (formerly ns Notes and Documentation), The VINT project," 2006.

[11] M. Ikeda and D. D. Siljak, "Optimality and robustness of linear quadratic control for nonlinear systems," *Automatica*, vol. 26, pp. 499-511, 1990.

[12] D. D. Siljak, *Decentralized control of complex systems*. Boston, MA: Academic Press, 1991.

[13] J. Liu, Y. Yuan, D. M. Nicol, R. S. Gray, C. C. Newport, D. F. Kotz, and L. F. Perrone, "Simulation validation using direct execution of wireless ad-hoc routing protocols," presented at the 18th Workshop on Parallel and Distributed Simulation (PADS'04), 2004.

[14] C. Newport, "Simulating mobile ad hoc networks: a quantitative evaluation of common MANET simulation models," Dartmouth College Science Technical Report TR2004-504, 2004.

[15] "ORiNOCO PC Card, Home, office, and Public Mobile Broadband Internet Access," 2000.

[16] M. Conti and S. Giordano, "Multihop Ad Hoc Networking: The Reality," *IEEE Communications Magazine*, vol. 45, pp. 88-95, 2007.

[17] 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, 2005.

[18] D. B. Johnson, D. A. Maltz, and J. Broch, *Ad Hoc Networking*. Boston, USA: Addison-Wesley, 2001.

[19] C. E. Perkins and E. M. Royer, "Ad hoc On-Demand Distance Vector Routing," presented at the 2nd IEEE Workshop on Mobile Computing Systems and Applications (WMCSA 99), New Orleans, LA, 1999.

[20] M. S. Hasan, C. Harding, H. Yu, and A. Griffiths, "Modelling delay and packet drop in Networked Control Systems using Network Simulator NS2," *the International Journal of Automation and Computing (IJAC)*, vol. 2, pp. 187-194, 2005.

[21] M. S. Hasan, H. Yu, A. Griffiths, and T. C. Yang, "Simulation of Distributed Wireless Networked Control Systems over MANET using OPNET," presented at the IEEE International Conference on Networking, Sensing and Control, London, UK, 2007.

[22] E. Altman and T. Jimenez, "NS Simulator for beginners," 2003.

[23] F. D. Pellegrini, D. Miorandi, S. Vitturi, and A. Zanella, "On the Use of Wireless Networks at Low Level of Factory Automation Systems," *IEEE Transactions on Industrial Informatics*, vol. 2, pp. 129-143, 2006.

[24] P. Albertos, A. Crespo, M. Valles, and I. Ripoll, "Embedded Control Systems: Some Issues and Solutions," presented at the 16th IFAC World Congress, Prague, Czech Republic, 2005.

[25] 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, pp. 12-16, 2005.