Modeling delay and packet drop in Networked Control Systems using network simulator NS2

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Modelling Delay and Packet Drop in Networked Control Systems using Network Simulator NS2

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Abstract: Wireless Networked Control Systems (WNCS) are used to implement a control mechanism over a wireless network that is capable of carrying real-time traffic. This field has drawn enormous attention from current researchers because of its flexibility and robustness. However, designing efficient WNCS over Mobile Ad Hoc Networks (MANET) is still a challenging topic because of its less-predictable aspects, such as inconsistent delay, packet drop probability, and dynamic topology. This paper presents design guidelines for WNCS over MANET using the Network Simulator version 2, NS2 software. It investigates the impact of packet delay and packet drop under the AODV and DSR routing protocols. The simulation results have been compared to MATLAB results for validation.

Keywords: Adhoc On-Demand Distance Vector (AODV) routing, Dynamic Source routing (DSR), Mobile Adhoc Networks (MANET), Wireless Networked Control Systems (WNCS).

1 Introduction

Networked Control Systems (NCS) [1], [2] implement a closed loop control mechanism over networks. Recently, attention is being paid to the wireless NCS (WNCS), also known as Closed Loop Over Wireless Network (CLOWN) [3]. WNCS offers flexibility, robustness and is suitable for various applications such as military use and rescue operation. It allows control applications to be used in remotely located systems, for instance: assembling space structures, exploring hazardous environment, executing tele-surgery [4], test bed engine monitoring, and online aircraft monitoring [5]. The basic distributed structure of the WNCS is shown in fig. 1. The state of the plant is sensed by sensors and is sent to the controller over the wireless network. The controller compares the state with the reference model and computes control signals accordingly. Then, the control signal is sent to the actuator through the wireless network to be implemented at the plant. This paper attempts to investigate the relationship between packet delay and sampling period, as well as the effect of packet delay and packet drop on the performance of a simple control mechanism using the simulation software NS2 and MATLAB.

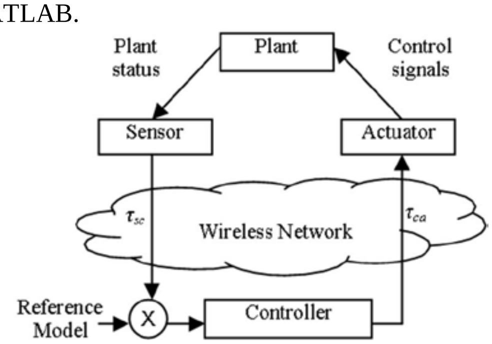

Fig. 1 The general structure of WNCS

The rest of the paper is organised as follows. Section 2 explores the design issues of the underlying network for successful implementation of NCS over MANET, section 3 explains the model used for the simulation, section 4 presents the results that are analysed in section 5 and finally, section 6 draws some conclusions.

2 Network Design Issues for NCS

Control networks generally produce small, compared to data networks, but time-critical packets [6]. The network must meet the following constrains:

- Frequent small sized packets.
- Bounded packet delay, however, it can be noted that the smaller the delay the better the performance.
- Quality packet delivery.

Delay and packet drop can degrade the performance of NCS significantly and even destabilise the entire NCS [7], [8]. Therefore, in this research paper, these two network issues are the main focus.

2.1 Delay

The total closed loop delay τ_{total} can be formulated as $\tau_{total} = \tau_{sc} + \tau_c + \tau_{ca}$, where τ_{sc} is sensor-to-controller, τ_c is controller computation and τ_{ca} is controller-to-actuator delays, respectively [3], [9]. However, for simplicity, the controller delay τ_c can be ignored as it is negligible compared to the delays τ_{sc} and τ_{ca} [2]. Therefore, the total delay is approximately $\tau_{total} \approx \tau_{sc} + \tau_{ca}$ [10]. If no delay compensation technique is implemented, the controller must receive the *j*-th sample from the plant before computation of the *j*-th control signal to ensure stable operation of the NCS. Therefore, total delay must satisfy the relation $\tau_{total} \le T$, where T is the sampling period.

2.2 Packet drop rate

NCS carries real-time traffic, therefore, it might be beneficial to drop a packet that can not be transmitted immediately [10] in order to avoid retransmissions. Thus, the tolerable packet drop rate must be analysed to maintain the desired system stability.

3 The Model for Simulation

A simple water tank model is chosen as the plant, shown in fig. 2, so that the controller delay τ_c can be ignored. The current water height is sent to the controller. The controller sends the controlled input flow to the tank, which is initially empty. The input flow is tuned according to the difference between the tank height and the desired height, *REF*.

3.1 Plant and controller model

The continuous time water tank model [11] is-

$$\tau\dot{y} + y = Ku \qquad (1)$$

where the time constant $\tau = 63.2456$, the gain $K = 15.8144$, y is the height and u is the input flow of the water tank.

Using the Newton approximation method, the discrete model of (1) is-

$$(\frac{\tau}{T} + 1)y(j) = Ku(j) + \frac{\tau}{T} y(j-1) \qquad (2)$$

where T is sampling period, $y(j)$ and $u(j)$ are the output and input at the *j*-th sample, respectively.

Here we use a simple proportional controller with proportional constant $K_P = 5$ and the control law is-

$$u(j) = K_P(REF - y(j)) \qquad (3)$$

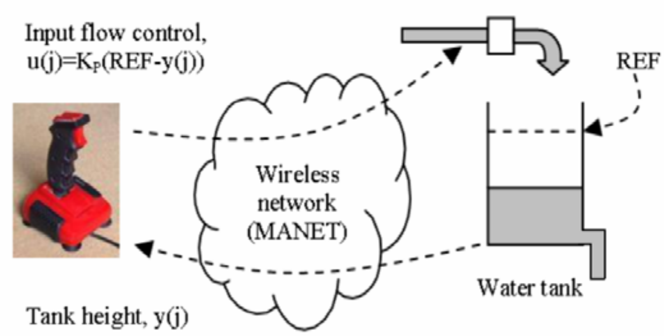

Fig. 2 Plant model used to analyse packet delay and drop rate

3.2 Network Simulator, NS2

NS2 is a discrete event network simulator that supports different types of protocols and has support for Ad Hoc Wireless Network (MANETs) [12]. For analysis purposes, NS2 produces a *trace* file containing individual packet details such as, source node, transmission time, packet size, destination node, and received time. It can also create a *nam* file for simulation animation. WNCS has been implemented as an extension over NS2 that simulates the NCS plant and the controller. Plant-controller system behavior and network events such as clock driven sampling and event driven controlling can be specified [13]. Routing protocol performance (AODV, DSR etc.), mobile node movement, packet delay, and transmission-reception power can all be simulated for WNCS.

3.3 Network topology

A 1000meter × 1000meter ground has been considered as the simulation ground. Fig. 3 and 4 show the network topology and node locations in the network. To analyse the effect of route rediscovery and packet drop, node 2 is moved to (185, 375) at simulation time 0.1s at speed 10m/s requiring the establishment of a new route via node 4 as shown in fig. 4. Therefore, the network topology involves mobile node movement as well as route rediscovery.

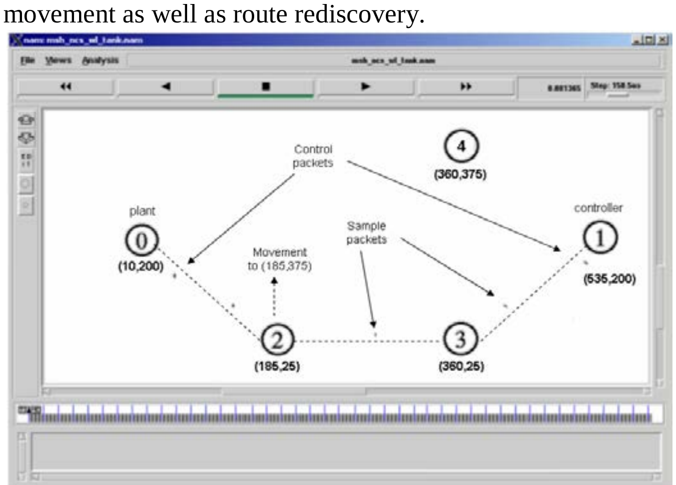

Fig. 3 Simulation snapshot - network topology and node locations before movement

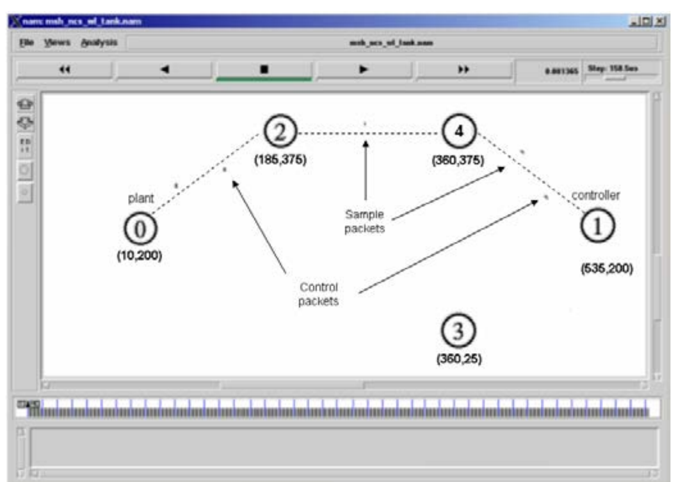

Fig. 4 Simulation snapshot - network topology and node locations after movement

3.4 Choice of sampling period, T

First the average packet delay between the plant node and the controller node is calculated using *constant bit rate traffic (CBR)* in NS2 as shown in fig. 5. It can be seen from fig. 5 that the maximum packet delay is 0.008s. Assuming, $\tau_{sc} \approx \tau_{ca}$, total delay can be calculated as $\tau_{total} = 0.008 * 2 = 0.016s$. The simulation uses, $T = 0.02s$. Therefore, the constraint $\tau_{total} \leq T$ is satisfied.

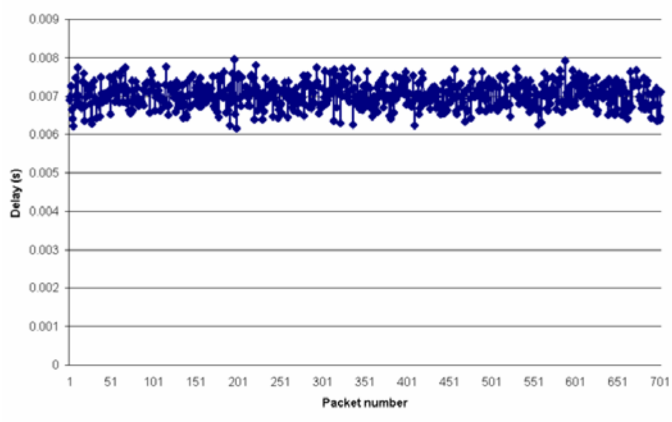

Fig. 5 Packet delay between node 0 (plant) and node 1 (controller)

For this simple network, the constraint on the delay $\tau_{total} \leq T$ may be satisfied. However, for a large shared network this criterion is not likely to be true. Therefore, there is a need to develop a more advanced predictive control system.

3.5 Routing protocols

The following two routing protocols are considered.

- Adhoc On-demand Distance Vector (AODV) [14]
- Dynamic Source Routing (DSR) [15]

AODV and DSR are both reactive protocols. They only send requests for a route when a node wishes to send a packet and there is no valid route in the route table. The advantage of reactive protocols is that less traffic is generated in the network. However, they have a disadvantage: there is a slight delay from the first packet being sent from the agent to the destination. Once the route has been established, the initial delay is removed [16]. Under the AODV protocol, when a node needs to transmit, it consults its routing table. If there is no valid route in the table, a route discovery process commences that will terminate at the destination or at a node that has an updated route to the destination. During route discovery, nodes update their routing tables accordingly. Then at every node, the data packet is forwarded to the neighbour towards the destination. On the other hand, in DSR, the source sets the entire route for a packet. If there is no valid route at the source, the Route Request (RREQ) packet is broadcast by the source. Whenever a node passes the RREQ packet it includes its address to the packet. This process continues until the destination or a node with a valid route is reached. Hence, the route back can be retrieved from the packet. However, AODV is unable to handle unidirectional links where as DSR can [17].

3.6 Simulation parameters

Table I summarises the parameters that have been used in the simulation. Clock or time driven samplings, event driven controls, and actuation mechanisms have been used in this simulation [3]. This approach does not require synchronisation between the plant and the controller. Control and actuation tasks are invoked when the state and control packet arrives, respectively; hence it also avoids blocking of computer resources.

TABLE I. Simulation Parameters

Parameter	Value
MAC protocol	Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA)
Data rate	11 Mbps maximum
Packet size	64 bytes
Sampling period, T	0.02s
Clock driven sampling	Plant height is sent to the controller in every T=0.02s. The time and height is saved in an output file that records the height change with time at the plant.
Event driven control	The controller computes control and sends it to the plant whenever it receives a height sample packet from the plant. The time and input flow are saved in another output file that records the flow change with time at the controller.
Simulation time	50s (containing initial route establishment, normal operation, disconnection, route rediscovery and normal operation)
Desired level, REF	2+sin(t) m
Radio signal propagation model	2 Ray Ground [12]

4 Results

For the purpose of analysis, the simulation creates the following files:

- Trace file: detailed packet information, for instance, send time, receive time, and source node. The explanation of the trace file format can be found in the appendix of this paper.
- Nam file: to execute animation of the WNCS.
- Plant output file: time vs. water height.

The following sections describe the plant outputs based on the routing protocol. Then the results of packet delay and packet drop, extracted from the trace file, are presented. As node 2 moves from (185,25) to (185,375), the plant experiences a disconnected period and does not receive any control packet from the controller. The input flow remains constant at the value before disconnection.

4.1 Plant output for REF = 2+sin(t) meter under the AODV protocol

To see the effect of variation, a hypothetical $2 + \sin(t)m$ is considered as REF and the output is depicted in fig. 6. The disconnection and reroute between the plant and controller was not reestablished which meant that the plant became unstable as shown in fig. 6.

4.2 Plant output for REF = 2+sin(t) meter under the DSR protocol

The plant output for hypothetical $REF = 2 + \sin(t)m$ is shown in fig. 6. However, it can be noted that DSR protocol allowed successful route discovery and maintained stability of the plant.

The AODV is a table driven protocol, as such when nodes change their location the tables are updated. It is limited, however, in its handling of unidirectional links, which might explain why the NS2 AODV implementation failed to reestablish the route after the movement of node 2.

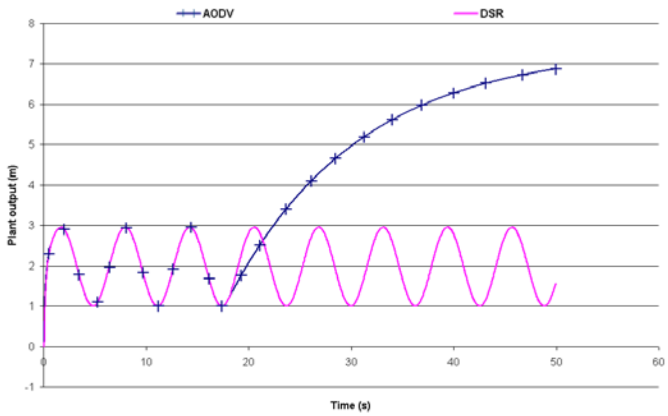

Fig. 6 Plant output change for REF = 2+sin(t)m under AODV and DSR protocol

4.3 Packet delay under the AODV protocol

The 50s of the simulation contains all the scenarios: initial route establishment, normal operation, as well as disconnection and route rediscovery. Fig. 7 shows the delays for the entire simulation, for which disconnection occurs at around 1800 packets.

The normal operation packet delay under AODV protocol is depicted in fig. 8. In particular, it shows the delays of the first 1800 packets of fig. 7 when the plant node is fully connected to the MANET. These delays give the values for τ_{sc} or τ_{ca} during normal operation of the NCS.

4.4 Packet delay under the DSR protocol

All packet delays for the simulation under DSR protocol have been shown in fig. 9. It can be noted that DSR protocol successfully reestablishes the new route and transmits more packets than the AODV protocol. During route switching, the packets experience larger delay because of the route rediscovery procedure.

Normal operation for a fully connected packet delay is shown in fig. 10. These delays can be used as τ_{sc} or τ_{ca}. In particular, the left and right parts of fig. 10 show the packet delays of routes shown in figures 3 and 4, respectively.

5 Analysis

Analyses have been performed in terms of packet delay, packet drop and comparing NS2 results with MATLAB results.

5.1 Obtaining NS2 Results

NS2 produces a trace file; this file contains information about the results of simulation. It also contains all the information about different levels of the protocol stack such as RTR (routing), AGT (application agent), node sending a packet, receiving the packet, protocol, and IP identifier. The first column of the trace file describes the event type: s-send, r-receive, d-drop and f-forward. The Ni and Ii columns represent the identifier of the node and packet respectively.

To extract the packet total delay and packet drop from the trace file only, the AGT level (Ni column) information is required. A number of the first AGT packet traces are given in the appendix. The plant sends a packet (marked as "s" in first column of trace file), the plant node is known to be node 0 (this is the column '–Ni 0'). The controller will receive (marked as "r") the packet at node 1 (-Ni 1). As NS2 is an Internet Packet (IP) simulator, a packet will be passed between the two agents with the same IP id (-Ii) value. This means it was possible to use Java to retrieve the IP packet IDs from sent "s" and match them to a received packet "r" with the same IP packet ID. If an "r" ID is not found then a packet was dropped on route to the destination.

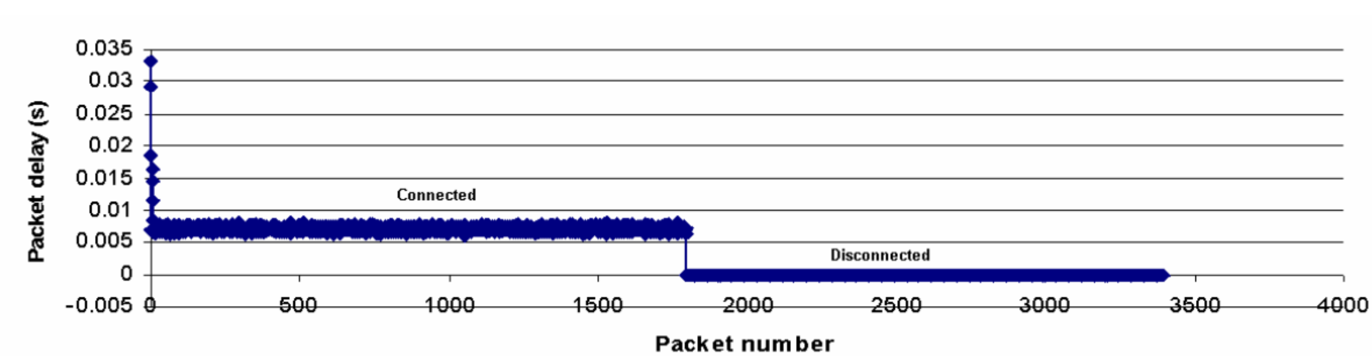

Fig. 7 Packet delay from simulation trace file under AODV protocol

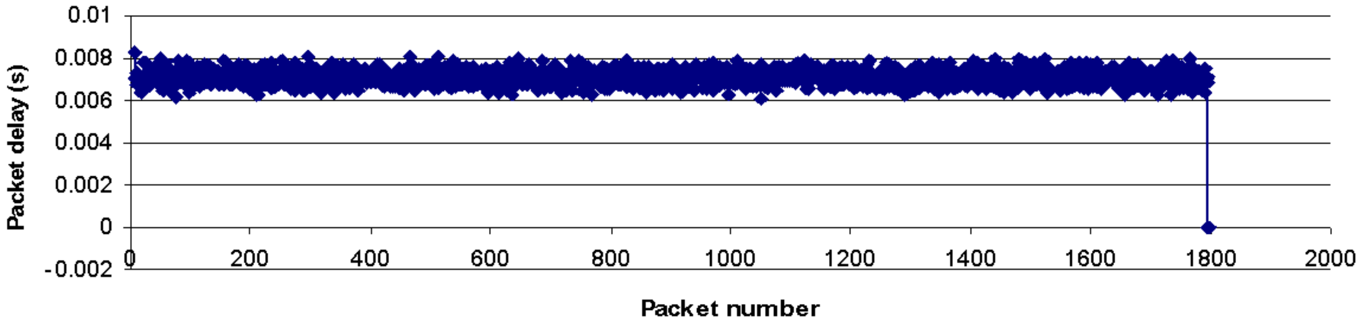

Fig. 8 Normal operation mode packet delay under AODV protocol

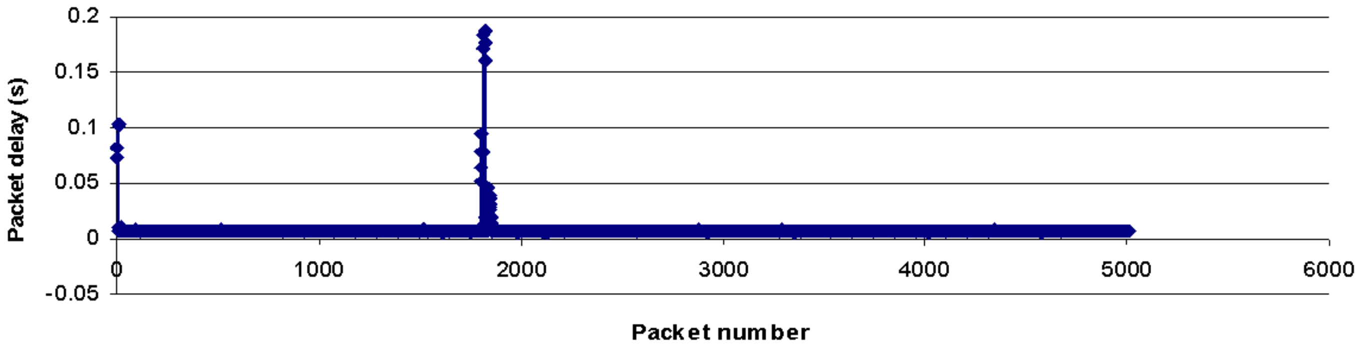

Fig. 9 Packet delay from simulation trace file under DSR protocol

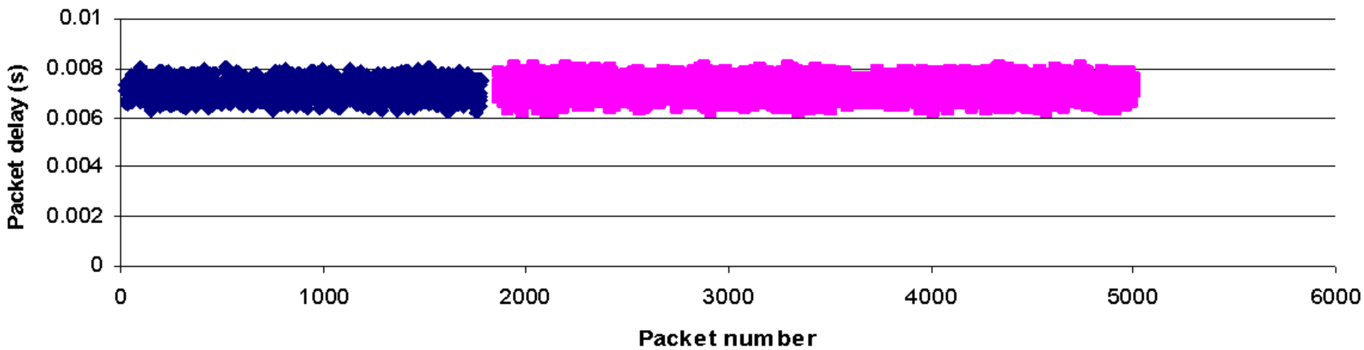

Fig. 10 Normal operation mode packet delay under DSR protocol

Java is used to retrieve the matching send and receive values and to place these into a *comma separated value (.CSV)* file that can be read and processed by EXCEL Graphs can then be produced based on the results. The entire procedure is shown in fig. 11.

5.2 Total delay and sampling period relationship, $\tau_{total} \leq T$

Figures 8 and 10 give the normal operation delay for τ_{sc} or τ_{ca}. The assumption, $\tau_{sc} \approx \tau_{ca}$, lead to $\tau_{total} = 0.008 * 2 = 0.016s$. So for $T = 0.02s$, the constraint $\tau_{total} \leq T$ is satisfied.

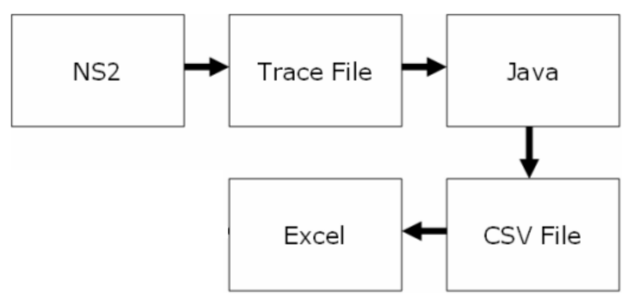

Fig. 11 Java Parsing of NS2 Trace File

5.3 Control mechanism performance

The step response of the plant under the DSR routing protocol with no packet drop is shown in fig. 12. The topology of fig. 3 has been considered with all static nodes. The following three criteria are used to evaluate the performance of a control mechanism:

1) Settling time T_S.

The final or steady state value was found to be $0.987511m$. Assuming settling percentage as 2%, the settling time was $T_S = 0.66s$.

2) Plant stability with packet drop.

The total number of generated packets can be calculated as follows:

Number of sample packets	$= \frac{1}{T} * time = \frac{1}{0.02} * 50 = 2500$
Number of control packets	$= 2500$

The plant model used in this paper was a slow first order system. To investigate the stability of the water tank model, 5%, 10%, 15%, and 20%, packet drops were introduced at the controller so that the control packet would not be sent back to the plant.

The system remained stable using the $REF = 2 + \sin(t) meter$ reference input. To validate these results, a MATLAB Simulink model, shown in fig. 13, was developed utilising the same controller and plant equations as (1) and (3). Setting the transport delays to 0.008s, the plant was found to be stable after a packet drop rate of 75% was introduced.

3) Statistic error.

The static error of the control loop over MANET can be found using the following formula:

$$Statistic\_error = \frac{y_{(\infty)} - REF}{y_{(\infty)}}$$

For simplicity, it can be assumed that $y_{(\infty)} = y_{3T_S}$. Therefore, the error was calculated 1.265%.

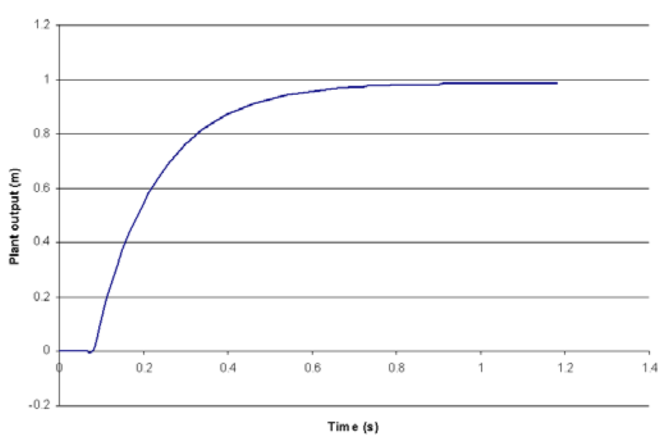

Fig. 12 Step response of the plant under the topology shown in fig. 3 using the DSR routing protocol.

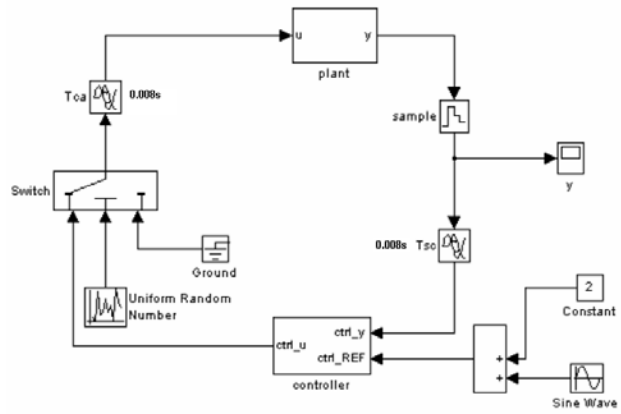

Fig. 13 MATLAB Simulink model for packet drop.

6 Conclusion

The main objective of this investigation was to model packet delay and packet drop for NCS using the simulation software Network Simulator, NS2 using a NCS agent over a MANET. It also provides guidelines for extracting packet delay and packet drop information from the trace file to verify the delay-sampling period relationship. Considering the stable water level, AODV and DSR exhibit similar performance rates on a static network. When using a mobile network where the route is established over a different path, it was found that AODV, in its native form within NS2, is unable to reconnect the network, thus the plant becomes unstable and over shoots the reference level.

It was been found that a slow first order system was stable with a packet drop rate of at best 75% over a MANET. Further work in this area will be to increase the traffic load over the network and examine the use of other propagation models in NS2 to more accurately simulate the MANET environment.

As AODV and DSR are reactive protocols the total delay and effect of packet drop needs to be analysed using proactive and hybrid routing protocols with a higher number of nodes and random movement and more dynamic network topology. Fast and higher order systems also need to be modelled, such as the inverted pendulum with cart. This will also allow the development of a simple algorithm to represent network delay in MATLAB NCS simulations.

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Biography

Mr. M Shahidul Hasan achieved his BSc and first MSc in Computer Science from the University of Dhaka, Dhaka, Bangladesh. He received his 2nd MSc in Computer & Network Engineering from Sheffield Hallam University, Sheffield, UK. Currently he is pursuing his PhD under the Faculty of Computing, Engineering and Technology, Staffordshire University, Stafford, UK in Networked Control Systems over MANET. His research interests include delay, packet drop, delay jitter, compensation techniques etc. for wireless networked control systems.

Mr. Chris Harding gained his BSc in Computing Science and Masters by Research from Staffordshire University in the United Kingdom. Currently he is studying his PhD in Wireless Networked Control Systems, specifically looking at NCS over MANETs, with research interests in this area concentrating on the network routing and effect of routing protocols on the NCS system.

Professor Hongnian Yu is Professor of Computer Science at Staffordshire University. He was a lecturer in Control and Systems Engineering at Yanshan University, China in 1985-1990, did his PhD in Robotics at King's College London (1990-1994), was a research fellow in Manufacturing Systems at Sussex University (1994-1996), a lecturer in Artificial Intelligence at Liverpool John Moore's University (1996-1999), a lecturer in Control and Systems Engineering at the University of Exeter (1999-2002), and a Senior Lecturer in Computing at the University of Bradford (2002-2004). He now leads the Mobile Computing and Distributed Systems Research Group at Staffordshire University. He was a founding member of the Modelling Optimisation Scheduling and Intelligent Control research group at the University of Bradford. He has extensive research experience in neural networks, mobile computing, modelling, control of robot manipulators, and modelling, scheduling, planning, and simulations of large discrete event dynamic systems with applications to manufacturing systems, supply chains, transportation networks, and computer networks. He has published over 100 research papers focusing on the following: neural networks, computer networks, adaptive and robust control of robot manipulators, analysis and control of hybrid machines, control of timed delay systems, predictive control, manufacturing system modelling and scheduling, planning, and supply chains. He has held several research grants from EPSRC, the Royal Society, and the EU, as well as from industry. He was awarded the F.C. William Premium for his paper on adaptive and robust control of robot manipulators by the IEE Council in 1997. Professor Yu is an EPSRC college member, a member of IEEE, and a committee member of several conferences and journal editorial boards.

Dr Alison Griffiths is a Senior Lecturer in Telecommunications at Staffordshire University and has been since 2003. She was a lecturer in Computing at Staffordshire University in 2002-2003. She was a Research Associate on an EPSRC funded project whilst doing her PhD on the convergence of Mobile Computing and Telecommunications at Staffordshire University (1999-2003). The investigation consisted of the communication of different types of media (voice, video conferencing, web browsing, and downloading) over a common network, using a mobile device. Problems considered were the complications that occurred when a user moves, and consequently changes their end-point in the network during communication, with respect to the type of service the user is provided with (delays and losses). She obtained both her MEng and 1st Class BEng (Hons) from Staffordshire University in 1999 and 1998 respectively. She is now part of the Mobile Computing and Distributed Systems Research Group at Staffordshire University. She has published 8 research papers focusing on quality of service and access between cellular and IP packet switched networks. Future directions include mobile agents and control of mobile wireless ad-hoc networks. Her current research interests have extended to Wireless Networked Control Systems, specifically looking at NCS over MANETs, with research interests in this area concentrating on the network routing and effect of routing protocols on the NCS system.

Appendix: Explanation and first few packet traces from the trace file

Event type	Time, -t	Id of this node, Hs	Id of next hop to destination, Hd	Node id, Ni	Node x coordinate value, Nx	Node y coordinate value, Ny	Node z coordinate value, Nz	Node energy level, Ne	Trace level, Nl	Reason for the event, Nw	Duration, Ma	Destination Ethernet address, Md	Source Ethernet address, Ms	Ethernet type, Mt	Source address .port number, Is	Destination address.port number, Id	Packet type, It	Packet size, Il	Flow id, If	Unique id, Ii	TTL value, Iv
s	-t 0.000000000	-Hs 0	-Hd -2	-Ni 0	-Nx 10.00	-Ny 200.00	-Nz 0.00	-Ne -1.000000	-Nl AGT	-Nw ---	-Ma 0	-Md 0	-Ms 0	-Mt 0	-Is 0.0	-Id 1.0	-It ncs	-Il 64	-If 0	-Ii 0	-Iv 32
s	-t 0.020000000	-Hs 0	-Hd -2	-Ni 0	-Nx 10.00	-Ny 200.00	-Nz 0.00	-Ne -1.000000	-Nl AGT	-Nw ---	-Ma 0	-Md 0	-Ms 0	-Mt 0	-Is 0.0	-Id 1.0	-It ncs	-Il 64	-If 0	-Ii 2	-Iv 32
s	-t 0.040000000	-Hs 0	-Hd -2	-Ni 0	-Nx 10.00	-Ny 200.00	-Nz 0.00	-Ne -1.000000	-Nl AGT	-Nw ---	-Ma 0	-Md 0	-Ms 0	-Mt 0	-Is 0.0	-Id 1.0	-It ncs	-Il 64	-If 0	-Ii 6	-Iv 32
s	-t 0.060000000	-Hs 0	-Hd -2	-Ni 0	-Nx 10.00	-Ny 200.00	-Nz 0.00	-Ne -1.000000	-Nl AGT	-Nw ---	-Ma 0	-Md 0	-Ms 0	-Mt 0	-Is 0.0	-Id 1.0	-It ncs	-Il 64	-If 0	-Ii 9	-Iv 32
r	-t 0.072726425	-Hs 1	-Hd 1	-Ni 1	-Nx 535.00	-Ny 200.00	-Nz 0.00	-Ne -1.000000	-Nl AGT	-Nw ---	-Ma 13a	-Md 1	-Ms 3	-Mt 800	-Is 0.0	-Id 1.0	-It ncs	-Il 64	-If 0	-Ii 0	-Iv 30
s	-t 0.080000000	-Hs 0	-Hd -2	-Ni 0	-Nx 10.00	-Ny 200.00	-Nz 0.00	-Ne -1.000000	-Nl AGT	-Nw ---	-Ma 0	-Md 0	-Ms 0	-Mt 0	-Is 0.0	-Id 1.0	-It ncs	-Il 64	-If 0	-Ii 11	-Iv 32
r	-t 0.086586700	-Hs 1	-Hd 1	-Ni 1	-Nx 535.00	-Ny 200.00	-Nz 0.00	-Ne -1.000000	-Nl AGT	-Nw ---	-Ma 13a	-Md 1	-Ms 3	-Mt 800	-Is 0.0	-Id 1.0	-It ncs	-Il 64	-If 0	-Ii 11	-Iv 30