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EVALUATION OF PERFORMANCES OF STRUCTURAL CONTROL BENCHMARK PROBLEM WITH TIME DELAYS FROM WIRELESS SENSOR NETWORK

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Abstract

Wireless sensor networks (WSNs) have become a novel approach for structural control of civil structures from natural hazards such as earthquakes and extreme weather conditions. Increasing number of research efforts have been made, both theoretically and experimentally, focusing on WSNs in control systems. Compared with traditional wired sensor networks, WSNs have advantages of low cost and convenience; however, bandwidth and wireless communication delay are issues associated with implementation of wireless control. The effects of wireless communication delay have not been carefully investigated in the wireless control systems. In this paper, a wireless control simulator is proposed which simulates a structural control benchmark model: linear active mass driver (AMD) control model with realistic wireless delay from wireless network environment simulation tool – TOSSIM. The control performance of this benchmark model is evaluated with realistic wireless delay. Later on, this simulator can become a test bed so that different controllers can be tested out in this simulator to evaluate their performances of dealing with time delays in wireless structural control systems.

1 Introduction

Over the last few decades, tremendous efforts have been made on structural control of civil structures from natural hazards such as earthquakes and extreme weather conditions (Casciati & Chen, 2012). Traditionally, structural control systems employ a large amount of cables for communication among sensors, actuators and controllers in an integrated control system (Rice & Spencer, 2009). In such a system, implementation of wired sensors and actuators are usually quite complicated and expensive, especially in large scale structures such as bridges and buildings. To reduce the laborious installation and maintenance cost (Miller et al., 2010), wireless sensor networks (WSNs) are proposed as a new approach for real-time structural control (Bertocco et al., 2008). Wireless sensors are capable of collecting data from structure, communicating with each other and sending back collected data to controller for structural control. With the rapid development of wireless sensor hardware, middleware and application software (Nagayama & Spencer, 2007; Spencer & Yun, 2010), as well as development of wireless control algorithms (Ploplys et al., 2004; Pajic et al., 2011; Lynch et al., 2008), implementation of WSNs into structural control systems has become a very attractive and promising field.

Numerous research works have been done involving WSNs in structural control systems. Researchers at Washington University have implemented wireless sensors on a 3-story steel frame for structural vibration control under earthquake. Magneto rheological (MR) dampers are adopted as actuators in this structural system and a bang-bang clipped optimal control algorithm is used to control the MR damper. The wireless control system has achieved reasonable performance in comparison with wired control system (Liu et al., 2007). Researchers from the University of Michigan deployed wireless sensor network on a six-story building. A partially decentralized control architecture is developed to work with the wireless sensor network. Onboard computation abilities of the smart wireless sensors are utilized for state estimation and desired control force calculation in this experiment. The wireless control system has shown to be effective in controlling the multi-story structure (Swartz & Lynch, 2009). In both of these efforts, WSNs are implemented on experimental structure to evaluate structural control performance and validate control algorithms. Clearly, evaluation of wireless control performance is necessary and important. However, evaluating wireless sensors performance and validating new control algorithms experimentally may not be the only option. In our approach, a wireless control simulator is developed which can simulate wireless control systems and evaluate performance of selected controllers.

In this paper, we made the following contributions. (1) We propose an integrated simulator for wireless structural sensing and control systems. (2) We build realistic wireless sensor model and time division multiple access (TDMA) wireless network model with noise traces and wireless topology from experimental test. (3) The proposed simulator can be used as a testbed for wireless control performance evaluation and wireless control algorithms validation.

2 Wireless control simulator

The proposed wireless control simulator is an integrated system that has three components: structural control component, coordination component and network component. The three components are working interactively during a wireless control simulation. Data generated from structural model in the structural control component goes through the coordination component into the network component. After simulation of wireless network, the network component sends the delayed data back to coordination component, then to structural model for structural control purpose as shown in Figure 1. The detailed function and content of these components are introduced as below.

2.1 Structural control component

The structural control component has structure model block, controller block, sensor block, earthquake input block, A/D and D/A conversion block, etc. The structural control component used in this simulator is from a benchmark structural control model developed by Spencer et al. (1998). This model is benchmark active mass driver (AMD) control model built in Simulink® (MATLAB®) as shown in Figure 2.

To interact with the coordination component, the benchmark AMD Simulink® model is modified as follow. First, the direct link from the quantizer to discrete controller in Simulink® model in Figure 2 is disconnected. Quantized data from simulation goes directly into coordination component. Also, discrete controller receives delayed data from coordination component for control purpose. Second, the full simulation which runs from time 0 to final time is changed to step simulation. In step simulation, AMD model runs for one step, update sensor data to coordination component and delayed sensor data from coordination component to discrete controller; then Simulink® moves to the next time step. After finishing the next step simulation, repeat the same data transmission process.

In the current AMD model, 4 acceleration sensor readings [a_1, a_2, a_3, a_m] from 1st floor, 2nd floor, 3rd floor of the 3-story building with the AMD are used for control force calculation. The controller uses an H2/LQG control algorithm provided with the problem statement. The simulation step in this model is 1msec. And there is a time scale of 1:5 in this Simulink® model which means 1ms in this simulation is 5msec in the real world (see Spencer et al. 1998 for more details of the benchmark problem; also see nees.org for a complete list of all benchmark problems).

Before using delayed sensor data from network component into controller, we need to account for the fact that sensor data from the wireless network simulation can have different delay for each sensor channel. Also, potential packet loss is simulated in the wireless network component. The received delayed data from coordination component has to be stored appropriately. In our approach, a delayed data table is generated for controller to use in each step. After every step simulation, the data in this table is updated based on the delay and sensor data from network component (see Table 1 as an example). If the data is lost in network communication, data from previous step is used.

2.2 Coordination component

The coordination component takes the role of coordinator between the control component and network component. Because these two key components of simulator are implemented in different software, the coordinator is needed to direct their interactions and pass appropriate information between the two portions of the simulator. The coordination component also isolates these two key components. Note that the control and network components are running independently from each other, connected only by the coordinator.

2.3 Network component

Network component is the other key component of this simulator. It simulates sensor sampled data going through wireless communication to base station for control purpose. Multi-hop and packet loss are considered in this network part. Also, to simulate wireless network communication realistically, noise traces and wireless topology from a 3-story building in Washington University in St. Louis is used in this simulator. The noise traces and wireless topology are put into network simulation tool – TOSSIM (Levis et al., 2003; Lee et al., 2007). TOSSIM builds a probabilistic wireless communication model based on the realistic noise traces, wireless topology, routing protocol, etc. Also, TDMA network model is adopted in our simulator. TDMA gives 10msec time slot (Han et al., 2011) to each sensor in our model. Within each time slot, only one sensor is transmitting data back to base station. This is a relatively conservative strategy, but can avoid network conflict between sensors. The 10msec time slot equals two Simulink® time steps because of the 1:5 time scale in the AMD model.

As the sampling rate of sensors in the AMD model is higher than the network communication rate, a strategy for data transmission has to be defined. For control purpose, the “fresh” data with less delay leads to better control performance. So when one sensor is transmitting data in its TDMA time slot, it should transmit the latest sampled data.

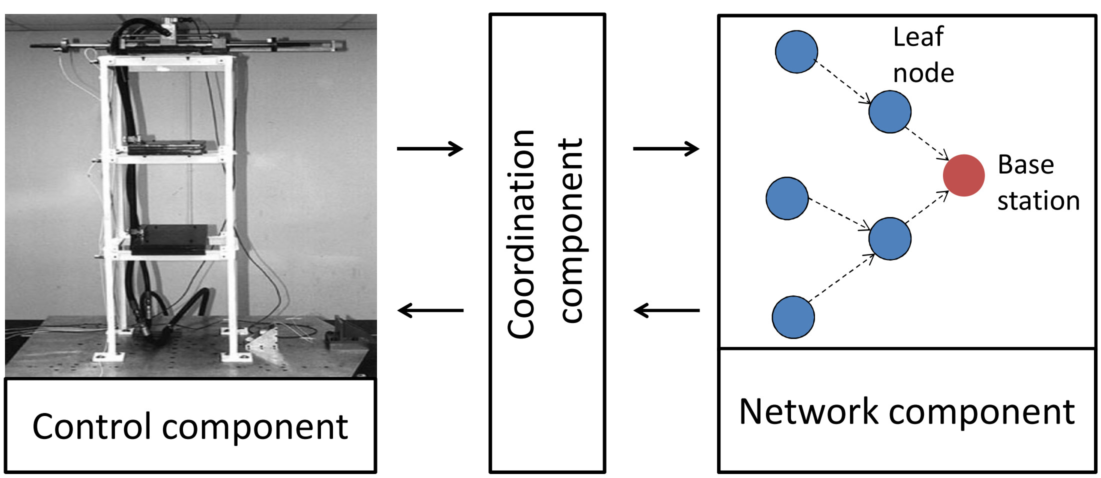

Figure 1. Integrated simulator architecture

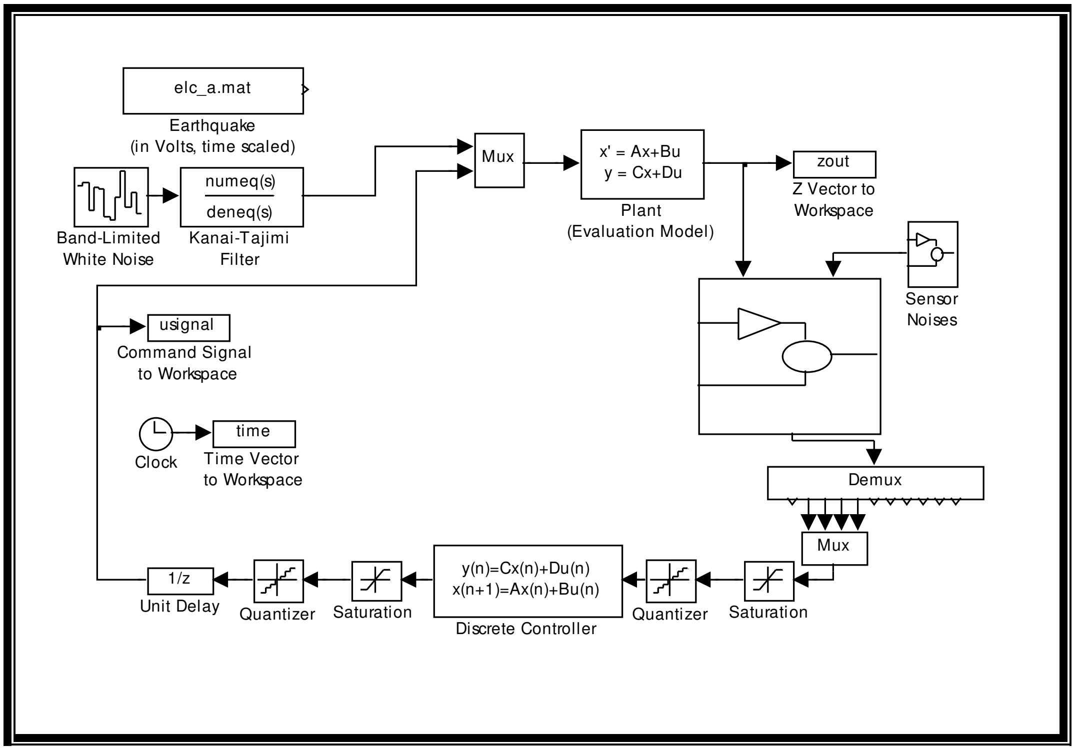

Figure 2. Simulink® model for benchmark active mass driver (AMD) control problem

Table 1. Sample data table (a), and delayed data table (b)

Step \ Sensor	1	2	3	4
i	Di_1	Di_2	Di_3	Di_4
i+1	Di+1_1	Di+1_2	D1+1_3	Di+1_4
i+2	Di+2_1	Di+2_2	D1+2_3	Di+2_4
i+3	Di+3_1	Di+3_2	D1+3_3	Di+3_4
i+4	Di+4_1	Di+4_2	D1+4_3	Di+4_4
i+5	Di+5_1	Di+5_2	D1+5_3	Di+5_4

(a) Data generated from i to i+5 step

Step \ Sensor	1	2	3	4
i+j	Di_1			
i+1+j		Di_2		
i+2+j				
i+3+j			Di_3	
i+4+j				
i+5+j				Di_4

(b) Delayed i^{th} step data for controller

3 Evaluation criteria and simulation results with constant delay

Certain evaluation criteria should be defined to evaluate the simulation with wireless delays. These evaluation criteria serve as bases for comparing different controllers' performance of dealing with wireless network delay. From the original benchmark AMD control problem (Spencer et al., 1998), the following evaluation criteria *J1- J5* are adopted. Two additional evaluation criteria *J6* and *J7*are added which are more sensitive to system going unstable.

$$J_1 = \max_{\omega_g,\xi_g}\left\{\frac{\sigma_{d_1}}{\sigma_{x_{3o}}},\frac{\sigma_{d_2}}{\sigma_{x_{3o}}},\frac{\sigma_{d_3}}{\sigma_{x_{3o}}}\right\} \tag{1}$$

$$J_2 = \max_{\omega_g,\xi_g}\left\{\frac{\sigma_{\ddot{x}_{a1}}}{\sigma_{\ddot{x}_{a3o}}},\frac{\sigma_{\ddot{x}_{a2}}}{\sigma_{\ddot{x}_{a3o}}},\frac{\sigma_{\ddot{x}_{a3}}}{\sigma_{\ddot{x}_{a3o}}}\right\} \tag{2}$$

$$J_3 = \max_{\omega_g,\xi_g}\left\{\frac{\sigma_{x_m}}{\sigma_{x_{3o}}}\right\} \tag{3}$$

$$J_4 = \max_{\omega_g,\xi_g}\left\{\frac{\sigma_{\dot{x}_m}}{\sigma_{\dot{x}_{3o}}}\right\} \tag{4}$$

$$J_5 = \max_{\omega_g,\xi_g}\left\{\frac{\sigma_{\ddot{x}_{am}}}{\sigma_{\ddot{x}_{a3o}}}\right\} \tag{5}$$

$$J_6 = \max_{\omega_g,\xi_g}\left\{\max_t\left\{\frac{|d_1(t)|}{d_{1_o}},\frac{|d_2(t)|}{d_{1_o}},\frac{|d_3(t)|}{d_{1_o}}\right\}\right\} \tag{6}$$

$$J_7 = \max_{\omega_g,\xi_g}\left\{\max_t\left\{\frac{|\ddot{x}_1(t)|}{\ddot{x}_{3_o}},\frac{|\ddot{x}_2(t)|}{\ddot{x}_{3_o}},\frac{|\ddot{x}_3(t)|}{\ddot{x}_{3_o}}\right\}\right\} \tag{7}$$

where ω_g, ξ_g are parameters of Kanai-Tajimi spectrum (see Spencer et al., 1998 for more detail) which is commonly used for simulated earthquake input. Here we choose ω_g =37.3 rad/sec, ξ_g=0.3. $\sigma_{x_{3o}}$ is the stationary rms displacement of the 3rd floor of the uncontrolled building, $\sigma_{\dot{x}_{3o}}$ is the stationary rms velocity of the 3rd floor of the uncontrolled building, $\sigma_{\ddot{x}_{a3o}}$ is the stationary rms acceleration of the 3rd floor of the uncontrolled building, d_{1_o} is the peak interstory drift of the 1st floor of the uncontrolled building and $\ddot{x}_{3_o}$ is the peak acceleration of the 3rd floor of the uncontrolled building.

Before evaluation the control performance of AMD model with realistic wireless network delay, constant delays are first added to the 4 sensor channels to examine the controlled performance. Peak interstory drift and peak accelerations are obtained for uncontrolled AMD model, controlled without delay model and controlled with 2-step constant delay up to 11-step constant delay model as shown in Figure 3 (a)-(b). Based on these simulation results, the system goes unstable after 8-step constant delay. In order to achieve a more indepth understanding, Monte Carlo simulations are performed with simulated earthquake input following Kanai-Tajimi spectrum. 1000 simulations are accomplished and the results for *J6* and *J7* criteria (the sensitive criteria for system unstable) with 8-step and 9-step constant delay are shown in Figure 4 (a)-(d). The red line in these plots is the threshold for system instabilities. From the results, it is clear that in most cases, *J6* criterion is satisfied with 8-step or 9-step delay; however, considering the *J7* criterion, it is clear that the behavior of the closed-loop system degrades with a 9-step delay.

4 Evaluation of simulation with realistic delay from TOSSIM

After evaluation with constant delay, control performances are evaluated with realistic delays from TOSSIM. The noise traces and wireless topology in TOSSIM are collected using TelosB sensors (Polastre et al., 2005) with 802.15.4 compliant CC2420 radio chip within a 3-story building on the Washington University in St. Louis campus. Wireless topology and wireless noise traces of two different wireless channels are collected. One of the channels is noisy channel that has overlapping area with WiFi spectrum (Sha et al., 2011). The other channel is relatively clean which has no overlapping area with WiFi. The wireless network delay simulated in TOSSIM for these two channels with TDMA network and wireless network delay from ideal TDMA network are applied in AMD model. Here we did not run the integrated simulator interactively, but sequentially used the simulated delays from TOSSIM in the AMD Simulink® model.

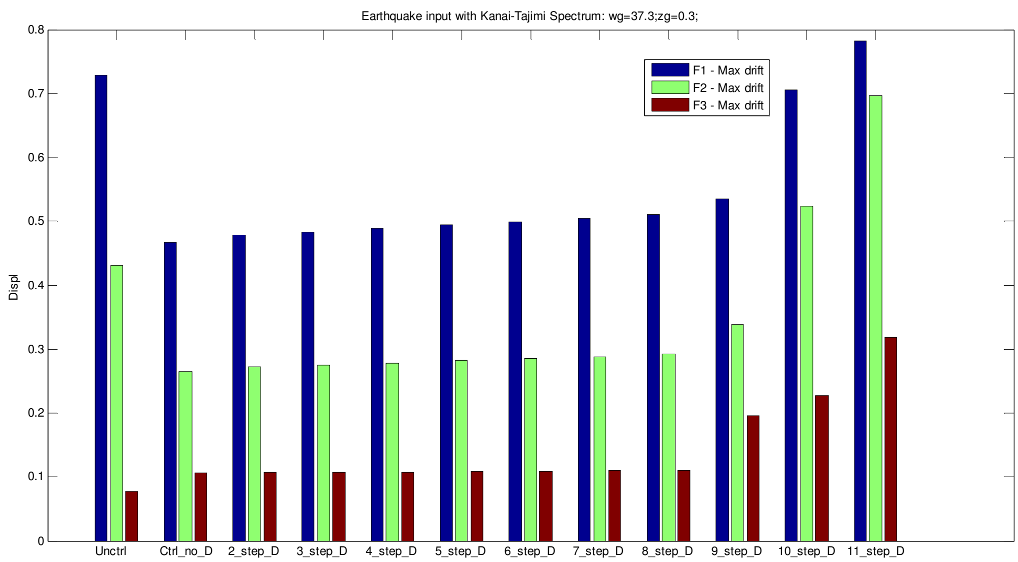

Figure 3(a). Peak interstory drift of 3 floors with different constant delay

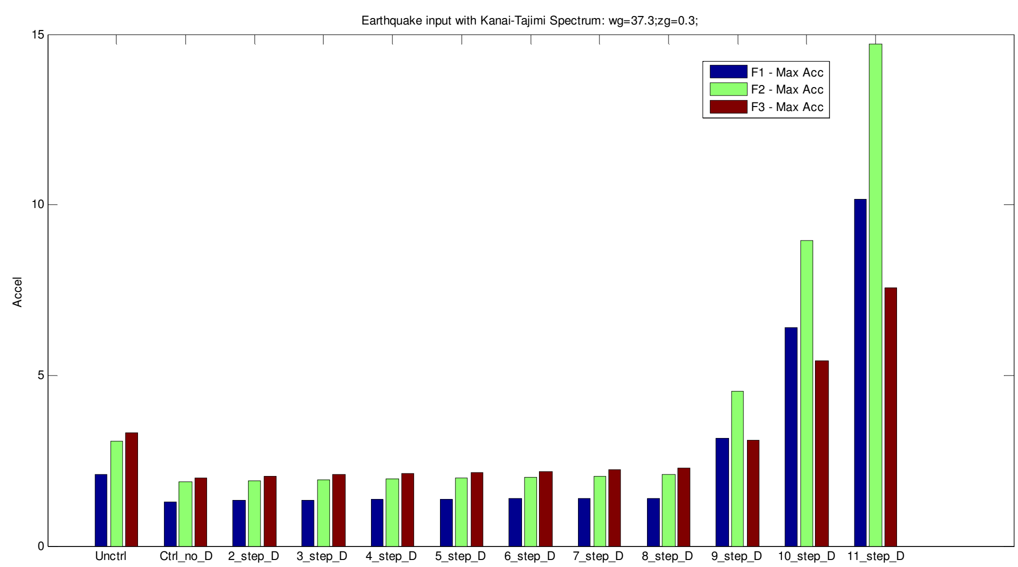

Figure 3(b). Peak acceleration of 3 floors with different constant delay

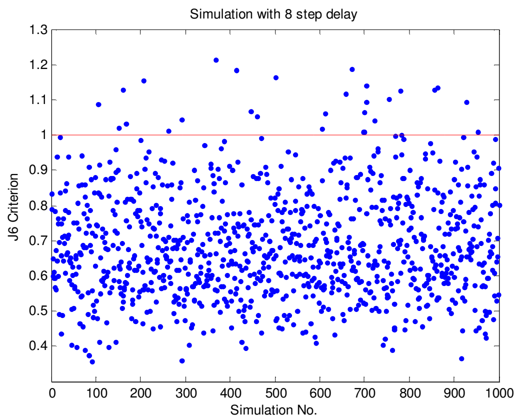

Figure 4(a). ***J6*** **sim with 8-step delay**

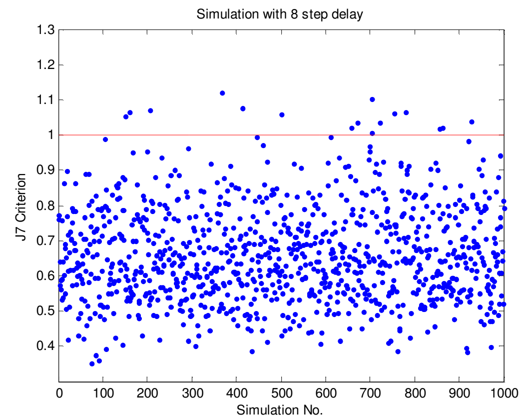

Figure 4(b). ***J7*** **sim with 8-step delay**

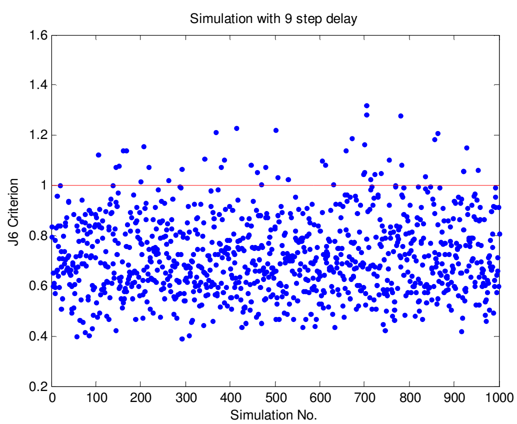

Figure 4(c). ***J6*** **sim with 9-step delay**

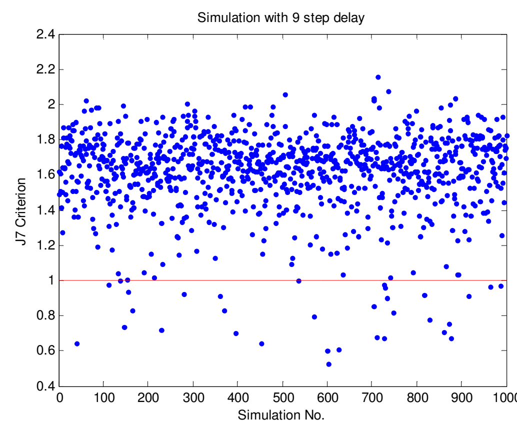

Figure 4(d). ***J7*** **sim with 9-step delay**

The evaluation results with ideal TDMA network, light noise TDMA network and heavy noise TDMA network are shown in Table 2 for EI Centro earthquake input, Hachinohe earthquake input and one realization of simulated earthquake follow Kanai-Tajimi spectrum. From the results, observe the performances of light noise TDMA network are almost identical as ideal TDMA network. The performances of heavy noise TDMA network are slightly worse than the previous two cases. From these evaluations, the impact of heavy noise TDMA is not significant compared with ideal and light noise TDMA network. Figure 5 shows the time history measurements of the interstory drifts of floor 1-3 (d1-d3) and 1st and 3rd floor accelerations (Acc1 and Acc3) for uncontrolled model, controlled without delay model and heavy noise TDMA model under EI Centro earthquake. The TDMA with heavy noise model matches well with the controlled case, which explains why the evaluation performances for heavy noise TDMA are close to those using the ideal TDMA. The influence of TDMA is minimal since we are not using a very aggressive controller. If one aggressive controller is adopted, the system may go unstable even with ideal TDMA network. This question will be investigated in the future.

Table 2. Simulation results with realistic wireless communication delay

		J1	J2	J3	J4	J5	J6	J7
EI Centro	Ideal TDMA	0.288	0.414	0.488	0.497	0.041	0.648	**0.719**
	Light noise	0.289	0.414	0.488	0.497	0.041	0.648	0.717
	Heavy noise	**0.292**	**0.418**	**0.489**	**0.502**	**0.044**	**0.649**	0.713
Hachinohe	Ideal TDMA	**0.297**	0.441	**0.545**	0.563	0.052	0.794	0.695
	Light noise	0.296	0.441	0.544	0.562	0.053	0.794	0.695
	Heavy noise	**0.297**	**0.443**	0.544	**0.569**	**0.057**	**0.802**	**0.712**
K-T	Ideal TDMA	0.322	0.530	0.456	0.435	0.061	0.826	0.734
	Light noise	0.322	**0.531**	**0.457**	0.436	0.061	0.826	**0.735**
	Heavy noise	0.322	**0.531**	**0.457**	**0.440**	**0.063**	0.826	0.724

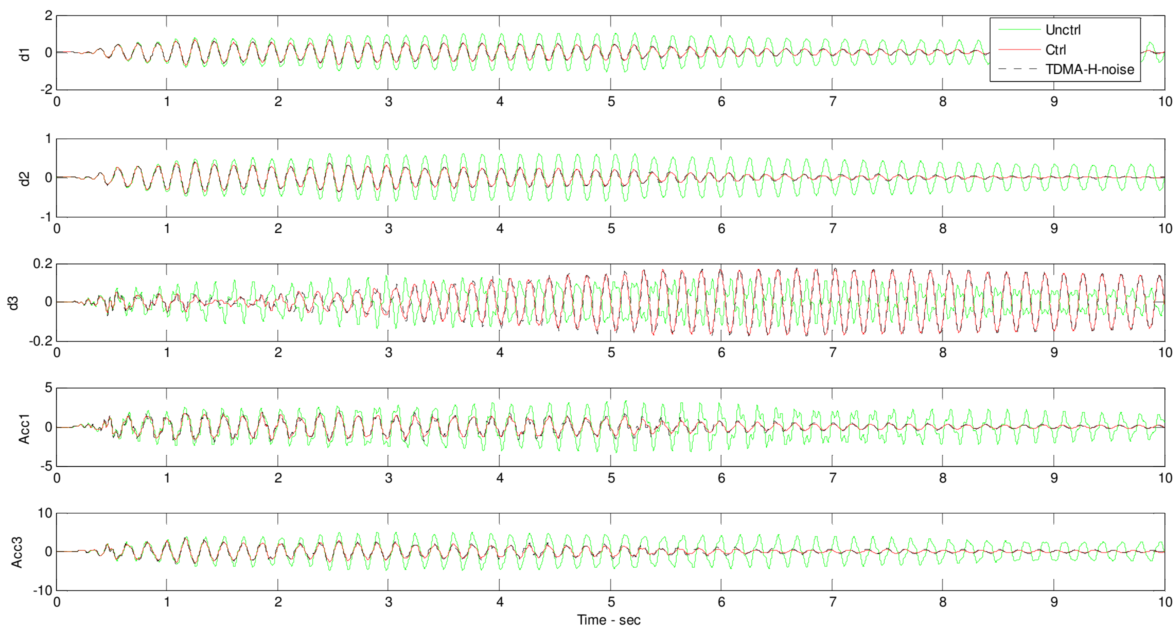

Figure 5. Responses of uncontrolled model, controlled model and TDMA with heavy noise model under EI Centro Earthquake

5 Conclusions

In this paper the authors have proposed an integrated wireless sensing and control system simulator. The newly developed system is used here for evaluating the performance of wireless control systems. The framework and functions of the components of the simulator are explained in detail. Seven evaluation criteria are introduced for this benchmark AMD model with delayed sensor measurements. Realistic TDMA wireless network delays are included in the simulation of the network component. The performance of the current controller is evaluated and compared under different noise level TDMA networks. Other applications of the new simulation tool will soon follow.

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