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Wireless Cyber-Physical Simulator and Case Studies on Structural Control

by

Bo Li

A thesis presented to the Graduate School of Arts and Sciences
of Washington University in partial fulfillment of the
requirements for the degree of

Master of Science

August 2013
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The whole work of mine is dedicated to the Li's family, for her always pursuing usefulness of the Science and goodness of the Human Being.

Bo Li

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August 2013

ABSTRACT OF THE THESIS

Wireless Cyber-Physical Simulator and Case Studies on Structural Control

by

Bo Li

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Washington University in St. Louis, August 2013

Research Advisor: Dr. Chenyang Lu

Wireless Structural Control (WSC) systems can play a crucial role in protecting civil infrastructure in the event of earthquakes and other natural disasters. Such systems represent an exemplary class of cyber-physical systems that perform close-loop control using wireless sensor networks. Existing WSC research usually employs wireless sensors installed on small lab structures, which cannot capture realistic delays and data loss in wireless sensor networks deployed on large civil structures. The lack of realistic tools that capture both the cyber (wireless) and physical (structural) aspects of WSC systems has been a hurdle for cyber-physical systems research for civil infrastructure. This advances the state of the art through the following contributions. First, we developed the Wireless Cyber-Physical Simulator (WCPS), an integrated environment that combines realistic simulations of both wireless sensor networks and structures. WCPS integrates Simulink and TOSSIM, a stateof- the-art sensor network simulator featuring a realistic wireless model seeded by signal traces. Second, we performed two realistic case studies each combining a structural model with wireless traces collected from real-world environments. The building study combines a benchmark building model and wireless traces collected from a multi-story building. The bridge

study combines the structural model of the Cape Girardeau bridge over the Mississippi River and wireless traces collected from a similar bridge (the Jindo Bridge) in South Korea. These case studies shed light on the challenges of WSC and the limitations of a traditional structural control approach under realistic wireless conditions. Finally, we proposed a cyber-physical co-design approach to WSC that integrates a novel holistic scheduling scheme (for sensing, communication and control) and an Optimal Time Delay Controller (OTDC) that substantially improves structural control performance.

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Chapter 1

Introduction

Wireless Structural Control (WSC) is a promising cyber-physical system technology for protecting our civil infrastructure in the event of earthquakes and other natural disasters. A WSC system employs a feedback control loop to control the dynamic response of a civil structure based on sensor data collected through wireless sensor networks. As a representative example of cyber-physical systems, a WSC system requires holistic system designs that crosscut cyber (wireless and control) and physical (structural dynamics) components.

Since deployments of control systems on large civil structures (e.g., bridges and buildings) are costly and labor intensive, to date WSC systems have mostly been evaluated using wireless sensors installed on small lab structures. Unfortunately, such networks cannot capture the delays and data loss in wireless sensor networks deployed on large civil structures in real-world environments. There is a critical need for simulation tools and case studies that realistically model wireless characteristics and the structural dynamics of WSC systems.

To meet this challenge in WSC research, we have developed a simulator specifically designed to support realistic simulations of wireless cyber-physical systems. Specifically, the contributions of this thesis are three-fold:

- First, we describe the *Wireless Cyber-Physical Simulator(WCPS)*, an integrated environment that combines realistic simulations of both wireless sensor networks and structures. WCPS integrates Simulink **??** and TOSSIM **??**, a state-of-the-art sensor network simulator featuring a realistic wireless model seeded by real-world wireless traces.

- Second, we present two realistic case studies each matching a structural model with wireless traces collected from real-world environments. The *building study* combines a benchmark building model and wireless traces collected from a multi-story building. The *bridge study* combines the structural model of the Cape Girardeau Bridge over the Mississippi River and wireless traces collected from a similar bridge (the Jindo Bridge) in South Korea. These case studies shed lights on the challenges of WSC and the limitations of traditional structural control approaches.

- Finally, we propose a *cyber-physical co-design* approach to WSC that integrates a holistic scheduling scheme (including sensing, communication and control) and an Optimal Time Delay Controller (OTDC), which substantially improves structural control performance in the presence of wireless communication delay and packet loss.

While this thesis focuses on WSC as case studies, the WCPS tool can be used to simulate other wireless control systems. Furthermore, our cyber-physical co-design approach and insights from the case studies can be generalized to other cyber-physical systems, especially large-scale wireless control systems. WCPS has been released as open-source software at

The rest of the thesis is organized as follows. Chapter 2 reviews related works. Chapter 3 presents the WCPS simulator. Chapter 4 describes explicit designs of the case studies. Chapter 5 details the cyber-physical co-design approach to wireless control. Chapter 6 presents the results of the case studies. Chapter 7 concludes the thesis.

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Chapter 2

Related Works

Wireless Structural Health Monitoring(WSHM) research has been active in the past decade [13, 16]. Recent efforts for WSHM include: a distributed wireless sensing system for WSHM [22], the first wireless system deployed on a tower of over 600 meters tall [24] , a networked computing approach in WSHM [15], a high quality sensor placement study for WSHM [21], a cyber-physical co-design of wireless distributed structural health monitoring [12], the largest wireless bridge monitoring system in the world [14] and Torre Aquila deployment for heritage building monitoring [6], to name a few.

However, close-loop wireless control for civil structures is still in its infancy. While early efforts developed control algorithms and prototype wireless control systems [23, 33, 34], all the previous experiments were performed on small-scale lab structures. In the lab settings, wireless sensors within a single hop and experience no data loss due to physical proximity of the devices.

Wireless control has been studied with promising results in other domains [3–5, 25]. The challenge in realistic experimentation with WSC systems motivates the development of our WCPS and case studies based on real-world wireless traces and realistic structural models. Our work thus expands the field of wireless control to the civil infrastructure domain. Moreover, WCPS can also be used to simulate other large-scale wireless control systems, and our scheduling-control co-design approach may be generalized to other wireless control systems. Research works using WCPS yet with more focus on civil structural analysis are introduced in [31, 32]

Truetime [7] is a well established control system simulator that enables holistic studies of CPU scheduling, communication and control algorithms. While Truetime supports wirelss networks, its wireless models are relatively simple and do not capture complex properties of wireless sensor

networks such as probabilistic and bursty packet receptions and irregular radio properties [18]. In addition, Truetime implements wireless models within Simulink. While a native implementation may improve efficiency, it cannot leverage existing wireless simulators that implement sophisticated wireless models.

NCSWT [11] is a recent simulator for wireless cyber-physical systems. Instead of implementing wireless simulations natively, it integrates with the NS-2 simulator with support for wireless networks. While WCPS shares a similar federated approach to incorporate an existing wireless simulator, we choose to integrate WCPS with TOSSIM [19] which features a more realistic wireless sensor network model than NS-2. Despite its wide adoption as a network simulator, the wireless models in NS-2 [11] suffers from being incapable of capturing the probabilistic and irregular packet receptions that are common in low-power wireless networks. Leveraging noise traces and statistical models, TOSSIM can capture complex temporal link dynamics that are crucial for realistic cyber-physical systems modeling. As the standard TinyOS simulator, TOSSIM has been widely used for wireless sensor network research and has been validated in diverse real-world environments [18]. Moreover, the trace-driven simulation approach of TOSSIM enables us to study the impacts of different wireless environments. We also provide the first set of realistic case studies based on real-world wireless traces, as well as a novel scheduling-control co-design approach to WSC.

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Chapter 3

Wireless Cyber-Physical Simulator

WCPS supports a general wireless control system model shown in Fig. 3.1. A wireless control system consists of a set of wireless sensors, a controller and a set of actuators. The sensors form a wireless mesh network connected with a base station hosting the controller. Since the controller is usually located close to the actuators in WSC systems, we assume the base station and actuators are connected by a wired network whose latency is negligible compared to that in the wireless sensor network. Following the centralized network management approach of the WirelessHART standard [28, 29], WCPS employs a centralized network manager to compute routing and transmission schedules for the wireless sensor network.

This chapter describes the design and implementation of WCPS [1].

WCPS employs a federated architecture that integrates (1) Simulink for simulating the physical system (structural) dynamics and the controller and (2) TOSSIM for simulating the wireless sensor network. Simulink has been widely used by control and structural engineers to design and study structural control systems, while TOSSIM is specifically designed to simulate wireless sensor networks based on realistic wireless link models that have been validated in diverse real-world environments [18]. By combining Simulink and TOSSIM, WCPS provides an integrated environment to simulate wireless control systems in a holistic and realistic fashion.

As shown in the architecture illustrated in Fig. 3.1, WCPS simulates the feedback control loop of the control system as follows. Sensor data is generated from structural models. Through a cross-platform function call from Simulink, sensor data is injected to the corresponding wireless sensors in TOSSIM. Following the routes and transmission schedule calculated by the network manager module, TOSSIM simulates the end-to-end wireless communication of the sensor data
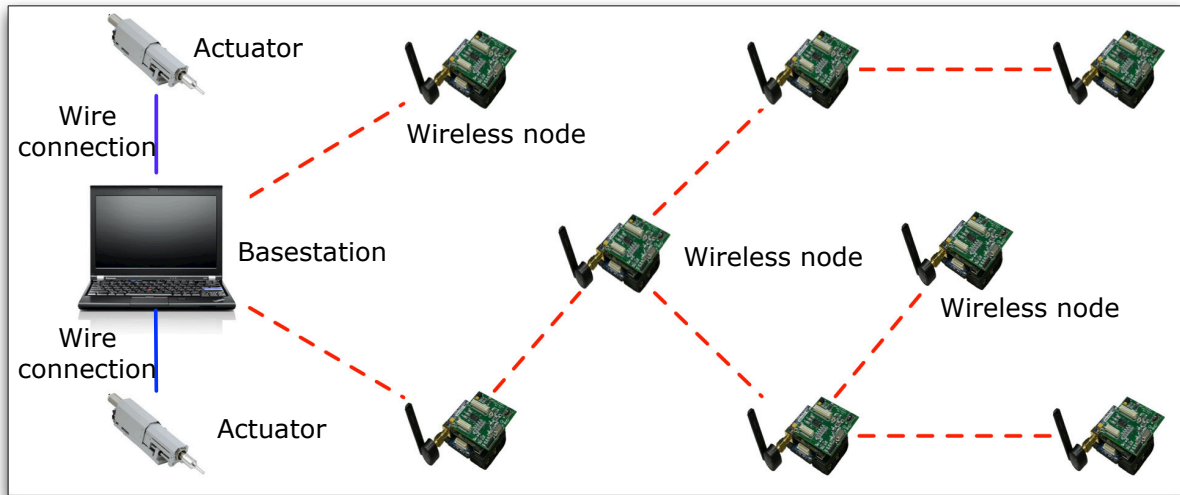
Figure 3.1: WSC System Model.

packets from the sensors to the base station, and then return the packet delay and loss to the Interfacing Block in Simulink through the Python interface. The Packet Collector module then to extracts packet delivery information(the delay and loss) from the message pool of returned values in Simulink. Sensor data and their loss and delay are then provided to the Data Block, which then feed the sensor data to the controller at the right time based on the packet delay (if the packet is not lost). WCPS utilizes basic API (e.g., the dos, UNIX command) of MATLAB to do cross-platform function calls. In TOSSIM, we re-implement a *printf* method in TinyOS to send TOSSIM simulation results to the Interfacing Block.

User inputs to WCPS includes excitation signals to the structure (e.g., acceleration caused by earthquakes) and wireless traces used as input to TOSSIM. Excitation signal of the structure is provided to the structure models in the format of MAT files.

The scheduler module calculates transmission schedules. Networking schedule is then deployed into the MAC layer code of wireless nodes and becomes effective after a TinyOS compilation. The TDMA MAC layer in WCPS is developed based on the MAC Layer Architecture (MLA) library [17] and further adapted for TOSSIM under TinyOS 2.1.1. Received Signal Strength Indication(RSSI) and wireless noises traces are collected from real-world environments and provided to the wireless model [18] used by TOSSIM for realistic wireless network simulations.
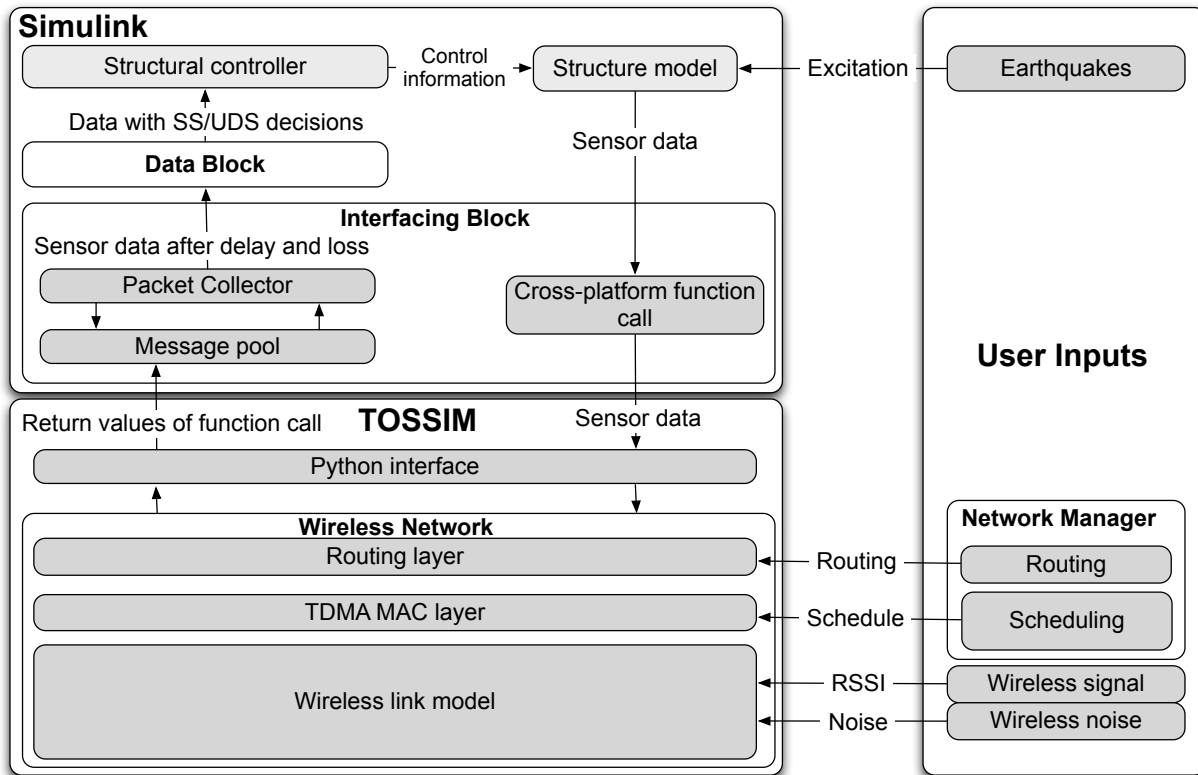
Figure 3.2: Component architecture of WCPS.

As shown in Fig. 3.2, the interfaces between the Simulink model and TOSSIM are encapsulated as two MATLAB embedded functions in Simulink: the Interfacing Block and the Data Block. The Interfacing Block extracts delay and loss information from TOSSIM messages, and the Data Block decides what data will be used for discrete control during each sampling period. The federated architecture of WCPS provides great flexibilities to incorporate different structural models and implement alternative scheduling-control approaches. Further details about WCPS (including user manual, documentation and the source code) is available at http://wcps.cse.wustl.edu.

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Chapter 4

Case Study Design

This chapter presents the design of the case studies on wireless control of a three-story building and a bridge, respectively.

4.1   Excitation Signal

To study structural response to an earthquake, we use measurements from a real earthquake as the excitation signal in both case studies. As shown in Fig. 4.1 the excitation signal was recorded at the Imperial Valley Irrigation District substation in El Centro, California, during the Imperial Valley, California earthquake of May 18, 1940 [10]. The EI Centro earthquake lasted 50 seconds with a maximum acceleration of $3m/s^2$ at the beginning.

4.2   Design the Building Study

4.2.1   Wireless trace collection

The wireless sensor network in the building design comprises a base station and four distributed sensors. Wireless traces were collected from Bryan Hall of Washington University. The base station is located on floor 3, and the wireless sensors (TelosB motes [26]) are placed on floor 0, 1, 2, and 3, respectively. The sensors record RSSI and noise traces on channel 26 of the IEEE 802.15.4 radio. Each TelosB mote is equipped with a Chipcon CC2420 radio with its transmission
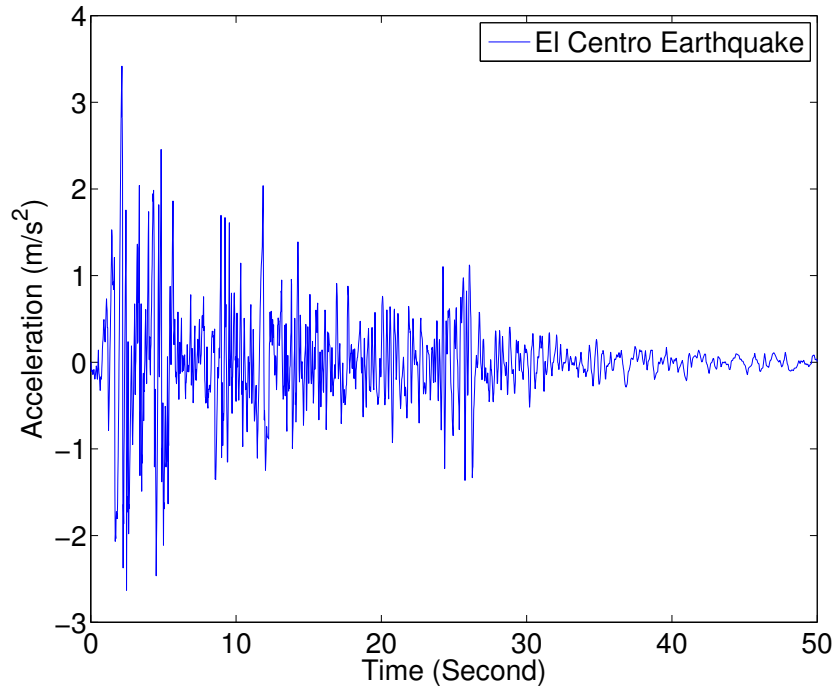
Figure 4.1: The El Centro earthquake as excitation signal of structural control [10] [30].

power set to 0 dBm. Our measurements show that the wireless signal of the TelosB motes can go through at most two floors. As a result the sensor on floor 0 needs a multi-hop route to send data to the base station on floor 3.

4.2.2 Building model

Our building model is based on a three-story test structure shown in Fig. 4.2(a) [30]. The test structure is subject to one-dimensional ground motion. The frame is constructed of steel, with a height of 158 cm. For control purposes, a simple implementation of an Active Mass Driver (AMD) is placed on the 3rd floor of the test structure (see Fig. 4.2(b)). The AMD actuation system has a single hydraulic actuator with steel masses attached to the ends of the piston rod. Since hydraulic actuators are inherently open-loop unstable, position feedback is employed to stabilize the actuator. The position of the actuator is obtained from an LVDT (linear variable differential transformer), rigidly mounted between the end of the piston rod and the third floor. The first three modes of

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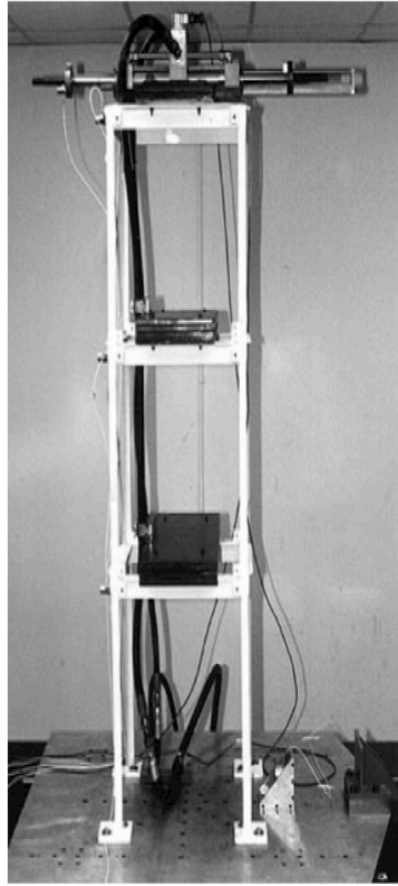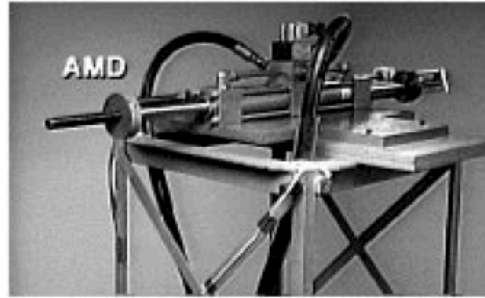
Figure 4.2: Building control system [30]: (a) The 3-story test structure; (b) Active Mass Driver actuation system.

the test structure are 5.81 Hz, 17.68 Hz and 28.53 Hz, with associated damping ratios of 0.33%, 0.23%, and 0.30%, respectively [30].

We developed a Simulink model (shown in Fig. 4.3) with reference to the steel test structure at a 1:1 ratio. The Simulink model is designed to simulate a real-world three-story building, with mapping ratios of: force = 1:60, mass = 1:206, displacement = 4:29 and acceleration = 7:2, and time =1:5. Since the time scales of the Simulink model and a real-world building have a 1:5 ratio, the natural frequencies of the model are approximately five times as large as those of a real-world building. Previous Simulink implementations of the building model was modeled as a continuous system and a time step of 0.0001 second was used to reduce integration errors. In WCPS we
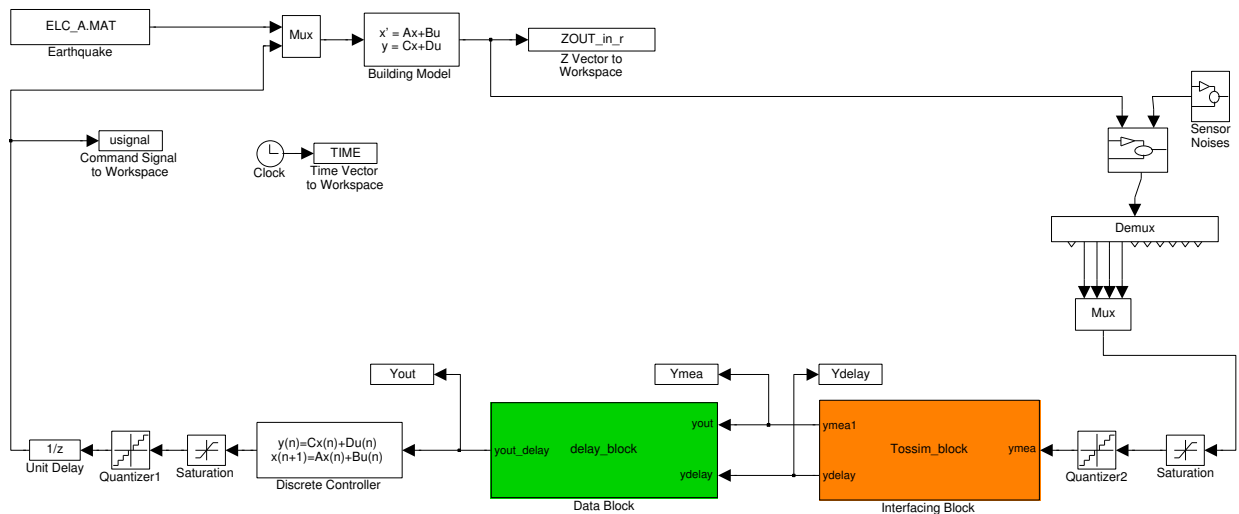
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Figure 4.3: Simulink diagram for wireless building control.

further discretize the Simulink model and perform step-by-step simulations with a step length of 1 ms, which corresponded to 5 ms in a real-world building. As the network used 10 ms slots for TDMA, a slot in the simulated wireless network therefore correspond to two run steps of the Simulink model.

As shown in Fig. 4.3, the structural response signal is first generated by the building model, then converted by the Analog to Digital Converter (ADC) to digital values, and fed to TOSSIM. TOSSIM delivers the sensor data along with its status (loss and delay) to the discrete controller. The output of the controller is then converted from digital values to analog signals by the Digital to Analog Converter (DAC). Eventually, sensor data with control information are fed back to the building model, which closes the control loop.

4.3 Design the Bridge Study

The bridge study simulates wireless control of the Cape Girardeau bridge in Missouri, USA. The cable-stayed bridge (see Fig. 4.7(b)) is the Missouri 74 Illinois 146 bridge spanning the Mississippi River near Cape Girardeau, Missouri, designed by the HNTB Corporation. Since no wireless sensors have been deployed on the bridge, we opt to use wireless traces collected from a wireless

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sensor network deployed on the Jindo bridge [14], South Korea, which shares similar dimensions (e.g., tower height and span range) and designs with the Cape Girardeau bridge. The sensor placement of the Jindo deployment is then mirror mapped onto the Cape Girardeau bridge. This approach takes advantage of the flexibility of WCPS to combine structural models and wireless traces from different (but similar) structures for integrated WSC simulations.
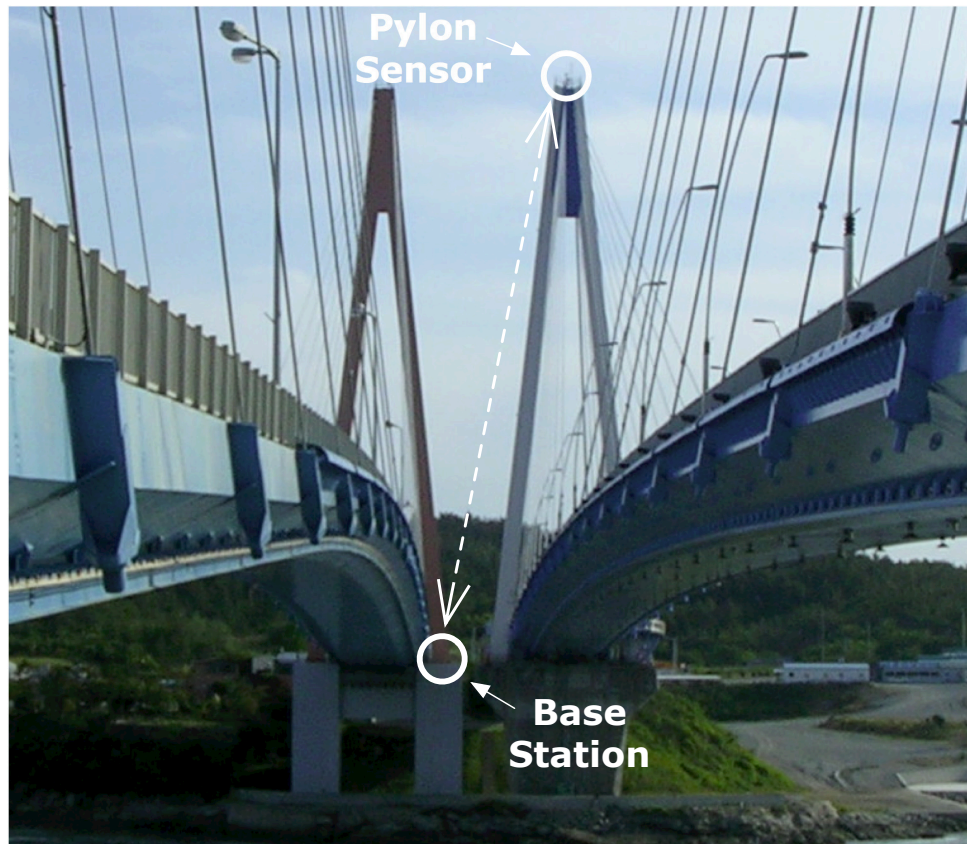
Figure 4.4: Wireless pylon sensor and base station placement on the Jindo bridge.

4.3.1 Wireless trace collection

The Jindo deployment utilizes the MEMSIC Imote2 platform and a total of 113 Imote2 sensor nodes with 659 distinct sensor channels. Each node integrates the Imote2, the ISM400 sensor board, and a rechargeable battery supplied by a solar panel. Combined with the Illinois SHM Services Toolsuite [2], these powerful nodes allow for synchronized data collection, aggregation,
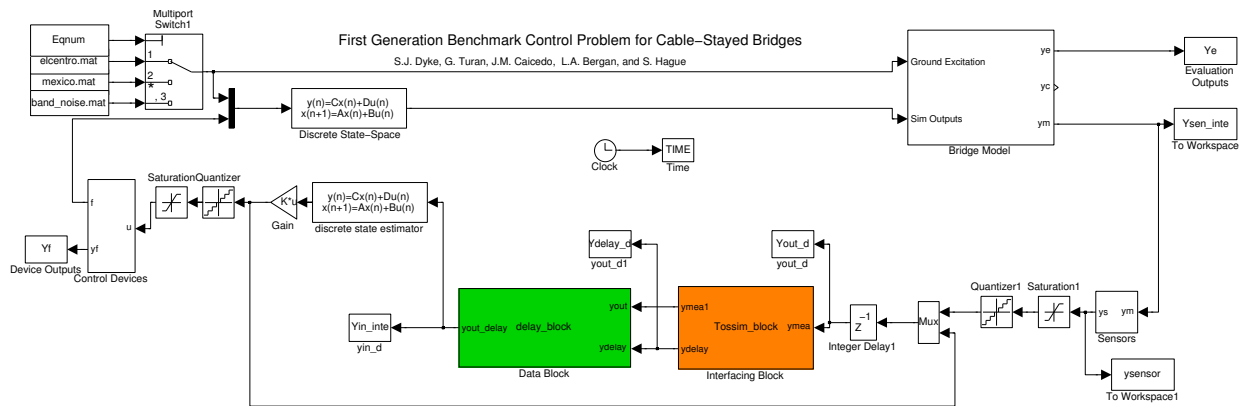
Figure 4.5: Simulink diagram for wireless bridge control.

synthesis and decision-making in real time. The system has successfully captured ambient traffic loading with peak acceleration ranging from less than 5 mg to over 30 mg. Further analysis of the data resulted in the successful identification of the first twelve modes of vibration on the deck, as well as tension forces of 10 cables with large tensile stresses [14]. To serve as input to the TOSSIM simulation, a subset of Imote2 nodes located along deck of the bridge and sensors on the top of the pylons are selected for wireless trace collection. With wireless traces collected from the Jindo bridge, we are able to build a 58-node routing network in TOSSIM for the Cape Girardeau bridge.

During our wireless trace collection on the Jindo bridge, sensors located on the top of the pylons pose a special case for trace collection. Whereas the sensors on the bridge deck form a connected graph, the pylon nodes are isolated. Due to the height of the pylons, these nodes are outside the maximum radio range of the deck nodes. In our Jindo deployment, pylon sensors are fitted with directional antennas, which are pointed away from the bridge deck towards a base station, located on the nearby Jindo Bridge(see Fig. 4.4). For the purpose of modeling a connected network, the real link quality measurements between the pylon sensor and base station node are mapped onto a virtual link in TOSSIM. During the network mapping, as the distances involved in Jindo bridge and Cape Girardeau bridge are similar and both bridges are in open areas, we assume this network mapping would correspond closely to a real wireless network setup.

Based on the structural model [10] we select sensor 240 and 353 located on the tow towers of the Cape Girardeau bridge, sensors 151 and 185 at the foots of towers and sensor 34 in the mid-span for structural control. Acceleration and displacement readings from the five selected sensors are sent to the base station located near sensor 185 using routes with the minimum ETX in the network.
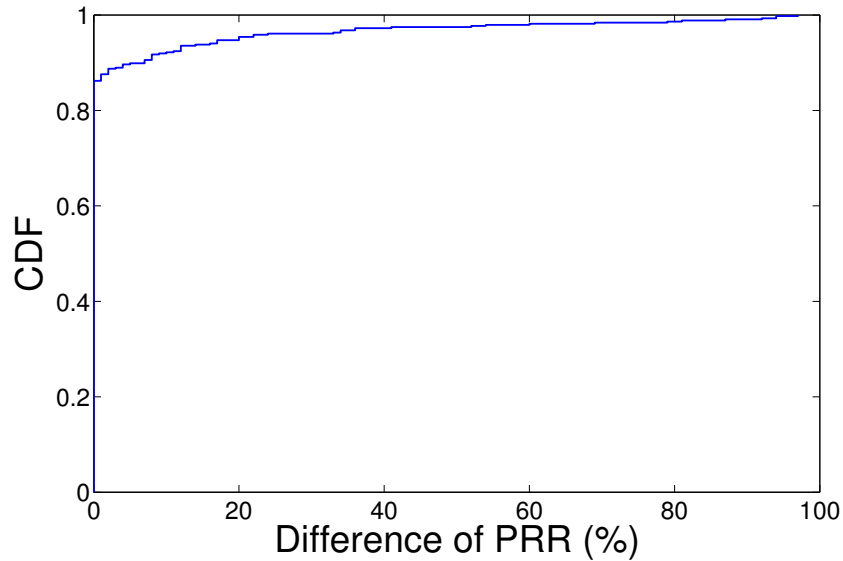
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Figure 4.6: PRR Difference between field measurement and TOSSIM simulation.

To test the accuracy of the TOSSIM simulation, we implement a test application in TOSSIM and compare the Packet Reception Ratio (PRR) of the simulation with that from the field test in Jindo. Fig. 4.6 plots the Cumulative Distribution Function (CDF) of the PRR difference between the field measurements and the TOSSIM simulations for all 467 wireless links. Of all the wireless links, over 85% of them have the same PRR in the field measurements and the simulation, indicating TOSSIM can deliver high fidelity link simulations based on real-world traces.

4.3.2   Bridge model

A high-fidelity Cape Girardeau bridge model (see Fig. 4.7(b)) was incorporated in WCPS for bridge control. A linear evaluation model was used for evaluation of the benchmark bridge model. However, the stiffness matrices used in this linear model are those of the structure determined through a nonlinear static analysis corresponding to the deformed state of the bridge with dead loads. Experimental study indicates that the longitudinal direction of the bridge is most destructive [10].

For control purposes the joints between the tower and the deck are disconnected and replaced by the control devices. As expected, the frequencies of this model are much lower than those of

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the nominal bridge model after incorporating the control device. The first ten frequencies of this second model are 0.1618, 0.2666, 0.3723, 04545, 0.5015, 0.5650, 0.6187, 0.6486, 0.6965, and 0.7094 Hz [10].
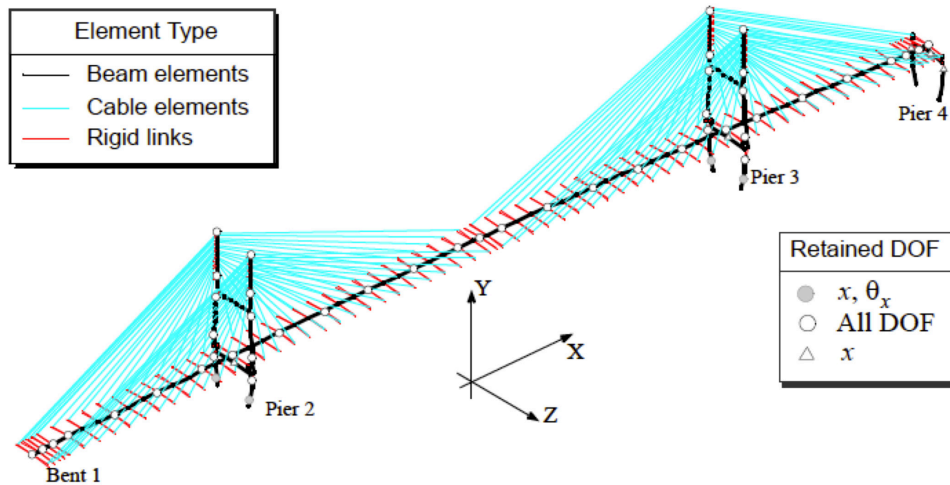
Figure 4.7: Cape Girardeau model in WCPS: (a) the Cape Girardeau bridge; (b) Simulink model of the Cape Girardeau bridge [10].

Fig. 4.5 shows the block diagram of the wireless bridge control system. Similar to the building control, the structural response of the bridge will go through ADC, a wireless network simulated in TOSSIM, and a discrete state estimator. The control inputs are converted by DAC to analog signals sent to the actuator.

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Chapter 5

Wireless Control Approaches

We implement and compare two alternative control approaches to WSC. Instead of isolating the designs of the control algorithm and wireless sensor networks, we study holistic cyber-physical co-designs that integrate control algorithms and scheduling strategies for data collection, communication and utilization. As a baseline design the first approach integrates a traditional structural control algorithm called the Sample Controller (SC) [30] and a scheduling strategy that minimizes sensing delays. The second approach integrates the Optimal Time Delay Controller (OTDC) [9] and a novel scheduling strategy that lead to uniform sensing delays. Note that both SC and OTDC controllers were originally designed for wired structural control. Our work provides the first case studies of these control algorithms when applied to wireless structural control.

5.1   Sample Controller

SC employs the Linear Quadratic Gaussian (LQG) optimal control algorithm [30]. LQG is a combination of linear quadratic estimator (LQE) and linear quadratic regulator (LQR). The cost function to be minimized in SC is defined in Equation 5.1, where x^r is the reduced states vector, u is the control force, C_r^Z and D_r^Z are system matrices for the regulated output vector, and Q and R are weighting matrices. More details of SC controller can be found in [30] and [10] .

$$J = \lim_{\tau \to \infty} \frac{1}{\tau} E\left[\int_0^\tau \left\{\left(C_r^Z x^r + D_r^Z u\right)^T Q \left(C_r^Z x^r + D_r^Z u\right) + u^T R u\right\}(dt)\right] \qquad (5.1)$$
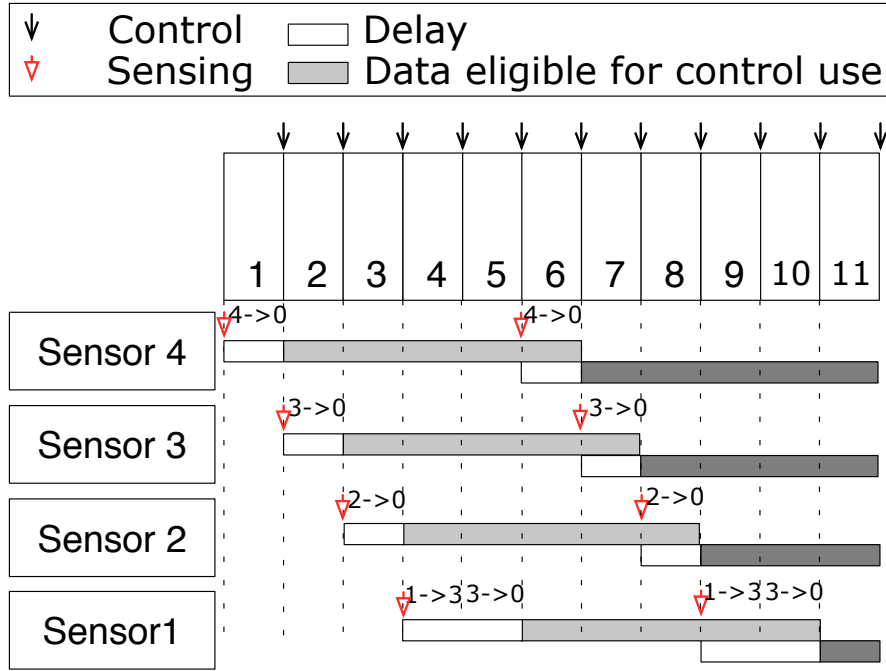
Figure 5.1: Example of baseline SC controller with Sequential Scheduler.

Specifically for SC, we implement a Sequential Scheduler (SS) which schedule one packet each TDMA time slot. Key data utilization mechanism for SS is to transmit the latest available data. For example, given vector $[y_1^x, y_2^x, y_3^x, y_4^x]$ as the data collected by sensor 1, 2, 3, 4 at the beginning of slot x, sensor 3 at the beginning of slot 2 (see Fig. 5.1) chooses to transmit y_3^2 instead of y_3^1 because y_3^2 is the latest reading. Similarly, sensor 2 chooses to transmit y_2^3 at the starting point of slot 3 because y_2^3 is the most up-to-date reading. SS makes sure that only latest sensor data is used for control, but it also sacrifices sensing synchronizations.

Fig. 5.1 illustrates working mechanism of SC and SS with a four-sensor network example. Sensor 1, 2, 3, 4 are located on floor 1, 2, 3, 4 of a building while the base station is located on the 4th floor. Since sensor 4, 3, and 2 have 1-hop distance to the base station, each needs one time slot to its data to the base station, while sensor 1 needs two because it is two hop away from the base station. SC control (denoted by dark arrows in Fig. 5.1) starts at the end of slot 1 with data vector $[0, 0, 0, y_4^1]$ as only the first reading (collected in slot 1) of sensor 4 has arrived. By the end of the slot 2, SC computes its control input with $[0, 0, y_3^2, y_4^1]$ because the second reading (collected in slot

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2) of sensor 3 has arrived. By the end of slot 3, SC uses $[0, y_2^3, y_3^2, y_4^1]$ to compute its control input. The same data vector is used again at the end of slot 4 because no reading from sensor 1 has arrived yet. By the end of slot 5, SC uses $[y_1^4, y_2^3, y_3^2, y_4^1]$ for control, which completes a communication cycle from all sensors. Starting from slot 6, another cycle of data collection and control occur using the same schedule. Intuitively, the combination of SC and SS aims to reduce the delay of the sensor data used for control. Henceforth, we refer to the control scheme combining SC and SS as SC for simplicity.

5.2 Optimal Time Delay Controller

OTDC [9] was originally designed for constant-delay system as shown in Equation 5.2, where l is the time delay. OTDC is designed to minimize the cost function J by selecting an optimal control force p_d in Equation 5.3. However, in a wireless sensor network data from different sensors will be delivered to the controller at different delays. To use OTDC to WSC effectively we design a novel scheduling strategy called the Uniform Delay Scheduler (UDS) that pushes sensor data to the controller at uniform delays.
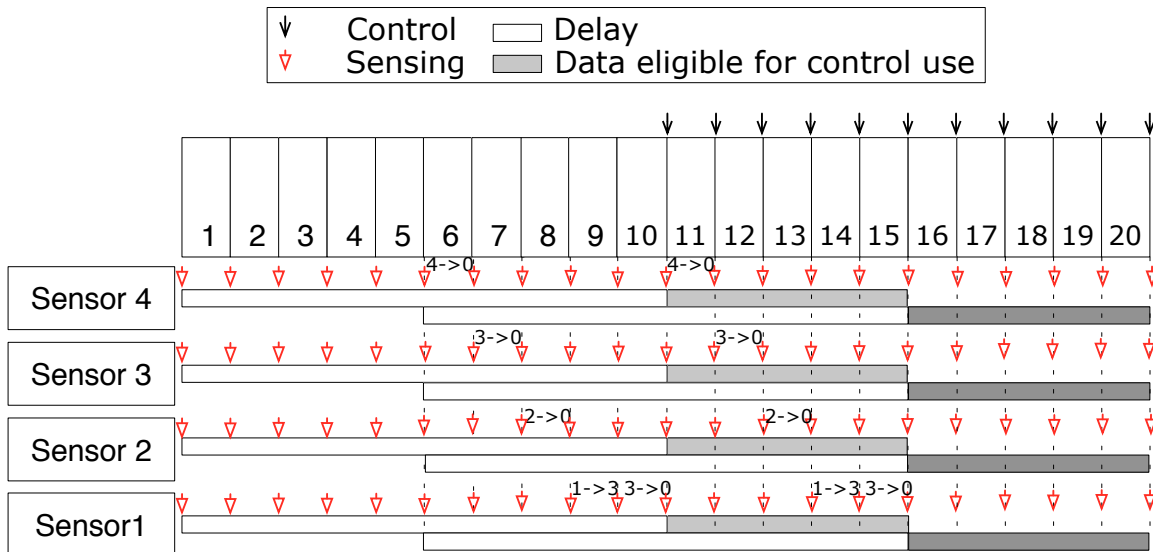

Figure 5.2: Example of OTDC-1 with UDS scheduler.

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$$z[k+1] = Az[k] + Bp_d[k-l] \tag{5.2}$$

Fig. 5.2 illustrates the schedule produced by UDS for the same four-sensor example used in the last subsection. UDS first buffers one batch of data (five readings for each sensor). Afterwards, a cycle of five time slots is used to deliver the batched data to the base station. By the end of slot 10, OTDC starts with data vector $[y_1^1, y_2^1, y_3^1, y_4^1]$, followed by $[y_1^2, y_2^2, y_3^2, y_4^2]$ in the next time slot, and $[y_1^3, y_2^3, y_3^3, y_4^3]$ in the time slot after. This pattern continues till the end of slot 14. In time slot 15 OTDC starts a new cycle and uses $[y_1^6, y_2^6, y_3^6, y_4^6]$ by the end of time slot 15. Under UDS data from different sensors shares a uniform network delay (10 time slots, or 100 ms in Fig. 5.2). UDS therefore trades one cycle of delay for uniform delays among sensors. This feature makes UDS particularly suitable for OTDC specifically designed for systems with constant delays. As shown in our case studies this scheduling-control co-design approach leads to an effective WSC system.

$$J|_{p_d} = \sum_{k=l}^{\infty} \left(z_d^T[k] Q z_d(k) + p_d^T[k-l] R p_d[k-l] \right) \tag{5.3}$$
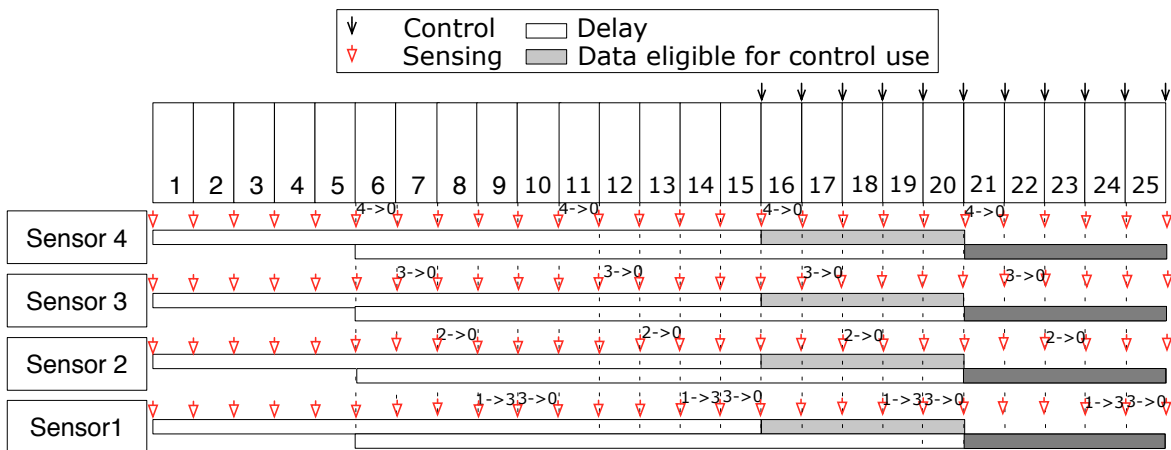

Figure 5.3: Example of OTDC-2 with UDS scheduler.

Another challenge introduced by wireless networks is packet loss. Since the basic version of UDS described above schedules only one transmission attempt for each sensor reading, a packet drop

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means losing one batch of readings (e.g., 5 readings in Fig. 5.2). To deal with packet loss we extend UDS to support multiple transmissions per sensor reading. Henceforth we use OTDC-k to denote a design that integrates OTDC and UDS that transmit each sensor reading k times. Due to the limited bandwidth of wireless sensor networks, OTDC-k retransmit sensor data from earlier cycles by merging them into packets of later cycles. The simple packet-merging mechanism in OTDC-2 avoids costly retransmissions of entire packets (e.g., as in WirlessHART). The number of batches that can be merged into a packet merging is limited by the packet payload size, e.g., over 100 bytes for IEEE 802.15.4 packets.

For example, in Fig. 5.3, though the batch of data $[y_1^1, y_1^2, y_1^3, y_1^4, y_1^5]$ from sensor 1 may be available by the end of slot 10, OTDC-2 waits for one more cycle (five time slots) before pushing the sensor data to the controller. At the same time $[y_1^1, y_1^2, y_1^3, y_1^4, y_1^5]$ is merged with $[y_1^6, y_1^7, y_1^8, y_1^9, y_1^{10}]$ and goes through another cycle of network communication. In this way, $[y_1^1, y_1^2, y_1^3, y_1^4, y_1^5]$ are transmitted twice and thus has better chance to be successfully delivered. OTDC-2 therefore trades additional network delay for higher reliability, while maintaining uniform delays across sensors. Increasing k in OTDC-k increases network delays while achieving higher reliability.

Chapter 6

Results of Case Studies

This section presents the results of the case studies under realistic structural and wireless models in WCPS. In both case studies we compare the performance of alternative wireless control approaches, SC and OTDC-1. We also study the tradeoff between delay and data loss by comparing OTDC with different numbers of retransmissions (OTDC-1, OTDC-2 and OTDC-3).

6.1   Wireless Building Control

The building remains stable under all control approaches throughout this case study. To evaluate the control performance we use three categories of metrics: resource requirement, structural response, and constraints of the control system. We refer interested readers to [30] for detailed definitions of these metrics. We perform simulations using four different wireless control approaches (SC, OTDC-1, OTDC-2, and OTDC-3). Experimental results presented below are from 25 simulations for each control approach and each simulation lasts 10,000 control steps.

Fig. 6.1 shows the end-to-end packet delivery ratio of the wireless network. The end-to-end delivery ratio means the fraction of packets from the sensors that are successfully delivered to the controller. As shown in Fig. 6.1 Sensor 1 has the lowest delivery ratio because it has a 2-hop route to the controller. Recall that OTDC-1 does not perform any retransmission, while OTDC-2 and OTDC-3 performs retransmit each packet once and twice, respectively. Under OTDC-1 Sensors 1 and 4 have delivery ratios of 70% and over 95%, respectively. As expected more retransmissions improve the deliver ratios of all sensors at the cost of longer delays as described earlier.
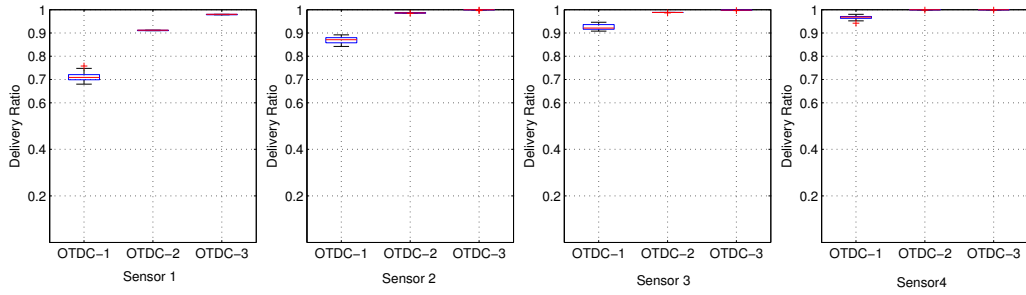
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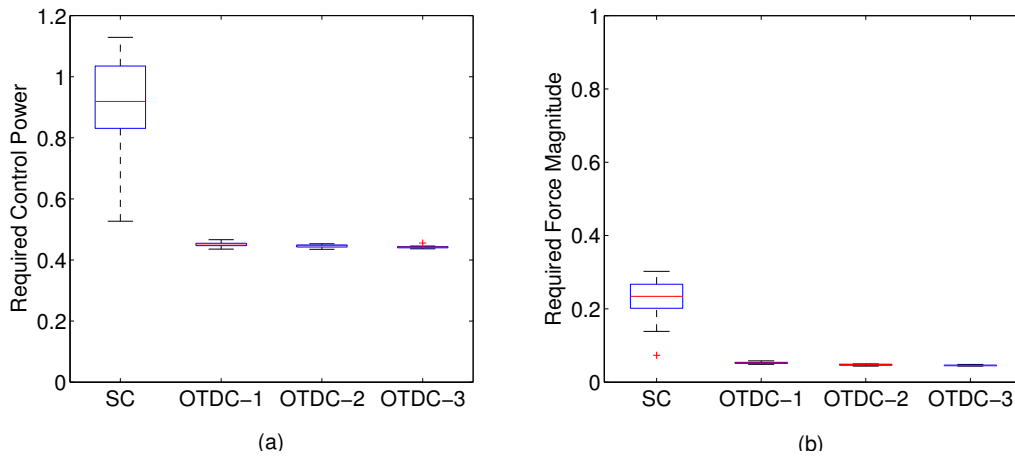Figure 6.1: End-to-End Packet Delivery Ratio of Sensors in Building Study

Figure 6.2: Required Resource for Wireless Building Control: (a) Required Control Power; (b) Required Force Magnitude.

Fig. 6.2 shows the resource requirement of different control approaches. OTDC-k approaches (see Fig. 6.2(a)) consistently require less control power than SC. As k increases, OTDC-k requires slightly less control power. Similarly, as shown in Fig. 6.2(b), OTDC-1 reduces control force by 80% when compared to SC. The differences in control force among different OTDC-k approaches are negligible. The results that OTDC-1 outperforms SC in both metrics indicate resource requirements are more sensitive to data synchronization than to sensing delays in this building control system. OTDC-k with larger k results in negligible reduction of control power and force, indicating resource requirements are not sensitive to network reliability in this case study.

The control performance regarding structural response is shown in Fig. 6.3. In term of peak inter-story drift in Fig. 6.3(a), OTDC-k achieves more reduction in inter-story drift than SC. Interestingly, higher k in OTDC-k *increases* peak inter-story drift. Recall a higher k leads to higher
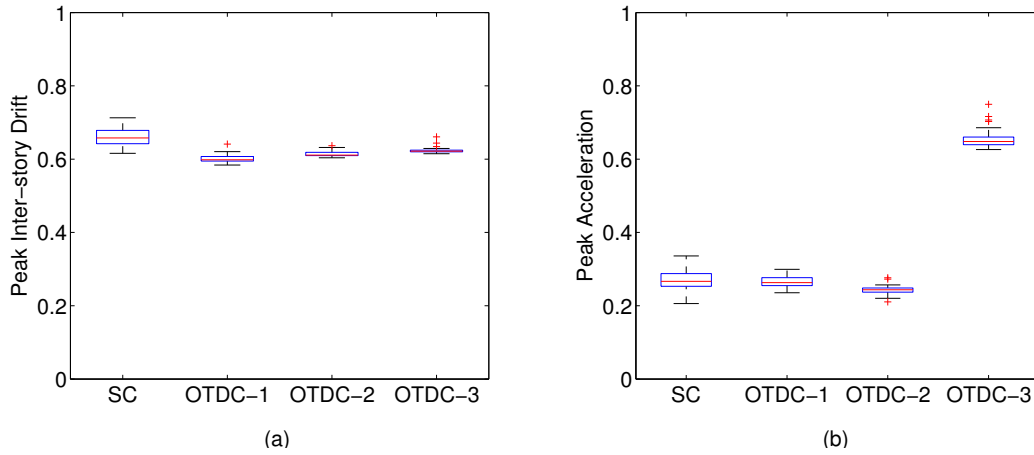
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Figure 6.3: Structural Response under Wireless Building Control: (a) Peak Inter-story Drift; (b) Peak Acceleration.

communication reliability but longer sensing delay. Inter-story drift is thus more sensitive to sensing delays than to data loss in this case study. Similarly, as shown in Fig. 6.3(b), OTDC-3 causes worse peak acceleration than all the other approaches. Hence, building structural responses are more sensitive to sensing delays than to data loss. In addition, OTDC-1 only slightly outperforms SC, which indicates limited impact of data synchronization on structural response.
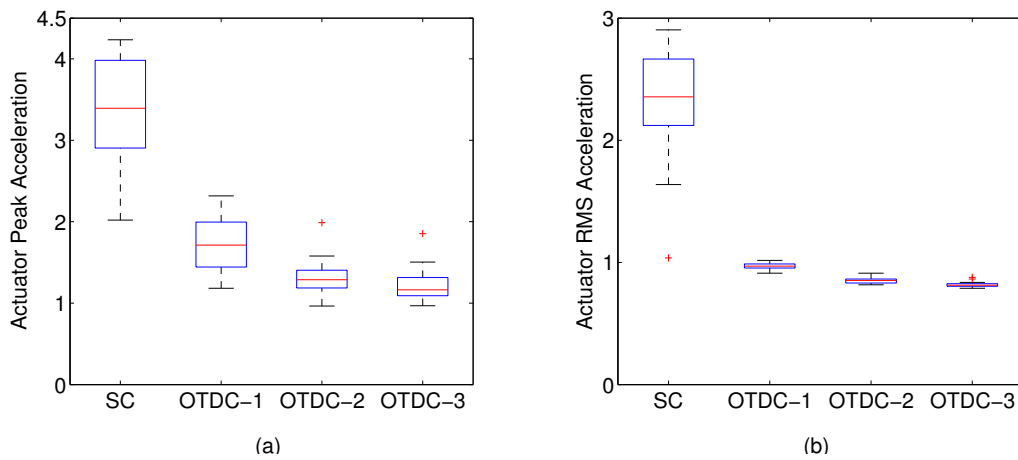

Figure 6.4: System Constraint under Wireless Building Control: (a) Actuator Peak Acceleration; (b) Actuator RMS Acceleration.

The control performance regarding control system constraints is shown in Fig. 6.4. Fig. 6.4(a) and (b) plot the actuator peak acceleration and Root Mean Square(RMS) acceleration, respectively. On

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both metrics OTDC-k approaches result in smaller actuator accelerations than SC. As k increases, we can see gradual decreases in peak and RMS accelerations, indicating that these metrics are more sensitive to improvement of communication reliability than to longer sensing delays. In addition, the comparison between OTDC-1 and SC shows that the better data synchronization under OTDC-1 has a larger impact than sensing delays.

In summary, we observe complex tradeoffs among data synchronization, sensing delay and communication reliability in wireless building control. Overall the OTDC approach combining a constant-delay control design and a scheduling scheme achieving data synchronization outperforms the SC approach that minimizes sensing delay without data synchronization. This result highlights the efficacy of our control-scheduling co-design approach to wireless control. Moreover, the design of the wireless communication protocol involves tradeoff between communication delay and data loss, with each having stronger influence on different performance metrics. For our specific building study OTDC-1 and OTDC-2 outperforms OTDC-3. The complex tradeoff among multiple design aspects confirms the importance of a realistic simulation tool in designing wireless control systems.
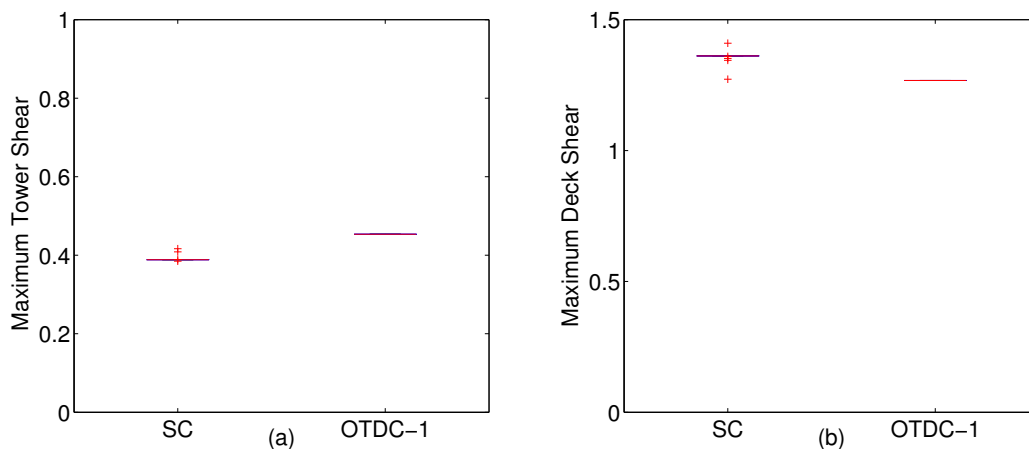
6.2   Wireless Bridge Control

Figure 6.5: Maximum Shear Force in Wireless Bridge Control: (a) Maximum Tower Shear; (b) Maximum Deck Shear.
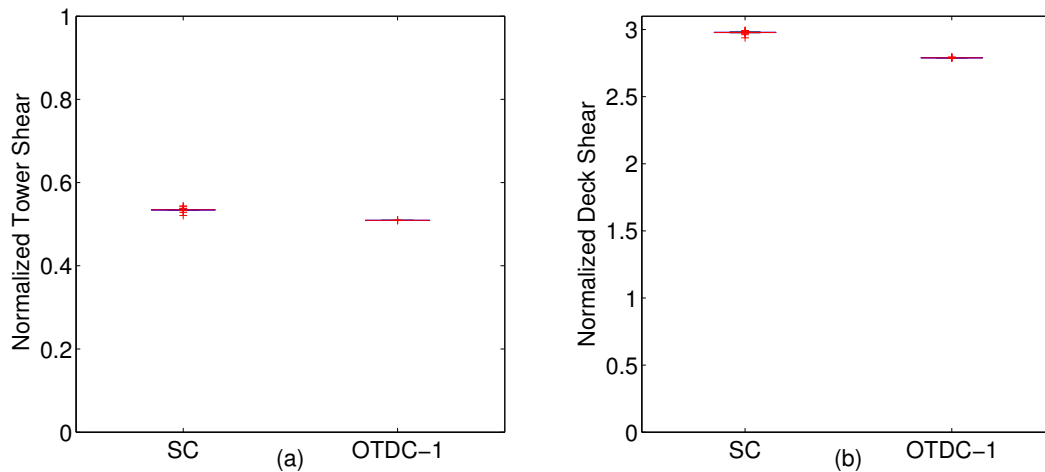
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Figure 6.6: Normalized Shear Force in Wireless Bridge Control: (a) Normalized Tower Shear; (b) Normalized Deck Shear.

Given the similarities in both the structural and wireless characteristics shared by the Jindo bridge and the Cape Girardeau bridge, wireless traces collected from the Jindo bridge were used to simulate the wireless sensor network used to control the Cape Girardeau bridge. The longest routing path is 3-hop. The results presented below are from 25 simulations for each control case and each simulation lasts 10,000 control steps. To mitigate large delays caused by large amount of packet deliveries for multiple sensors, network scheduling in bridge control adopts an in-network aggregation approach [8] through packet merging.

The bridge network is highly reliable (99% PRR for almost all links with the Jindo trace) due to the relatively clean wireless environment on the Jindo bridge as well as the fact that the Jindo deployment has line-of-sight sensor placement and strong radio antennas. As such, retransmission is not needed to achieve reliable communication. Therefore we only present the results of SC and OTDC-1 in this case study.

Since buildings and bridges have distinct structural properties, we adopt three different sets of metrics for performance evaluation. The metrics include maximum shear force, normalized shear force and required control power. We refer interested readers to [10] for the mathematical details of the metrics.

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Fig. 6.5 plots the maximum shear force at the tower and the deck of the bridge. A smaller shear force is desirable in structural control. SC performs slightly better in reducing the maximum tower shear while OTDC-1 performs slightly better for reducing the maximum deck shear, respectively. Fig. 6.6 plots the normalized shear force at the tower and the deck. OTDC-1 slighly outperforms SC for reducing normalized shear force.
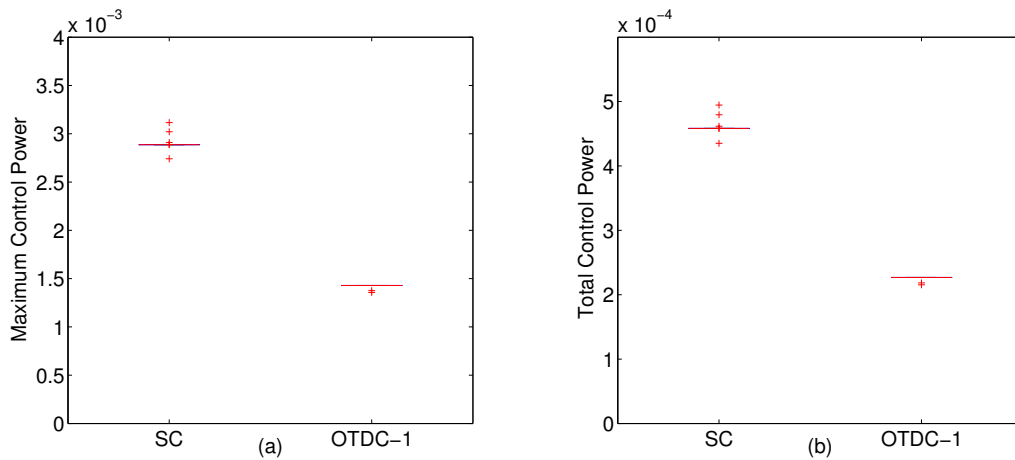
Figure 6.7: Control Power Requirement Performances for Wireless Bridge Control: (a) Maximum Control Power; (b) Total Control Power.

While OTDC-1 did not show significant advantage over SC in term of shear force, it reduces both the required maximum control power and the total power requirement by nearly 50% compared to SC (see Fig. 6.7). This result again demonstrated the effectiveness of the control-scheduling co-design approach adopted by the OTDC design.

Chapter 7

Conclusion

Wireless Structural Control (WSC) systems are a representative class of cyber-physical systems that have the promise to protect our civil infrastructure in the event of earthquake and other natural disasters. To develop WSC systems it is critical to capture both the cyber aspects (wireless communication and control) and the physical aspects (structural dynamics) through realistic and holistic simulations. We have developed the Wireless Cyber-Physical Simulator (WCPS) that integrates a high-fidelity wireless simulator (TOSSIM) and a standard control system simulator (Simulink). With WCPS, we performed two case studies on structural control systems. Each case study combines a realistic structural model and wireless simulations driven by traces collected from real-world deployments. Our case studies leads to three important insights. First, there exist complex tradeoffs among data synchronization, sensing delay, and network reliability under realistic wireless structural control settings. Second, a realistic, integrated wireless control simulator like WCPS is critical in exploring the design tradeoffs in wireless control design. Finally, a control-scheduling co-design approach is effective in wireless control design. In both case studies the integration of a contant-delay control design and a scheduling scheme achieving data synchronization lead to substantial improvement in control performance when compared to a traditional control design. Our cyber-physical simulation methodology and scheduling-control co-design approaches presented in this work not only represent a promising step toward smart civil infrastructure, but also provide useful insights and tools that can be generalized to other cyber-physical systems employing wireless control. The WCPS tool and the case studies have been released as open source software at `http://wcps.cse.wustl.edu`. The work presented in this thesis has been published at [20].

References

[1] http://wcps.cse.wustl.edu.

[2] http://shm.cs.uiuc.edu.

[3] J. Araujo, A. Anta, M. Mazo, J. Faria, A. Hernandez, P. Tabuada, and K. Johansson. Self-triggered control over wireless sensor and actuator networks. In *DCOSS*, 2011.

[4] Jia Bai, Emeka P. Eyisi, Fan Qiu, Yuan Xue, and Xenofon D. Koutsoukos. Optimal cross-layer design of sampling rate adaptation and network scheduling for wireless networked control systems. In *ICCPS*, 2012.

[5] Girish Baliga, Scott Graham, Lui Sha, and P.R. Kumar. Etherware: Domainware for wireless control networks. In *Proceedings of the 7th IEEE International Symposium on Object-oriented Real-time Distributed Computing*, 2004.

[6] Matteo Ceriotti, G. P. Picco, Murphy L. Amy, S. Guna, Michele Corr, Matteo Pozzi, Daniele Zonta, and Paolo Zanon. Monitoring heritage buildings with wireless sensor networks: The torre aquila deployment. In *Proceedings of the 8th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN/SPOTS), San Francisco, CA, USA, 2009*.

[7] Anton Cervin, Dan Henriksson, Bo Lincoln, Johan Eker, and Karl-Erik rzn. How does control timing affect performance? analysis and simulation of timing using jitterbug and truetime. *Proceedings of PWC 2003: Personal Wireless Communication, Lecture Notes in Computer Science*, 23(3):16 – 30, June 2003.

[8] Octav Chipara, Chenyang Lu, J.A. Stankovic, and G.-C. Roman. Dynamic conflict-free transmission scheduling for sensor network queries. *IEEE Transactions on Mobile Computing*, 10(5):734–748, May 2011.

[9] L.L. Chung, C.C. Lin, and K.H. Lu. Time-delay control of structures. *Earthquake Engineering and Structural Dynamics*, 24(5):687–701, 1995.

[10] S. Dyke, J. Caicedo, G. Turan, L. Bergman, and S. Hague. Phase I benchmark control problem for seismic response of cable-stayed bridges. *Journal of Structural Engineering*, 129(7):857–872, 2003.

[11] Emeka Eyisi, Jia Bai, Derek Riley, Jiannian Weng, Yan Wei, Yuan Xue, Xenofon D. Koutsoukos, and Janos Sztipanovits. NCSWT: An integrated modeling and simulation tool for networked control systems. In *The 15th International Conference on Hybrid Systems: Computation and Control (HSCC)*, 2012.

[12] Gregory Hackmann, Weijun Guo, Guirong Yan, Chenyang Lu, and Shirley Dyke. Cyberphysical codesign of distributed structural health monitoring with wireless sensor networks. In *ICCPS*, pages 119–128, April 2010.

[13] Gregory Hackmann, Fei Sun, Nestor Castaneda, Chenyang Lu, and Shirley Dyke. A holistic approach to decentralized structural damage localization using wireless sensor networks. In *RTSS*, pages 35–46, December 2008.

[14] S. Jang, H. Jo, S. Cho, K. Mechitov, J. Rice, S.-H. Sim, H.-J. Jung, C.-B. Yun, B.F. Spencer, and G. Agha. Structural health monitoring of a cable-stayed bridge using smart sensor technology: deployment and evaluation. *Smart Structures and Systems*, 6(5):439–460, 2010.

[15] A. Jindal and M. Liu. Networked computing in wireless sensor networks for structural health monitoring. In *SPIE Symposium on Smart Structures and Materials, Nondestructive Evaluations and Health Monitoring, San Diego, CA*, March 2011.

[16] Sukun Kim, Shamim Pakzad, David Culler, James Demmel, Gregory Fenves, Steven Glaser, and Martin Turon. Health monitoring of civil infrastructures using wireless sensor networks. In *IPSN*, 2007.

[17] Kevin Klues, Gregory Hackmann, Octav Chipara, and Chenyang Lu. A component-based architecture for power-efficient media access control in wireless sensor networks. In *Sensys*, 2007.

[18] HyungJune Lee, Alberto Cerpa, and Philip Levis. Improving wireless simulation through noise modeling. In *IPSN*, 2007.

[19] Philip Levis, Nelson Lee, Matt Welsh, and David Culler. TOSSIM: Accurate and Scalable Simulation of Entire TinyOS Applications. In *Sensys*, 2003.

[20] B Li, Z Sun, K Mechitov, C Lu, D Dyke, G Agha, and B Spencer. Realistic case studies of wireless structural control. In *ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS'13)*, April 2013.

[21] Bo Li, Dan Wang, Feng Wang, and YiQing Ni. High quality sensor placement for structural health monitoring systems: Refocusing on application demands. In *Proc. IEEE INFOCOM'10, San Diego, CA, Mar.*, 2010.

[22] Xuefeng Liu, Jiannong Cao, Wen-Zhan Song, and Shaojie Tang. Distributed sensing for high quality structural health monitoring using wireless sensor networks. In *The 33rd IEEE Real-Time Systems Symposium (RTSS'12)*, 2012.

29

[23] J.P. Lynch, Y. Wang, R.A. Swartz, K.-C. Lu, and C.-H. Loh. Implementation of a closed-loop structural control system using wireless sensor networks. *Structural Control and Health Monitoring*, 15(4):518–539, 2011.

[24] YiQing Ni, Bo Li, K.H. Lam, Dapeng Zhu, Yang Wang, Jeremy Lynch, and K.H. Law. In-construction vibration monitoring of a super-tall structure using a long-range wireless sensing system. *Smart Structures and Systems*, 7(2):83–102, March 2011.

[25] M. Pajic, S. Sundaram, J. Ny, G. Pappas, and R. Mangharam. Closing the loop: A simple distributed method for control over wireless networks. In *IPSN*, 2012.

[26] Joseph Polastre, Robert Szewczyk, and David Culler. Telos: enabling ultra-low power wireless research. In *Proceedings of the 4th international symposium on Information processing in sensor networks*, IPSN '05, Piscataway, NJ, USA, 2005. IEEE Press.

[27] J. Rice, K. Mechitov, S.-H. Sim, B.F. Spencer, and G. Agha. Enabling framework for structural health monitoring using smart sensors. *Structural Control and Health Monitoring*, 15(8):574–587, 2011.

[28] A. Saifullah, P. Tiwari, B. Li, C. Lu, and Y. Chen. Accounting for failures in delay analysis for wirelesshart networks. In *Tech. Rep., WUCSE-2012-16, Washington University in St Louis*, 2012.

[29] Abusayeed Saifullah, You Xu, Chenyang Lu, and Yixin Chen. Real-time scheduling for wirelesshart networks. In *RTSS*, 2010.

[30] B.F. Spencer, S. Dyke, and H. Deoskar. Benchmark problems in structural control: part i-active mass driver system. *Earthquake Engineering and Structural Dynamics*, 27(11):1127–1139, 1998.

[31] Zhuoxiong Sun, Bo Li, S.J. Dyke, and Chenyang Lu. Evaluation of performances of structural control benchmark problem with time delays from wireless sensor network. In *Proc. EMI/PMC 2012*, 2012.

[32] Zhuoxiong Sun, Bo Li, S.J. Dyke, and Chenyang Lu. A novel data utilization and control strategy for wireless structural control systems with tdma network. In *Proc. ASCE IWCCE 2013*, 2013.

[33] Y. Wang and K.-H. Law. Structural control with multi-subnet wireless sensing feedback: experimental validation of time-delayed decentralized h control design. *Advances in Structural Engineering*, 14(1):25–39, 2011.

[34] Y. Wang, R.A. Swartz, J.P. Lynch, K.H. Law, and C.-H. Loh. Performance evaluation of decentralized wireless sensing and control in civil structures. In *Proceedings of SPIE 14th International Symposium on Smart Structures and Materials and Nondestructive Evaluation and Health Monitoring*, March 2007.

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Realistic case studies of wireless structural Control. B. Li, Z. Sun, K. Mechitov, C. Lu, S. J. Dyke, G. Agha, and B. F. Spencer. ACM/IEEE International Conference on Cyber-Physical Systems (ICCPS'13), April 2013.

Evaluation of performances of structural control benchmark problem with time delays from wireless sensor network. Z. Sun, B. Li, S. J. Dyke, and C. Lu. in Proc. EMI/PMC 2012, Notre Dame, IN, June 17-20, 2012.

High quality sensor placement for structural health monitoring systems: refocusing on application demands. B. Li, D. Wang, F. Wang, and Y.Q. Ni. in Proc. IEEE INFOCOM'10, San Diego, CA, Mar. 2010.

A high speed DMA transaction method for PCI Express Devices. Y. Peng, B. Li, D. Liu, and X. Peng. in Proc. IEEE Circuits and Systems International Conference on Testing and Diagnosis, Chengdu, China, Apr. 2009.

August 2013

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WCPS and Case Studies on WSC, Bo Li, M.S. 2013