Information Driven Wireless Sensing and Control for Civil Structures

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ABSTRACT: With recent advances in wireless technology, wireless networks can potentially offer a low-cost alternative to traditional cable-based systems, while providing flexible and reconfigurable information architectures tailored for sensing and control systems. Compared to cabled systems, wireless networks need to deal with the constraints of communication bandwidth, latency, range, and reliability. A prototype wireless sensing and control system has been developed to address some of the above mentioned information constraints. This paper discusses the design concepts of the prototype system that include embedded computing, communication protocol design using finite state machines, and decentralization of information architectures.

Keywords: structural monitoring, structural control, wireless communication

1 INTRODUCTION

Structural monitoring and control have undergone significant research and development over the last few decades. In order to transfer measured response information, monitoring and control systems are installed using coaxial cables as a means for data communication. To eradicate the high installation and maintenance cost of cabled systems, wireless communication technologies have been explored for sensing and monitoring of civil structures (Lynch *et al.* 2006, Straser & Kiremidjian 1998). Additionally, wireless systems allow the sensor network to be easily reconfigured for supporting different topological and information requirements. Furthermore, by incorporating an actuation interface, the wireless sensing unit can be extended to command actuators for structural control applications (Wang *et al.* 2007a).

The purpose of a structural health monitoring (SHM) system is to predict, identify, and locate the onset of structural damage based on data collected from sensing devices. Sensors are typically deployed in a passive manner, primarily for measuring structural responses. Control systems, on the other hand, need to respond in real time to mitigate excess dynamic response of structures. Typical feedback control systems require real-time information and measurements to instantly determine control decisions. Although structural monitoring and control applications pose different needs and requirements, efficient information flow plays a key and critical role in their implementation. The transmission latency and limited bandwidth of wireless devices can impede real-time operations as required by control or monitoring systems. Communication in a wireless network is inherently less reliable than that in cable-based systems, particularly when node-to-node communication ranges lengthen. These information constraints, including bandwidth, latency, range, and reliability, need to be considered carefully using an integrated system approach and pose many challenges in the selection of hardware technologies and the design of software/algorithmic strategies.

The development of self-sensing and actuating devices for structural monitoring and control applications represent an intriguing, interdisciplinary research paradigm. The purpose of this paper is to introduce the design of a prototype system. Design concepts including embedded computing, robust communication protocols and decentralized information management and processing, that address the information constraints required for structural monitoring and control applications are discussed.

2 A PROTOTYPE WIRELESS SENSING AND ACTUATION UNIT

Fig. 1 shows the overall hardware design of the wireless sensing unit, and the two optional off-board auxiliary modules for conditioning analog sensor signals and generating actuation signals. The wireless sensing unit consists of three functional modules: sensor signal digitization, computational core, and wireless communication. The sensor signal conditioning module assists in amplifying, filtering, and

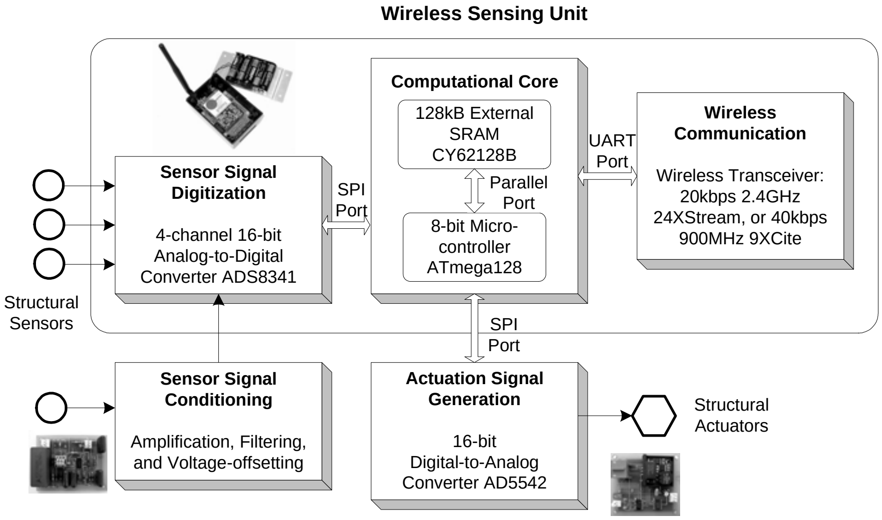

Figure 1. Functional diagram detailing the design of the wireless sensing unit.

offsetting analog sensor signals prior to digitization. The actuation signal generation module offers an interface through which the wireless unit sends analog commands to structural actuators. For structural monitoring applications, the wireless unit collects and analyzes sensor data. For control applications, the sensing unit, in addition to collecting and analyzing the data, computes in real-time optimal control forces and issues commands to structural actuators via the actuation interface. The wireless communication channel serves to connect individual sensing and control units into a monitoring or control network. In its current design, the wireless sensing unit can support up to 4 structural sensors simultaneously through a 16-bit analog-to-digital (A2D) converter and the actuation module is designed to accommodate a variety of actuators for active sensing or control applications. Detailed descriptions of the hardware modules can be found in (Wang *et al.* 2007a, Wang *et al.* 2007b).

The key parameters of the prototype wireless sensing unit are summarized in Table 1. The wireless unit is designed to balance low power consumption while supporting high data transfer rates and long communication ranges typically required for civil structural applications. Peer-to-peer communication among wireless units is supported for collaborative data analysis. Local data processing capability is enabled by the microcontroller coupled with ample internal and external memory. The embedded computational capability serves not only for analyzing sensor data and computing control decisions, but may also assist in reducing energy consumption and enhancing system scalability during deployed operation. The following sections discuss the design and constraints of the wireless communication and computational cores, and the protocol designs in supporting monitoring and control applications.

Table 1. Key parameters of the wireless sensing unit.

Design Parameter	Specification	
Computing Core		
Microcontroller	8-bit, up to 16MIPS at 16MHz	
Flash Memory	128K bytes	
Internal SRAM	4K bytes	
External SRAM	128K bytes	
Power Consumption	30mA active, 55µA standby	
Wireless Transceiver	*9XCite*	*24XStream*
Operating Frequency	902-928 MHz	2.40 - 2.48 GHz
Data Transfer Rate	38.4 kbps	19.2 kbps
Range	300' (90m) indoor, 1000' (300m) outdoor	600' (180m) indoor, 3 miles (5km) outdoor
Power Consumption	55mA transmitting, 35mA receiving, 20µA standby	150mA transmitting, 80mA receiving, 26µA standby

3 COMMUNICATION CONSTRAINTS

As noted in Table 1, the sensing unit is designed to support two wireless transceivers: MaxStream’s 900 MHz 9XCite and 2.4 GHz 24XStream (MaxStream 2004, MaxStream 2005). This dual transceiver support allows the wireless sensing and actuation unit to operate in different regions around the world. Wireless communication poses four major constraints to the information flow within a structural monitoring and control network: bandwidth, latency, reliability, and range. It is thus important to assess the communication constraints of the transceivers.

Bandwidth and latency are about the timing characteristics of the communication links. Bandwidth refers to the data transfer rate once a communication link is established. The data transmission time T_{Trans} is thus the product of the bandwidth and the amount of data packaged for wireless transmission. Latency $T_{Latency}$ measures the time for one bit to travel from the transmitter to the receiver. Total delay of a single wireless transmission is the sum of $T_{Latency}$ and T_{Trans}. By properly setting radio parameters, the achievable latency is about 5ms for the 9XCite transceiver, and about 15ms for the 24XStrean transceiver. This amount of latency typically has minimal effect for most monitoring applications, but has noticeable effects to the sampling time in control applications.

The other two constraints, reliability and range, are related to the attenuation of the wireless signal traveling along the transmission path. The path loss PL (in decibel) of a wireless signal is measured as the ratio between the transmitted power, $P_{TX}[\text{mW}]$, and the received power, $P_{RX}[\text{mW}]$ (Molisch 2005):

$$PL[\text{dB}] = 10\log_{10}\frac{P_{TX}[\text{mW}]}{P_{RX}[\text{mW}]} \qquad (1)$$

Path loss generally increases with the distance, d, between the transmitter and the receiver. However, the loss of signal strength varies with the environment along the transmission path and is difficult to quantify precisely. Experiments have shown that a simple empirical model may serve as a good estimate to the mean path loss (Rappaport & Sandhu 1994):

$$\overline{PL}(d)[\text{dB}] = PL(d_0)[\text{dB}] + 10n\log_{10}\left(d/d_0 \right) + X_\sigma[\text{dB}] \qquad (2)$$

Here $PL(d_0)$ is the free-space path loss at a reference point close to the signal source (d_0 is usually selected at approximately 1 meter). X_σ represents the variance of the path loss, which is a zero-mean log-normally-distributed random variable with a standard deviation of σ. The parameter n is the path loss exponent that describes how fast the wireless signal attenuates over distance. Basically, Eq. 2 indicates an exponential decay of signal power:

$$P_{RX}[\text{mW}] = P_0[\text{mW}]\left(d/d_0 \right)^{-n} \qquad (3)$$

where P_0 is the received power at the reference distance d_0. Typical values of n are reported to be between 2 and 6. Table 2 shows examples of measured n and σ values in different buildings for 914 MHz signals (Rappaport & Sandhu 1994).

A link budget analysis can be used to estimate the range of wireless communication (Molisch 2005). To achieve a reliable communication link requires:

$$P_{TX}[\text{dBm}] + AG[\text{dBi}] \geq PL(d)[\text{dB}] + RS[\text{dBm}] + FM[\text{dB}] \qquad (4)$$

where AG denotes the total antenna gain for the transmitter and the receiver, RS the receiver sensitivity, FM the fading margin to ensure quality of service, and $PL(d)$ the realized path loss at some distance d within an operating environment. Table 3 summarizes the link budget analysis for the 9XCite and 24XStream transceivers, and their estimated indoor ranges. The path loss exponent n is selected to be 2.8, which is the same as the soft-partitioned office building in Table 2. (Generally, 2.4GHz signals typically have higher attenuation than 900MHz signals, and, thus, a larger path loss exponent n.) The transmitter power P_{TX}, receiver sensitivity RS, and fading margin FM of the two wireless transceivers are obtained from the MaxStream datasheets. A total antenna gain AG of 4 is employed by assuming that low-cost antennas are used by the transceiver and receiver. The free-space path loss at d_0 is computed using the Friis transmission equation (Molisch 2005):

$$PL(d_0)[\text{dB}] = 20\log_{10}\left(4\pi d_0/\lambda \right) \qquad (5)$$

where λ is the wavelength of the corresponding wireless signal. Finally, assuming that the variance X_σ is zero, the mean communication range can be derived from Eq. (2) as:

$$\bar{d} = d_0 10^{\left(\overline{PL} - PL(d_0)\right)/(10n)} \qquad (6)$$

Table 3 shows that the transceivers can achieve the communication ranges indicated in Table 1. It is important to note the sensitivity of the communication range with respect to the path loss exponent n in Eq. 6. For instance, if the exponent of 3.3 for indoor traveling (through brick walls) as reported by Janssen & Prasad (1992) for 2.4 GHz signals is used for the 24XStream transceiver, its mean communication range would be reduced by half to 87m.

Table 2. Values of path loss exponent n at 914MHz.

Building	n	σ[dB]
Grocery store	1.8	5.2
Retail store	2.2	8.7
Suburban office building – open plan	2.4	9.6
Suburban office building – soft partitioned	2.8	14.2

Table 3. Link budget analysis to the wireless transceivers.

	9XCite	24XStream
P_{TX} [dBm]	0.00	16.99
AG [dBi]	4.00	4.00
RS [dBm]	-104.00	-105.00
FM [dB]	22.00	22.00
$\overline{PL} = P_{TX}+AG-RS-FM$ [dB]	86.00	103.99
$PL(d_0)$ [dB], $d_0 = 1$ m	31.53	40.05
$\overline{PL} - PL(d_0)$ [dB]	54.47	63.94
n	2.80	2.80
$\bar{d}$ [m]	88.20	192.18

4 EMBEDDED COMPUTATIONAL CORE

A low-cost, low-power 8-bit Atmel AVR microcontroller (ATmega128) is selected to coordinate the hardware components of the wireless unit and to provide the capability for local data interrogation. As shown in Fig. 2, the ATmega128 microcontroller (with 128kB of in-system reprogrammable flash memory) is responsible for storing a “thin” embedded system software layer that manages low level details pertaining to peripherals and hardware components. Additionally, software can be implemented and embedded in the wireless units to support engineering algorithms, such as the fast Fourier transform (FFT), autoregressive (AR) analysis, linear quadratic regulator (LQR) control, and Kalman filtering, that are suitable for monitoring and control applications. One feature of the embedded software implementation is the ability for multithreaded tasking; the unit is capable of collecting data from the sensing interface and simultaneously performing another operational task, such as transferring data over the wireless transceiver or executing a computational algorithm to interrogate sensor data (Wang *et al.* 2007b).

Dense deployment of wireless sensors presents a significant challenge in streaming large amount of data in real-time over a low-power wireless network with limited bandwidth. With application software (e.g. algorithms) available in the wireless unit, embedded computing may significantly reduce the requirement in communication bandwidth. For instance, the FFT can be executed on-board as soon as the sensor data is collected, but only the results within a specified frequency spectrum of interests are to be transmitted from the sensors to the server. As an example, a 4096-point FFT on data sampled at 200Hz, can be reduced to 614 (i.e. 307 complex) numbers for a frequency spectrum within 15Hz - an 85% transmission reduction rate. For multi-hop routing, the effectiveness of embedded computing in overcoming bandwidth constraints can be even more significant.

It may be interesting to compare the relative energy consumption (in joules) between embedded computing, which includes onboard computations and transmission of analysis results, and offline computing, which requires only the wireless transmission of raw data. Table 4 compares the energy consumption required for two computations commonly employed for structural monitoring applications (Lynch *et al.* 2004): (1) a complete FFT of 4096 points and the transmission of 307 complex frequency response values, and (2) an autoregressive (AR) analysis of 1024 points and the transmission of 20 AR coefficients. The computational time is measured directly by executing the algorithms on the wireless sensing unit, and the transmitting time is estimated using the data rate achieved by the implemented communication protocol (which is about two thirds of the data transfer rate shown in Table 1). Energy consumption, *E*, is the product between the operation time, *T*, and the operating power of the wireless unit, *P*. Based on the datasheets of the components in the wireless sensing unit, the total power consumption for data transmission (including the necessary operations by the microcontroller, memory units, the transceivers, etc.) is estimated to be 0.425 and 0.9 W, respectively, for the 9XCite and the 24XStream transceivers. For computation, the microcontroller together with the external memory consumes about 0.15 W. Because of the lower data transfer rate and higher power consumption, the energy saving is realized for the wireless unit with the 24XStream transceiver. On the other hand, for the case of using 9XCite transceiver, embedded computing may actually consume more energy because of: 1) the radio's higher data transfer rate, 2) its low power consumption, and 3) the relatively low speed of the 8-bit ATmega128 microcontroller. This result indicates that, if the wireless unit is to be designed for specific computing applications, careful consideration should be paid for assigning the computations as well as the selection of microcontroller and transceiver to achieve a good balance with respect to energy consumption. For instance, a faster microcontroller, such as the MPC555 microcontroller employed by Lynch *et al.* (2004), may result in better energy saving from embedded computing for the two computational algorithms implemented.

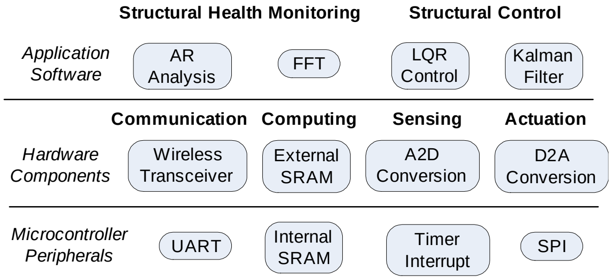

Figure. 2. Software layers of the microcontroller in the wireless sensing and actuation unit.

5 COMMUNICATION PROTOCOLS

To ensure reliable performance of a wireless structural monitoring and control network, communication protocols should be carefully designed and implemented. To minimize the overhead in a low-power wireless network, simple and efficient protocols are needed; yet the protocols should be sufficiently robust to properly address possible transmission failure. Finite state machine concepts are employed in designing the communication protocols for the wireless monitoring and control system. A finite state machine consists of a set of states and definable transitions between the states, which can be used to efficiently represent task sequences in the communicating (Tweed 1994).

5.1 *Sensing and Monitoring Applications*

Table 4. Energy consumption comparison: embedded computing versus transmitting raw data (FFT and AR analysis).

		Embedded computing					Offline computing		Energy saving by on-board computing
		Computing		Transmission		Total	Transmission		
		T [s]	*E* [J]	*T* [s]	*E* [J]	*E* [J]	*T* [s]	*E* [J]	
FFT4096	24XStream	16.50	2.48	1.89	1.70	**4.18**	12.60	**11.34**	**63.18%**
	9XCite	16.50	2.48	0.95	0.40	**2.88**	6.30	**2.68**	**-7.41%**
AR1024	24XStream	7.00	1.05	0.06	0.06	**1.11**	3.15	**2.84**	**61.02%**
	9XCite	7.00	1.05	0.03	0.01	**1.06**	1.58	**0.67**	**-58.78%**

The communication protocol designed for wireless monitoring inherits some useful features of TCP (Transmission Control Protocol, one of the core protocols for Internet), such as data packetizing, sequence numbering, timeout checking, and retransmission. Based upon pre-assigned arrangement between the server and the wireless units, the sensor data stream is segmented into a number of packets, each containing a few hundred bytes. A sequence number is assigned to each packet so that the server can request the data sequentially. To simplify the communication protocol, special characteristics of structural health monitoring applications are exploited. For example, since the objective in structural monitoring is normally to transmit sensor data or analysis results to the server, the server is assigned the responsibility for ensuring reliable wireless communication.

In a structural monitoring application, the network server starts by initializing and synchronizing the wireless network. Then the server starts collecting sensor data or analysis results from the wireless units. Fig. 3 and Fig. 4 show the communication state diagrams of the server for sensor data collection, and the corresponding state diagram of the wireless sensing units, respectively. Note that the server and the units have separate sets of state definition. At the beginning of data collection, the server and all the units are all set in State 3 (see Fig. 3 and Fig. 4). Starting with the first wireless unit in the network, the server queries the sensor for the availability of data by sending the '01Inquiry' command. If the data is not ready, the unit replies '02NotReady', otherwise the unit replies '03DataReady' and transits to State 4. After the server ensures that the data from this wireless unit is ready for collection, the server transits to State 5. To request a data segment from a unit, the server sends a '04PlsSend' command that contains a packet sequence number. One round of data collection from one wireless unit is ended with a two-way handshake, where the server and the unit exchange '05EndTransm' and '06AckEndTransm' commands. The server then moves on to the next unit and continuously collects sensor data round-by-round.

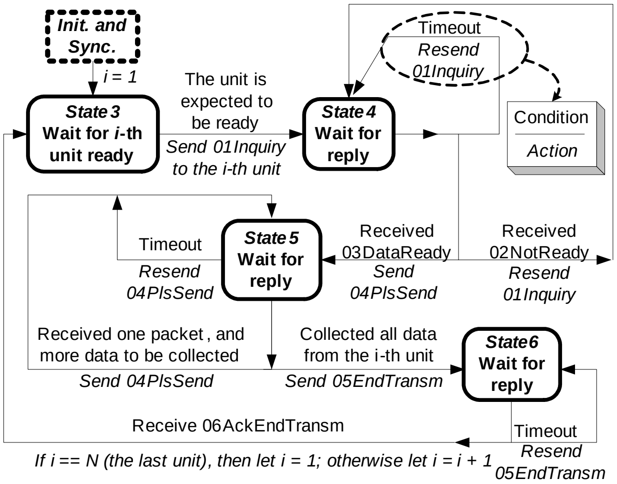

Figure 3. Communication state diagram of the server.

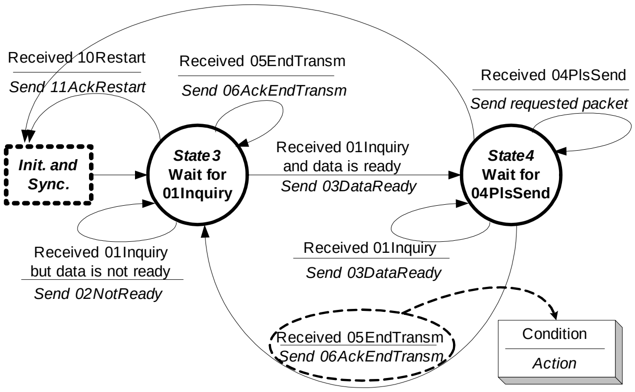

Figure 4. Communication state diagram of wireless sensing units.

5.2 *Structural Control Applications*

For application in wireless feedback structural control, real-time communication is important for system performance. Limited wireless communication range poses another challenge while instrumenting a large-scale structure with the wireless sensing and control system. This section describes the design concepts that address these challenges resulted from information constraints.

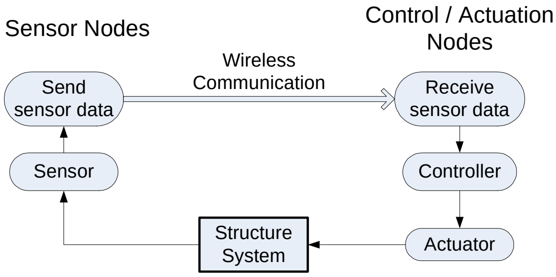

Figure 5. Feedback control loop between the sensing nodes and control/actuation nodes.

In real-time feedback control, a steady sampling time step is essential for the system performance. The feedback control loop designed for the prototype wireless sensing and control system is illustrated in Fig. 5. As shown in the figure, sensing is designed to be clock-driven, while control and actuation are designed to be event-driven. The wireless sensing nodes collect sensor data at a preset sampling rate and transmit the data during the assigned time slot. Upon receiving the required sensor data, the control/actuation nodes immediately compute control decisions and apply the corresponding actuation signals to the actuators.

Fig. 6 illustrates the communication state diagrams of a coordinator unit and other wireless units within a wireless sensing and control subnet. To initiate the system operation, the coordinator unit first broadcasts a start command '01StartCtrl' to all other sensing and control units. Once the start command and its acknowledgement '03AcknStartCtrl' are received, the system starts real-time feedback control

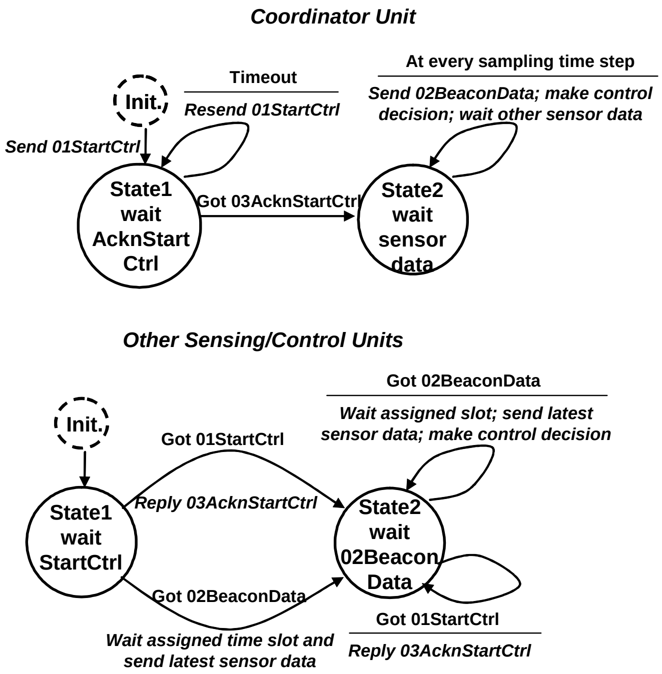

Figure 6. Communication state diagram of a coordinator unit and other sensing/control units in one wireless subnet.

operation, i.e. both the coordinator and other units are in State 2. At every sampling time step, the coordinator unit broadcasts a beacon signal '02BeaconData' together with its own sensor data, announcing the start of a new time step. Upon receiving the beacon signal, other sensing units broadcast their sensor data following a preset transmission sequence, so that transmission collision is avoided. The wireless control units responsible for commanding the actuators receive the sensor data, calculate desired control forces, and apply control commands at each time step. In order to guarantee a constant sampling time step and to minimize feedback latency, timeout checking or retransmission is not recommended during the feedback control operation. Instead, if a control/actuation node doesn't receive the expected sensor data at one time step, it may use a previous data sample, or can be assigned to take no action at all. This design is suitable for both centralized control (where all sensing/control and coordinator units are all within a single network) and decentralized control (where each wireless subnet includes only the sensing/control and coordinator units within the decentralized system).

6 SUMMARY AND CONCLUSION

This paper describes the information-driven design for wireless structural monitoring and control networks. For different structural applications, design concepts have been proposed to address the information constraints in a wireless sensor network, such as bandwidth, latency, range, and reliability. The issues of communication and embedded computing are discussed. Reliable communication protocol design for centralized and decentralized information architectures for control applications is also presented. Large-scale laboratory and field validation tests have been conducted to validate the efficacy and robustness of the information management schemes implemented in the wireless structural monitoring and control system (Wang *et al.* 2007a, Wang 2007, Wang *et al.* 2007b).

7 ACKNOWLEDGEMENTS

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REFERENCES

Janssen, G.J.M. & Prasad, R. 1992. Propagation measurements in an indoor radio environment at 2.4 GHz, 4.75 GHz and 11.5 GHz. *Proceedings of IEEE 42nd Vehicular Technology Conference, Denver, CO, May 10 - 13*.

Lynch, J.P., Sundararajan, A., Law, K.H., Kiremidjian, A.S. & Carryer, E. 2004. Embedding damage detection algorithms in a wireless sensing unit for operational power efficiency. *Smart Materials & Structures* 13(4): 800-810.

Lynch, J.P., Wang, Y., Loh, K.J., Yi, J.-H. & Yun, C.-B. 2006. Performance monitoring of the Geumdang Bridge using a dense network of high-resolution wireless sensors. *Smart Materials and Structures* 15(6): 1561-1575.

MaxStream, Inc. 2004. *9XCite™ OEM RF Module Product Manual v1.1*. Lindon, UT.

MaxStream, Inc. 2005. *XStream™ OEM RF Module Product Manual v4.2B*. Lindon, UT.

Molisch, A.F. 2005. *Wireless Communications*. Chichester, West Sussex, England: John Wiley & Sons, IEEE Press.

Rappaport, T.S. & Sandhu, S. 1994. Radio-wave propagation for emerging wireless personal-communication systems. *Antennas and Propagation Magazine, IEEE* 36(5): 14-24.

Straser, E.G. & Kiremidjian, A.S. 1998. *A Modular, Wireless Damage Monitoring System for Structures*. Report No. Report No. 128, Stanford, CA: John A. Blume Earthquake Eng. Ctr., Stanford University.

Tweed, D. 1994. Designing real-time embedded software using state-machine concepts. *Circuit Cellar Ink*, (53), 12-19.

Wang, Y., Swartz, R.A., Lynch, J.P., Law, K.H., Lu, K.-C. & Loh, C.-H. 2007a. Decentralized civil structural control using real-time wireless sensing and embedded computing. *Smart Structures and Systems*: in press.

Wang, Y. 2007. *Wireless Sensing and Decentralized Control for Civil Structures: Theory and Implementation*. (under preparation) PhD Thesis. Department of Civil and Environmental Engineering, Stanford University. Stanford, CA.

Wang, Y., Lynch, J.P. & Law, K.H. 2007b. A wireless structural health monitoring system with multithreaded sensing devices: design and validation. *Structure and Infrastructure Engineering* 3(2): 103-120.