Wireless Structural Sensors using Reliable Communication Protocols for Data Acquisition and Interrogation

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Agenda

- Research background
- Hardware design of the latest wireless sensing unit prototype
- Software design of the latest wireless SHM system
- Laboratory validation tests
- Field validation tests
- Future direction

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Structural Health Monitoring (SHM)

- S. Chase (2001), National Bridge Inspection Program (NBIP): Nearly 60,000 bridges in U.S. evaluated as structurally deficient.
- Over 580,000 highway bridges in U.S. mandated by Federal Highway Administration for biannual evaluations.

Human Visual Inspection:
resource consuming;
visible damages only

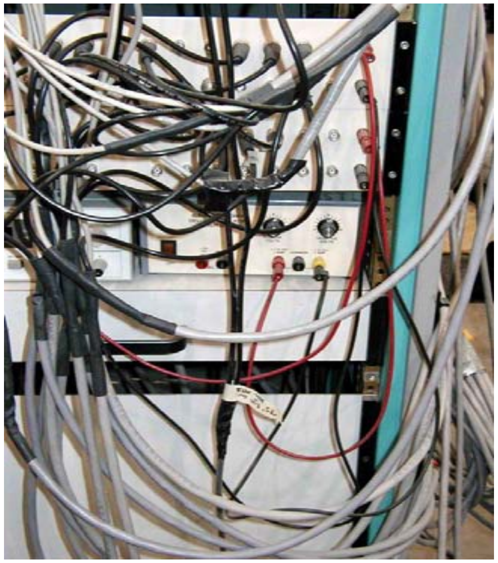
↓

Advanced Sensing Technology
for Autonomous SHM:

Rapid, accurate, low-cost

From Wire-based Sensing to Wireless Sensing

Traditional DAQ System: wire-based



Future Wireless DAQ System

This wireless SHM prototype system is Jointly developed by researchers in Stanford University and the University of Michigan

- E. G. Straser, and A. S. Kiremidjian (1998), Installation of wired system can take about 75% of testing time for large structures
- M. Celebi (2002):

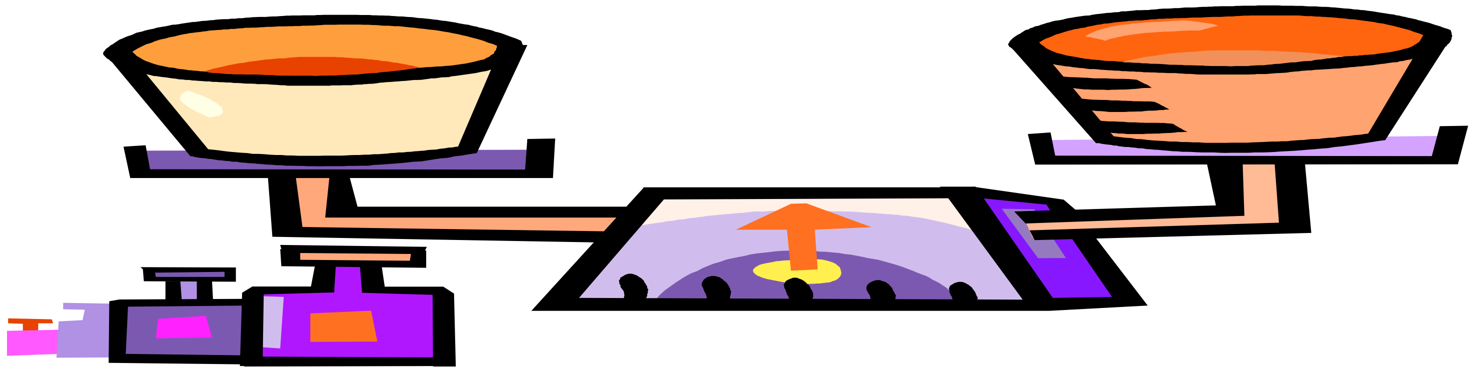
Estimation for each sensor channel and data recording system: $2,000;
Installation (cabling, labor, etc.) per wired channel: $2,000. (Total: $4000)

Challenges in Wireless SHM (1)

- Limited power consumption: The wireless units most likely run on batteries.

BETTER PERFORMANCE: Long-distance high-speed wireless acquisition; Extensive local data processing.

LOWER POWER: Wireless communication consumes lots of power; Likewise for extensive local data processing

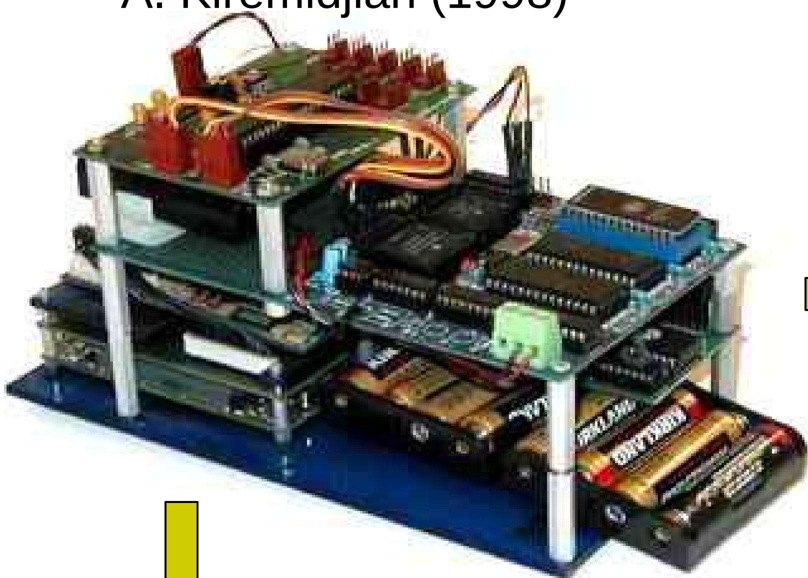


Challenges in Wireless SHM (2)

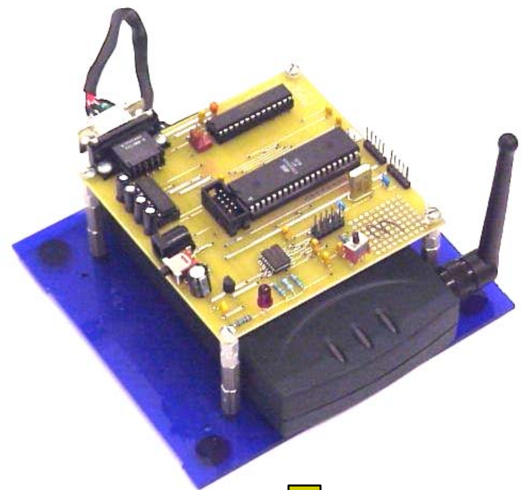
- Synchronization for data collected from multiple sensing units
- Communication range
- Limited bandwidth of wireless communication: impedes high-speed real-time data collection from multiple sensors
- Failures in wireless data transmission
- Communication protocol for the network: real-time data collection; multiple sensing units; synchronization; robust data transmission

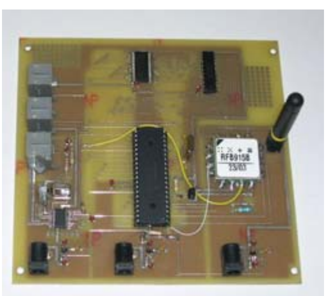
Wireless SHM Unit Prototypes from Stanford and UMich

Dr. E. G. Straser, Prof. A. Kiremidjian (1998)



Dr. J. P. Lynch, Prof. K. H. Law *et al*. (2002)





L. Mastroleon, Prof. A. Kiremidjian *et al* (2004)

Y. Wang, Prof. J. P. Lynch, Prof. K. H. Law (2005)

Design Objective

- Relatively low power
- Long communication range for civil structural applications
- Robust communication protocols for reliable data acquisition
- Near-real-time, non-stopping wireless data collection, from multiple sensors, at an acceptable sampling frequency
- Near-synchronized data collection
- High-precision analog-to-digital conversion from multiple heterogeneous analog sensors
- Considerable local data processing capability
- Point-to-multipoint, and peer-to-peer communication
- Low cost

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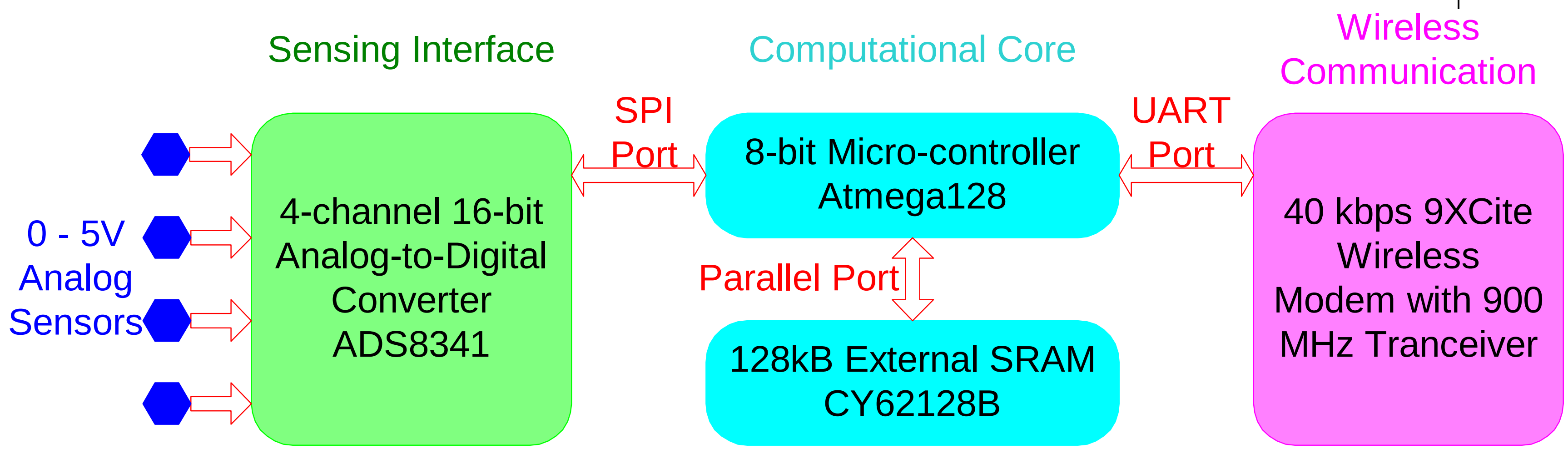
Functional Diagram of the Latest Prototype



Major power consumption when components are active:

9XCite – 45mA average between transmitting and receiving.

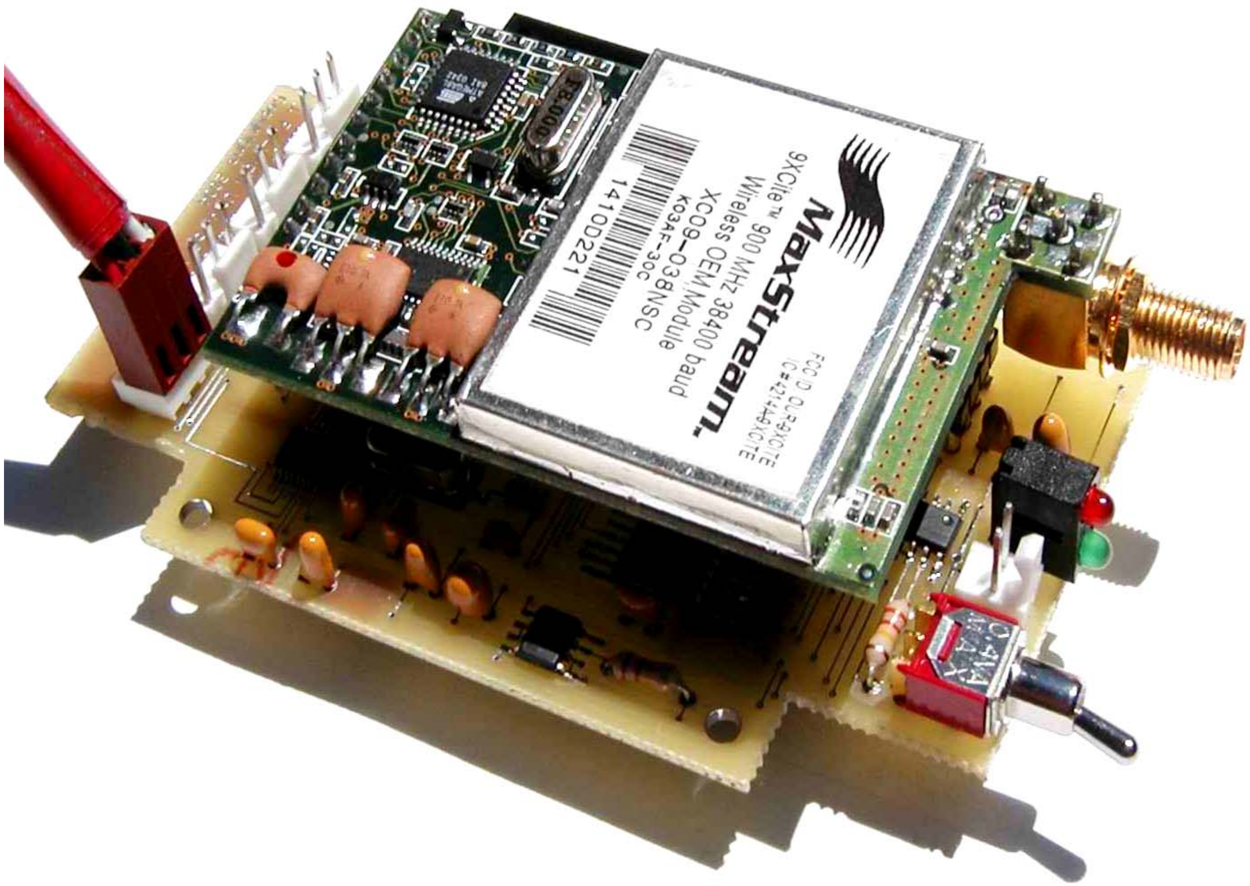
Atmega128 – 15mA running at 8MHz

CY62128B – 15mA

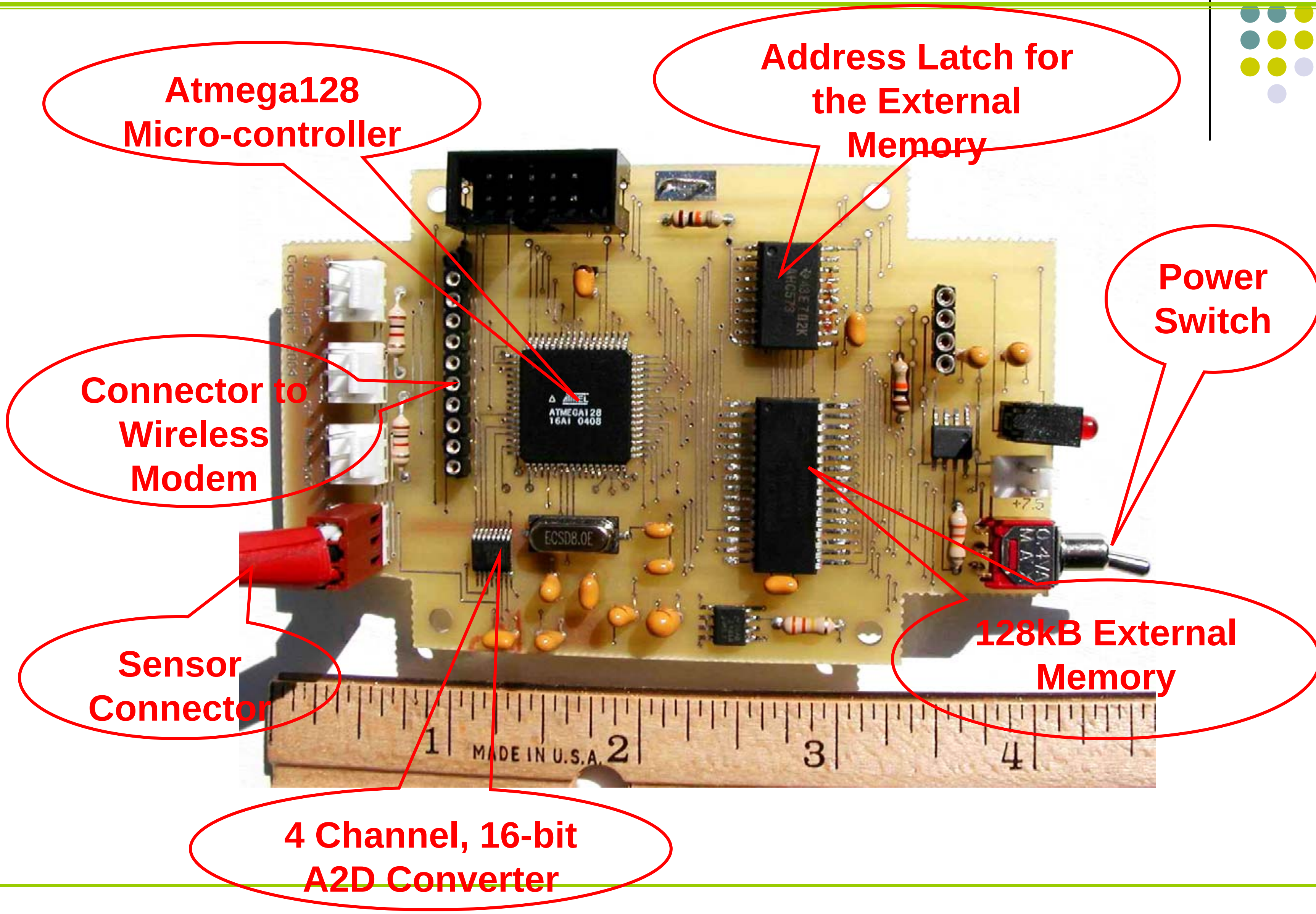
Hardware Performance Summary

- Power consumption: 75 – 80mA when active; 0.1mA standby
- Communication range: 90m indoor, 300m outdoor
- Near-real-time, non-stopping wireless data collection, from multiple sensors: up to 24 sensors at 50Hz sampling frequency
- Near-synchronized data from multiple wireless sensing units
- 16bit Analog-To-Digital conversion, 4 A2D channels, 100kHz F_s
- Local data processing: 4096-point float-point number FFT
- Point-to-multipoint, and peer-to-peer communication
- Total hardware cost: $130.00 each for small quantity production

Picture of the Prototype with Wireless Modem



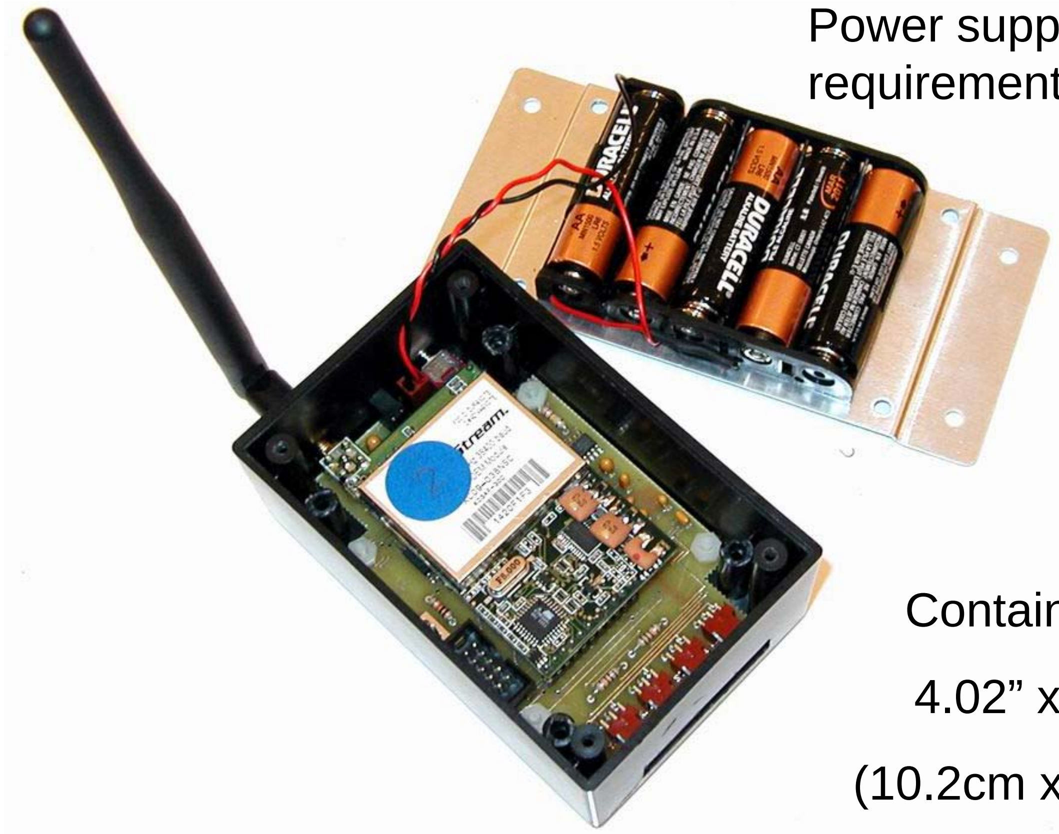
Prototype Double-layer Circuitry Board



Wireless Sensing Unit Prototype Package

Antenna Length:
5.79” (14.7cm)

Power supply
requirement: 5V



Container Dimension

4.02” x 2.56” x 1.57”

(10.2cm x 6.5cm x 4.0cm)

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Wireless Sensing Network

- Server-side software: Computer server manages network of multiple wireless sensing units
- Firmware: Atmega128 micro-controller organizes different hardware modules of the wireless sensing units
- Simple star topology

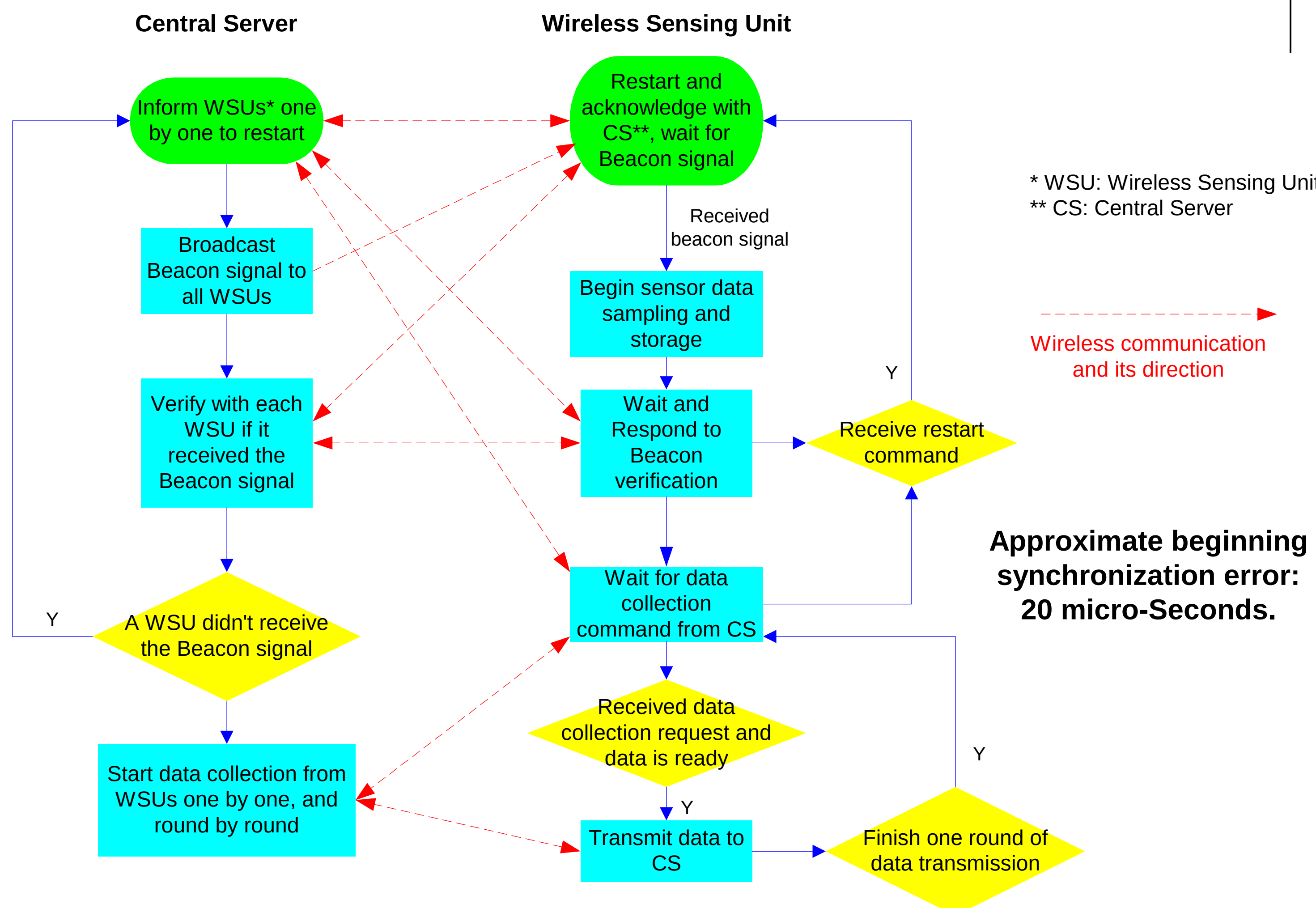
Objectives of Communication Protocol Design

Major Challenge: Address Unreliability of Wireless Communication

- Sufficiently reliable: detect the wireless communication failures; Successfully recover the system whenever a communication failure happens
- Central server: active – responsible for reliability
- Sensing units: passive – save power
- Synchronization among different wireless sensing units
- Retry and acknowledgement protocol to ensure the fidelity of data transfer

Reliable Beacon Signal Synchronization Protocol

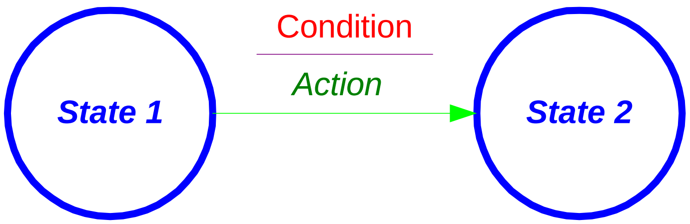
- Straser and Kiremidjian (1998)



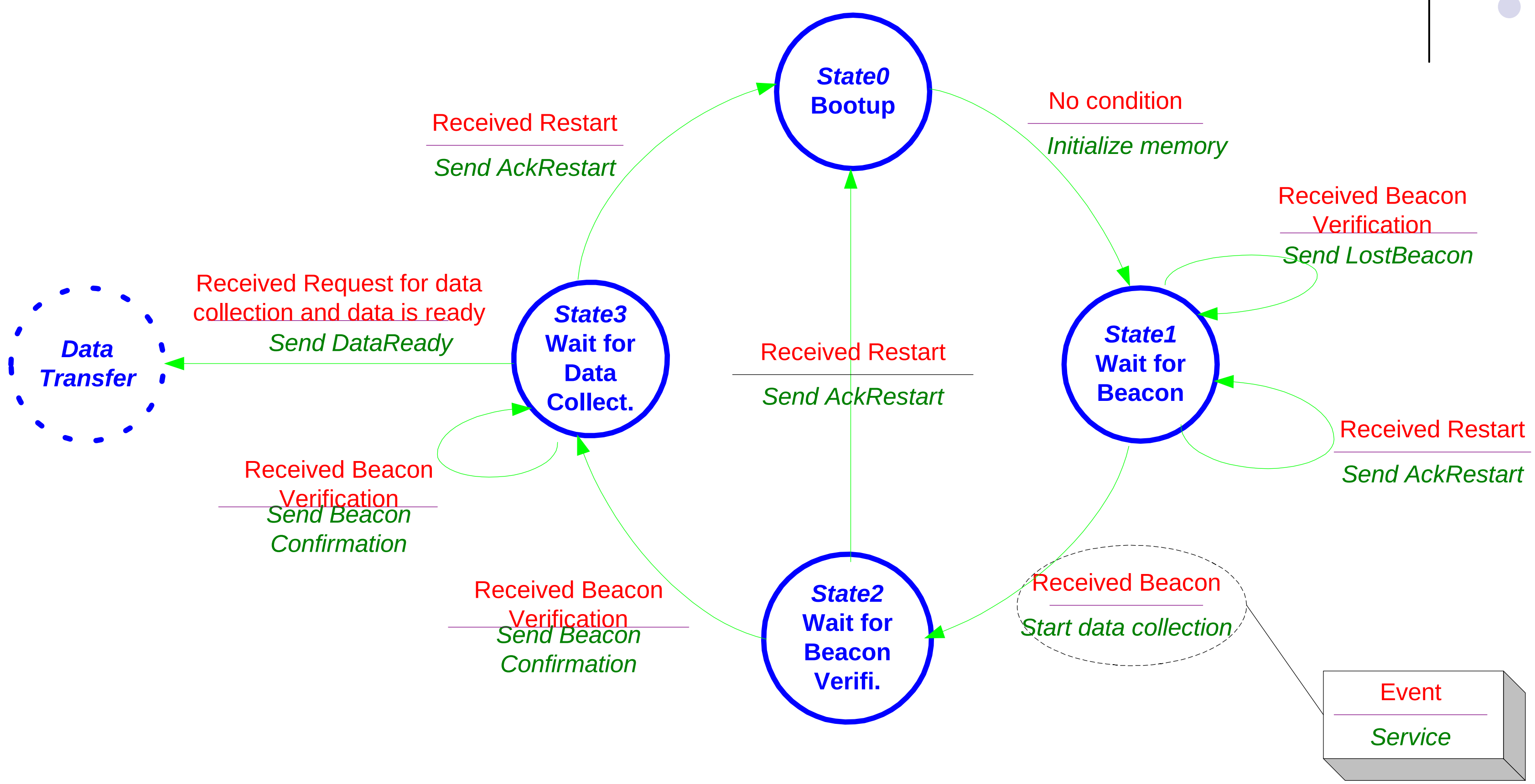
Approximate beginning synchronization error: 20 micro-Seconds.

State Machine Concept for Software Design

- System complexity incurred by the unreliability of the wireless communication -> state machine concepts
- A set of states
- A set of transitions among these states.
- At any point in time, the state machine can only be in one of the possible states.
- In response to different events, the machine transits between its discrete states.
- Visualize the communication protocol

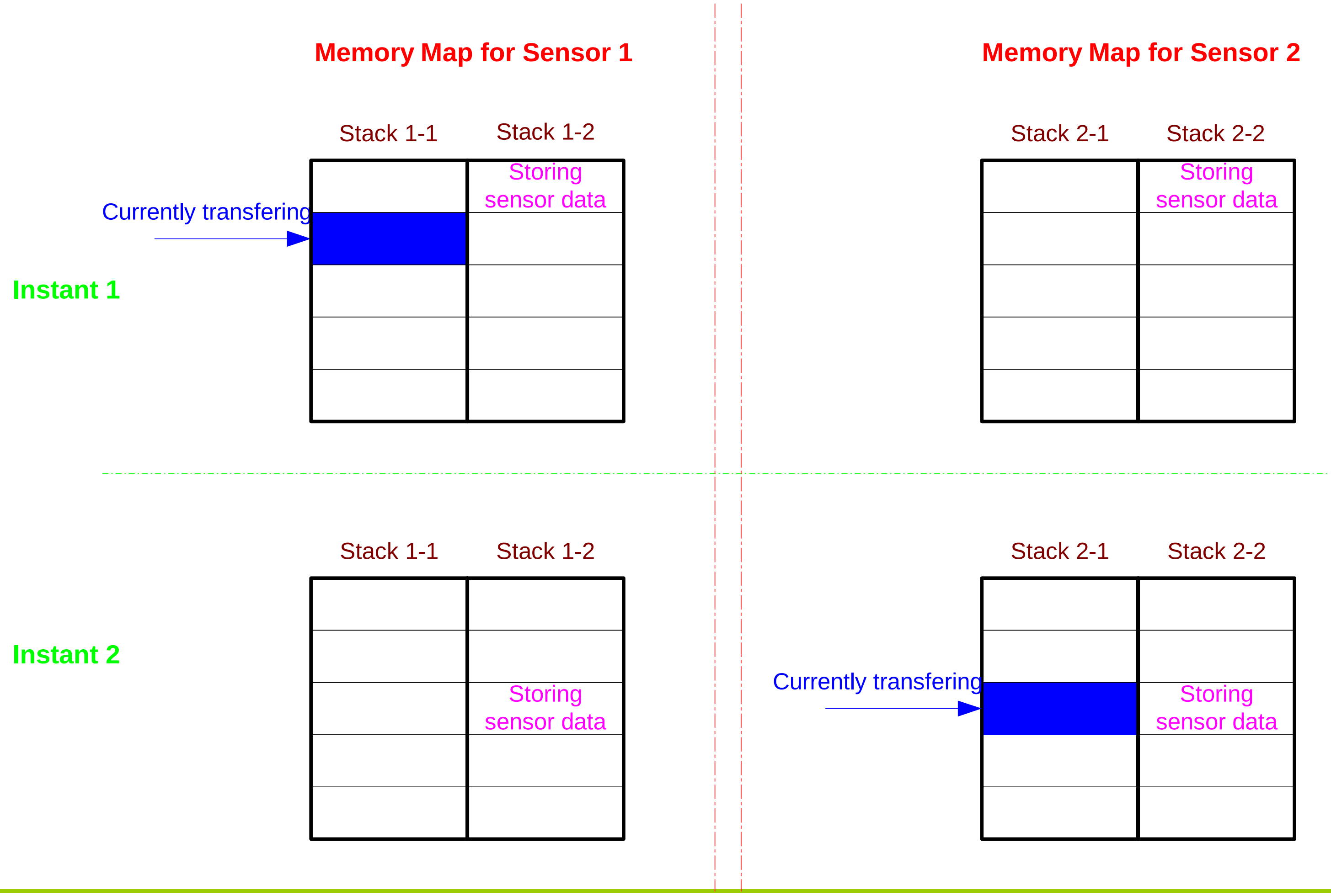


Communication State Diagram for Wireless Sensing Unit



Dual Stack Memory Allocation for Non-stopping DAQ

- Straser and Kiremidjian (1998)
- Lynch and Law *et al*. (2002)



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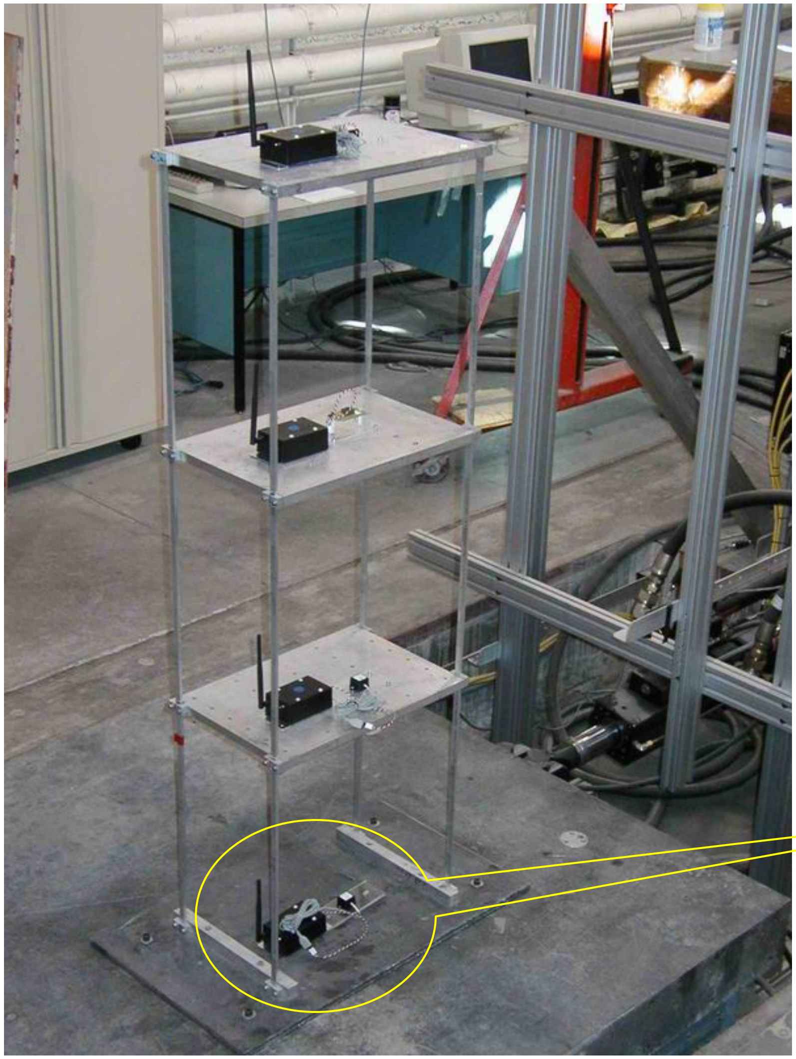
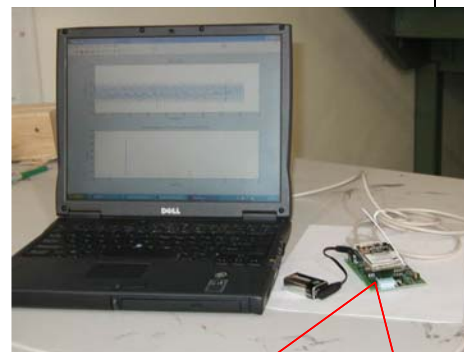
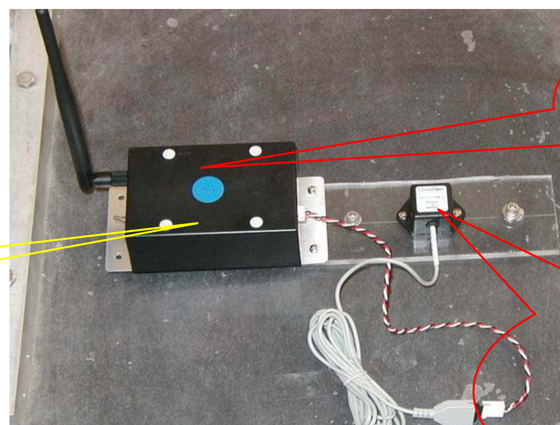
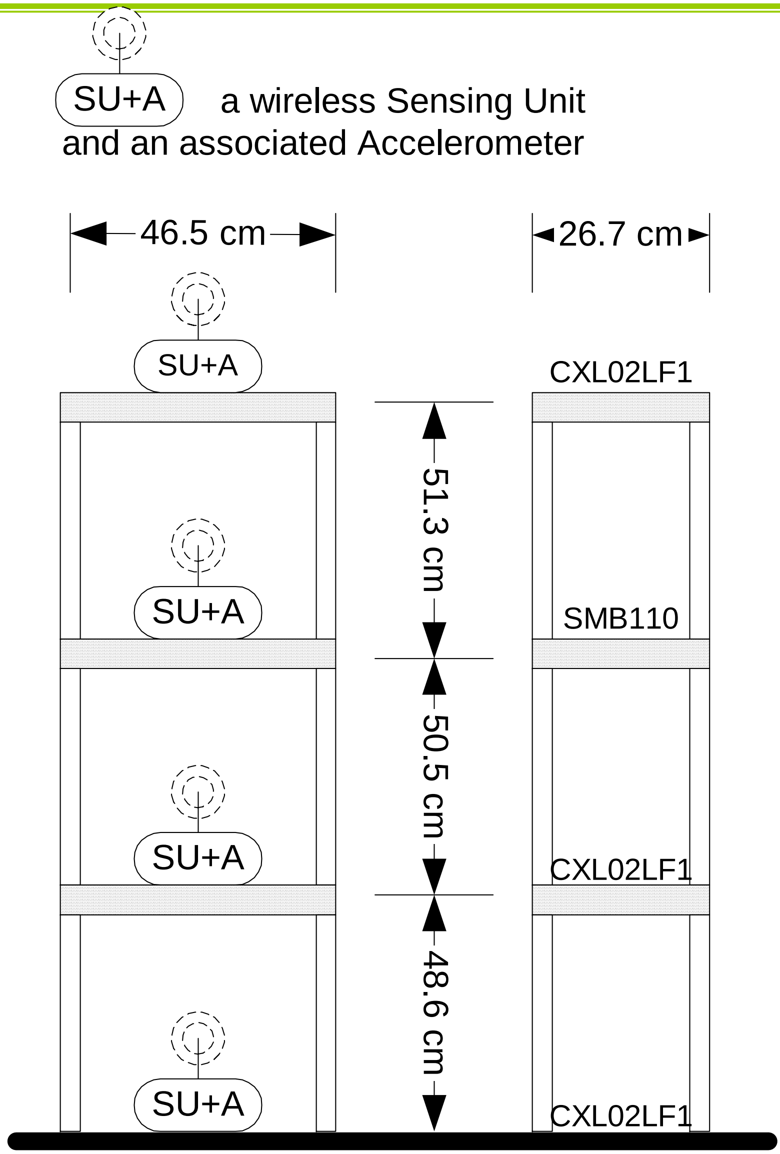
Lab Validation Tests





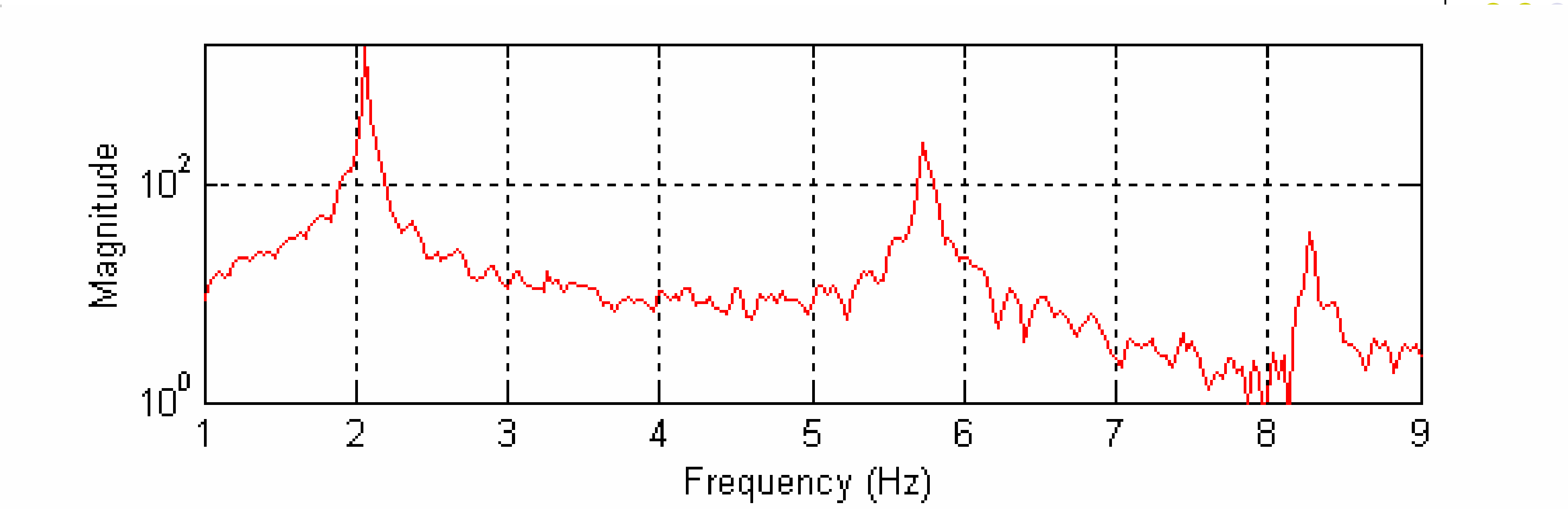


Some Test Parameters



- Sampling frequency: 200Hz. Sampling resolution: 16 bits
- Real-time non-stopping data collection from four wireless sensing units
- Crossbow CXL02LF1 accelerometer, RMS noise floor of 1mg
- Bosch SMB110 accelerometer, RMS noise floor of 7mg

First Lab Test: Free Vibration



Discrete Fourier Transform of the third-floor acceleration during free-vibration

Three theoretical natural frequencies: 2.08Hz, 5.71Hz, and 8.18Hz

Second Lab Test: Chirping-signal Ground Motion

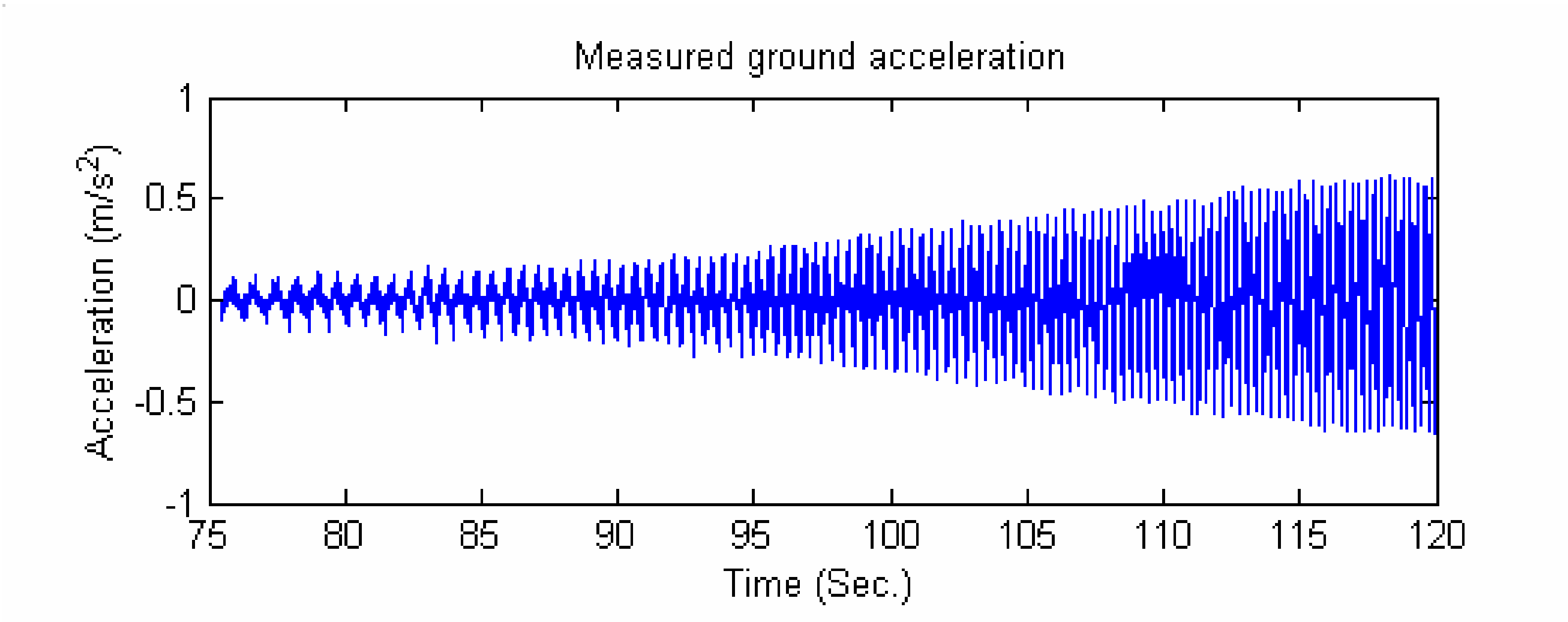
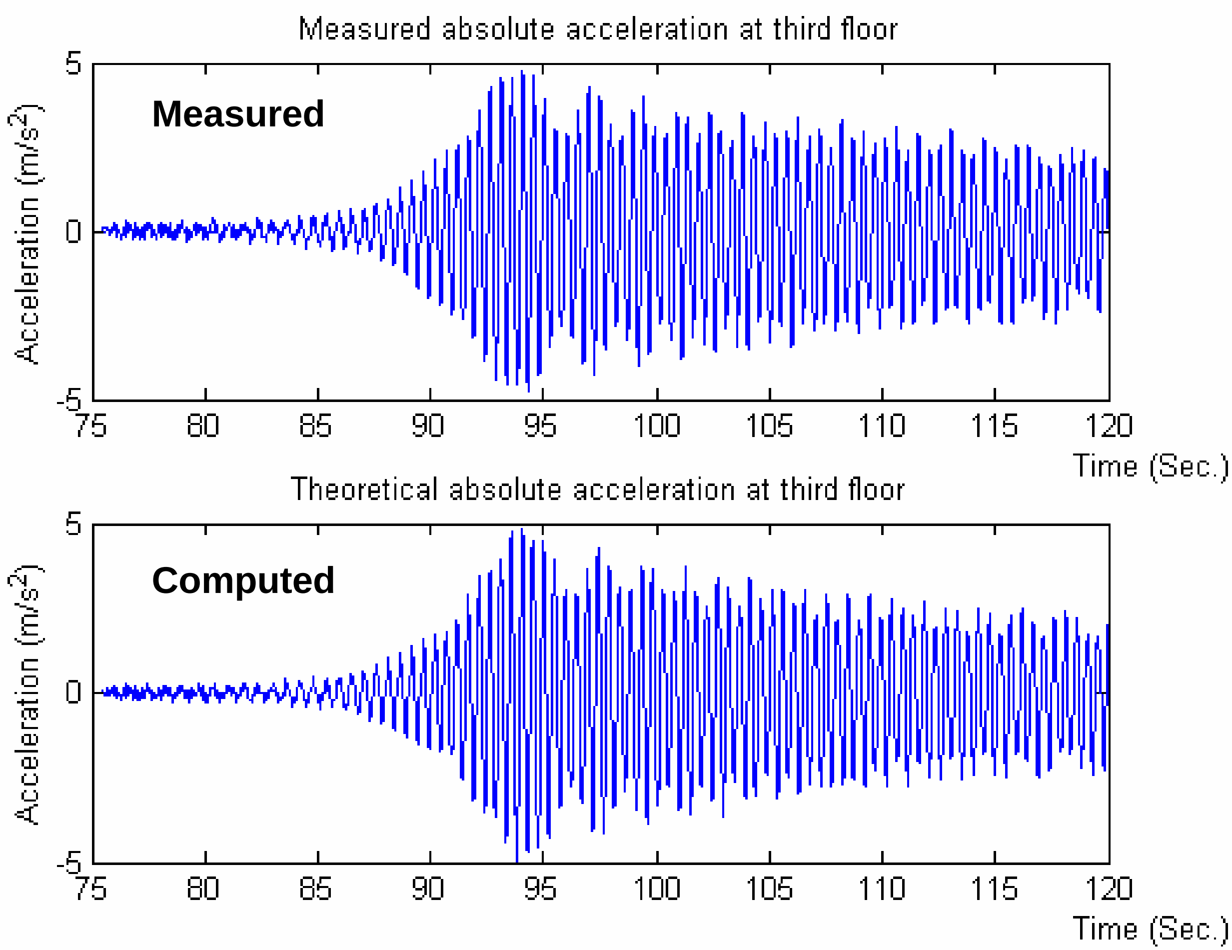


Figure 7 – Ground acceleration time history

Absolute Acceleration at Third Floor



Comparison of measured and theoretical absolute acceleration at third floor

Maximum Absolute Acceleration at Three Floors

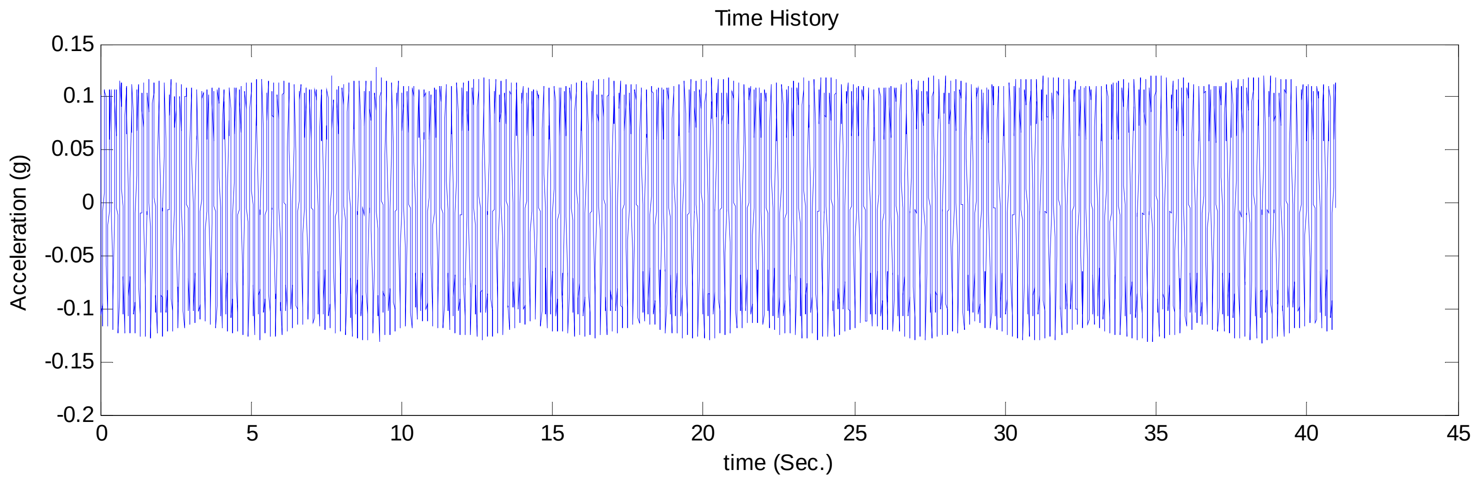
	1st floor	2nd floor	3rd floor
Measured (m/s^2)	2.14	3.35	4.74
Theoretical (m/s^2)	2.07	3.76	4.93
Relative Difference	3.32%	11.5%	3.93%

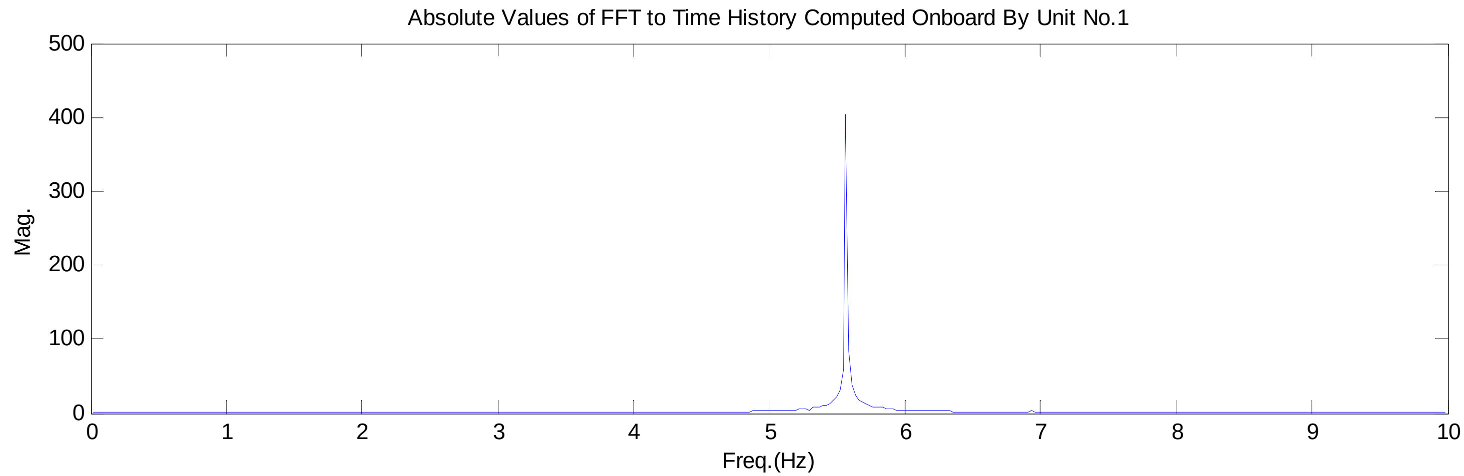
Comparison of measured and theoretical maximum absolute acceleration

Third Lab Test: Sinusoidal Ground Motion

Acceleration Data and FFT Results of the Shake-table Excited by 5.7Hz Sinusoidal Input

Sampling Frequency: 100Hz. Total time: 40.96 Seconds. Total Number of Pts: 4096

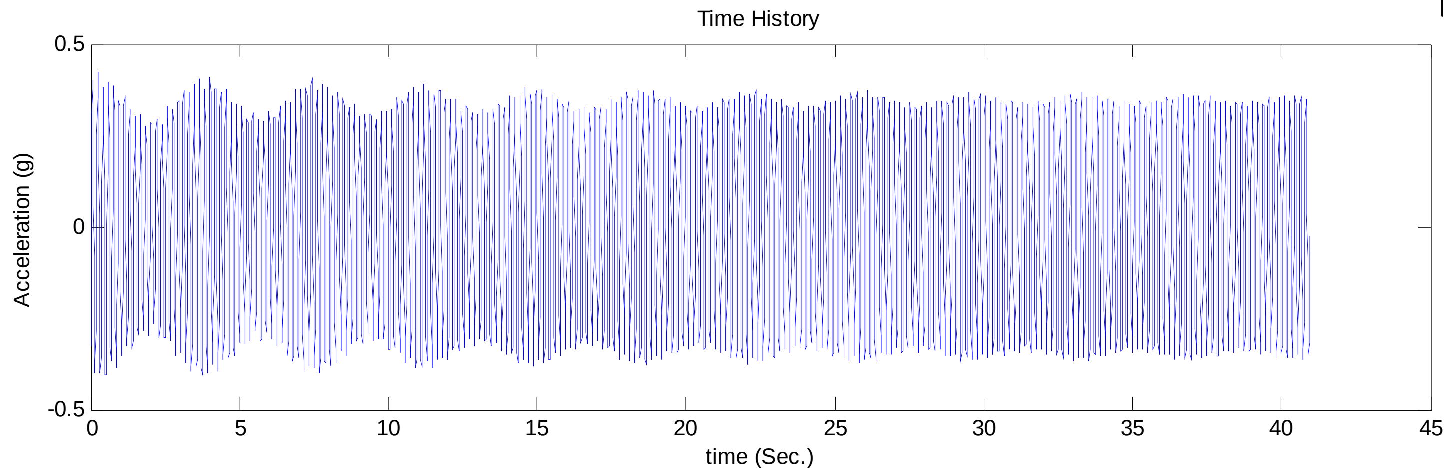


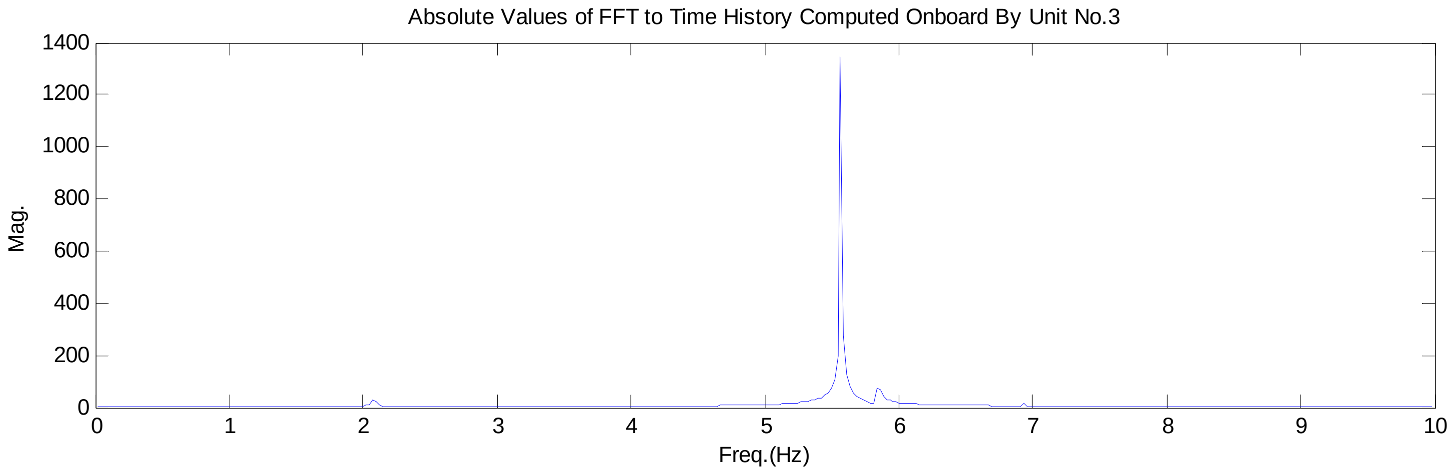


Third Test: Sinusoidal Ground Motion

Third-floor Acceleration Data

Sampling Frequency: 100Hz. Total time: 40.96 Seconds. Total Number of Pts: 4096





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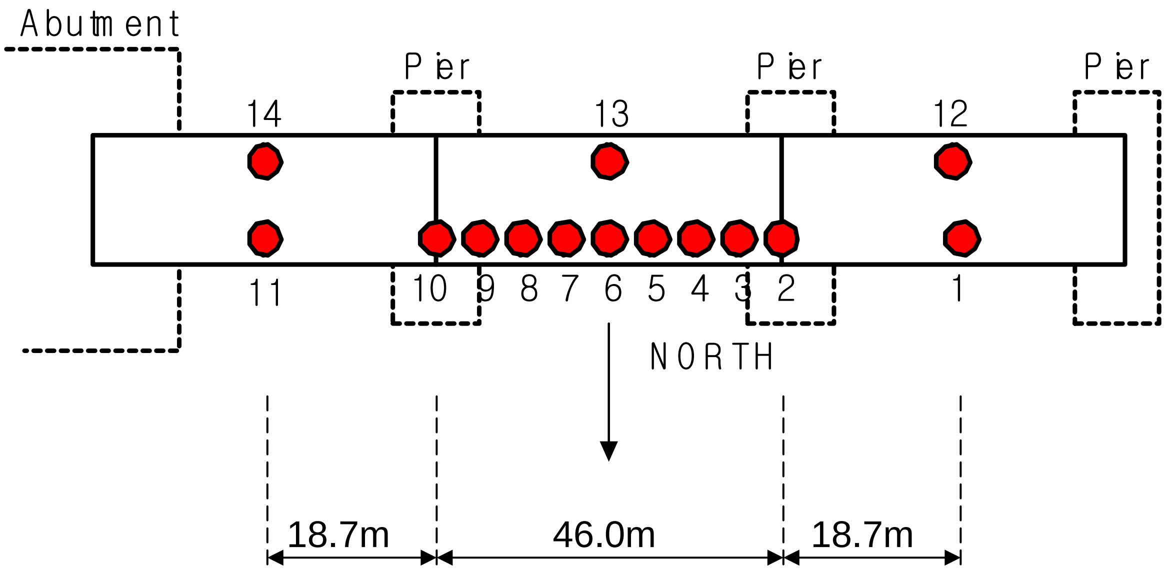
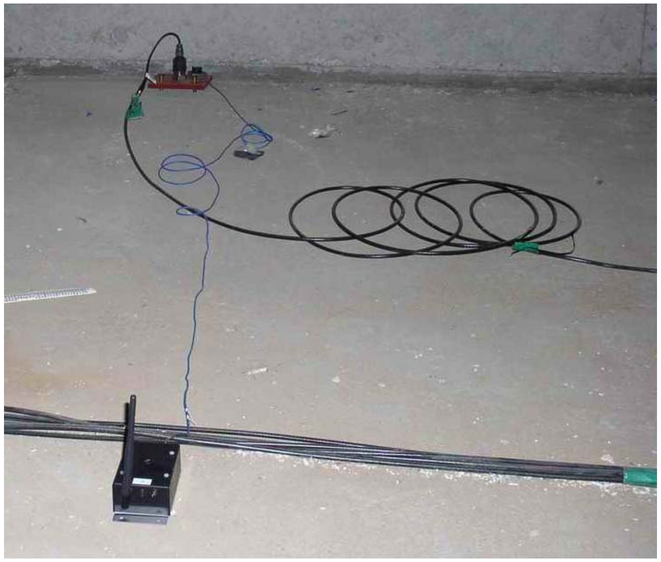
Geumdang Bridge Test, Korea

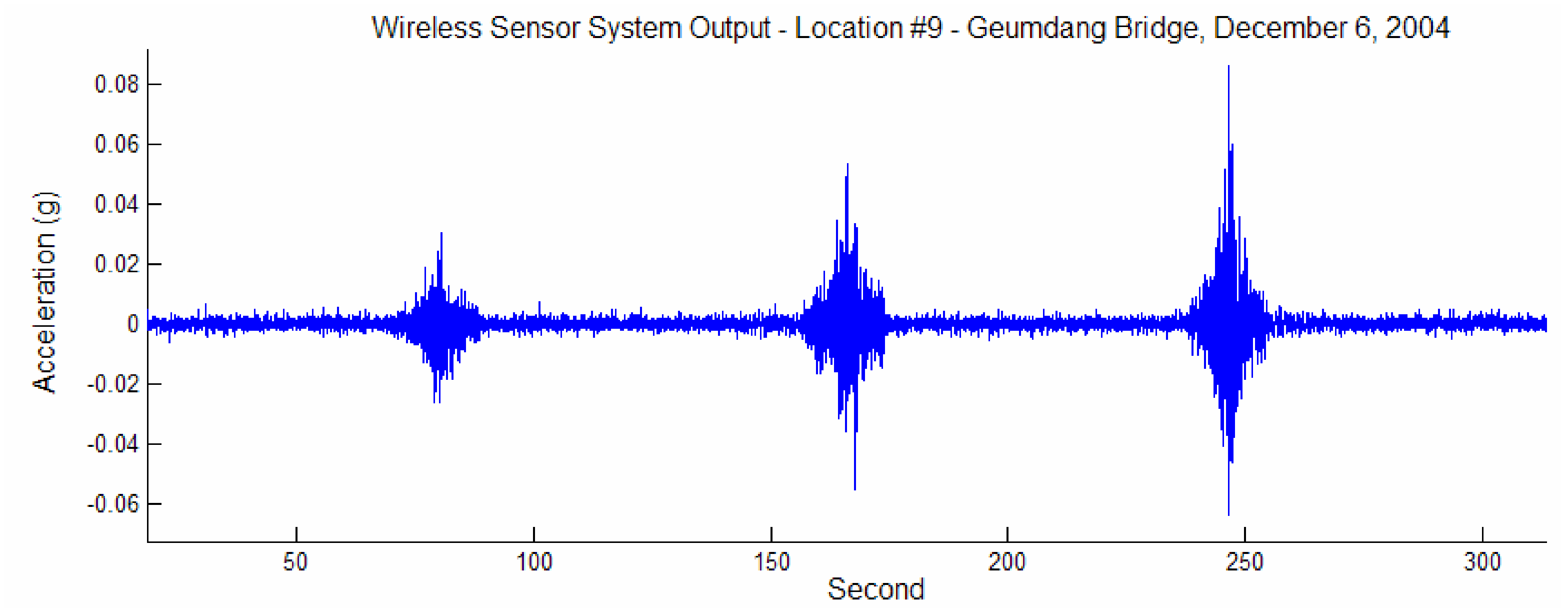


Wire-based System versus Wireless System

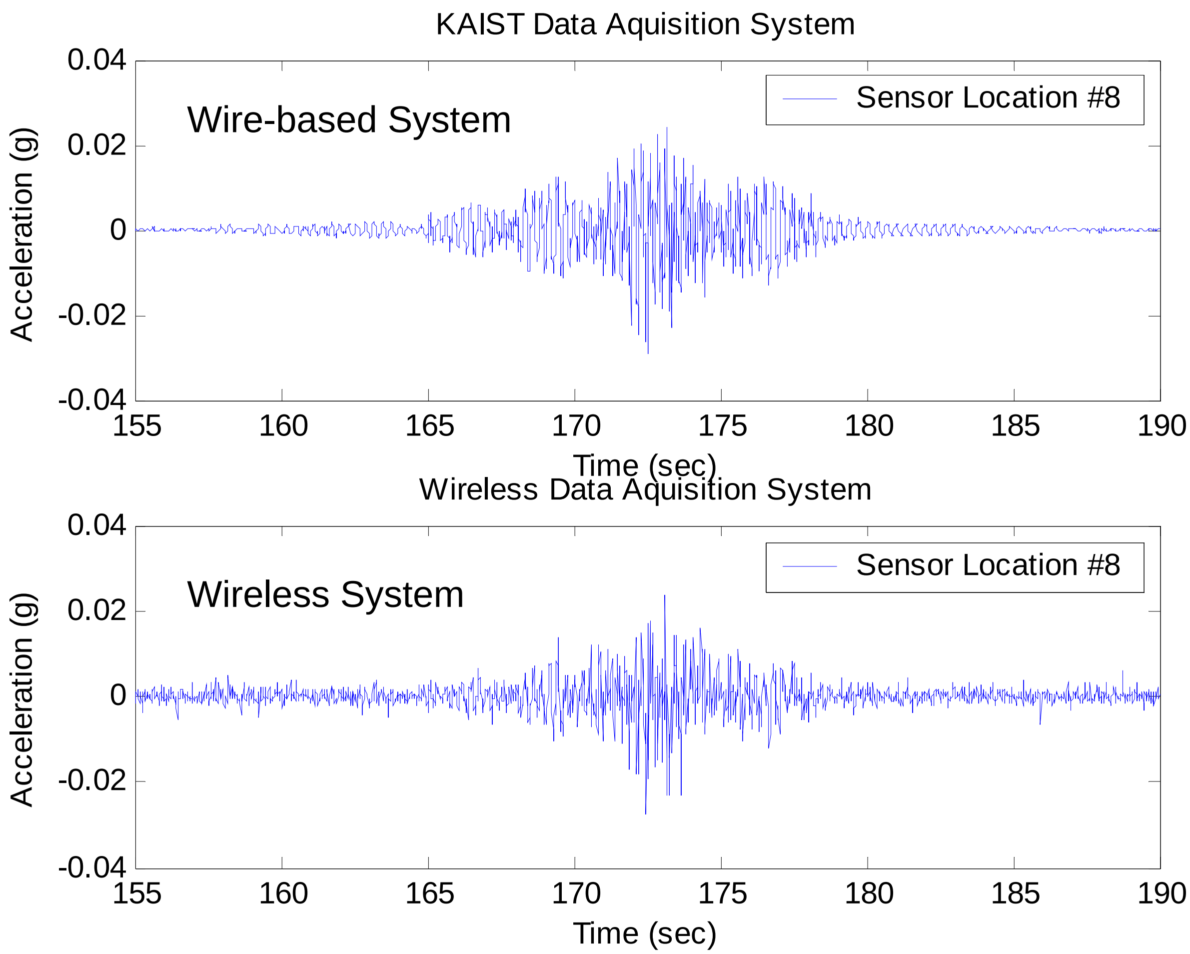


Sensor Property	PCB Piezoelectric (Cable System)	PCB MEMS Capacitive (Wireless System)
Maximum Range	1 g	3 g
Sensitivity	10 V/g	0.7 V/g
Bandwidth	2000 Hz	80 Hz
RMS Resolution (Noise Floor)	50 μg	0.5 mg
Sampling Frequency	200Hz	70Hz

Bridge Traffic Excitation

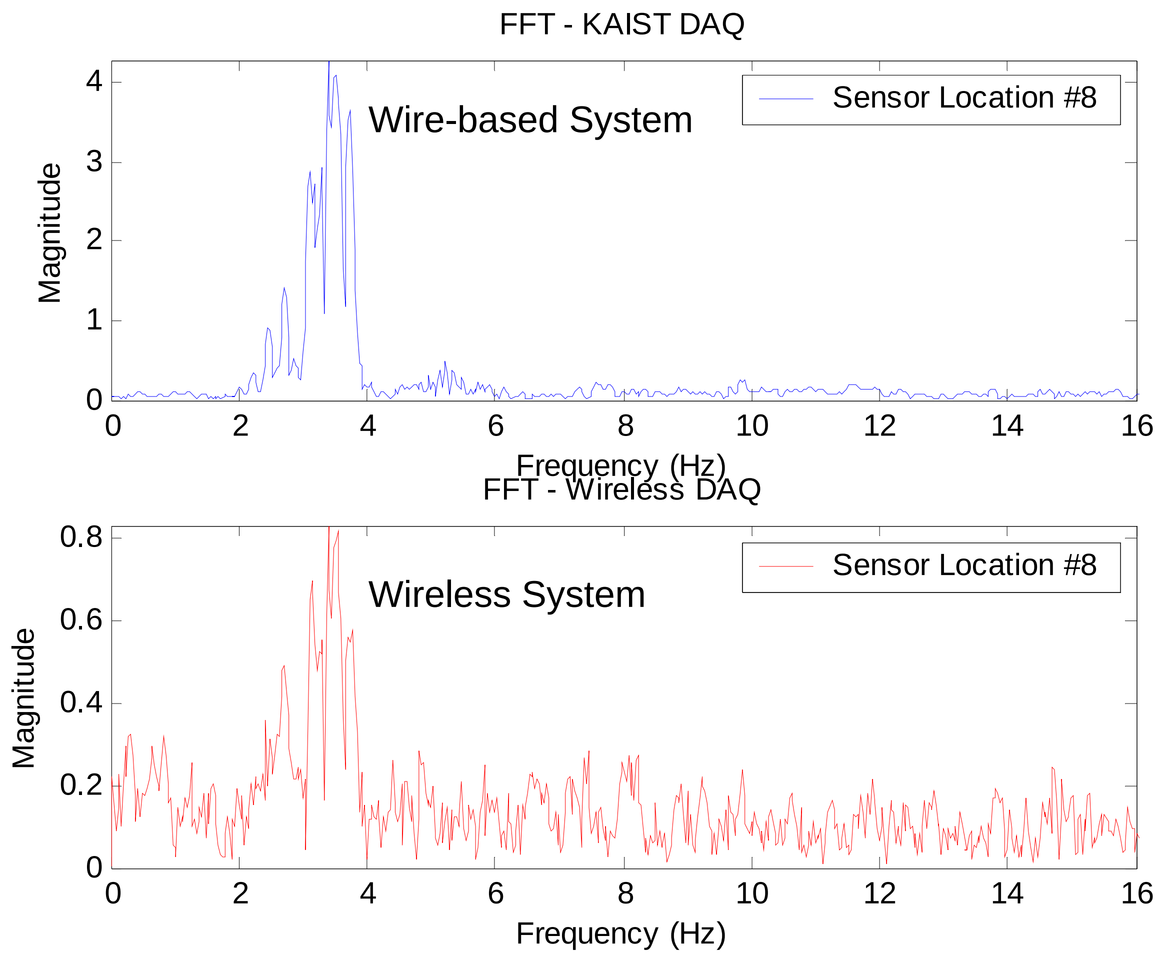


Time History Comparison Between Two Systems



- Difference in sensor and signal conditioning

Comparison of FFT to Time History



Validation Results Summary

- Rapid installation, and low cost
- Communication range: 50 – 60m in box girder
- Networked real-time and non-stopping data collection: 14 wireless sensors at 70Hz sampling frequency
- Data is near-synchronized
- Robust communication protocols for reliable data acquisition
- Local data processing capability
- Analog-to-digital precision
- Point-to-multipoint, and peer-to-peer communication

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Future Direction

To be improved for current prototype system:

- Power design, anti-noise circuits design
- Accommodation for digital sensors
- Greater wireless communication range, higher data rate
- Multiple receivers at different channels to improve data rate
- Large-scale data collection from densely allocated sensors
- More local data analysis and damage identification algorithm
- Handling mal-functioning sensing units
- Further field validation tests

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The End

Thank You