Remote Bridge Health Monitoring

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Outline

- Background
- Wireless Sensor Technology
  - Wireless sensor networks
- Decentralized Structural Health Monitoring
- Experimental study
- Future Research

BACKGROUND

Structural Health Monitoring (SHM)
- Ageing Infrastructure
- Growing population accelerates ageing and deterioration
- Earlier deterioration due to poor construction quality and heavy usage by overloaded vehicles

Partial Solution
- More cost-effective management of ageing infrastructure
- Condition-based maintenance and longer-service lives

Sydney Harbour Bridge – Rail/Highway, 19 March 1932

Length-1149m, arch span--503m, height-134m.

Tibetan timber buildings

BACKGROUND

SHM--Challenges

- High cost of sensor networks
  - Sensors with high costs
  - High installation costs with wired monitoring system
  - High cost of maintenance
- Big data
  - Dense sensor arrays or high sampling rates
  - Lack of the efficient big data analytics
  - Lack of the efficient data management
- Uncertainties
  - Unknown inputs
  - System modelling
  - Measurement errors

Wired monitoring system

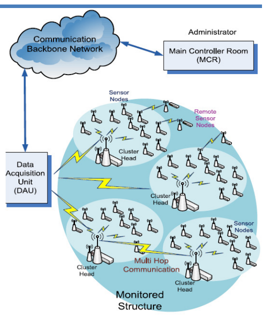
Data inundation

Wireless SHM

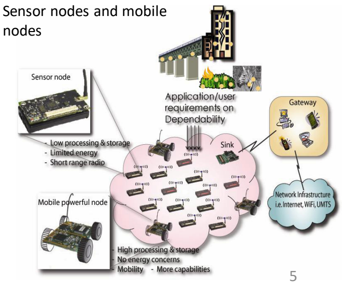
Wireless SHM

- Wireless Monitoring systems
  - Wireless communication—no expansive cabling
  - Ad-hoc connectivity—peer-peer, ad-hoc communication
  - On-board computation---sensor-based data interrogation
- Challenges
  - Power consumption—energy harvesting, reduced communication
  - Time synchronization
  - Reliable data transmission
  - Limited computational capacity---reduced computational requirements

WSN architecture for SHM



Sensor nodes and mobile nodes



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Wireless sensor role in SHM

1. On-board microprocessor
2. Sensing capability
3. Wireless communication
4. Battery powered
5. low cost

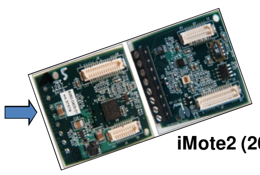
Prototype by Lynch (2002)

U3 (2002)

BTnode rev3 (2004)

Berkeley Mote Mica2 (2004)

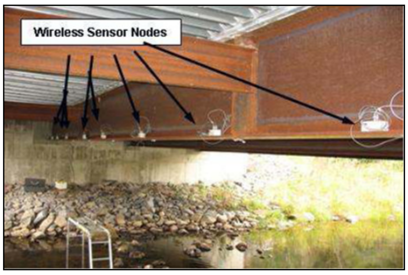
Microprocessor	XscalePXA271
Active Power (mW)	44 @ 13 MHz, 570 @ 416 MHz
Clock speed (MHz)	13 - 416
RAM (bytes)	256 K + 32 M external
Program flash (bytes)	32 M
802.15.4 radio (ChipCon 2420)	

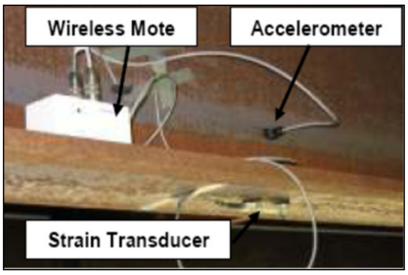


iMote2 (2004)

Previous implementations

- Clarkson University researchers have implemented a wireless sensor system for modal identification of a full-scale bridge structure in New York

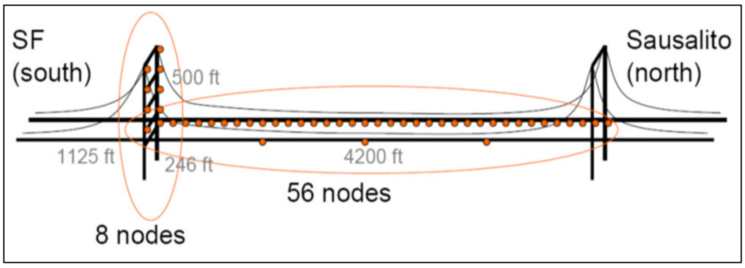




WS nodes deployed on one of the beam girders (after Gangone et al, 2007)

Previous implementations

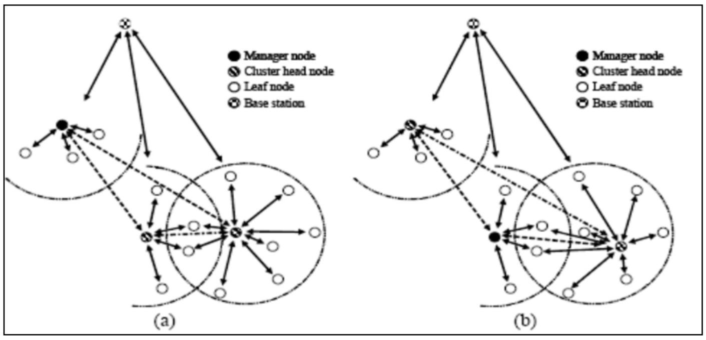
- At the University of California, Berkeley researchers have designed and deployed a wireless sensor network on the Golden Gate Bridge.



Layout of nodes deployed on The Golden Gate Bridge (after Kim et al., 2007)

Previous implementations

- Researchers at the UIUC have experimentally validated a SHM system employing a smart sensor network deployed on a scale three-dimensional truss model



SHM implementation under hierarchical architecture
(after Spencer and Nagayama, 2006)

Different Network topologies :
Peer-to-Peer network

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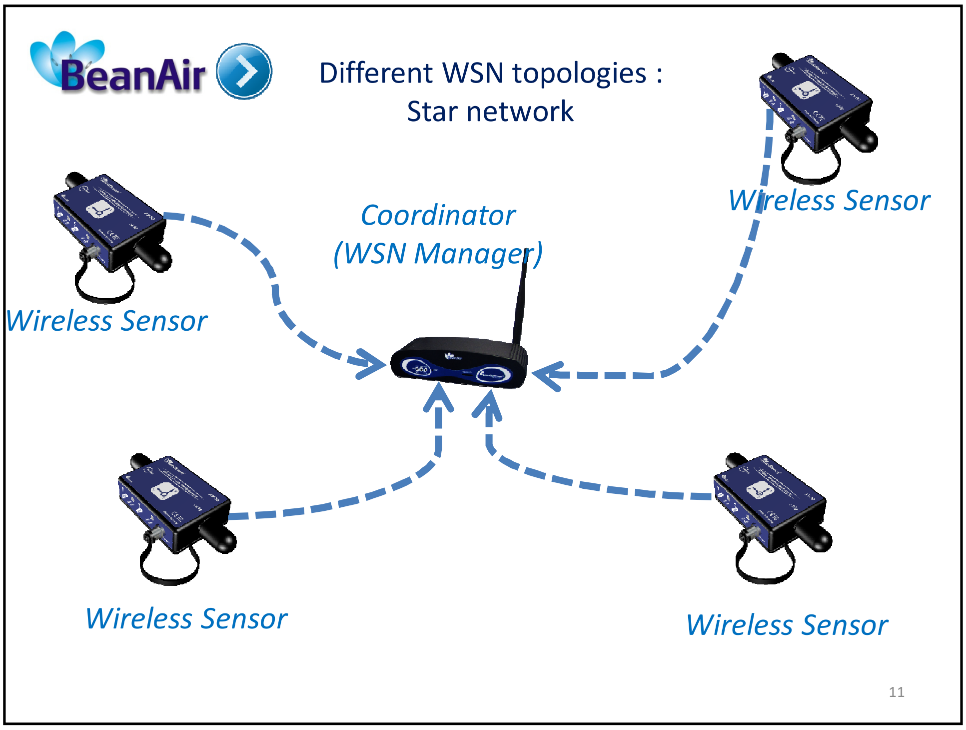
BeanAir
Different WSN topologies :
Star network
Coordinator
(WSN Manager)
Wireless Sensor
Wireless Sensor
Wireless Sensor
Wireless Sensor
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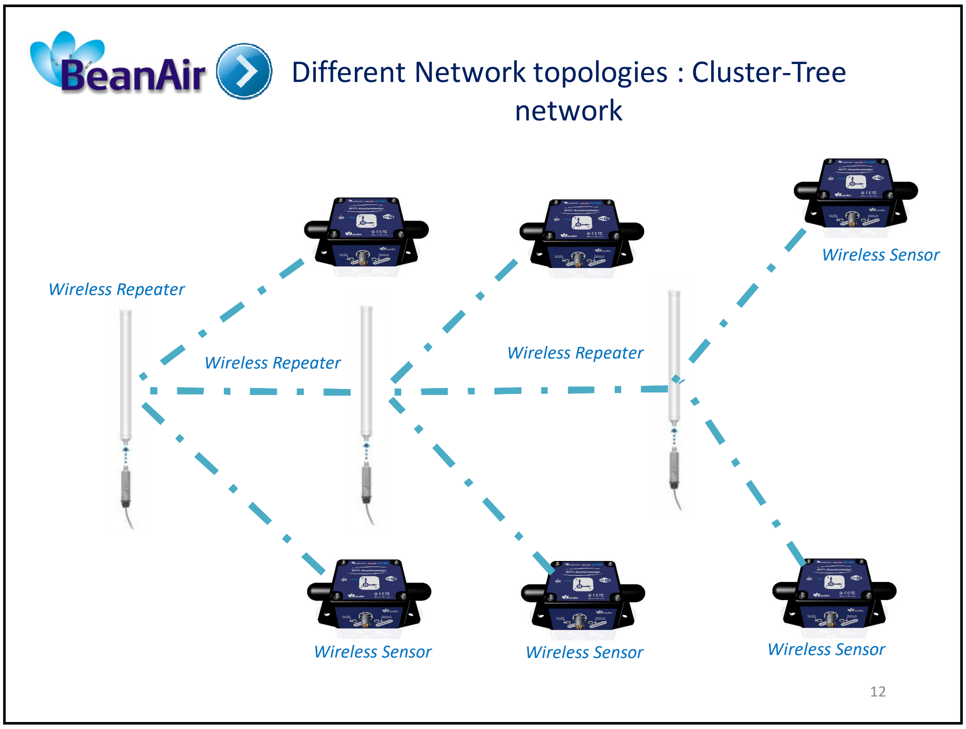
BeanAir
Different Network topologies : Cluster-Tree
network
Wireless Repeater
Wireless Repeater
Wireless Repeater
Wireless Sensor
Wireless Sensor
Wireless Sensor
Wireless Sensor
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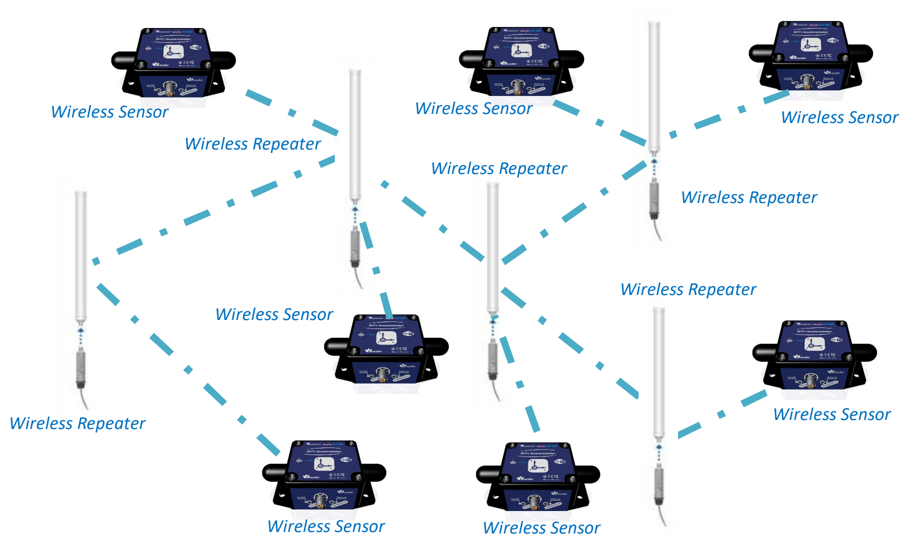
Different Network topologies : Mesh network



Different Network topologies : WSN technology benchmark

Radio technology	Network topology
Ultra low power Wifi (avoid to use Bluetooth)	Peer-to-Peer, Star and Cluster Tree Networks, Wifi Mesh possible but not standard
IR-UWB (Impulse radio Ultra Wide Band)	Peer-to-Peer, Star and Cluster Tree Networks
SigFox, Lora Wan, NB-IOT	Peer-to-Peer and Star Networks

Different Network topologies :
WSN technology benchmark

WSN Topology	PROS	CONS
Peer-to-Peer Star Network	• Easy to setup • Short-time latency	• Wireless range an not be extended
Cluster-Tree Network	• Wireless range can be extended • Still compatible with high sampling rate measurement	• Only one radio path is possible
Mesh Network	• Wireless range can be extended • No more network dead zone • Self-healing and scalable WSN	• Not easy to setup • Not compatible with high sampling rate measurement • No warranty on time-latency

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Example n°1: Highway Bridge in Montreal (Canada)

More than 300 Wireless sensors (Wireless Tiltmeter, Wireless accelerometers and wireless displacement sensors) are deployed on the monitoring site

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BeanAir Example n°1: Highway Bridge in Montreal (Canada)

Customer's problems

Need to monitor and predict structure collapsing during the highway bridge extension

Measurement type	***Targets***
Vibration	Analyzing resonance frequencies allows to predict future cracks
Cracks	Tracking visible cracks on pillar
Inclination	Tilt with 0.5deg were observed on several pillars

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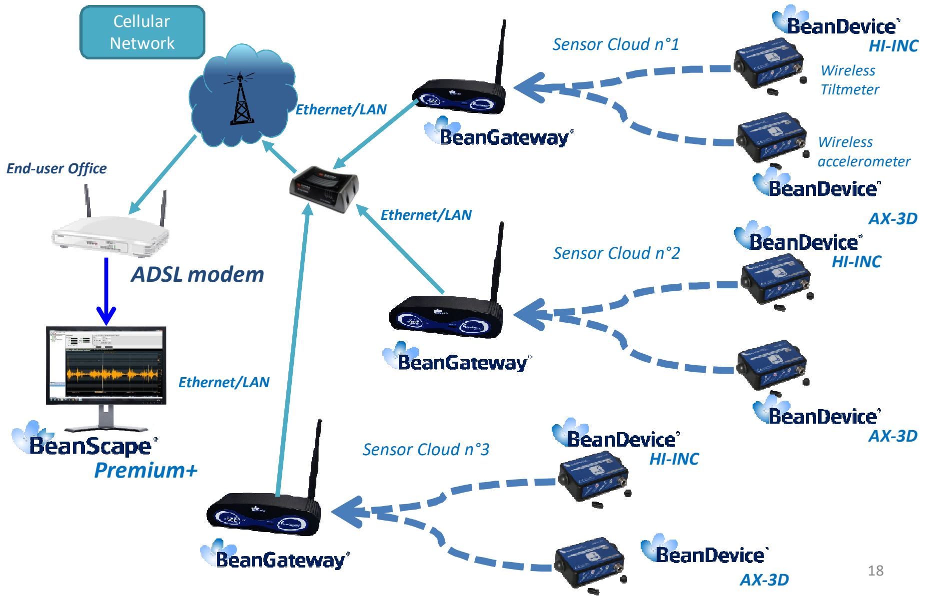
BeanAir Example n°1: Highway Bridge in Montreal (Canada)



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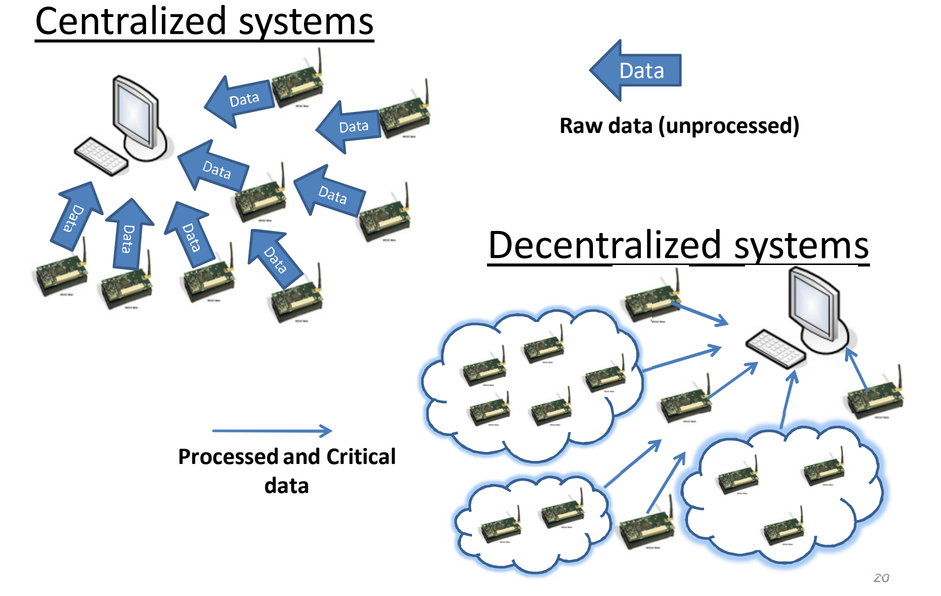
BeanAir Example n°1: Highway Bridge in Montreal (Canada)

Measurement technology	Measurement Heartbeat	Number of devices managed by each receiver/wireless coordinator
Vibration	100 Hz on concrete structure (resonance frequencies should be analyzed)	• 6-7 wireless accelerometers with a PER of 1.5%
Inclination	Every 10 minutes	• 35 wireless sensors working with the same wireless coordinator
Crackmeter	Every hours	• 35 wireless sensors working with the same wireless coordinator

Decentralised Monitoring Systems



DECENTRALIZED SHM

- Disadvantages of Centralized approaches:
  - Higher energy consumption
  - Limited data collection – in a reasonable time frame
  - High latency in extreme events

→Thus, Decentralized (Distributed) approaches

- Challenges in decentralized approaches
  - High energy consumption (but less than centralized)
  - Low accuracy decisions
  - Dependency on structural model
  - High complexity in-sensor data processing – time consuming

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Decentralised SHM

1 **Sensor Configuration and Data acquisition** ⟷
- Optimal sensor placement, energy-efficient protocol
- Use of compressive sensing technique for data acquisition in SHM

2 **Distributed Damage Detection Algorithms** ⟷
- Develop a distributed damage detection algorithm

3 **Statistical Classifiers for Damage Decision making** ⟷
- Comparative analysis of existing statistical classifiers
- Identify novel classifiers

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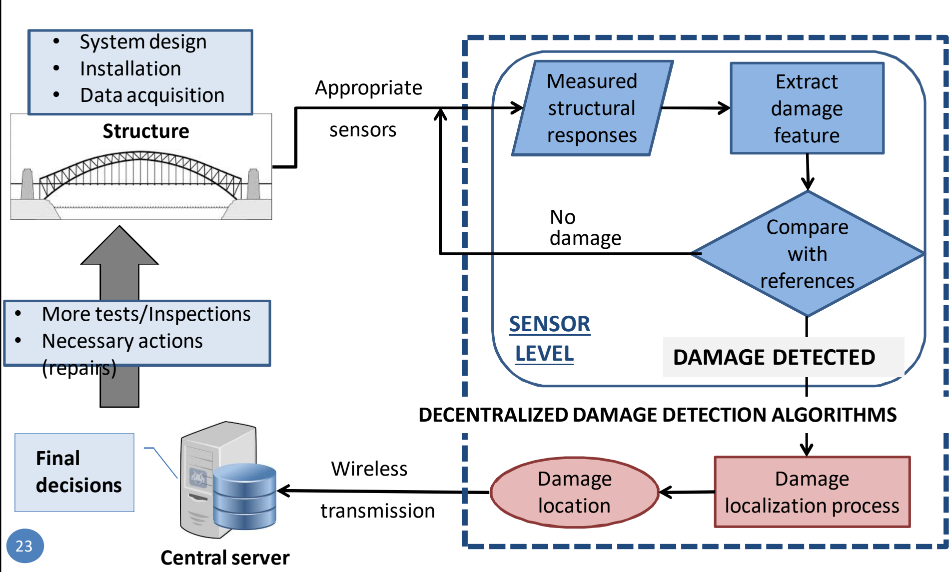
DECENTRALIZED SHM PROCESS



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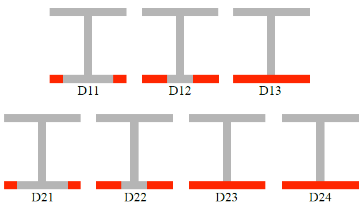
Experimental study--Damage Scenarios



Different damage scenarios

Damage Scenario	D11	D12	D13	D21	D22	D23	D24
	Damage one			Damage two			
Location (m)	0.85	0.85	0.85	2.40	2.40	2.40	2.40
Depth(mm)	16.5	33.0	49.5	16.5	32.0	49.5	49.5
Width (mm)	3.0	3.0	3.0	3.0	3.0	3.0	29.0

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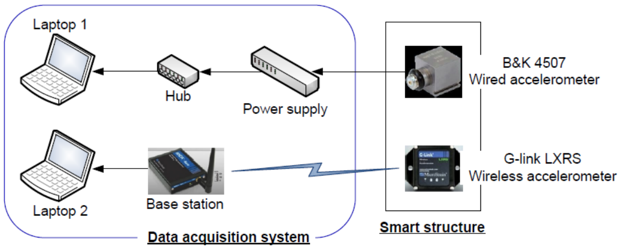
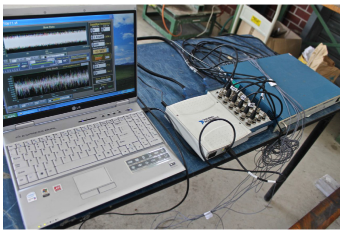
Measurement systems

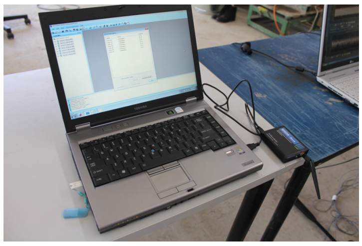
Experimental systems



Wired system



Wireless system



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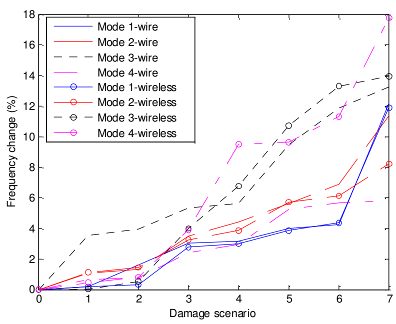
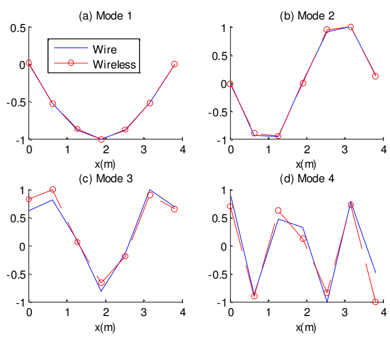
Comparison from wired and wireless sensors

The first five natural frequencies

Mode	Wired (Hz)	Wireless (Hz)	Difference (%)
1	23.65	23.60	0.21
2	90.53	90.62	0.10
3	176.51	180.02	1.99
4	373.82	395.96	5.92
5	459.38	455.84	0.77



The first four mode shapes



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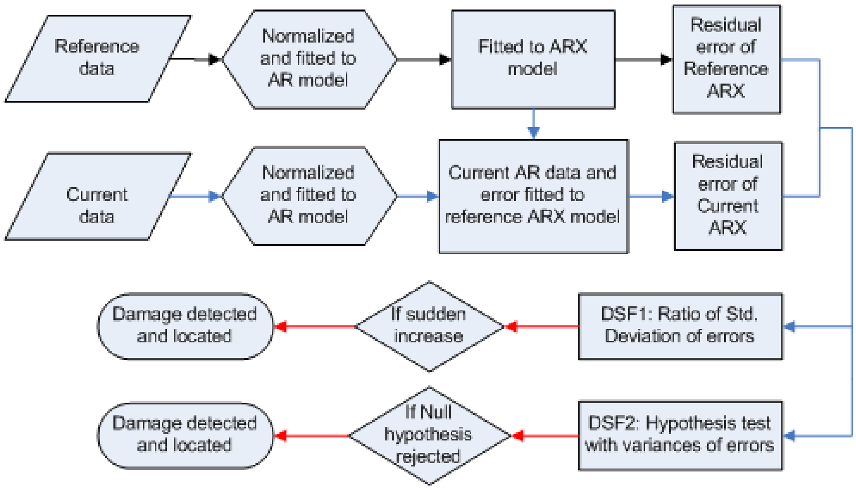
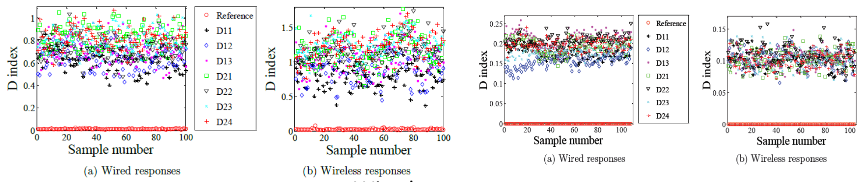
AR-ARX Method

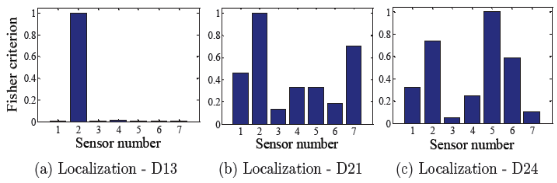
Auto regressive – auto regressive with exogenous input (AR-ARX)



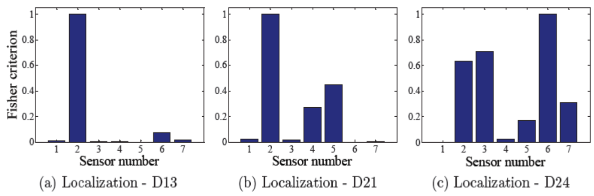
Damage detection using ARD-index



Wired sensors

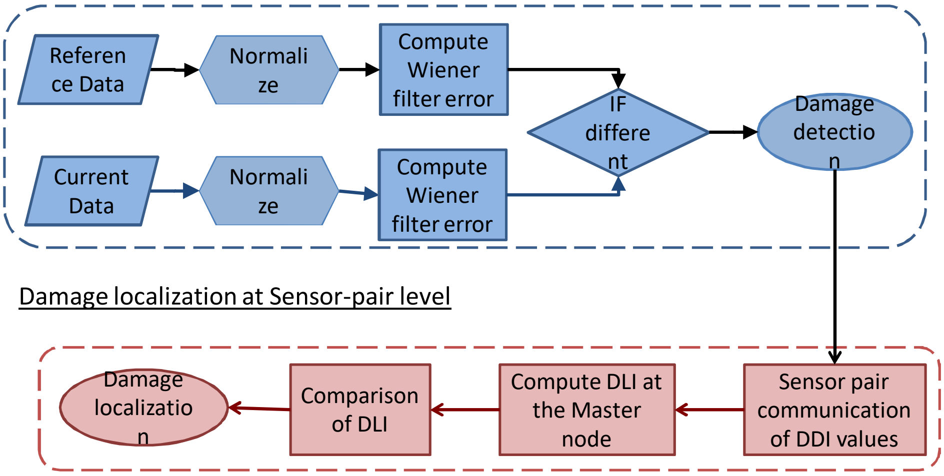


Wireless sensors

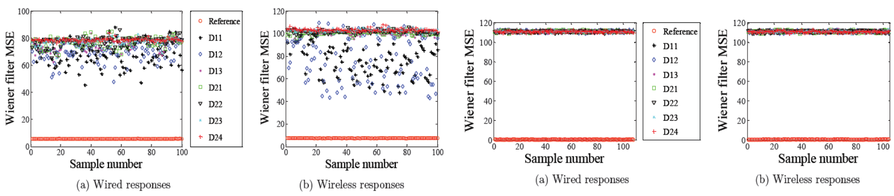


WIENER FILTER BASED ALGORITHM

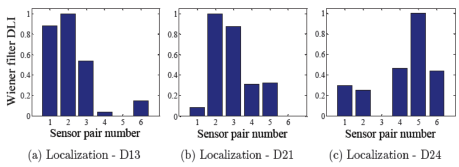
Damage detection at sensor level



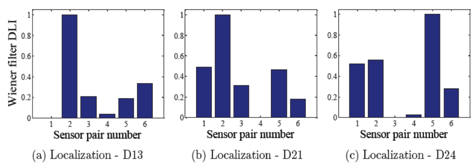
Damage detection using Wiener filter



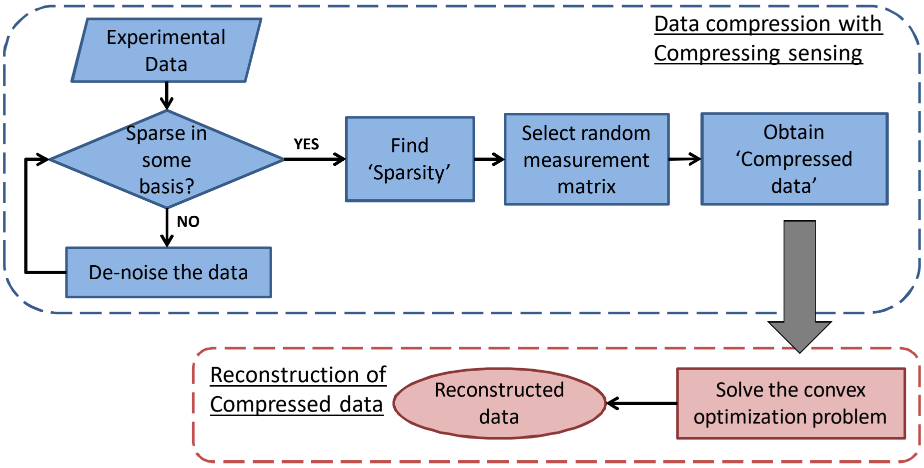
Wired sensors



Wireless sensors



COMPRESSIVE SENSING FOR SHM



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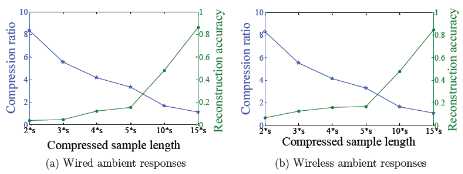
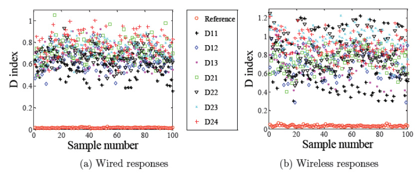
Damage detection using compressive sensing

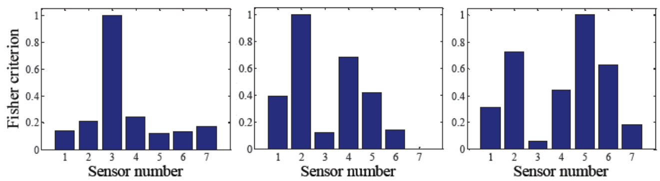
Compression ratio & reconstruction accuracy



ARD index using compressive sensing



Damage detection using ARD index



Note: M.Jayawardhana, X.Q. Zhu, R. Liyanapathirana and U. Gunawardana (2017) "Compressive sensing for efficient health monitoring and effective damage detection of structures." Mechanical Systems and Signal Processing, 84, 414-430.

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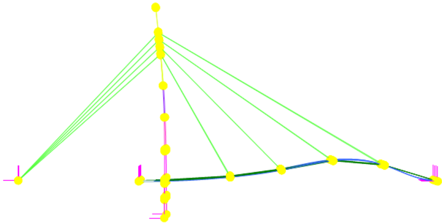
Field Study

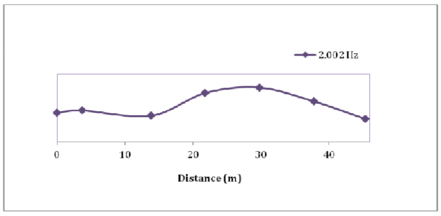
Full-scale bridge

Mode No.	Model Frequency (Hz)	Test Frequency (Hz)
1	2.0365	2.002
2	3.2200	3.879
3	4.1935	5.881
4	5.2340	7.007
5	6.2591	9.009

Finite element model



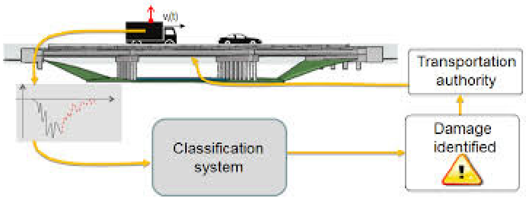
Experimental results



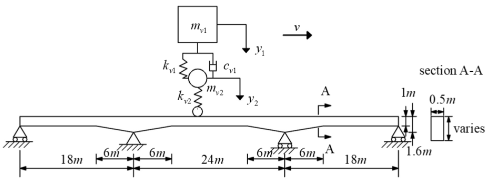
Indirect bride health monitoring

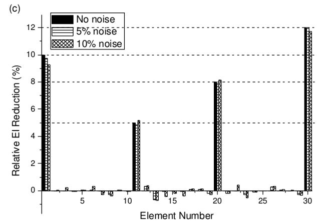
Instrumented vehicle:

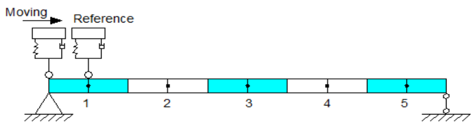
- The moving vehicle is a moving sensor to capture the bridge information.
- A passing vehicle to scan the bridge.
- A moving vehicle to catch the bridge response information.



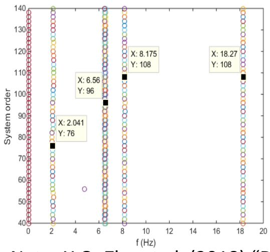
Indirect bridge health monitoring

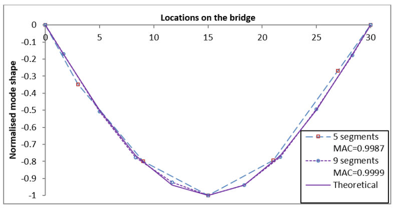






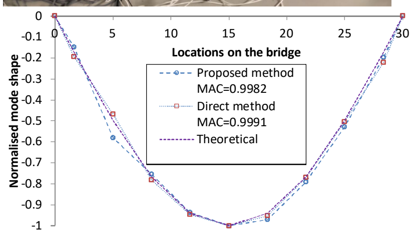
- Bridge condition assessment from dynamic responses of an instrumented passing vehicle
- Bridge modal parameters extraction from passing instrumented vehicles



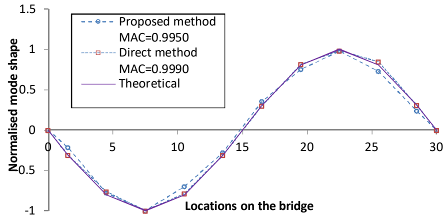


Note: X.Q. Zhu et al. (2018) "Damage identification of supporting structures with a moving sensory system", Journal of Sound and Vibration, 415, 111-127.

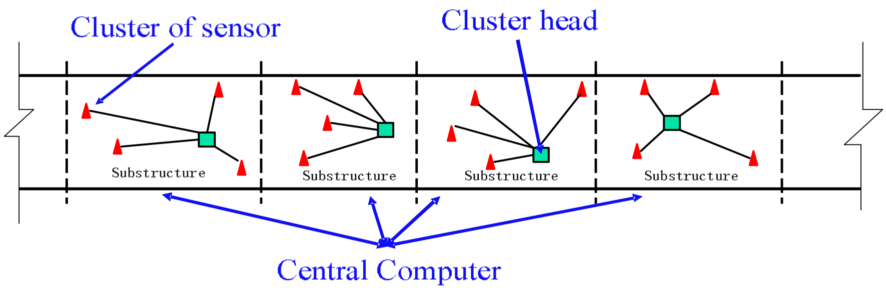
Indirect bridge health monitoring



- The moving vehicle is a moving sensor to capture the bridge information.
- The mode shapes are identified from the vehicle response only by the proposed method.
- The direct method is using the wireless sensors on the bridge.
- From the results, the mode shapes from the instrumented vehicle and the wireless monitoring system on the bridge agree well with the true values.



Substructure Technique for Bridge Condition Assessment



- Distributed sensors grouped into clusters in a substructure
- A cluster head to co-ordinate sensors in a substructure
- The identification algorithm is embedded in the on-board computation core of each cluster head
- Condition assessment can be done by distributed and parallel computing

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Cyberinfrastructure based Structural Health Monitoring