# Resource-Efficient Vibration Data Collection in Cyber-Physical Systems

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# Outline

- Cyber-Physical Systems (CPS)
  - WSNs and SHM
- Motivations
- Vibration Data Collections and Algorithms
- Performance Evaluations
- Conclusion and Limitation

# Cyber-Physical Systems (CPS)

Cyber-physical system (CPS) refers to a broad range of systems, with applications in diverse areas such as power grids, transportation, chemical processes and healthcare. CPS lies in the cyber part of the system, which consists of a network of interacting computing devices and physical part, which consists of physical objects.

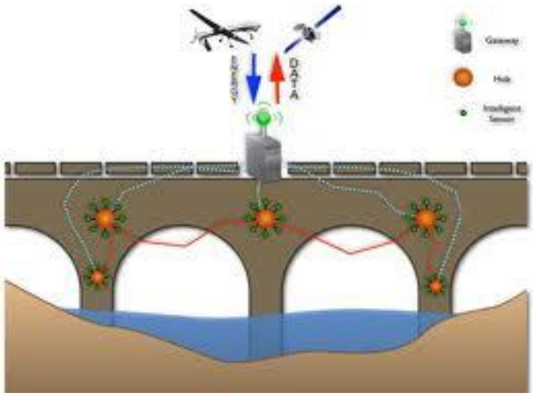
- **Wireless Sensor Network (WSN) system**
- **Structural Health Monitoring (SHM) system**

# What is a SHM System?

**A type of system that provides information about any damage occurring in the structure.**

- e. g. buildings, bridges, aircrafts, nuclear plants

**Damage- is a significant changes in the structure**



# Why SHM?

A road bridge in Fenghuang, China collapsed at 2007, killing 64 people and injuring 22

A road bridge in Zhuzhou, China, collapsed at 2009, killing ... and injuring 16

**American Airlines 587, Airbus A300-600, Nov. 12, 2001.**

**USAF F-16 aircraft at an airshow at Mountain Home Air Force Base, Idaho, on Sept. 14, 2003**

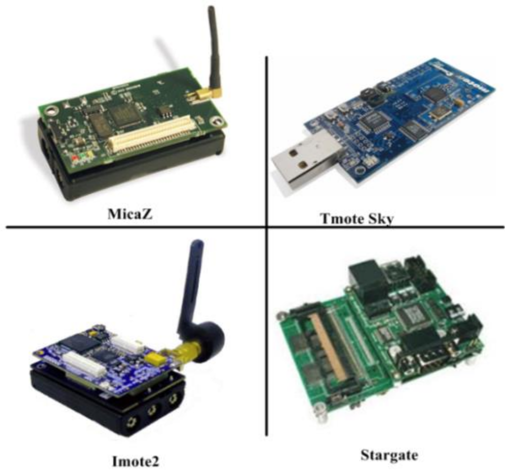
**[1]Structural Failure (damage) is about 25%**

[1]http://www.planecrashinfo.com/cause.htm

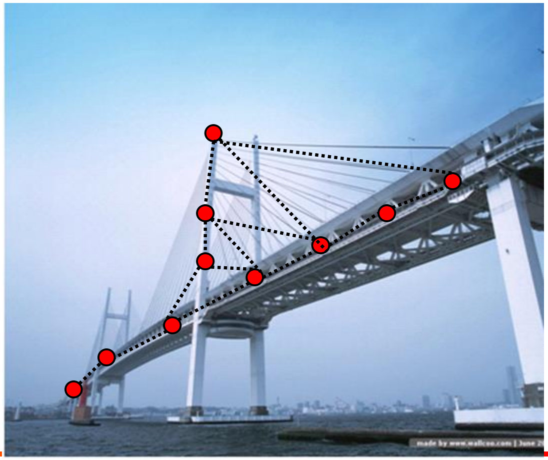
# Designing a SHM System

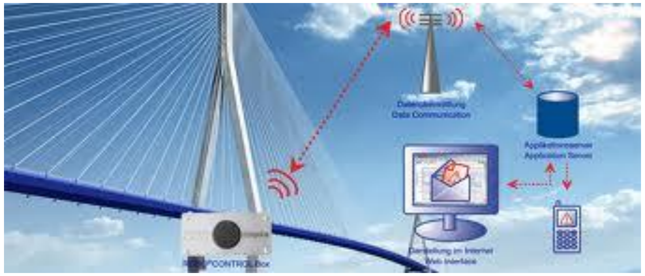
- In designing a SHM system, we need to know:
  - The structural phenomena to be monitored
  - Sensors
  - Time strategies
  - Damage detection algorithms
  - Data transfer and storage mechanism

# A Cyber-Physical Codesign of SHM with WSNs




- Smart sensor nodes
  - Sensors
  - CPU
  - Wireless transceivers
- Wireless sensor networks



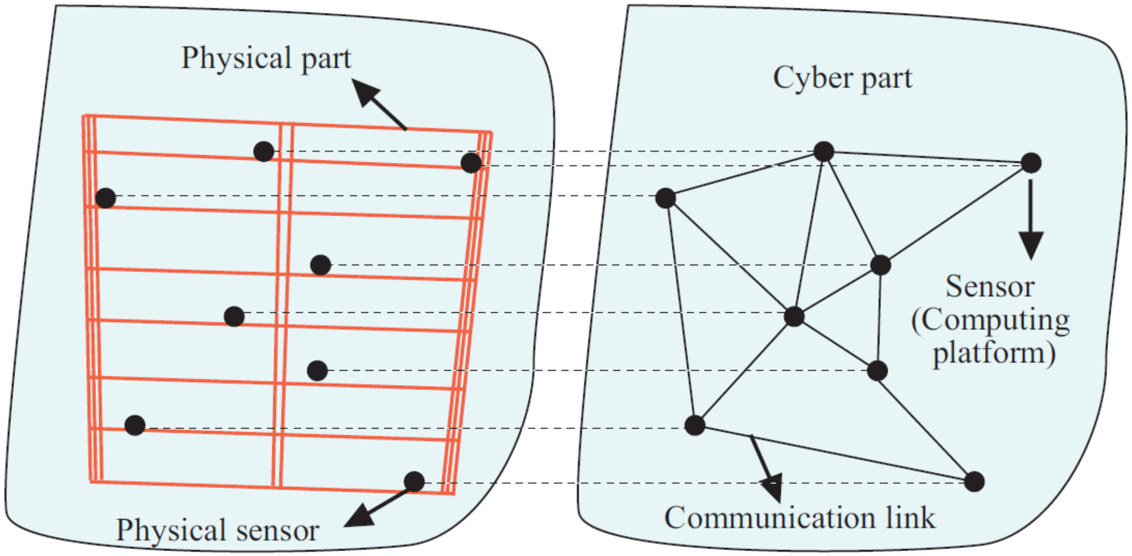


# Research Done!

- **Md Zakirul Alam Bhuiyan**, Jiannong Cao, Guojun Wang, and Xuefeng Liu, "Energy-Efficient and Fault-Tolerant Structural Health Monitoring in Wireless Sensor Networks," Accepted to appear in Proceedings of the 31st International Symposium on Reliable Distributed Systems (SRDS 2012), 8-11 October 2012, California, USA.
- **Md Zakirul Alam Bhuiyan,** Guojun Wang, and Jiannong Cao, "Sensor Placement with Multiple Objectives for Structural Health Monitoring in WSNs," Proceedings of the 2012 IEEE 14th International Conference on High Performance Computing and Communications (HPCC 2012), Liverpool, UK, pp. 699-706, June 25-27, 2012.
- **Md. Zakirul Alam Bhuiyan**, Jiannong Cao, and Guojun Wang, "Deploying Wireless Sensor Networks with Fault Tolerance for structural Health Monitoring," to appear in Proceedings of the 8th IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS 2012), Hangzhou, China, May 16-18, 2012.
- Xuefeng Liu, Jiannong Cao, **Md. Zakirul Alam Bhuiyan**, Steven Lai, Hejun Wu, and Guojun Wang, "Fault Tolerant WSN-Based Structural Health Monitoring," Proceedings of the 41st Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN 2011), pp. 37-48, Hong Kong, China, June 27-30, 2011.
- **Md. Zakirul Alam Bhuiyan**, Jiannong Cao, and Guojun Wang, "Backup Sensor Placement with Guaranteed Fault Tolerance for Structural Health Monitoring," Proceedings of the 6th BJ-HK International Doctoral Forum 2011, August 1-4, 2011, Shenzhen and Hong Kong SAR.

# Motivation

- Existing SHM Approaches
  - Deployments
  - Data Collection
  - Data Processing
  - Data Transmissi



# Wired vs. WSN based SHM Systems

| SHM requirements | | Wired System | Wireless System |
|---|---|---|---|
| Low cost | Equipment | Expensive | Low-cost |
| | Cabling | Long cables | No cables |
| | Deployment time | Months ~ years | Hours ~ days |
| High spatial density | | X0~X00 | X00~X000 |
| Sampling | Fast on command/event triggered | Delay <μs | Seconds ~ minutes (due to the wireless link) |
| | High frequency and synchronized | Frequency >10KHz<br>Sync error <1μs | Frequency < 10KHz<br>Large sync error |
| Fast and reliable data delivery | | 100% data delivery, instant delivery | Data can get lost, single hop bandwidth < 100kbps |
| Reliable and accurate damage detection | | Benefit from centralized algorithms, but constraint by low density & inflexibity | Constraint by limited computation power, but benefits from high density and flexible |

# Motivation

| | Other applications | SHM application |
|---|---|---|
| | | Vibration, (also acoustics) |
| | | (1) The raw data from multiple sensor nodes are collected<br>(2) Some vibration characteristics are identified<br>(3) The changes of characteristics → damage occurrence? |
| | | Complicated and centralized:<br>SVD, Eigen-system realization,…. |
| | | X00 times per second |
| | | Raw measured at each sensor node:<br>X000~X0000 bytes |

# Motivation

- **Existing SHM System**
  - **Deployments**
  - **Data Collection**
  - **Data Processing**
  - **Data Transmission**

SHM requires huge amount of data

Can a WSN is able transmit all the data to a central station?

Low radio communication bandwidth and communication range, and energy must be addressed to meet the generally high requirements of SHM systems.

# Vibration Data Collections

- The fundamental tool of vibration data collection is the fast Fourier transform (FFT).
  - FFT is used for the frequency domain analysis of signals. They require a relatively large buffer for storing the intermediate results since the whole spectrum is considered.
  - To achieve a frequency resolution below 1 Hz, one would need to use more than 256-point FFT when monitoring with sampling rate of 256 Hz. FFT algorithm suffers from the burden of synthesizing cosine and sine signals.
  - However, most of the existing WSN-based SHM systems are suggested data acquisition at 560Hz or more to analysis Damage information. >> bring difficulties to WSNs

# Our Approach

- We assume that there is no memory space for performing, say, 512-point FFT on a sensor node. In fact, event of interest, e.g., damage, is concentrated on a relatively small portion of the vibration spectrum.
- In addition, we have observed that the changes in vibration frequencies are very small, thus requiring relatively accurate monitoring.

# Goertzel algorithm

- We use a method called the Goertzel algorithm
  - Ben Goertzel (born December 8, 1966) is an American, author and researcher in the field of artificial intelligence.
  - It is used for computing a small number of selected frequency components, it is more numerically efficient

# FFT Analysis to Goertzel algorithm

- In our case, it is used to convert the raw accelerations into amplitude of vibrations, it can reduce the amount of transmitted data significantly, thus to reduce energy consumption.
- It is able to monitor a single narrow frequency band with even fewer requirements.
  - More specificity, we calculate only specific bins instead of the entire frequency spectrum through the Goertzel algorithm, which can be thought of as a second order infinite impulse response (IIR) filter for each discrete Fourier transform (DFT) coefficient.
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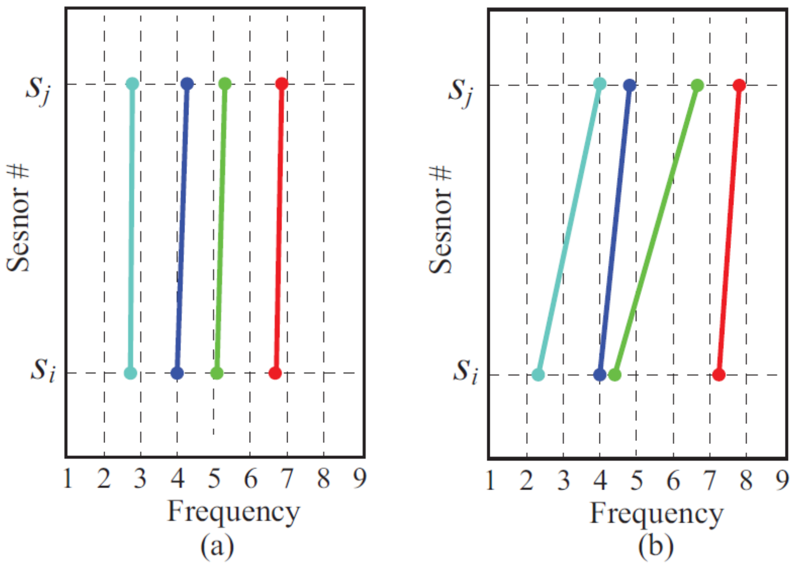
# Damage-Sensitive Parameter Indication

- We calculate a damage-sensitive parameter (DPI) on the signal amplitude to represent the "damage" /"undamaged" and the area of damaged location (if any) of the structure
  - Every sensor computes the DPI that can provide estimate of a possible physical change (or damage) in a set of frequency contents, by using a comparability function

- **The comparability function is defined as the ratio of acceleration amplitudes measured by any pair of sensors, $s_i$ and $s_i$ in its local area:**

$$\frac{\left|f_{s_i}^{r-k} - f_{s_j}^{r-k}\right|}{\left|f_{s_i}^{r-k} + f_{s_j}^{r-k}\right|} \leqslant c(s_i, s_j, f)\%$$



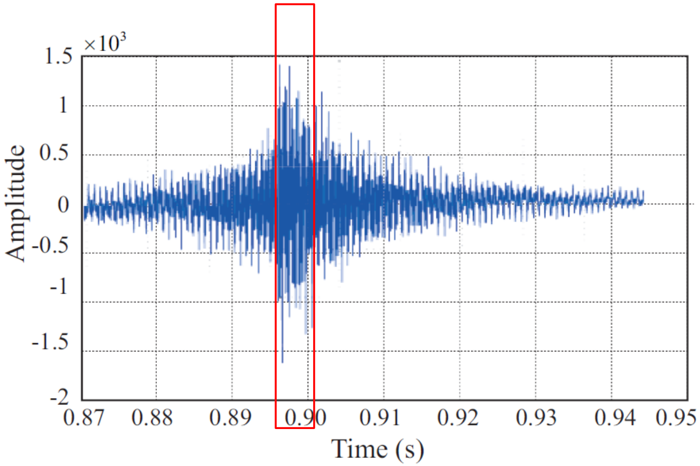
# Performance Evaluation

(a) The sink location


(b) Test infrastructure and sensor deployment on it

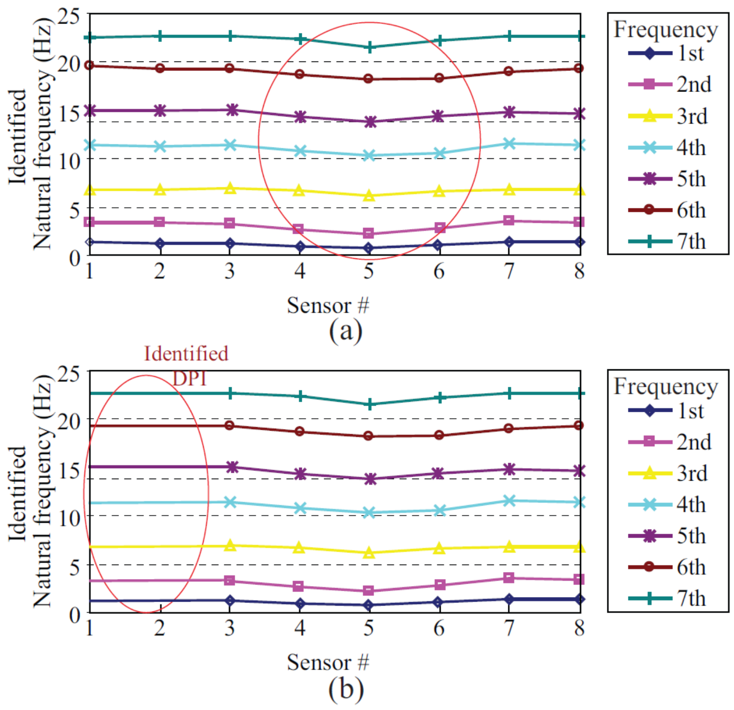
CPS design

Impact of Hammer strike



# Performance Evaluation

- **Impact of Hammer strike at the sensor locations**
  - **Identified by the DPI algorithm**



# Conclusions and Limitations

- A new way to incorporate both WSN and SHM requirements and make use of traditional engineering method for resource-constrained WSNs.

## Limitations:

- Detailed theoretical analysis and the cost of damage sensitivity algorithm
- Network performance under physical damage injection.

# Q&A

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