Enabling Accurate and Scalable Structural Health Monitoring with COTS-based Wireless Sensor Networks

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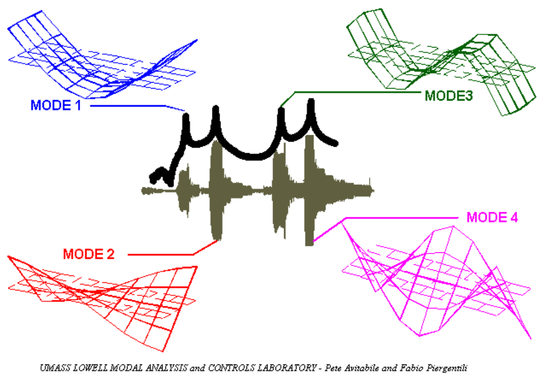
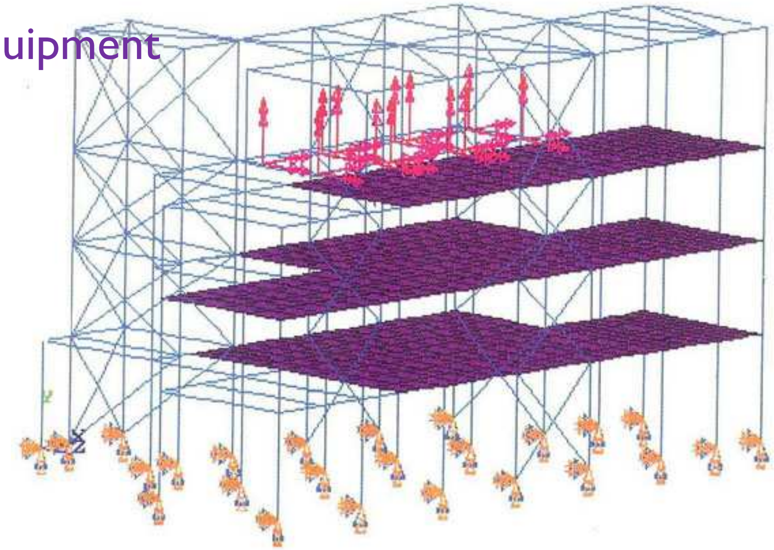
Damage Identification – How to…

- Modal analysis
  - The study of the dynamic properties of structures
    - Usually with accelerometers, but strain gages can also be used
  - Input-Output and Output-Only techniques.
- Output-Only techniques (operational modal analysis) are preferred
  - Excitation from ambient noise
  - Less costly and easier to implement
  - However, it needs extremely sensitive equipment





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Motivation 1

- Damage identification is relevant to all engineering fields as service loads and accidental actions may cause damage to the integrity of a structure
  - May cause loss of lives
  - Industrial machinery, vehicles, bridges, buildings...
- Or natural phenomena
  - Evaluating the structural health of a bridge after an earthquake
  - Visual inspection, is expensive both in time and cost (biennial visual inspection of a major bridge such as the Brooklyn Bridge in New York is reported to last for over 3 months at a cost of $1 million)
- The importance of preserving historical constructions goes beyond economical reasons.
  - They greatly define the cultural heritage of many cities, regions and countries.
  - Expenses with maintenance of civil infrastructures - between 8-15% of countries gross domestic product

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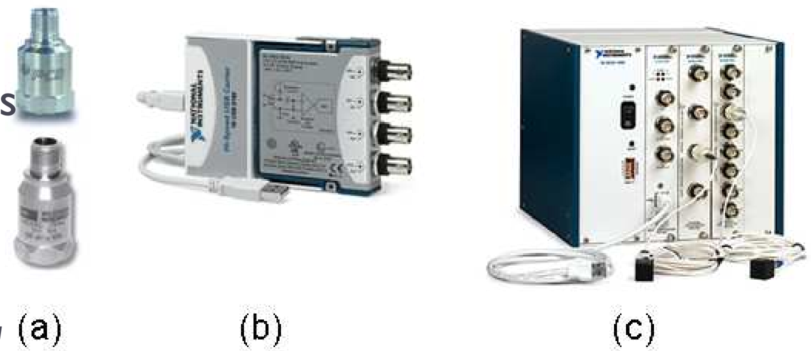
Motivation 2

- Conventional techniques are wired...
  - Aesthetic concerns
  - Cumbersome to deploy
  - Access to Power Supply required
  - Rely on centralized data acquisition systems
  - Too Expensive (10 000 €) which limits the scale of such systems
    - Installation labour costs can approach well over 25% of the total system cost (Lynch et al., 2000).
  - Installation time of a SHM system for bridges and buildings can consume over 75% of the total testing time

These installation time and device costs can be greatly reduced via Micro-Electro-Mechanical Systems (MEMS) based sensors integrated in Wireless Sensors Networks.



Conventional equipments used for dynamic identification. (a) Accelerometers models PCB 393B12 and WR 799M [3], [4]; (b) and (c) USB data acquisition equipment models NI USB-9233 with 24 bits and NI SCXI-1531 with 16 bits [5].

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Motivation 3

- Available wireless equipment
  - Either still in prototyping
    - Largest deployment – 70 nodes in a bridge in South Korea
  - not ready for operational modal shape analysis
- Challenges for SHM
  - Synchronization (all nodes)
    - Mandatory for modal shape analysis
  - Reliability - complex communication architecture
  - Energy-efficiency
  - Scalability
- Our proposal
  - Blends the advantages of standard and COTS technologies
    - Only a minimum set of custom-designed signal acquisition hardware
  - Accurate for measuring both low and high amplitude vibrations (confirmed in the time and frequency domains) and is suited for operational modal analysis
  - Compared against a reference wired system
  - We show how to scale the system

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State of the Art

- SHM has been a very active research area among both academics and industrialists, especially in what concerns recent developments in WSN
- Our proposal overcomes most of the limitations:
  - High sampling resolution (24 bits ADC) connected to a sensitive MEMS accelerometer
    - typically 8-12 bits systems are used (invalidates SHM based on operational modal analysis)
  - Tight synchronization between sensor measurements, through an in-network synchronization mechanism
  - Based on COTS technologies (more cost-effective)
    - Communication Protocols (IEEE 802.15.4/ZigBee)
    - Hardware Platform (TelosB)
    - Operating System (TinyOS)

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Previous Work

- Implemented a MICA2-based WSN to carry out a few tests at the Chimneys of "Paço dos Duques" (XV century) at Guimarães. (System strictly relying on COTS MICA2 +TinyOS)
  - Limitations
    - the lack of enough sensitivity of the acceleration sensors,
    - low resolution of the Analogue-to-Digital Converter (ADC) embedded in the WSN platform,
    - the lack of synchronization algorithms.

Poor performance for the detection of modal shapes

- A "FEW" Challenges
  - Synchronization (all nodes)
  - Reliability - complex communication architecture
  - Energy-efficiency

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Requirements

Sample in a synchronized fashion multiple accelerometers placed at different locations in a structure and forward the data to a central station for processing.

- We aim at
  - solving the limitations from our previous work
  - blend both the advantages of using COTS and customized hardware and standard software technologies.
  - target other kinds of applications where mechanical constructions (e.g. industrial machinery, vehicles) under stress (natural or induced) require structural integrity monitoring and/or analysis.
- We need
  - XYZ accelerometer (triaxial)
  - Max. measurement range: ± 1 g
  - Minimum sensitivity: 1000 mV/g
  - Typical resolution: 1 mg
  - Frequency response, 3 dB: 0 - 100 Hz
  - Max. sampling rate: 100 Hz
  - Max. sampling drift between sensors : 5 ms
  - ADC resolution: 24 bits
  - 0% sample lost during sampling process

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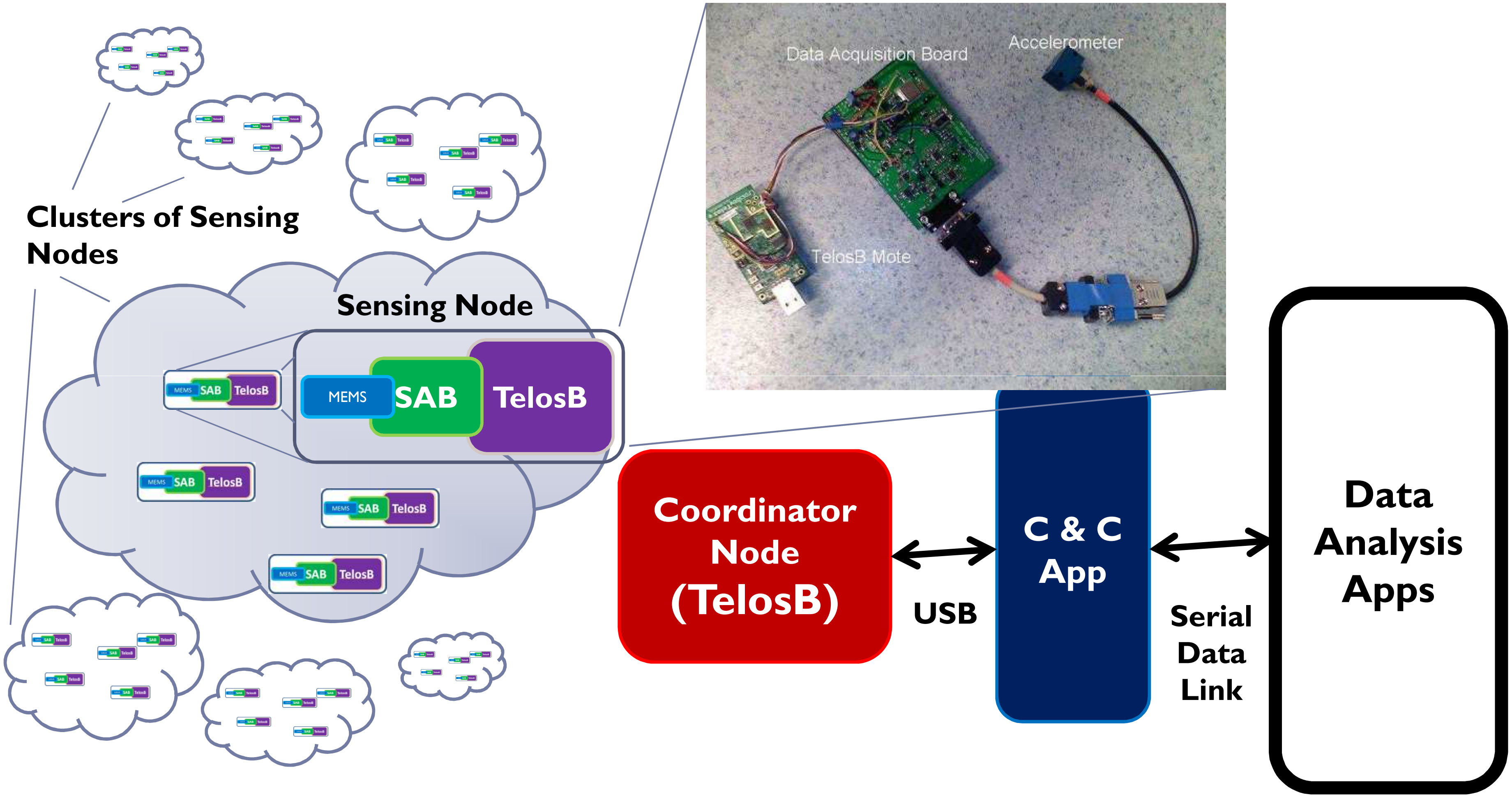
Snapshot of the System Architecture



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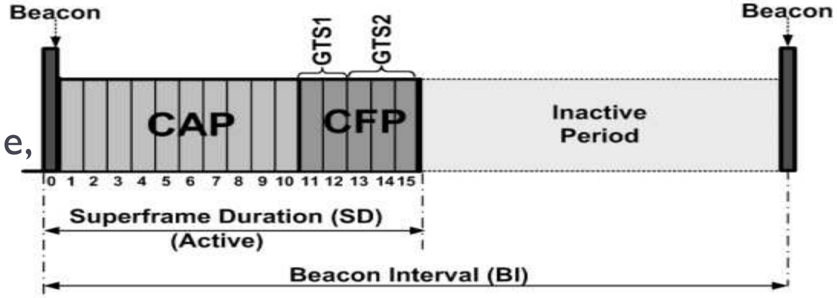
On the Technologies

- IEEE 802.15.4 and ZigBee are interesting for this kind of application since they enable to fulfil some of the requirements like:
  - energy-efficiency (dynamically adjustable duty-cycle, low data-rates and coverage)
  - timeliness (best effort/guaranteed traffic differentiation)
  - Synchronization (in beacon-enabled mode)
- Open-ZB open-source implementation in nesC/TinyOS of the IEEE 802.15.4/ZigBee protocols
- CrossBow TelosB Mote to support the WSN network
  - TI MSP430 16-bit uC, CC2420 RF transceiver,
  - temperature, humidity and light sensor on board.
  - 32.768 Hz Citizen CMR200T Crystal – Need to synchronize every 250 sec at most.
- Highly Sensitive MEMS Triaxial accelerometer



ASC 5631-002 characteristics

Range	±2 g
Sensitivity	1000 mV/g
Frequency	100 Hz ±3 dB
Linearity	±1.0 % FSO
Signal output	500 mV to 4500 mV (DC)
Zero output	2500 mV ±100 mV
Supply voltage	5 V ±0.1 V
Current consumption	7 mA (max.)
Cost	250 Eur + VAT

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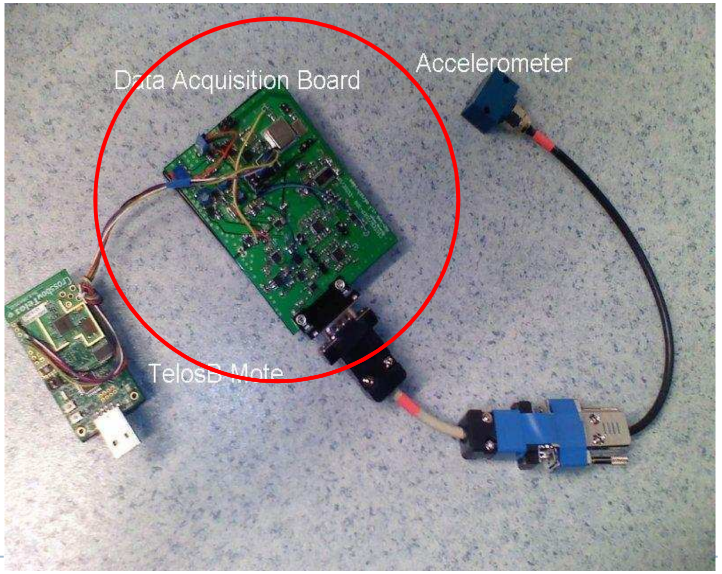
Signal Acquisition Sub-System

- Custom designed Signal Acquisition Board with
  - High resolution 24-bit ADC
  - Enough memory for storing sampled data (32MB)
  - One single power source for TelosB and SAB
    - Possible to switch off onboard analogue circuitry to save power



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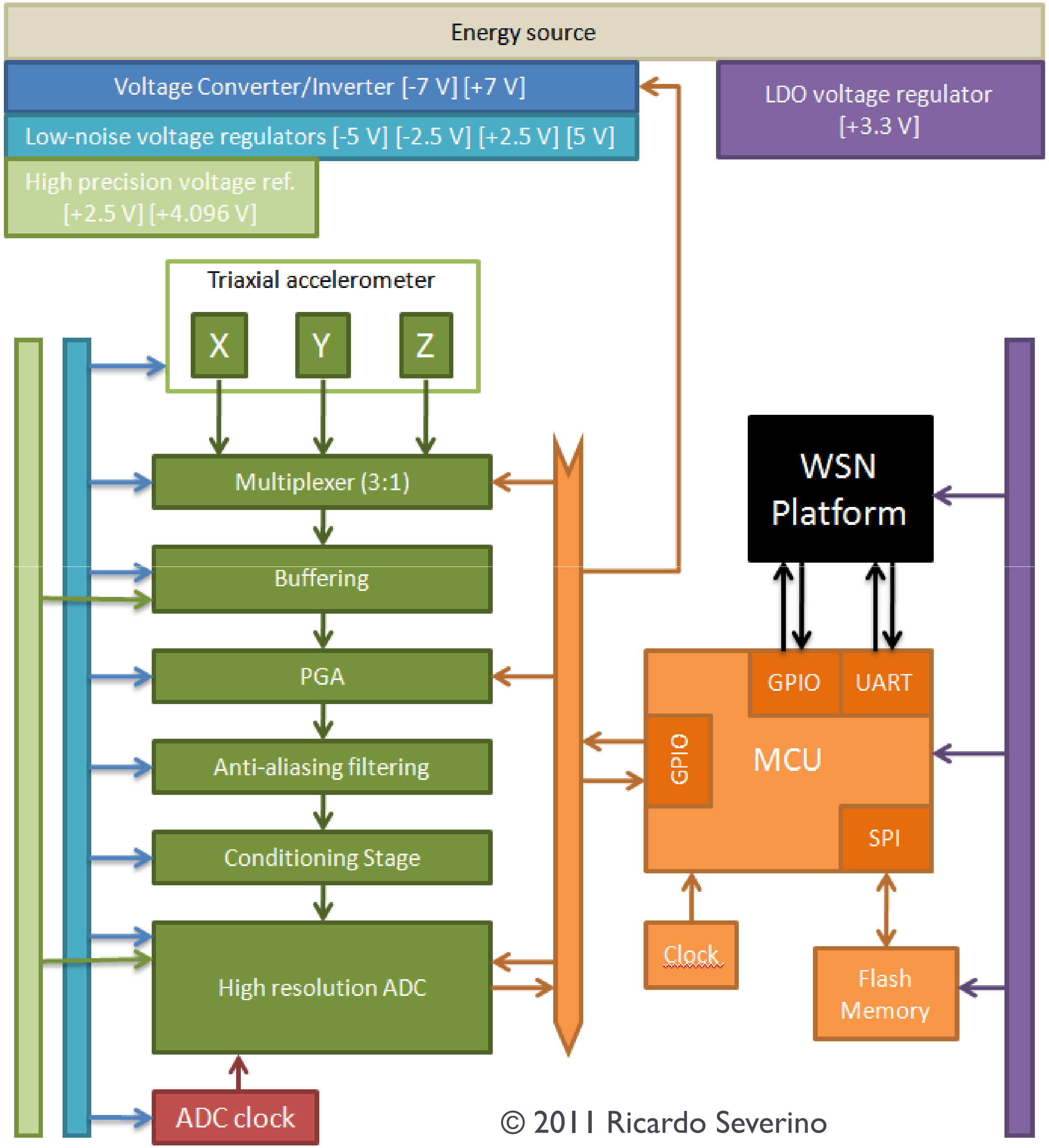

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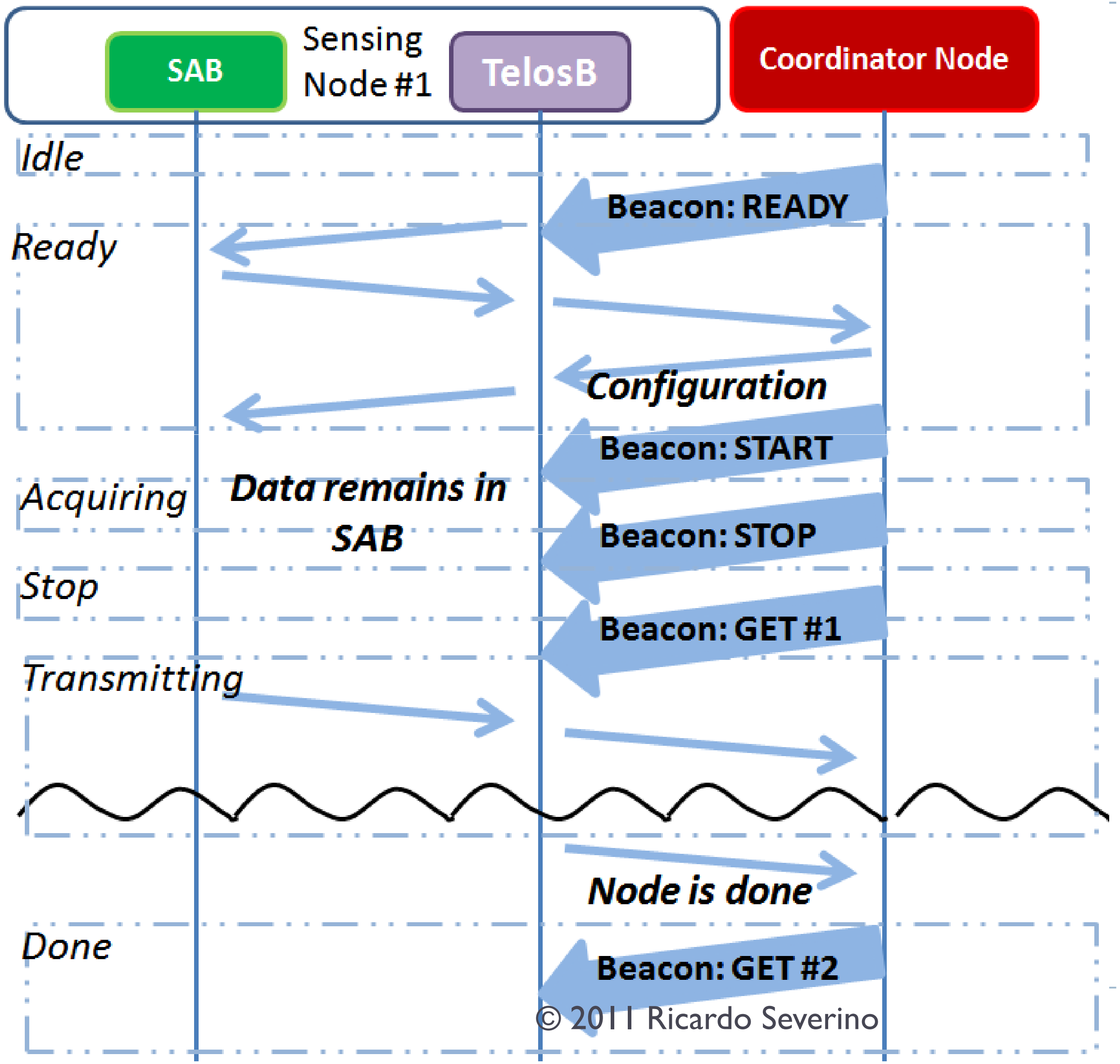
WSN Communication Architecture 1



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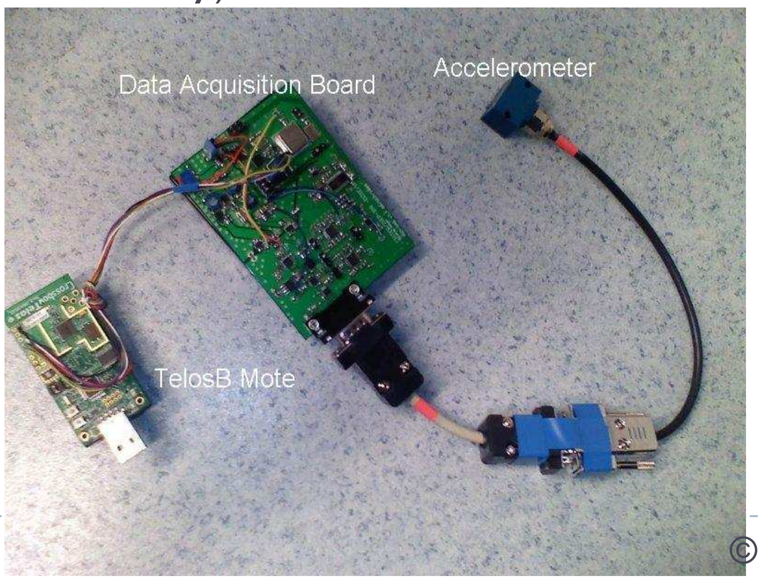
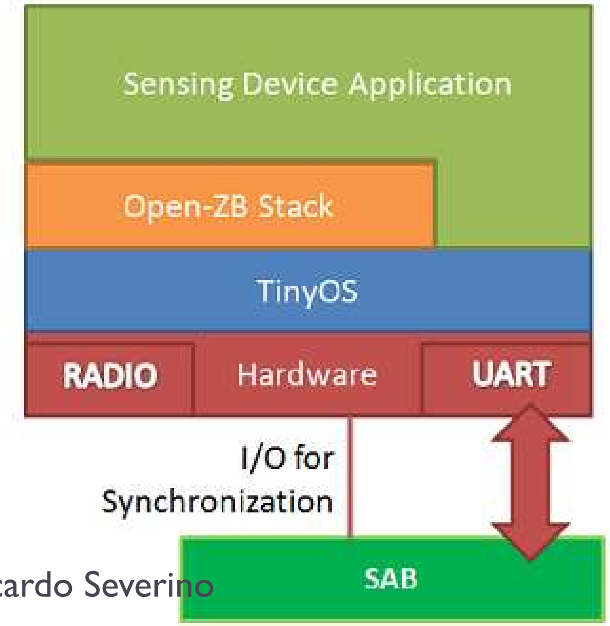
WSN Communication Architecture 2

- Coordinator Node (ZigBee Coordinator)
  - Synchronizes the network
  - Manages application and configures SAB
  - Serves as a sink for the sampled data
- Sensing Nodes (ZigBee End-Devices)
  - Control and Synchronize acquisition of the SAB
  - Carry out acquisition of the onboard sensors (temperature, humidity, voltage, luminosity)





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COMMAND & CONFIGURATION APP

- Developed in C#
- C&C App enable full control over the acquisition configuration parameters
  - (i.e. axis selection, sampling rate, sampling period, sampling duty cycle)
- Provides a quick evaluation of the presence of the system nodes.

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Test and Validation 1

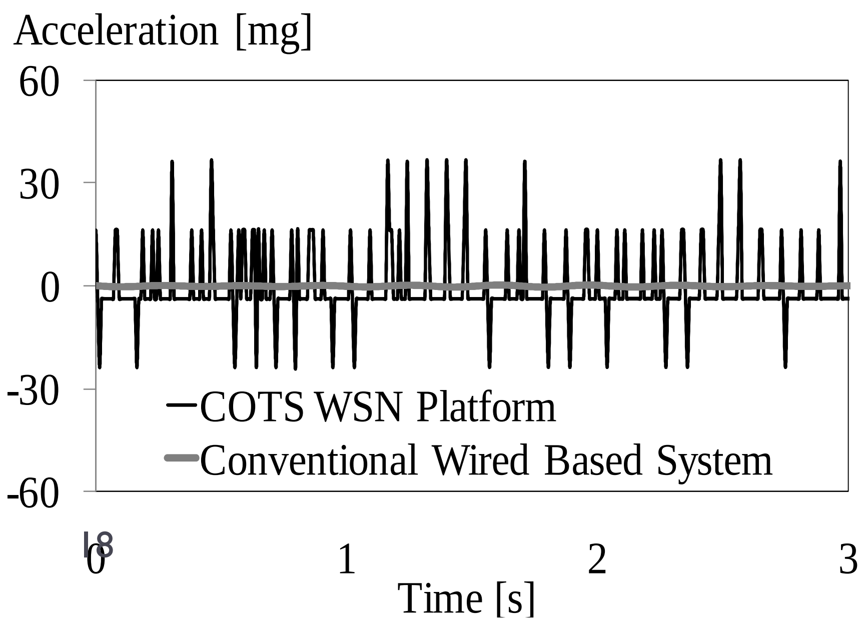
Laboratory Specimen

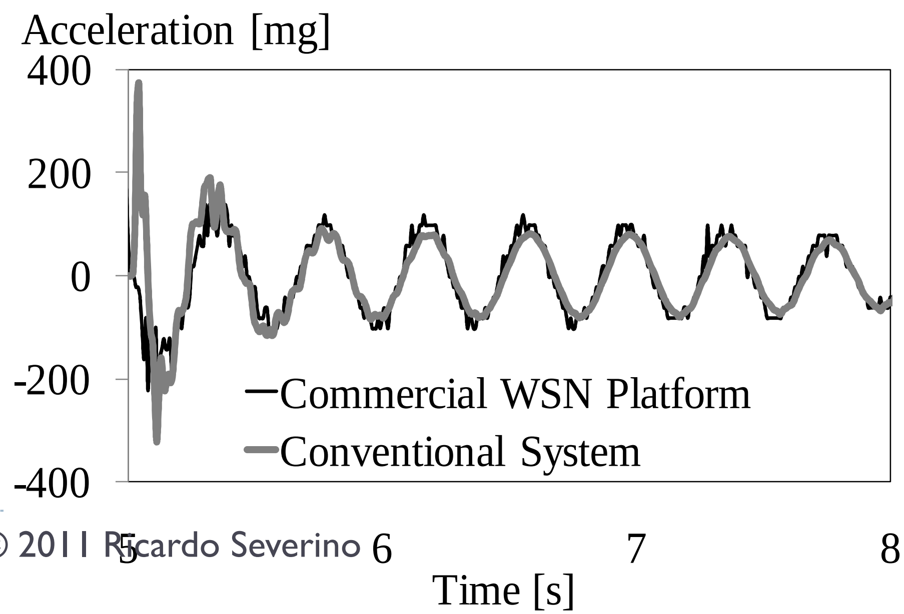
Tests using off the shelf technology

Tests using the 1st prototype of the developed tool

Test and Validation 2

- COTS WSN Platform (MICA2)
  - Good performance of the commercial WSN platforms for measuring high amplitude vibrations.
  - For signals with amplitudes below 20 mg, the WSN platforms recorded only noise (small resolution of the micro-accelerometers and the ADC)
    - In SHM studies of civil engineering structures, vibrations with amplitudes below 2 mg are commonly found.
  - Impossible to carry out mode shape detection due to the lack of synchronization algorithms in the commercial WSN platforms.





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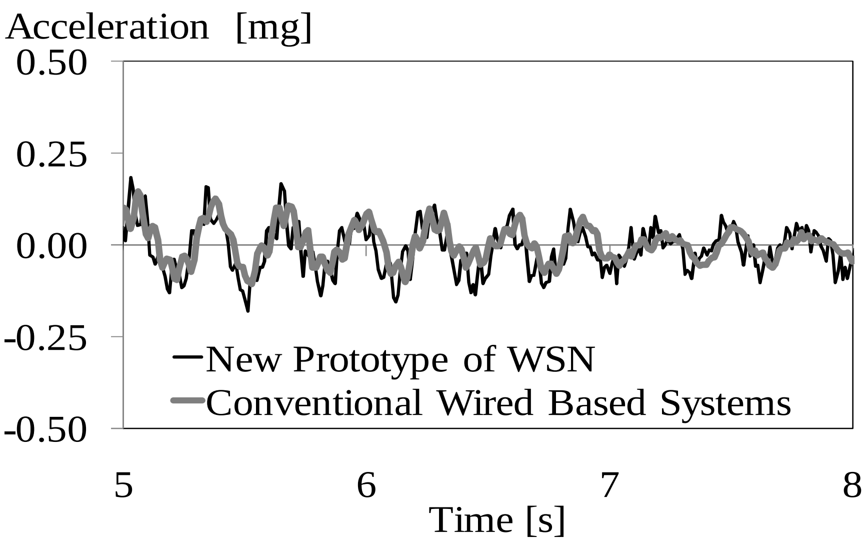
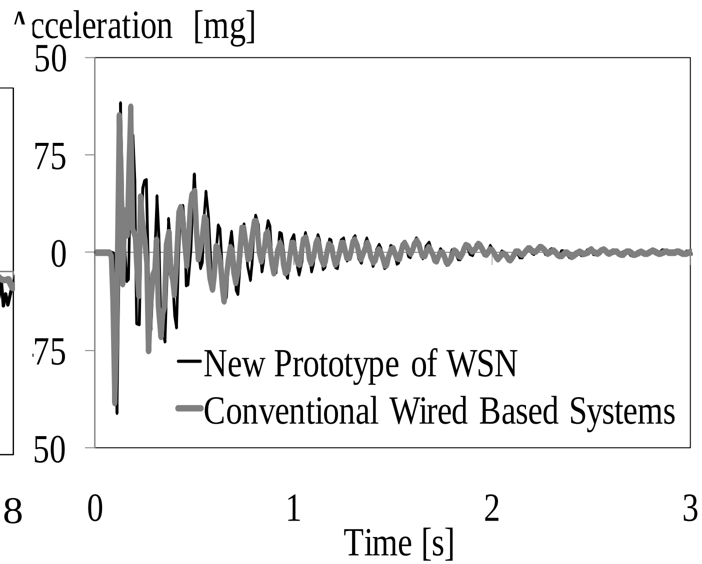
Test and Validation 3

- New WSN Platform Prototype
  - Good similarity both for high and lower amplitude excitation (even at amplitudes below 0.25 mg)





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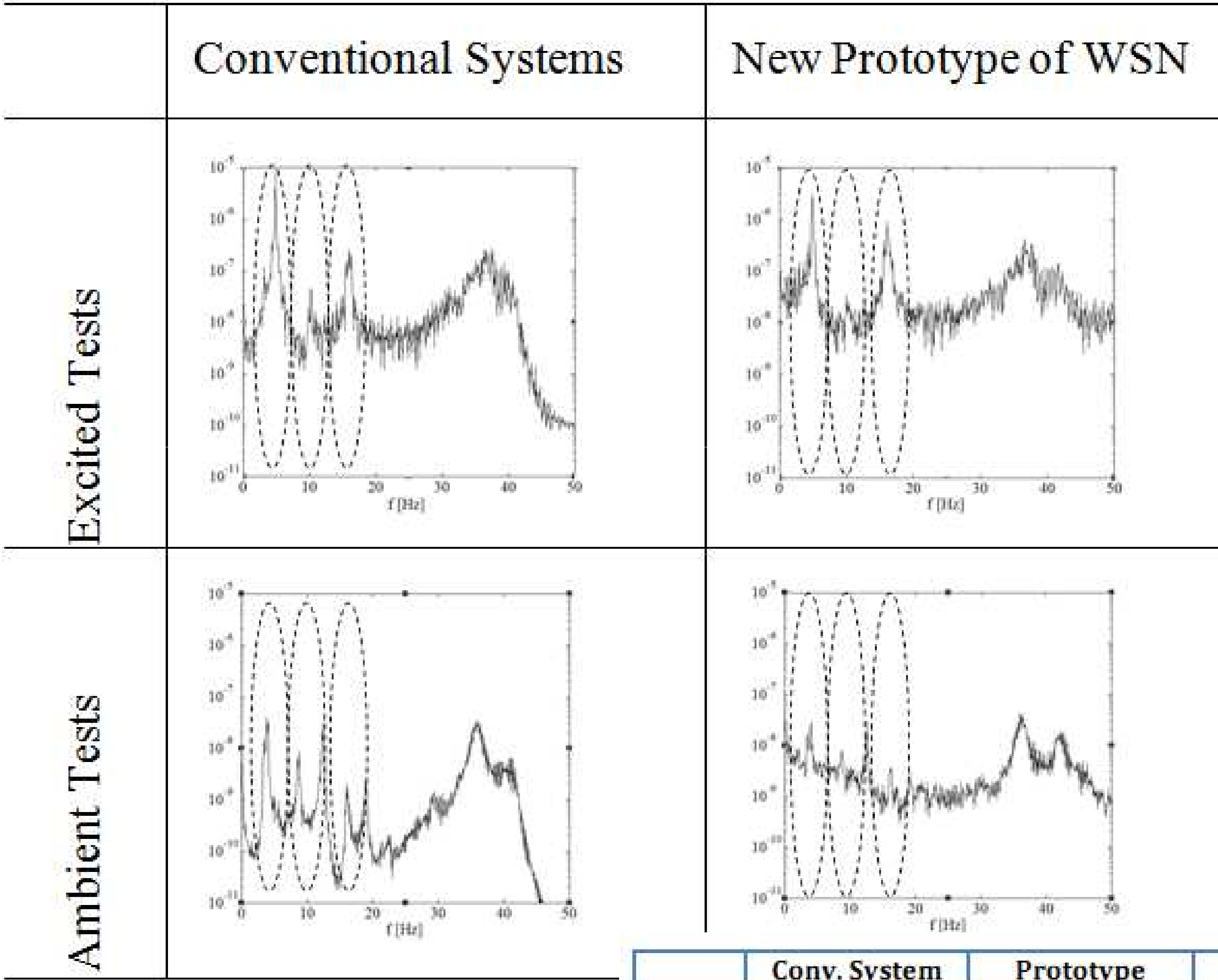
Test and Validation 4



	Conv. System		Prototype		Error	
Mode	f (Hz)	ξ (%)	f (Hz)	ξ (%)	Δf(%)	Δξ(%)
1	3.26	2.0	3.34	2.4	2.5	20.0
2	5.00	2.3	4.94	1.9	1.2	17.4

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Scaling up to Multiple Clusters

- Initial prototype system
  - Based on a single cluster WSN (star topology).
  - Theoretically can support up to 2^{16} devices in one cluster
  - Not realistic
    - Small coverage area of a star topology
    - Connectivity between SNs and the Coordinator Node (CN) must be guaranteed.
- However, in larger structures (e.g. long span bridges or tunnels)
  - Hundreds to thousands of SNs may be needed to assess the integrity of the structure.
  - Network architecture must cope with the tight synchronization requirements imposed by SHM applications.

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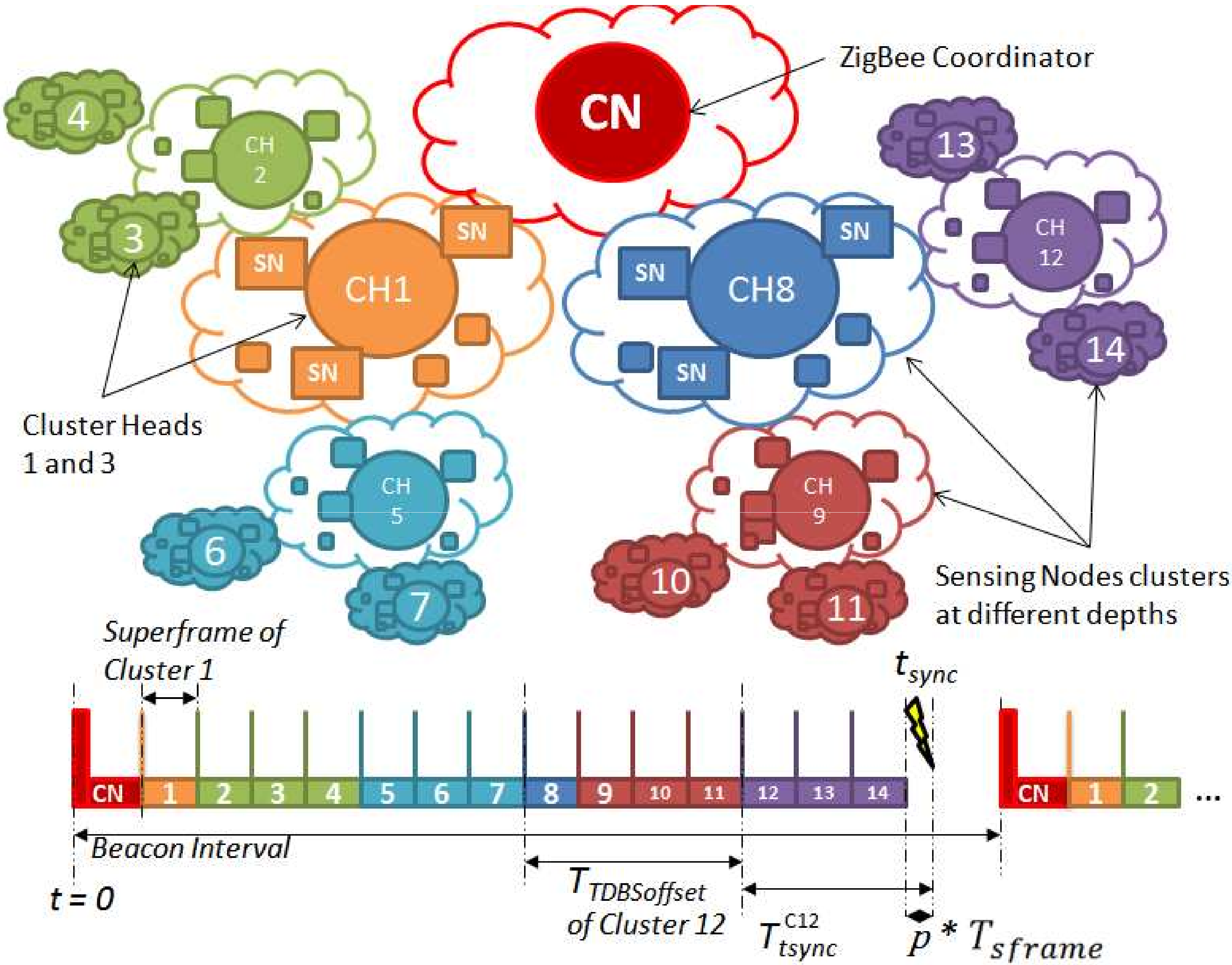

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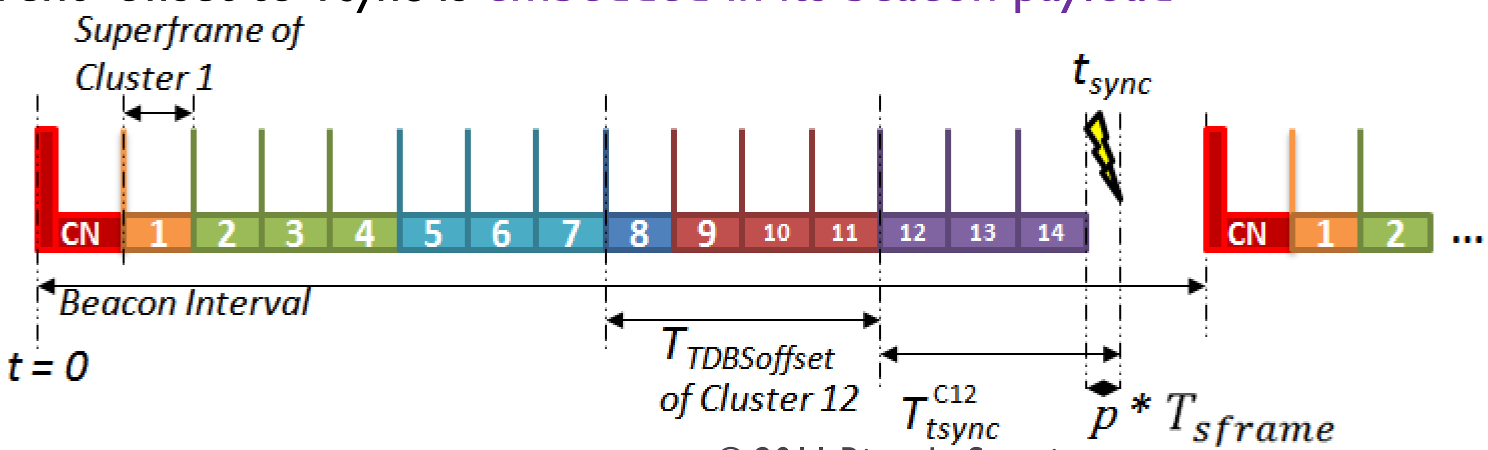
Scalable Synchronization Mechanism

- All SNs will simultaneously trigger their measurements at *Tsync*
- SNs must receive this information (time offset to that instant) before starting data acquisition.
- We denote the devices at cluster *x* by *Cx*, where *x* also represents the order at which cluster *Cx* is active in the clusters schedule.
- The time offset (T_{tsync}^{Cx}) from the beacon of CH *x* to *Tsync* is computed as follows:

$$T_{tsync}^{Cx} = T_{tsync}^{Cparent} - T_{TDBSoffset}^{Cx}$$

- Parent offset to *Tsync* is embedded in its beacon payload



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Computing Scalability Limit

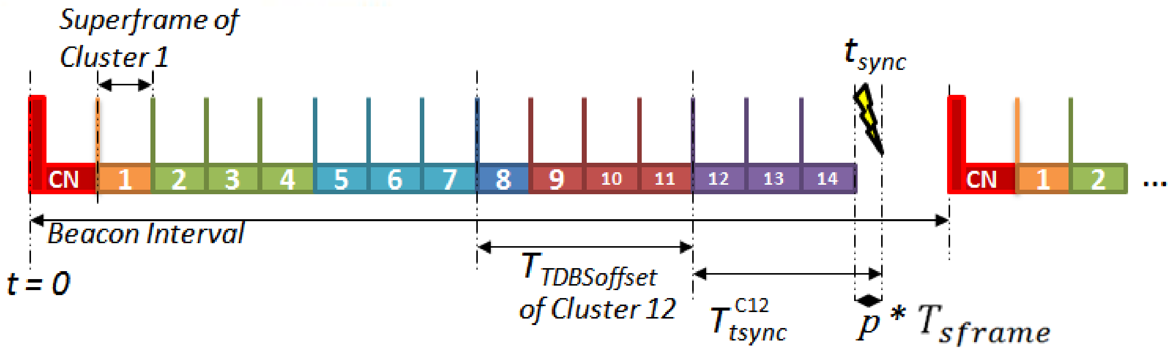
- Each cluster will have to wait for a finite amount of time – T_{tsync}^{Cx}
- Hardware timer with finite precision
  - Each Sensing Node presents a different clock drift during this period.
- This error will increase with the size of the network.
- Question is how big can we grow?
- The maximum drift for a SN at cluster *Cx* and depth *D* is represented as the sum of three components:

$$\Delta_{max}^{Cx,D} = \Delta_{tsync}^{Cx} + \Delta_{P\to C}^{Cx} + T_{BP}^{D}$$

$$\Delta_{P\to C}^{Cx} = x\,\Delta_{sframe}$$

$$T_{BP}^{D} = D\,T_{BP}$$

$$\Delta_{Tsync}^{Cx} = (n_{clusters} + p - x)\,\Delta_{sframe}$$



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Computing Scalability Limit

- Combining all of this, assuming a worst-case situation where all drifts will be cumulative, the drift for a SN in a cluster at Depth *D* is computed as:

$$\Delta^{D}_{max} = (n_{clusters} + p)\,\Delta_{sframe} + D\,T_{BP}$$

- It does not depend of the place of the cluster in the cycle
- Only depends on network depth, superframe size and number of clusters.
- Computing for different network settings we get:

nclusters	SO/BO	Depth	Max. Δ (μs)
5	5/8	2	116
15 (Fig. 11)	4/8	3	160
25	4/9	4	260

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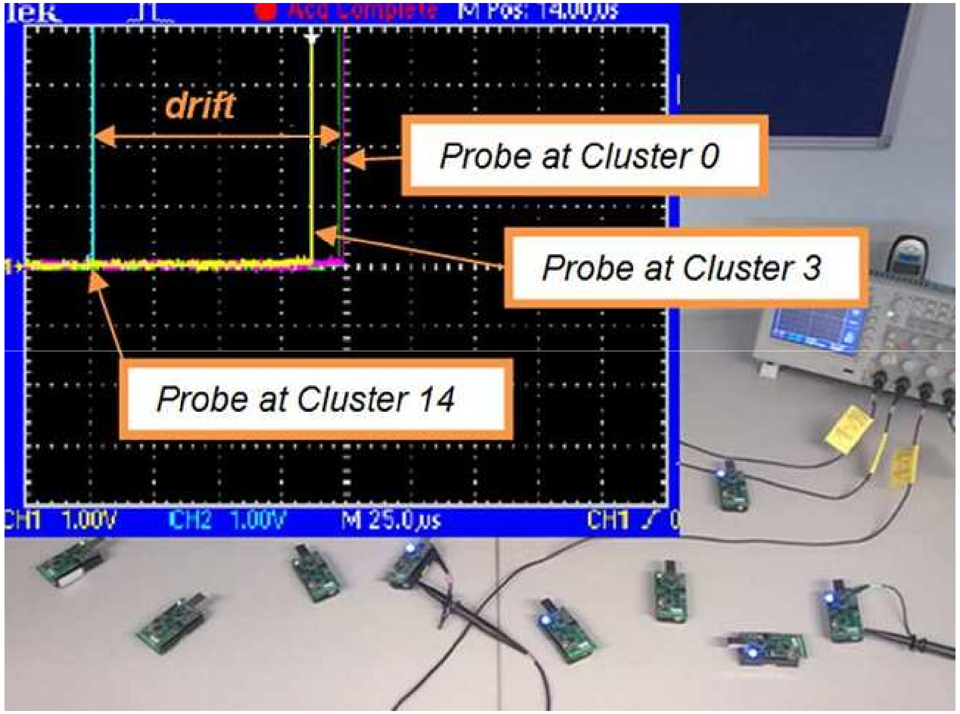
Experimental Analysis

- We have implemented the proposed synchronization mechanism in nesC/TinyOS,
  - over the official TinyOS implementation of the 15.4/ZigBee protocols
  - 15 clusters
  - The TDBS cluster schedule was chosen so that there would be no overlapping clusters – BO and SO were set to 8 and 4
- Observed maximum drift - 100 μs with an average of 39 μs (considering all 15 clusters).



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Final Remarks

- Solution is mostly based on standard and COTS, namely in what concerns hardware platforms, operating system and communication protocol.
  - Only a minimum set of custom-designed signal acquisition hardware was designed, in order to serve as an interface between the accelerometers and the sensing nodes.
- Our solution is low-power and low-cost and guarantees accurate and time synchronized measurements.
- Synchronization is closely coupled with timeliness both at software and hardware level
  - We had to look into task management strategies (Operating System), processing time, interference from external sources and clock drift.
  - Specially with TinyOS
  - Control of the data acquisition had to be transferred to a secondary processing unit, integrated in the signal acquisition board (SAB).
- In the future we intend to test this WSN architecture in larger structures,
  - We need to equip every Sensing Node with the signal acquisition hardware (SAB + MEMS)

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Thank you for your attention

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