Improving QoS for Large Scale WSNs

PhD Thesis Presentation

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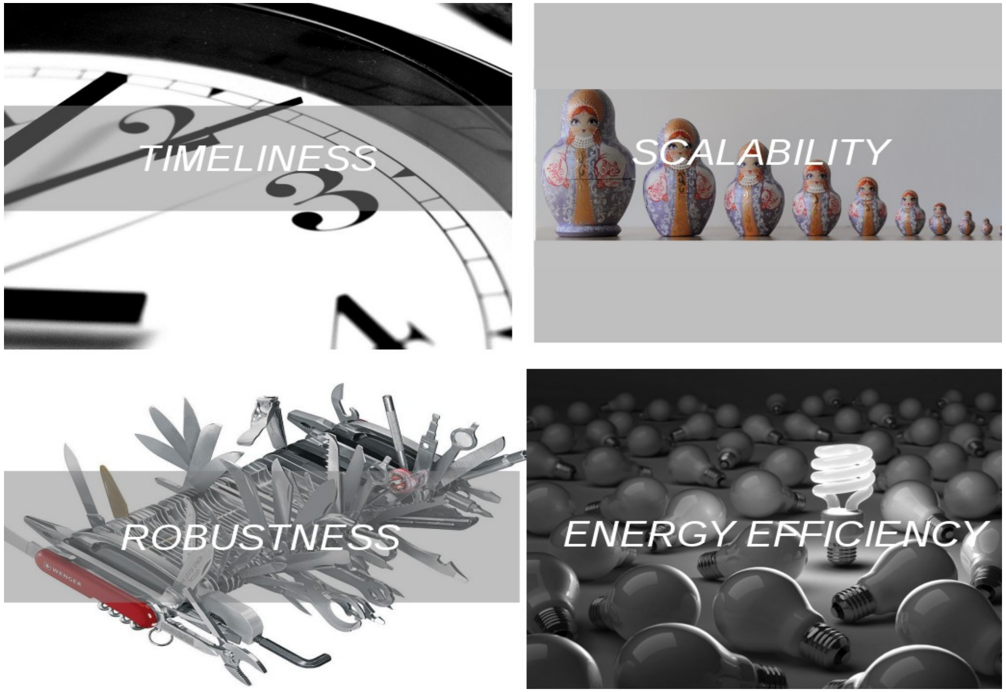
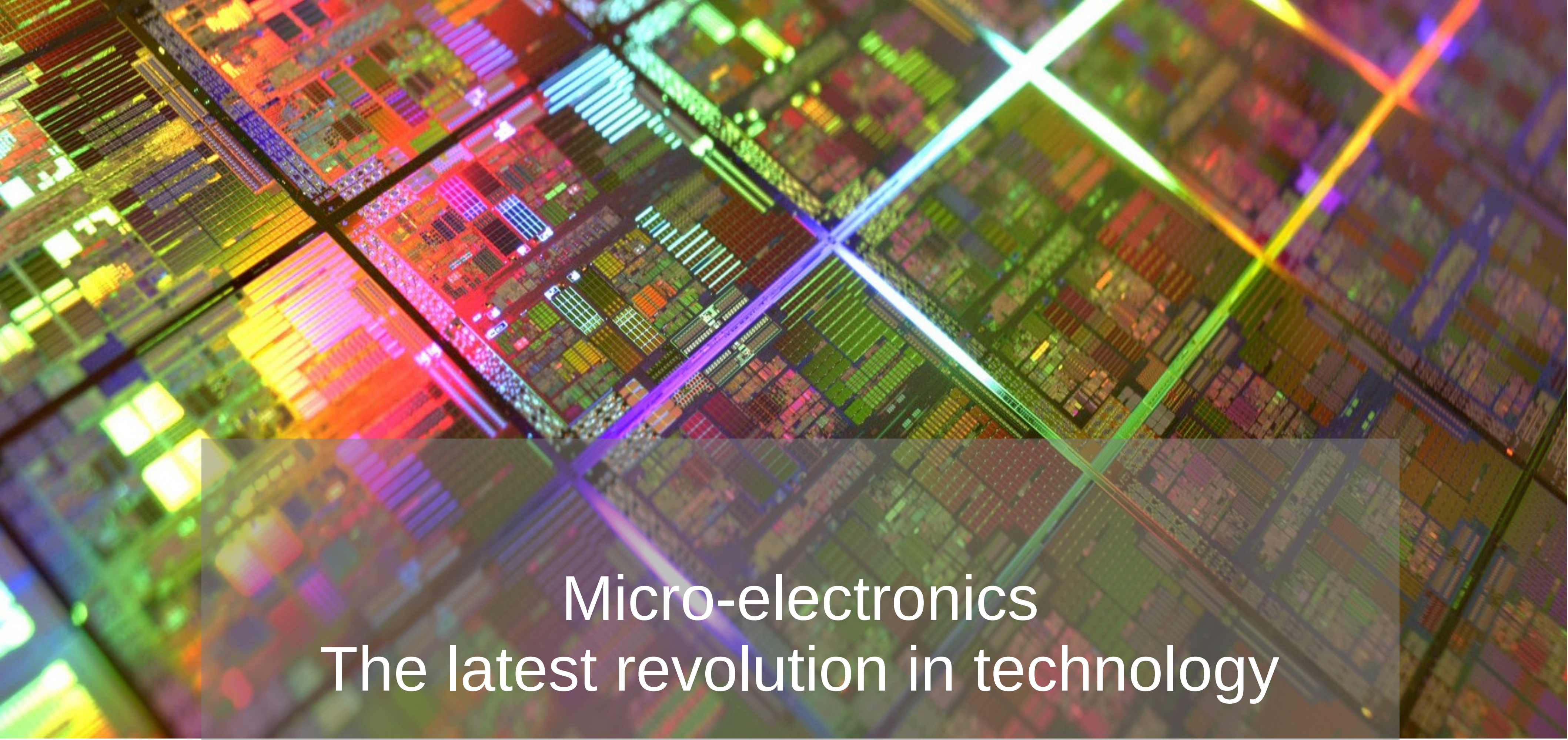
Outline

- Motivation
  - Towards the WSNs paradigm
- Challenges
- Approach
- Application Scenarios
  - Structural Health Monitoring
  - Datacenter Monitoring
- QoS Proposals
  - Timeliness
  - Scalability
  - Robustness
  - Energy Efficiency
- Final Remarks
- Future Directions
  - Towards a QoS Balancing Framework
  - On the Engineered Application Scenarios

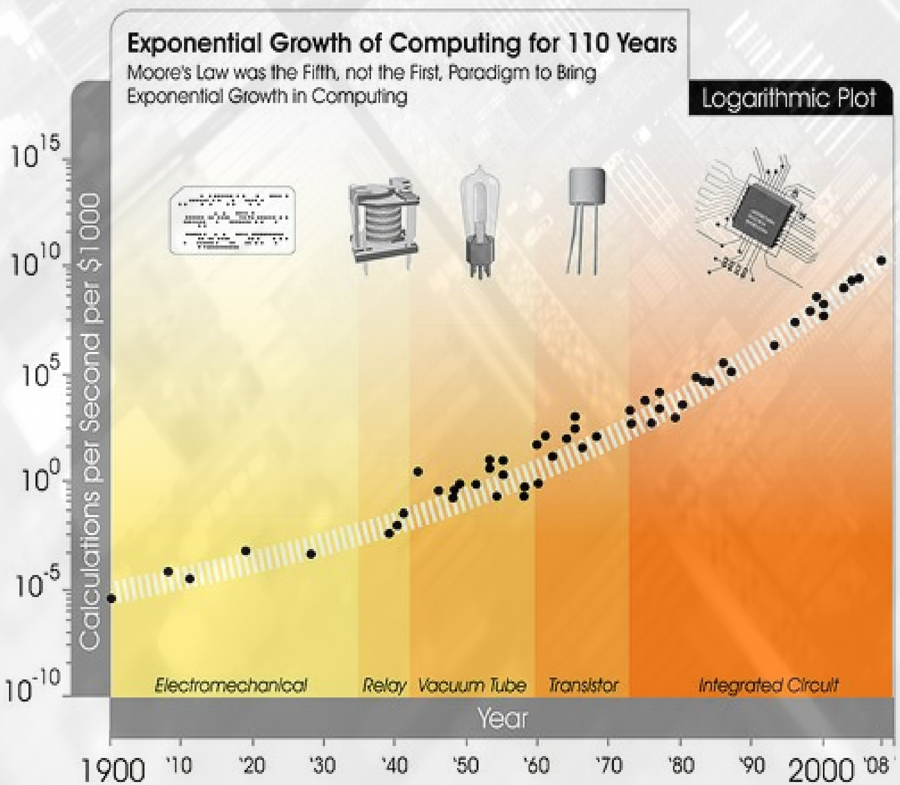


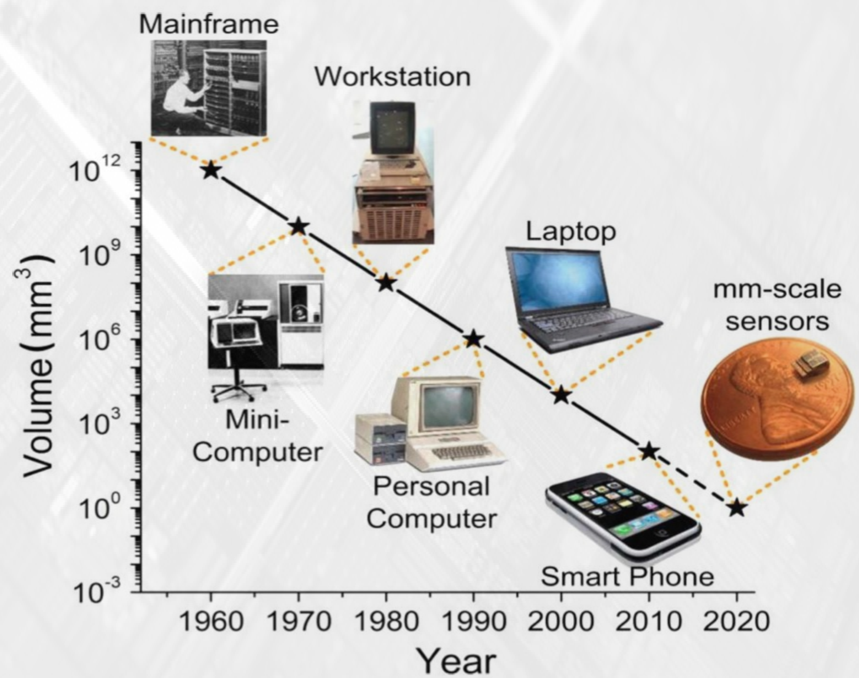


Micro-electronics
The latest revolution in technology

Faster, smaller, in everything, everywhere

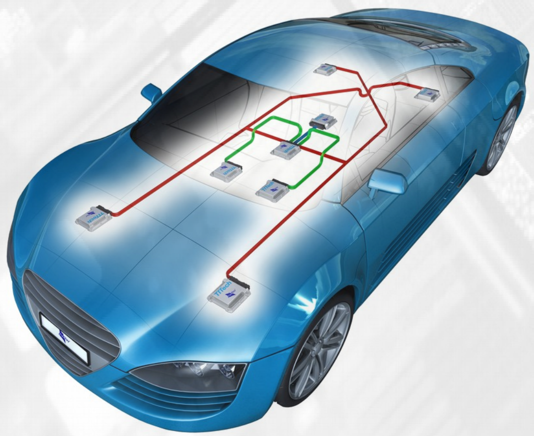
The Semi-conductor => Micro-electronics => Micro-controller => Embedded Systems





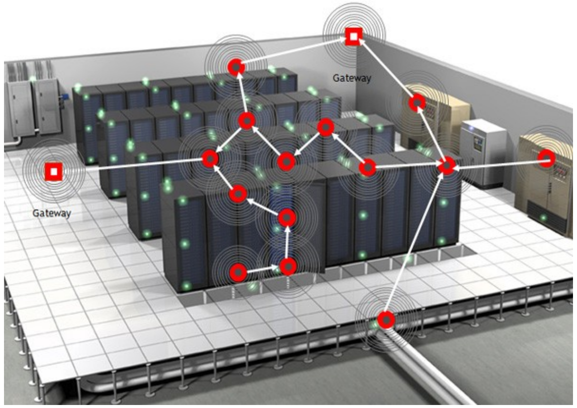
Faster, smaller, in everything, everywhere

The Semi-conductor => Micro-electronics => Micro-controller => Embedded Systems => Smart "everything"



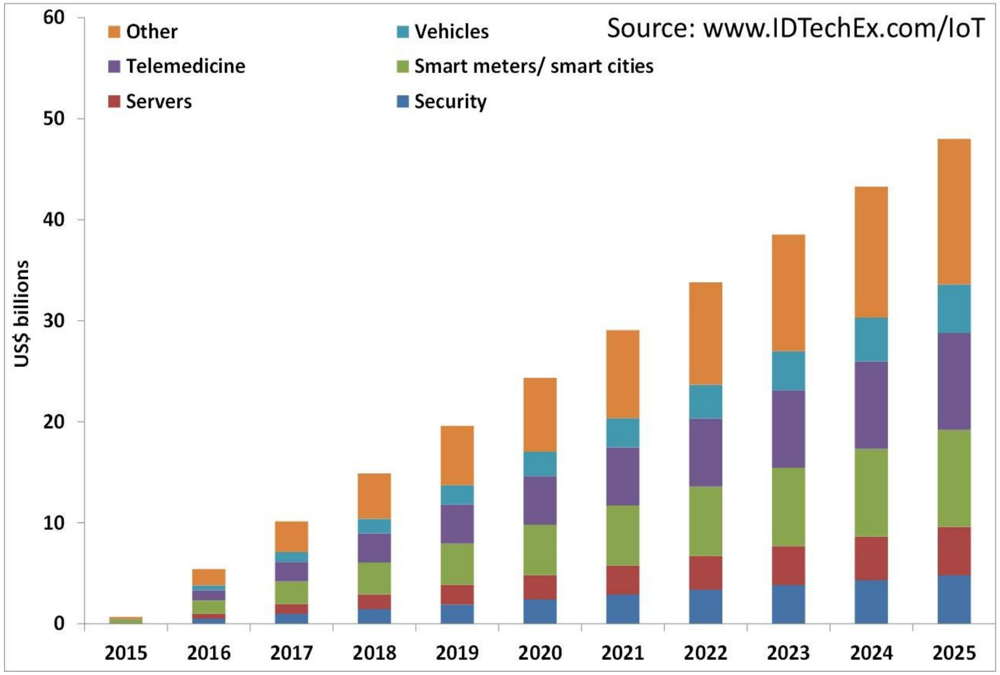
Lets put sensors in it

- Pervasiveness and ubiquity of embedded systems + wireless technologies
- Eagerness to control and monitor everything, everywhere
- Wireless Sensor Networks
  - The Internet of Things (IoT)
  - Cyber-Physical Systems (Timeliness in environmental monitoring/industrial automation and process control)
    - Tighter interaction between sensing and actuation
    - Communications must be logically correct but also produced on time



Market forecasts...

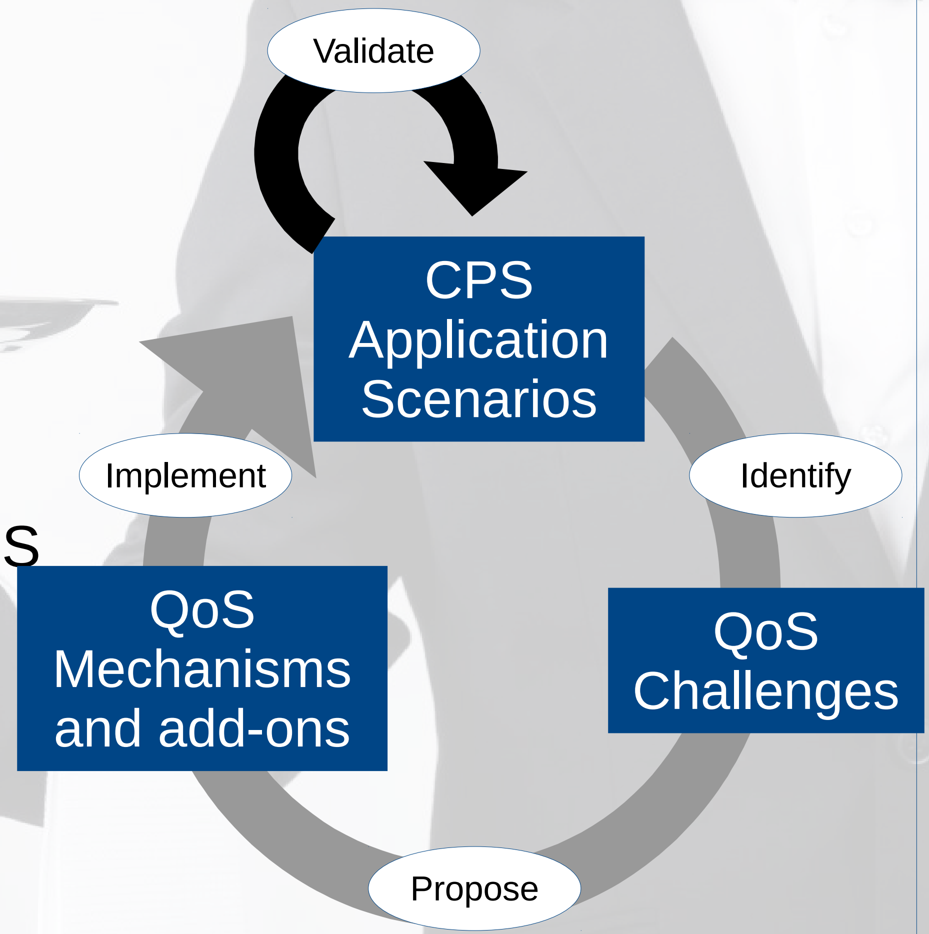
- Cisco IBSG predicts 25 billion IoT devices by 2015 and 50 by 2020;
- IDTechEx market value for IoT IP-addressed sensing nodes to grow from less than $1 Billion (US) in 2015 to greater than $48 Billion (US) by 2025.
- However, there is a lack of:
  - real world application and even fewer commercial applications
    - specially where QoS is important to ensure
  - matureness
  - solutions (protocols, software/hardware architectures, technology)



“A Quality of Service complaint, Sir?”

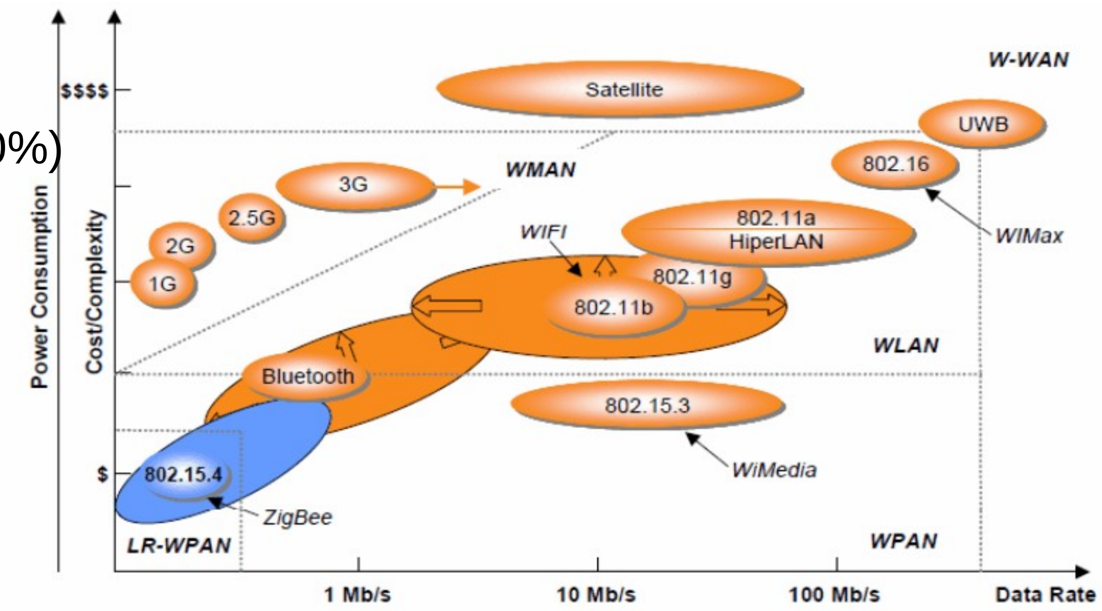
Approach

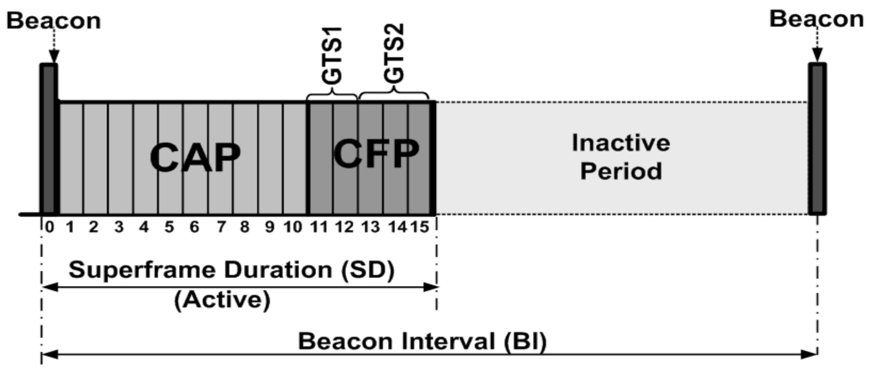
- A hands-on approach
  - Structural Health Monitoring scenario
  - Datacenter Monitoring Scenario
- Technologies
  - IEEE 802.15.4/ZigBee
  - COTS – Commercial Of-The-Shelf technologies
- Focus on selected non-functional QoS properties
  - Timeliness
  - Scalability
  - Robustness
  - Energy Efficiency (indirectly)



IEEE 802.15.4/ZigBee

- Energy-efficiency
  - adaptable duty-cycles (100% → ≈ 0%)
  - low data rates (20-250 kbps)
  - Low radio coverage (<70 m)
- Flexible MAC protocol
  - Real-Time traffic
    - Guaranteed Time Slots (GTS)
  - Best-effort traffic
    - CSMA/CA mechanism
- Scalable network topologies
  - mesh, **cluster-tree (predictability)**
  - up to 65000 nodes in each PAN
- Availability of tools
  - Open-ZB framework
  - TinyOS WGs (ZigBee, 15.4)





Beacon Interval and Superframe Structure

Objectives

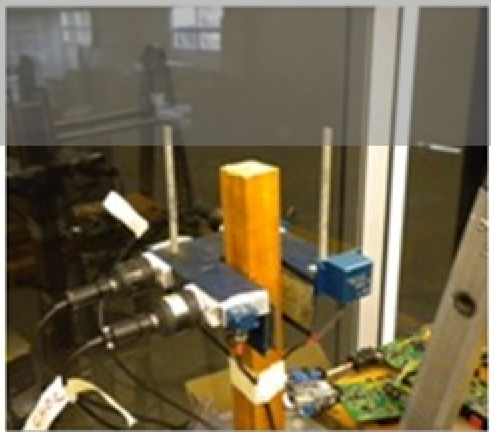
- devise architectural solutions (mechanisms, algorithms, protocol add-ons) for supporting real-time and reliable communications in large-scale WSNs.
  - Relying on IEEE 802.15.4 and ZigBee set of protocols and on Commercial-off-the-shelf (COTS) technologies as much as possible.
  - implement and experimentally validate proposals on real-world application scenarios.

“The IEEE 802.15.4/ZigBee set of protocols, complemented with a set of QoS mechanisms can effectively support the requirements future embedded computing systems may impose”.

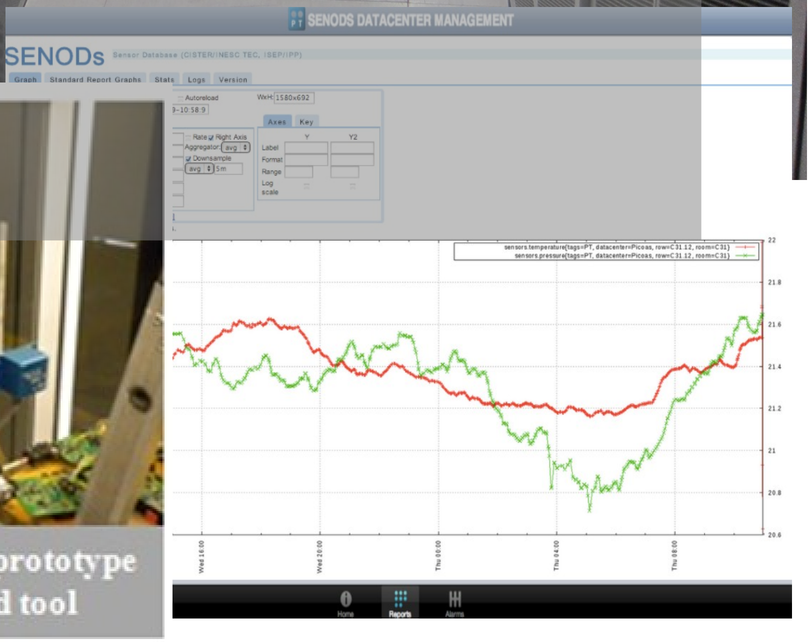
Application Scenarios

Laboratory Specimen

Tests using off the shelf technology



Tests using the 1st prototype of the developed tool



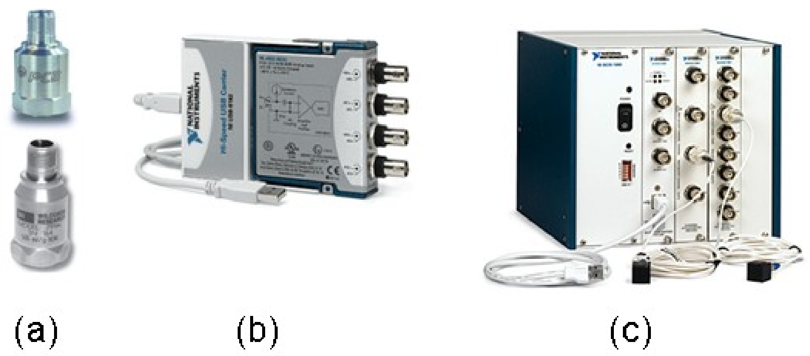
Structural Health Monitoring

Motivation

- Damage identification is relevant to all engineering fields as service loads and accidental actions or natural phenomena may cause damage to the integrity of a structure.
  - industrial machinery, vehicles, bridges, buildings, evaluating the structural health of a bridge after an earthquake
- Visual inspection, is expensive and time consuming
- Sensor installation
  - labour costs can approach well over 25% of the total system cost
  - Installation time of a SHM system for bridges and buildings can consume over 75% of the total testing time

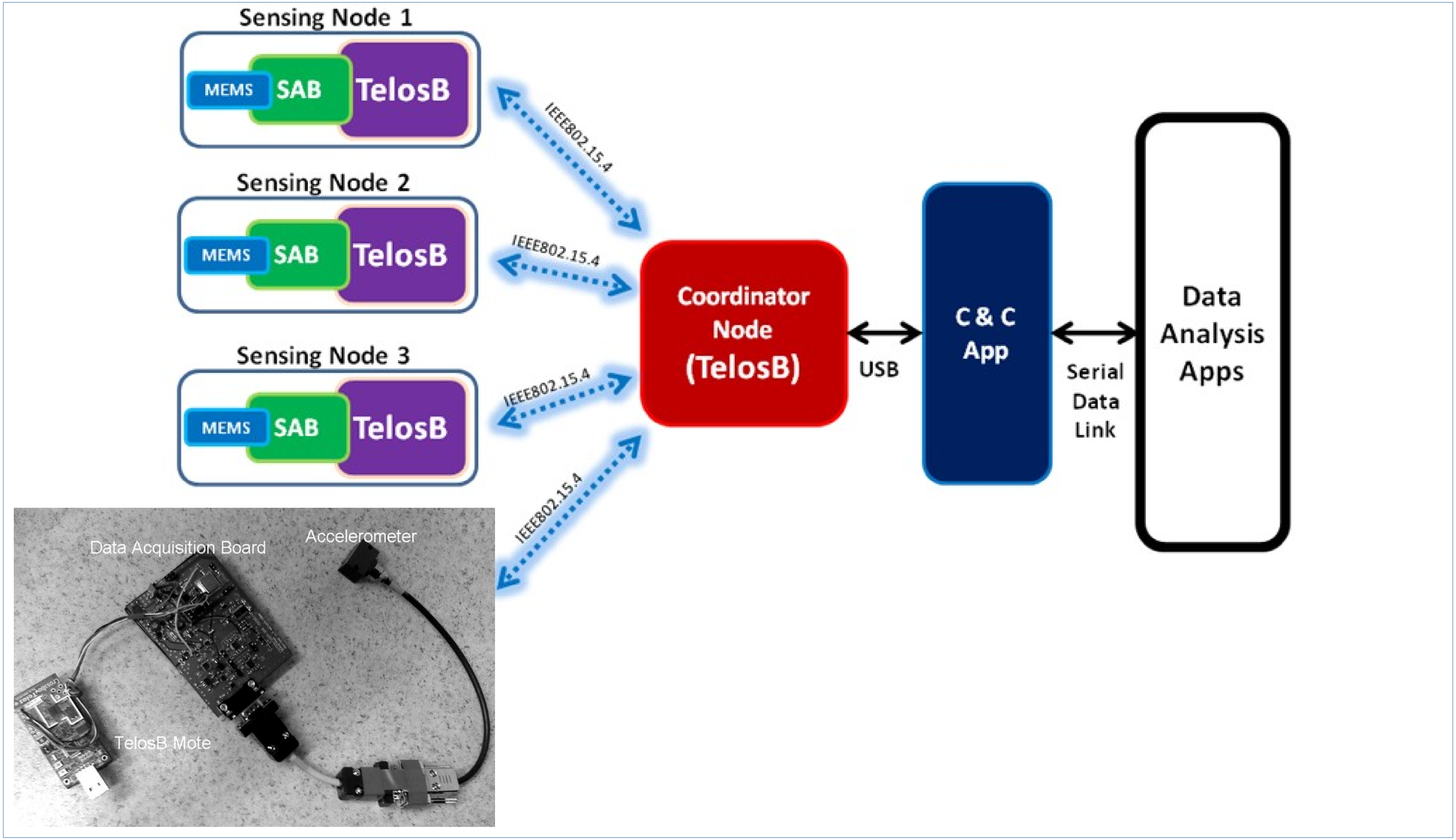
Motivation

- 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
- Available wireless equipment either still in prototyping (Largest deployment – 70 nodes in a bridge in South Korea) or not ready for operational modal shape analysis (sync problems, low resolution data)



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].

System Overview



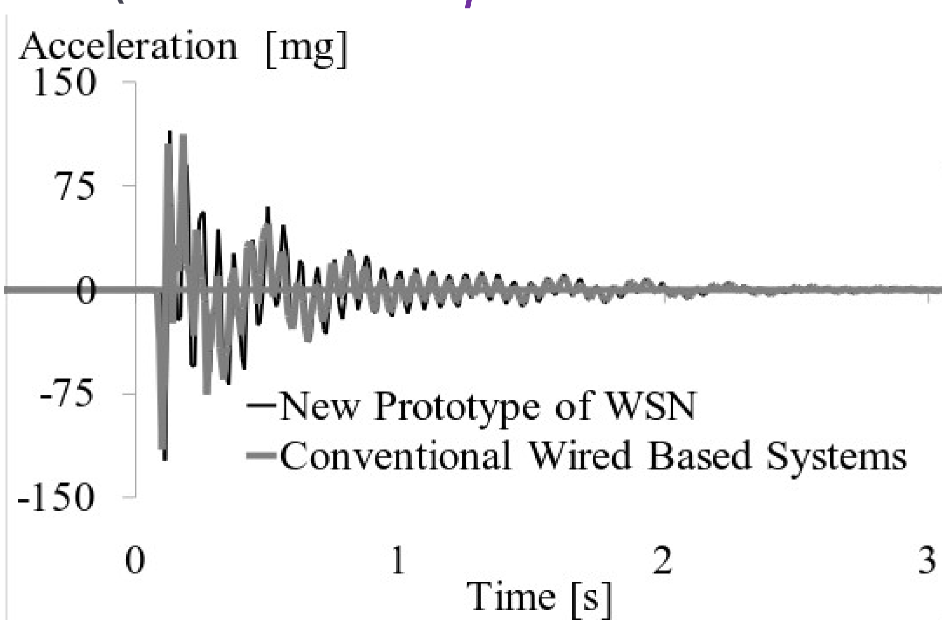
Experimental Evaluation

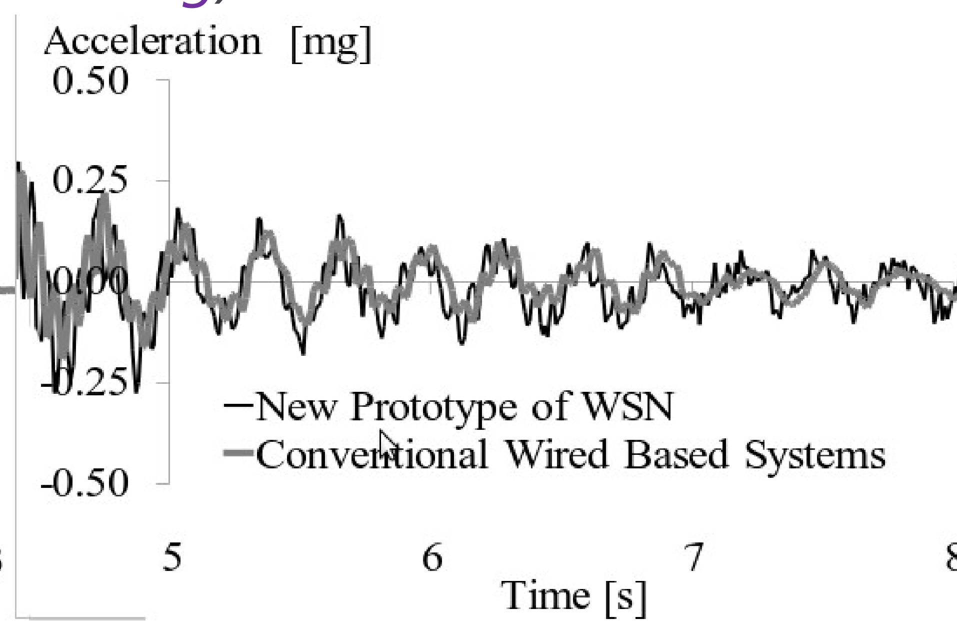
Laboratory Specimen

Tests using off the shelf technology

Tests using the 1st prototype of the developed tool

Good similarity both for high and lower amplitude excitation (even at amplitudes below 0.25 mg)

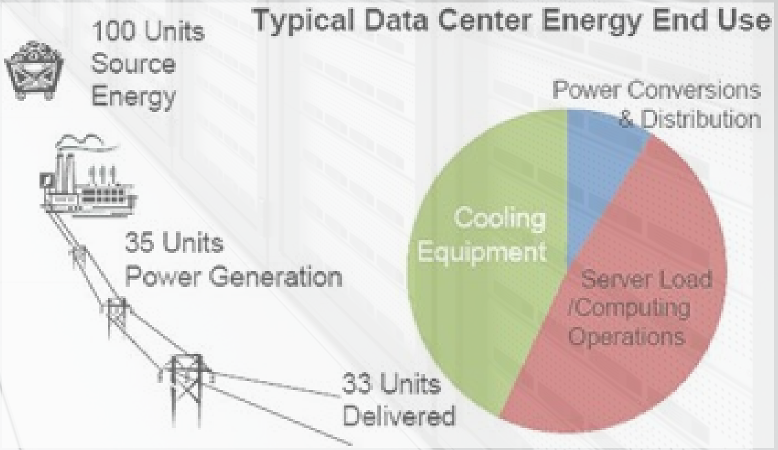




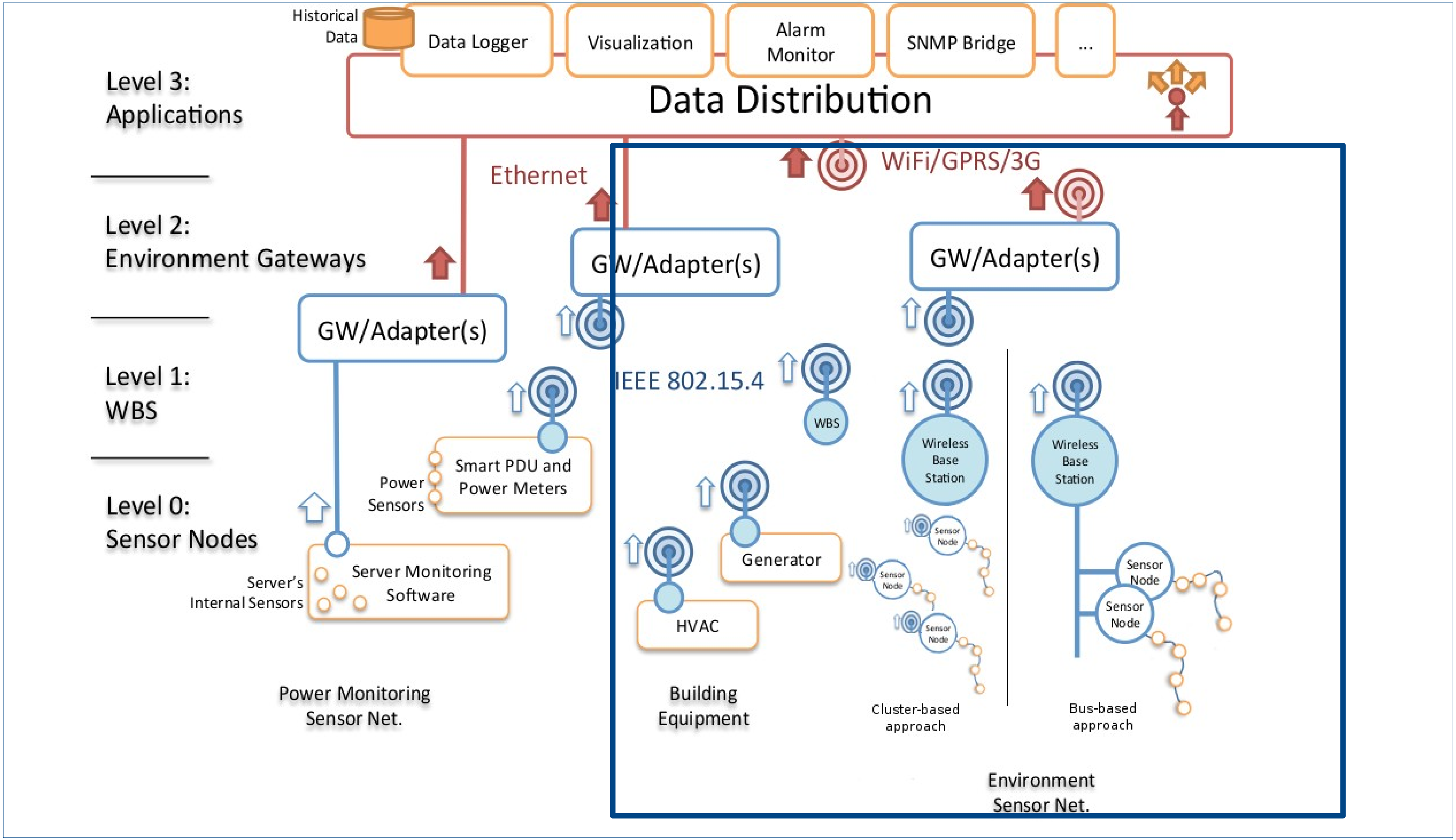

Datacenter Monitoring Scenario

Motivation

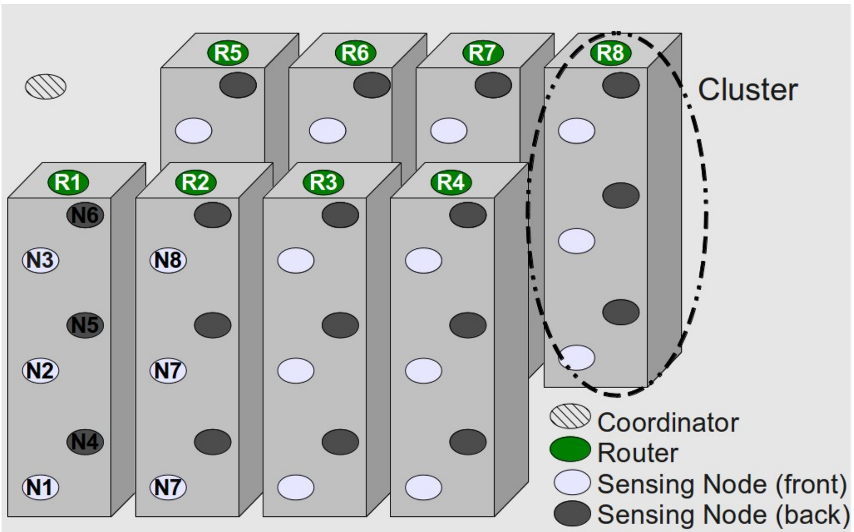
- The average data center is still largely inefficient.
- PT was building a new SOTA datacenter (biggest in Europe and in the top 10 biggest in the world)
  - 75000 m2, 3000 racks, 50000 servers
- By employing distributed sensing technologies
  - to provide fine-grained monitoring of power consumption, cooling and data center environmental variables
  - to identify, model, analyze and optimize energy costs
  - to support alerts and notifications of actual or pending failures

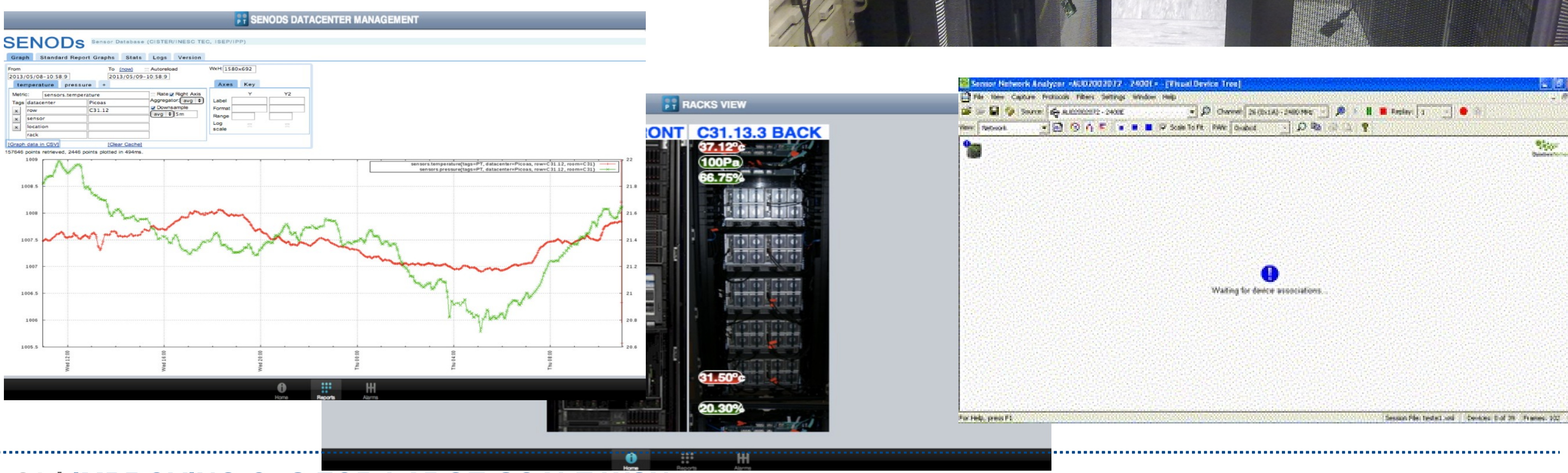


System Model



Results


R5
R6
R7
R8
Cluster
R1
R2
R3
R4
N6
N3
N8
N5
N2
N7
N4
N1
N7
Coordinator
Router
Sensing Node (front)
Sensing Node (back)


SENODS DATACENTER MANAGEMENT
SENODs
RACKS VIEW
C31.13.3 BACK
37.12°c
100Pa
66.75%
31.50°c
20.30%
Waiting for device associations.

QoS IMPROVEMENT PROPOSALS

TIMELINESS

Contributions

- IEEE 802.15.4 MAC sub-layer
  - No traffic differentiation in best-effort based communications
    - Performance evaluation of TRADIF traffic differentiation mechanism over a real-time OS
    - Extension of TRADIF to support intra-cluster communications, cluster level CSMA-CA parameters control.
  - Unavailability of GTS mechanism to support strict timeliness application requirements
    - Implementation of the IEEE 802.15.4 GTS in TinyOS
- ZigBee NWKL
  - lack of flexibility in adapting to changes in bandwidth and delay requirements at run-time. Particularly visible in the SHM application scenario
    - DCS: Dynamic Cluster Scheduling support to synchronized cluster-based networks
      - reduce the end-to-end latency by 93% and the overall data stream transmit duration by 49%

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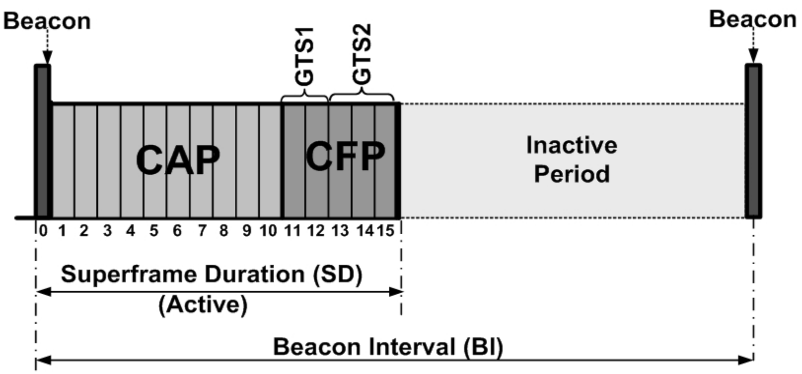
Motivation

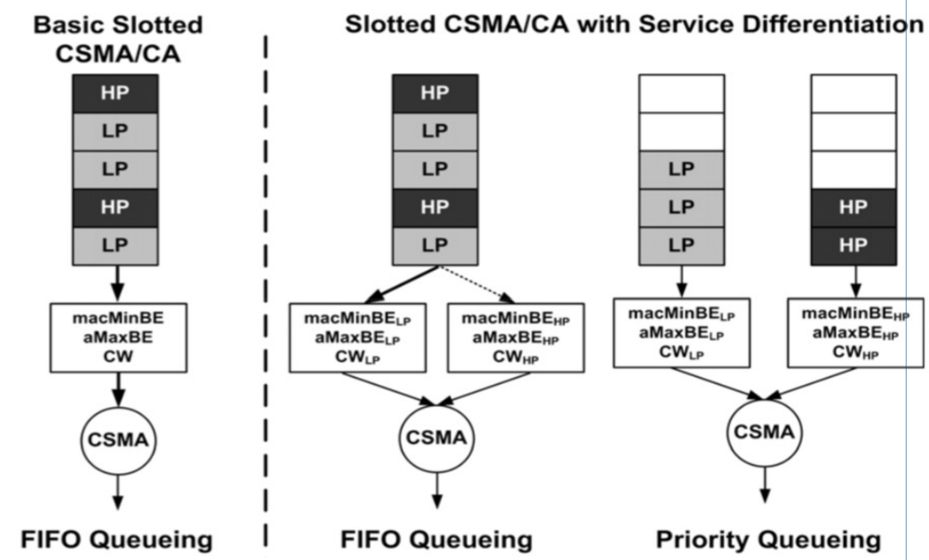
- The GTS mechanism of IEEE 802.15.4 presented some limitations which call for an extension of QoS support to the CAP
  - restriction on the distribution and amount of traffic that can avail the service.
  - GTS limits any node to the length of the slot allocated to it.
  - allocation must be preceded by an allocation request transmitted in the CAP.
  - GTS mechanism may also face coexistence problems
- In the Datacenter Monitoring scenario:
  - Support the possibility to zoom in specific zones of the datacenter by increasing the data sampling rate of specific racks – HIGHER PRIORITY

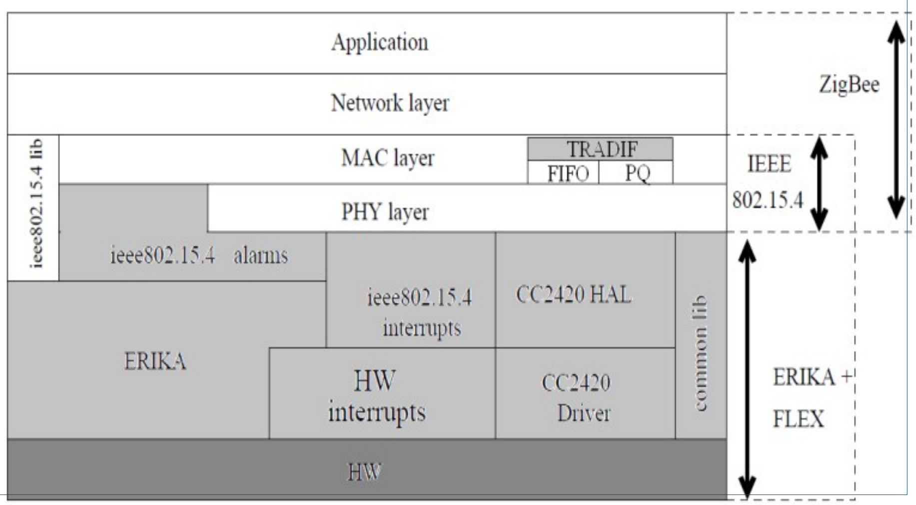


Beacon Interval and Superframe Structure

System Overview

- TRADIF is particularly based on the macMinBE, macMaxBE and CWinit parameters.
- Implemented over the Open-ZB IEEE 802.15.4 stack implementation in ERIKA real-time operating system kernel for embedded devices.
  - Both modes supported (FIFO and PQ)
  - Command frames as HP.
  - Why using the ERIKA version?
    - specially designed to cope with the stringent timing requirements imposed by the IEEE 802.15.4 operating in beacon-enabled mode.
  - What about TinyOS?
    - Does not provide any kind of real-time guarantees.
    - The stack becomes unstable with high network traffic.

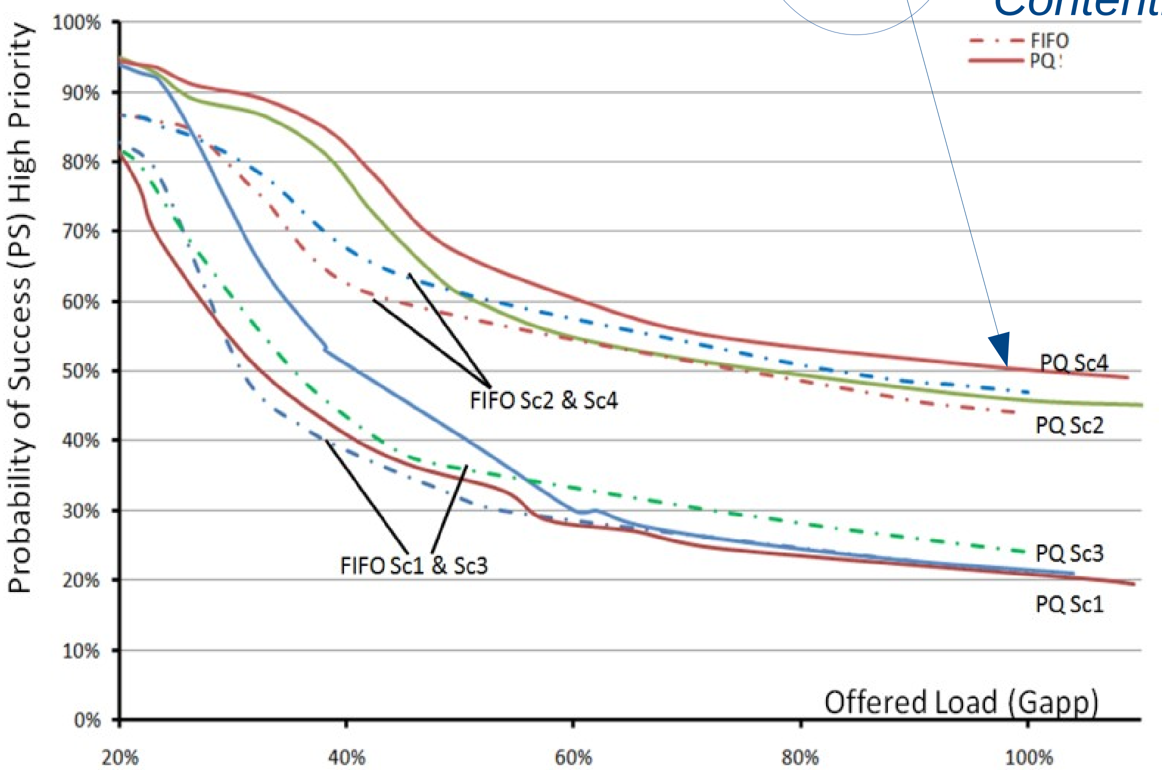


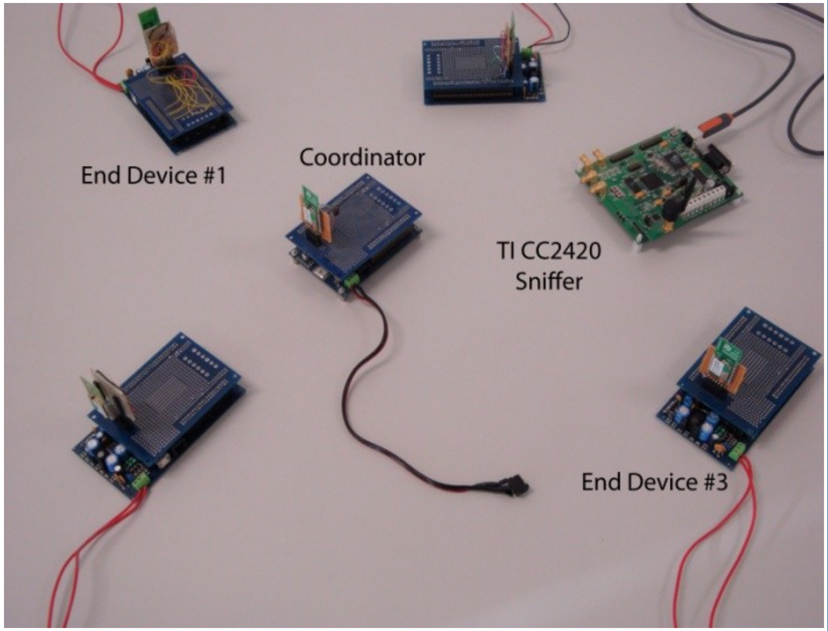


Results

Scenario	[macMinBE$_{HP}$, aMaxBE$_{HP}$]	[macMinBE$_{LP}$,aMaxBE$_{LP}$]	CW$_{HP}$	CW$_{LP}$
Sc1	[2,5]	[2,5]	2	2
Sc2	[2,5]	[2,5]	2	3
Sc3	[0,5]	[2,5]	2	2
Sc4	[0,5]	[2,5]	2	3

“Contention Window makes PS better!”





Contributions

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  - Unavailability of GTS mechanism to support strict timeliness application requirements
    - Implementation of the IEEE 802.15.4 GTS in TinyOS
- ZigBee NWKL
  - lack of flexibility in adapting to changes in bandwidth and delay requirements at run-time. (interference with network functionality and specially without imposing high inaccessibility times) particularly visible in the SHM application scenario
    - DCS: Dynamic Cluster Scheduling support to synchronized cluster-based networks
      - reduce the end-to-end latency by 93% and the overall data stream transmit duration by 49%

Just a few notes...

- Strengths
  - Efficient GTS database management
  - Reliable handling of multiple requests
- Submitted to TinyOS 15.4 WG and distributed in the official release
  - The implementation was made available to the TinyOS community and is included in the official TinyOS 2.x distribution in its TinyOS code repository (*https://github.com/tinyos/tinyos-main*). The implementation files can be found under */tos/lib/mac/tkn154*.

Contributions

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- ZigBee NWKL
  - lack of flexibility in adapting to changes in bandwidth and delay requirements at run-time. **Particularly visible in the SHM application scenario**
    - DCS: Dynamic Cluster Scheduling support to synchronized cluster-based networks
      - reduce the end-to-end latency by 93% and the overall data stream transmit duration by 49%

Motivation/Challenges

- With DCS (Dynamic Cluster Scheduling) we are able to
  - adapt on-the-fly to different bandwidth and end-to-end delay requirements imposed by incoming traffic streams changing the cluster's duty-cycle and scheduling
  - without requiring long inaccessibility times
  - no re-association of the nodes.
- Importantly, the method although not optimum it is fast and always gives a better solution
- In DCS we propose two techniques
  - DCR – Dynamic Cluster Reordering
  - DBR – Dynamic Bandwidth Redistribution

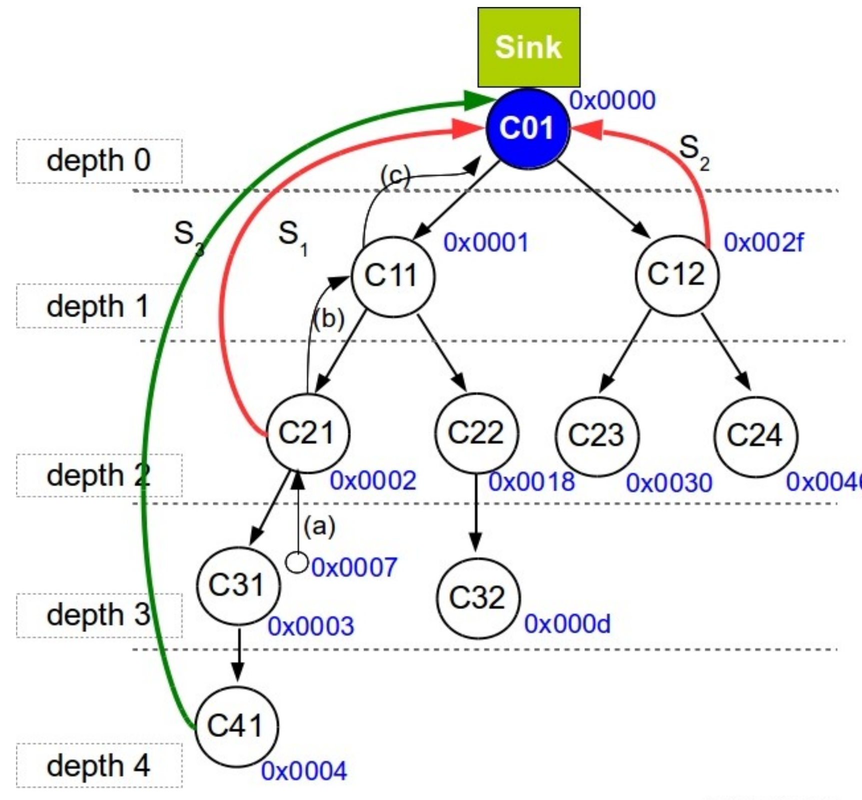
Dynamic Bandwidth Redistribution

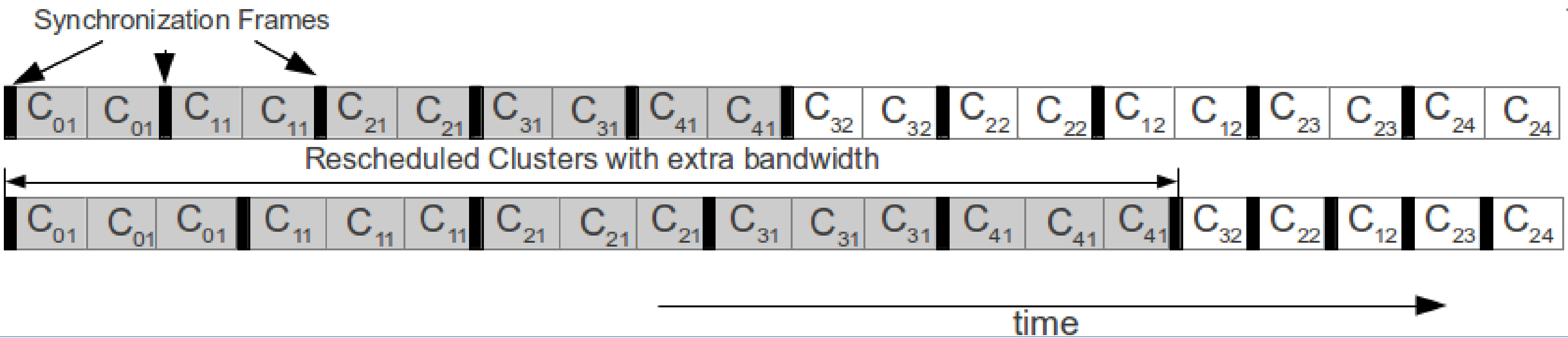
- To reduce stream transmission time

  bandwidth must be reallocated, by increasing the bandwidth for the clusters involved in the stream.

  - Define minimum bandwidth unit
  - look for free space in the schedule that has not been reserved
  - distribute in an equal fashion the available space by the Clusters involved in the stream

- If not, reduce bandwidth of other clusters
  - Careful not to compromise network stability

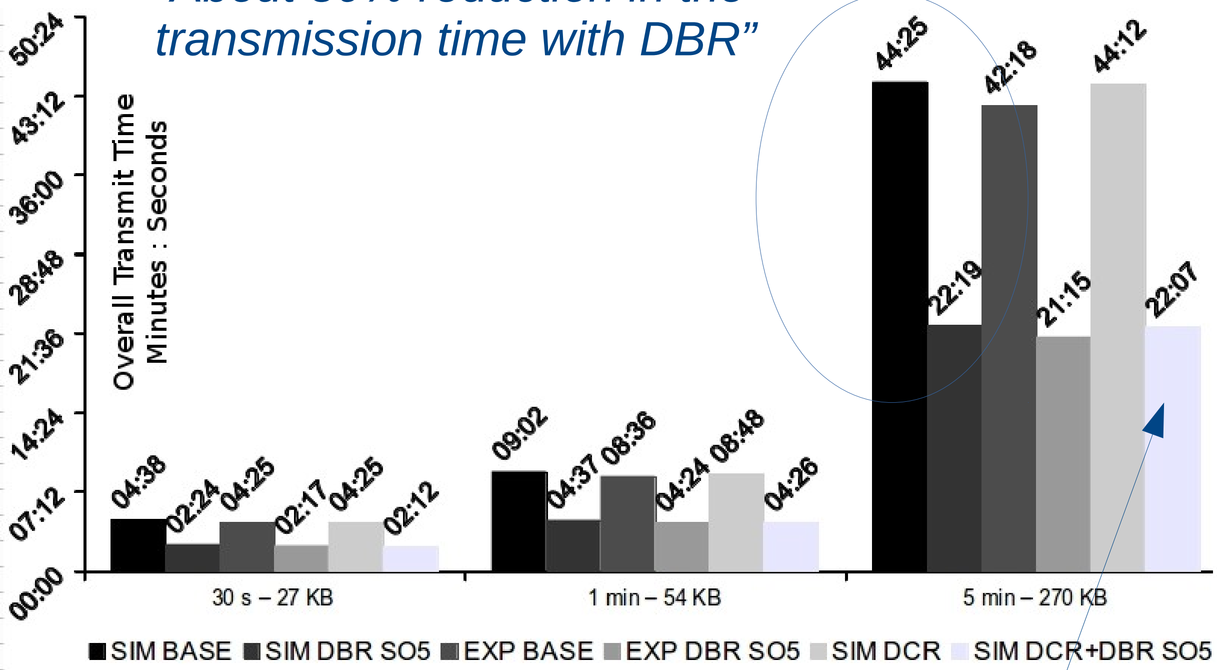


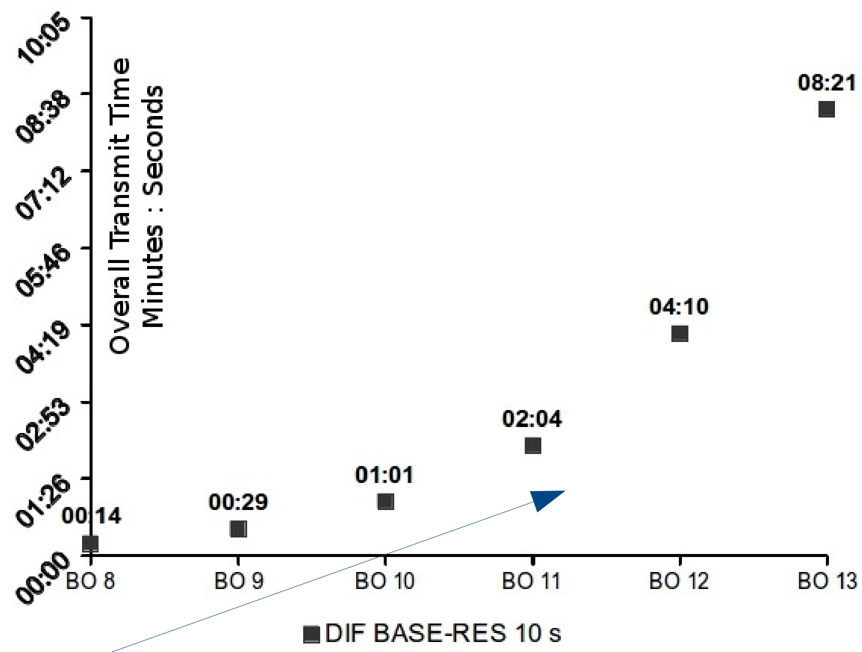


Results

"How much time does it take to transmit the SHM data?"

"About 50% reduction in the transmission time with DBR"





"DCR does not make a significant difference for BO = 8" (14 seconds less)

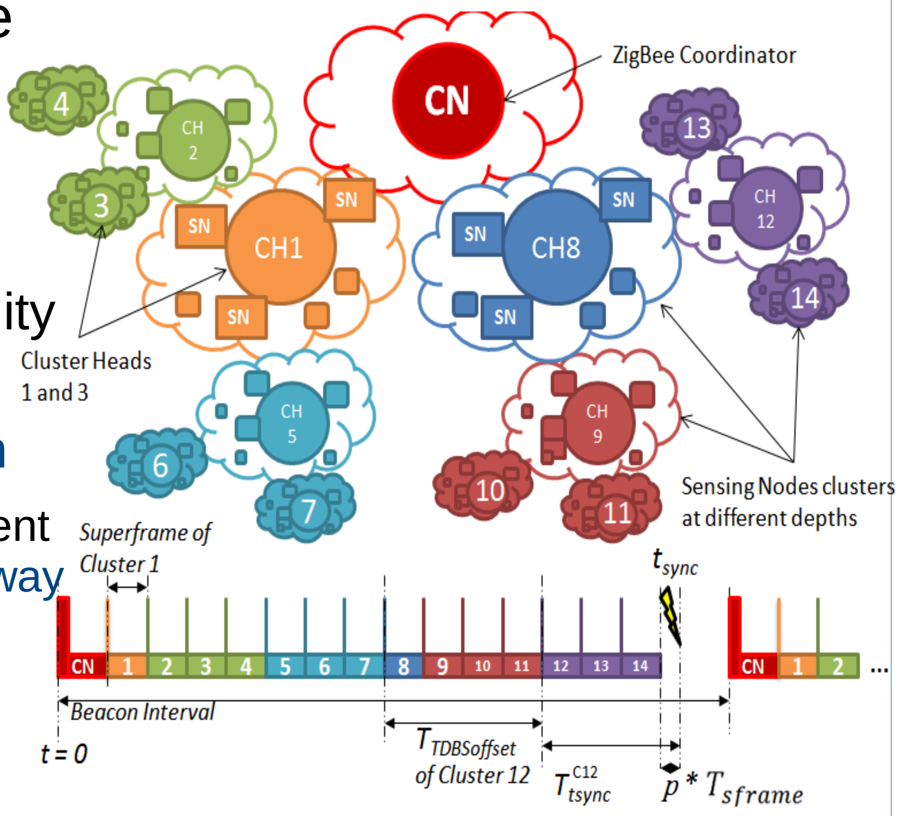
"However for longer BOs..."

"due to the re-ordering of the clusters' schedule the transmission will end sooner"

SCALABILITY

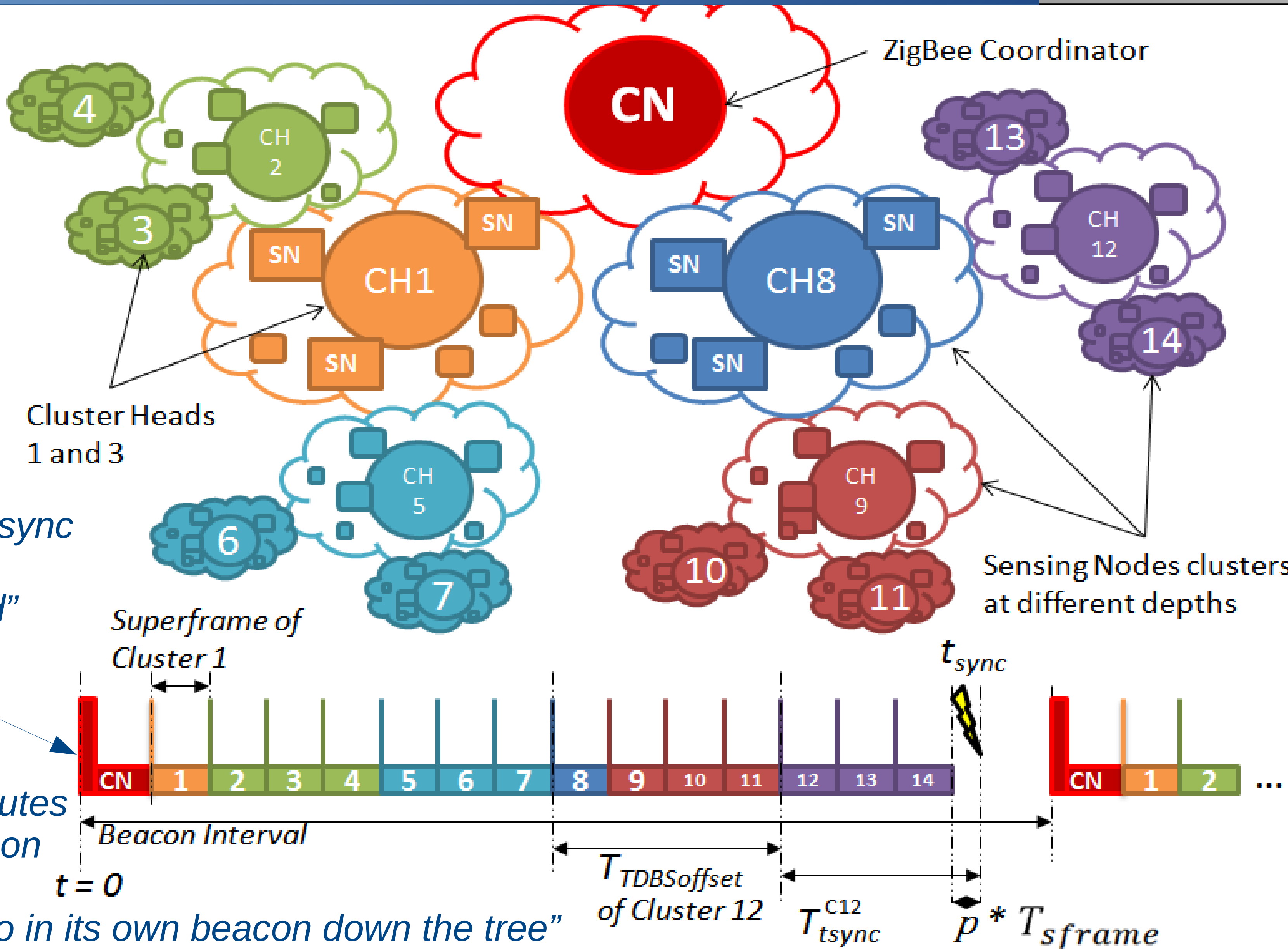
Inter-cluster Synchronization

- ZigBee proposes mesh and cluster-tree network topologies
  - timeliness, can only be adequately addressed by the latter.
  - there are applications in which the scalability requirements go even beyond this
  - the structural health monitoring application
    - samples from all sensors, even those in different clusters, must be acquired in a synchronized way
    - Using TDCS (Anis Koubaa et. al) this is not possible



- SSYNC enables nodes at different clusters to synchronize to one specific moment
  - IEEE 802.15.4 beacons enable globally synchronized data acquisition.

System Overview



"Symbols until tsync embedded in beacon payload"

"each CH computes its offset based on its parent and forwards the info in its own beacon down the tree"

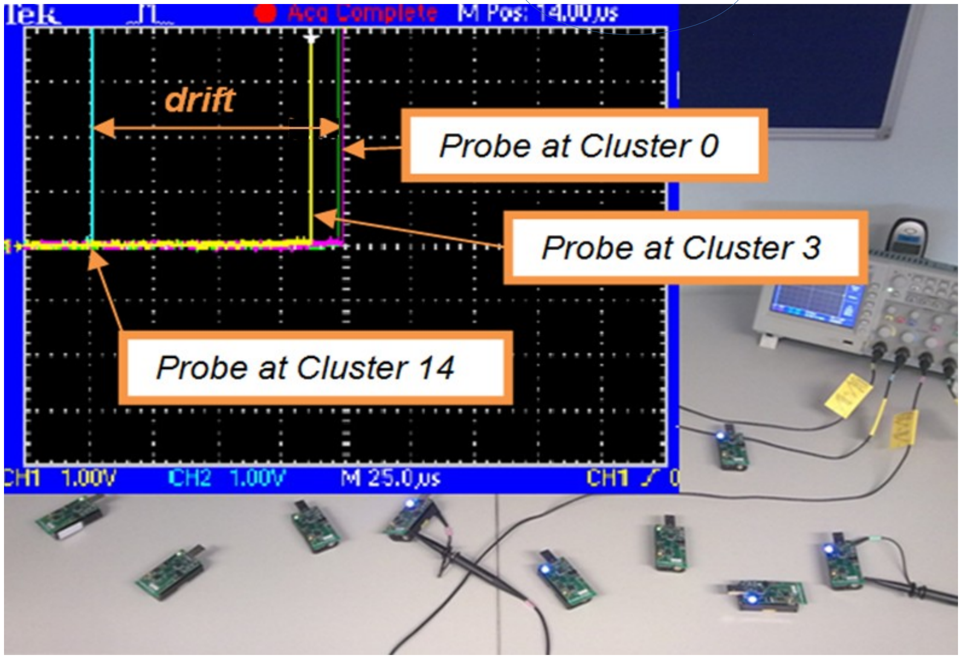
Experimental Validation

- Implemented the synchronization mechanism in nesC/TinyOS, over the official TinyOS implementation of the 15.4/ZigBee protocols.
  - 15 clusters.
  - The TDCS 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).

Number of Clusters	SO/BO	Max. δ (μs)
5	5/8	111
15	4/8	152
25	4/9	252
50	3/14	249
100	2/14	1230

“Less than max value given by theoretical analysis”



ROBUSTNESS

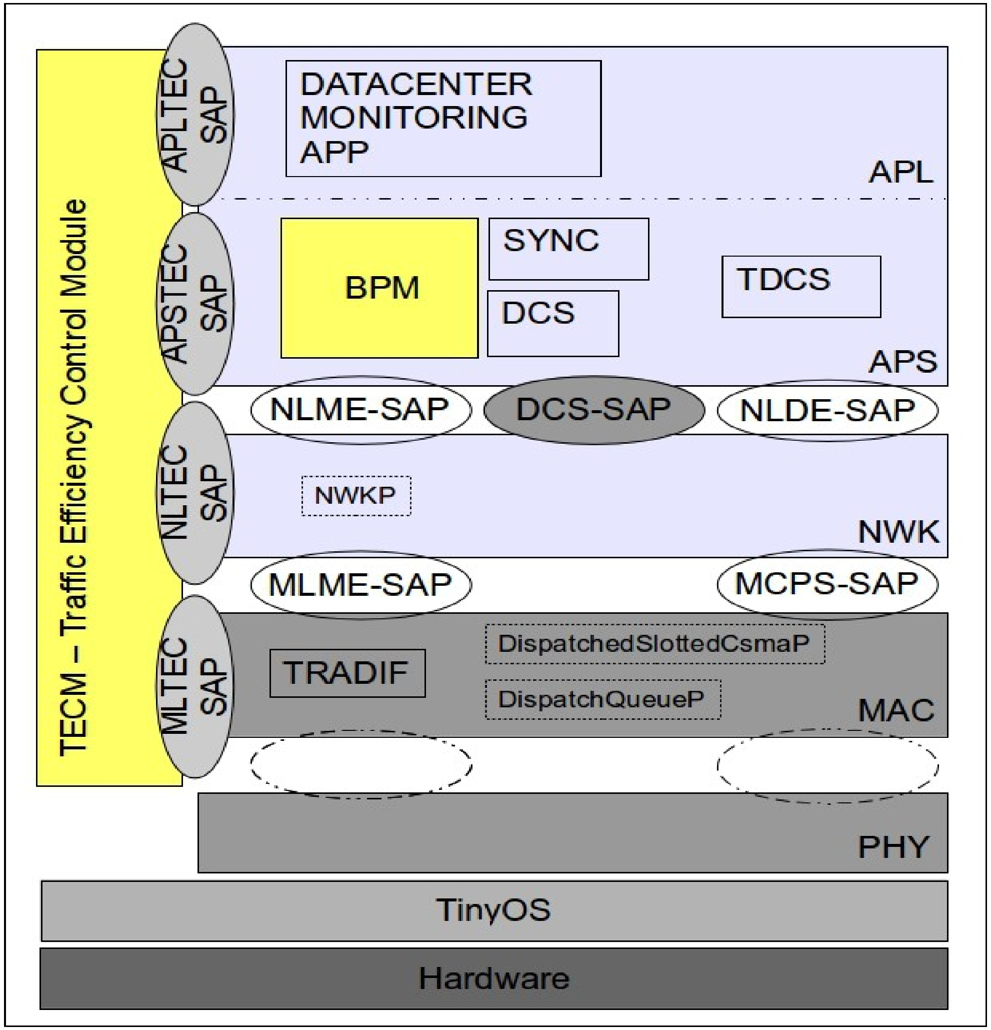
Traffic Efficiency Control Module

- The need to zoom into selected parts of Datacenter
  - Higher reporting frequency (and priority) – TRADIF
  - Network had troubles coping with increased traffic – Bandwidth - DBR
- a cross-layer QoS management framework for ZigBee cluster-tree networks
  - on-line control of a set of parameters at the MAC sub-layer and NWKL
  - improving
    - successful transmission probability (TRADIF + extension)
    - and minimizing the memory requirements and queuing delays through an efficient bandwidth allocation at the network clusters (DBR).
- Beacon Payload Management module (BPM)
  - DCS + TRADIF + SSYNC + other application

Overview

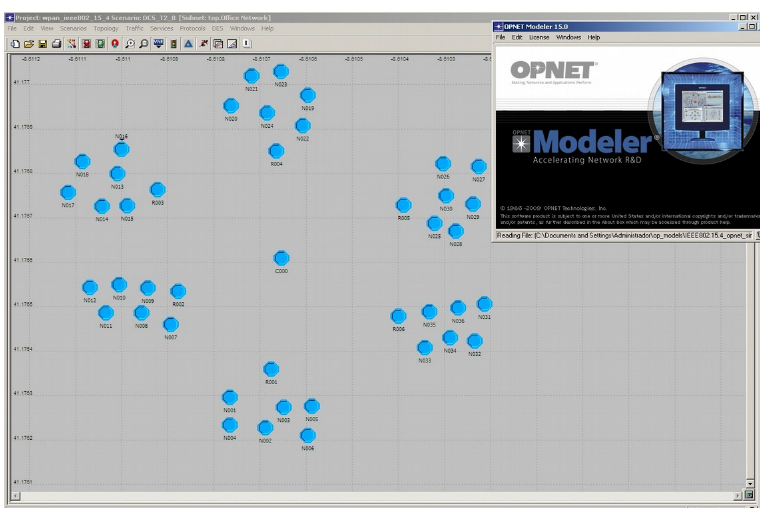
- New set of service access points for each layer.

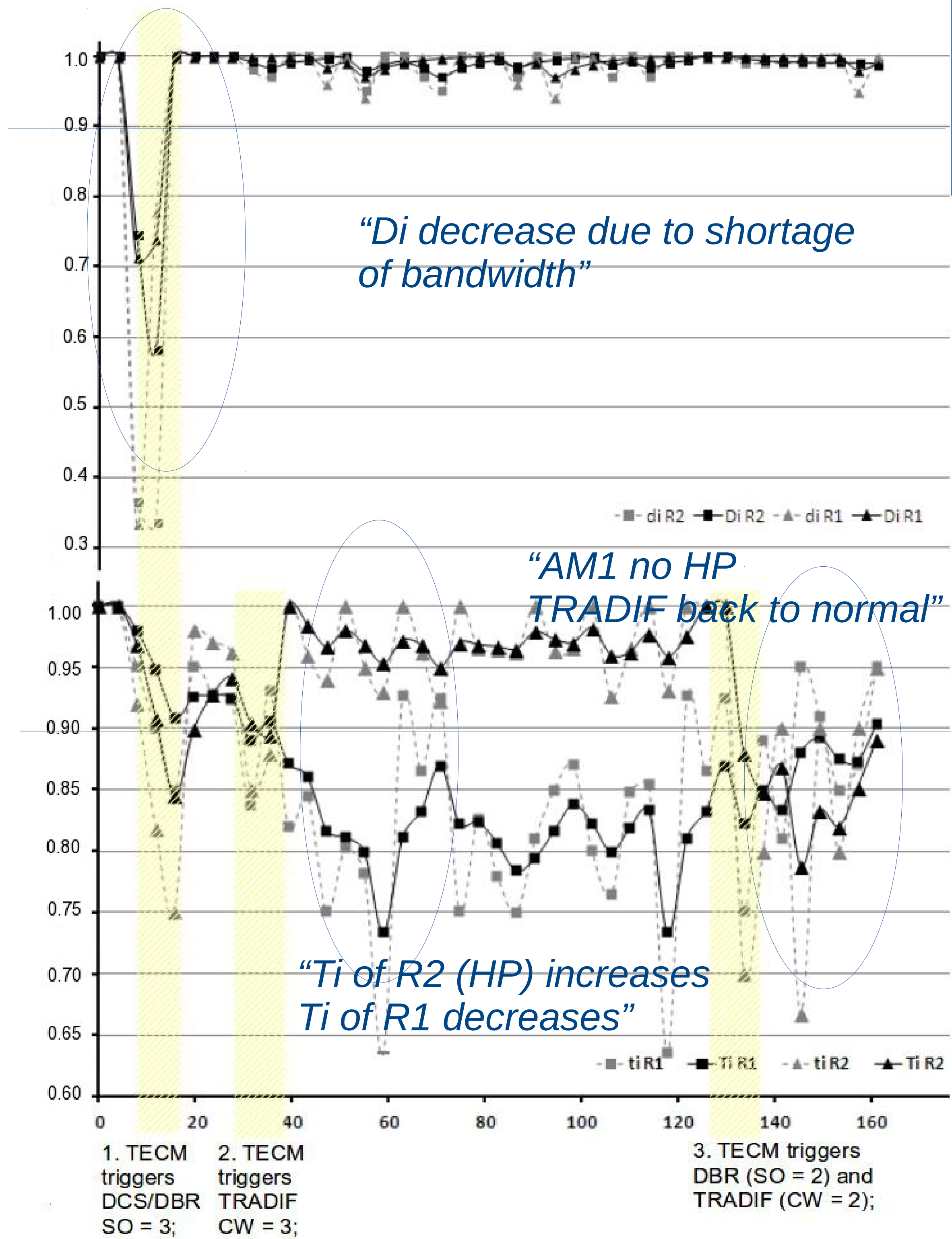
  Performance indicators
  - d_i, relationship between incoming and outgoing traffic, which gives a measurement of the bandwidth requirements of a node.
  - t_i, concerns behavior of the MAC layer concerning successful transmissions,
    - a ratio between the number of successfully transmitted packets (c_success) and the number of packets which entered the Slotted CSMA-CA algorithm (c_success + c_fail).
- Algorithm has 2 parts
  - (1) analyzes bandwidth requirements and increases or decreases DCS/DBR service
  - (2) packet delivery success probability analysis – for HP nodes only – increases/decreases TRADIF service.

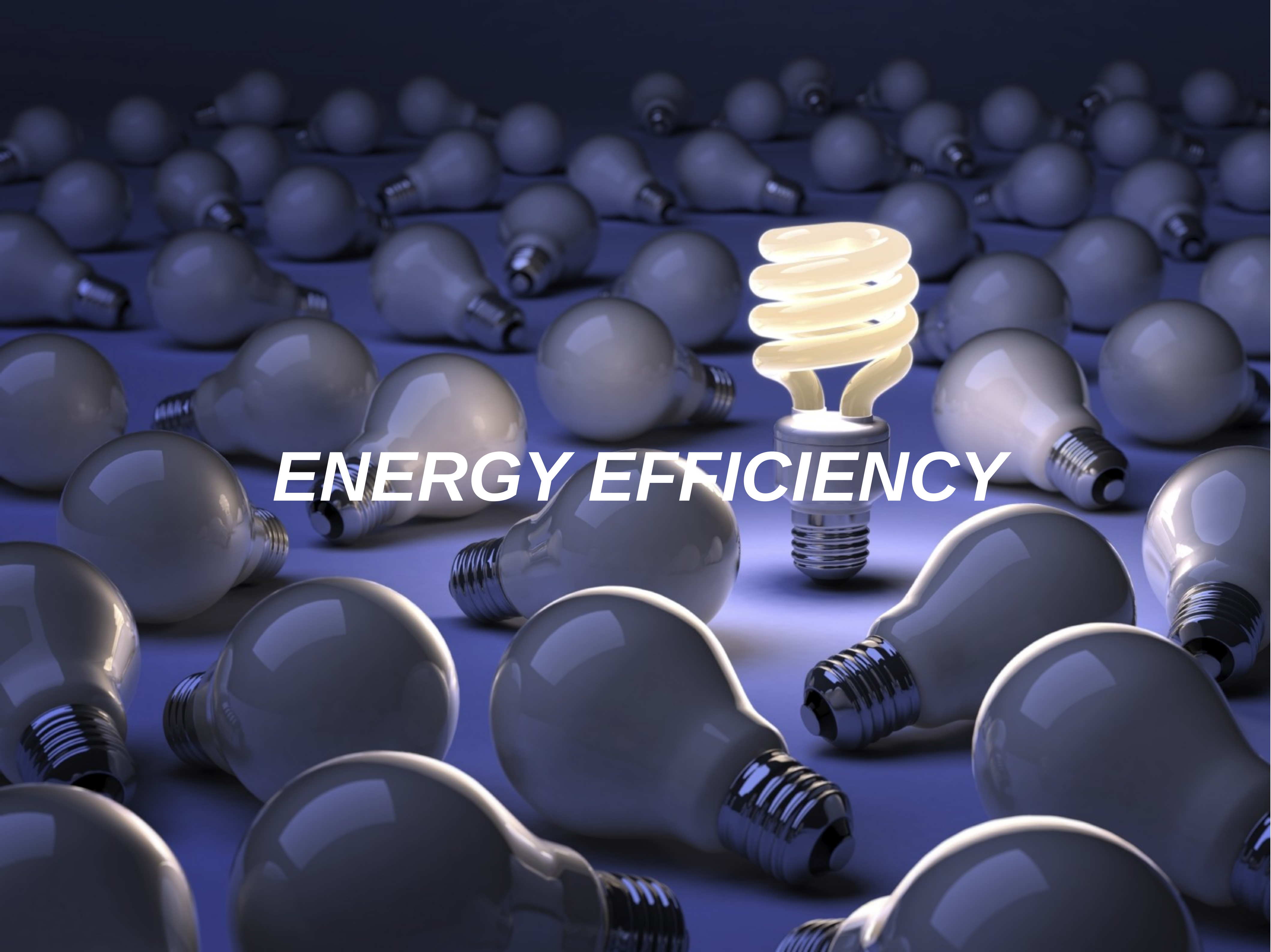


Application modes

- AM1: Normal: asynchronous data acquisition of all racks with a relaxed report every 8 seconds.
- AM5: Rack Zoom In: user selects one rack for a non synchronized data acquisition with report every 0.8 seconds while the other racks report every 2 seconds.






ENERGY EFFICIENCY

"and where is the Energy Efficiency?"

- The choice of IEEE 802.15.4 Beacon-enabled mode
- GTS Implementation, TECM and TRADIF
  - *Less collisions higher energy-efficiency*
- DCS/DBR
  - *Lower stream transmit time higher efficiency*

Final Remarks

- Provided contributions to four important QoS aspects
  - Timeliness (TRADIF, DCS, GTS)
  - Scalability (SSYNC)
  - Robustness (TECM, BPM)
  - Energy Efficiency (indirectly approached)
- Relied on real-world application scenarios for validation and demonstration
  - Structural health monitoring scenario
  - Datacenter monitoring scenario
- Relied on COTS

“We confirmed the initial hypothesis of this thesis, i.e., the use of IEEE 802.15.4 and ZigBee set of standard protocols as a baseline, combined with a set of QoS mechanisms can effectively support the requirements that future embedded computing systems may impose.”

Publications

2015

- R. Severino, S. Ullah, E. Tovar, ***A Cross-layer QoS Management Framework for ZigBee Cluster-Tree Networks***, Accepted for publication in Springer's Telecommunication Systems
- N. Pereira and S. Tennina and J. Loureiro and R. Severino and B. Saraiva and M. Santos and F. Pacheco and E. Tovar, ***A Microscope for the Data Center***, International Journal of Sensor Networks (IJSNet) Inderscience, 2015.

2014

- R. Severino, N. Pereira, and E. Tovar, ***Dynamic cluster scheduling for cluster-tree WSNs***, Springer-Plus Communication Networks, 3(493), 2014.

2013

- R. Severino, N. Pereira, and E. Tovar, ***Dynamic cluster scheduling for cluster-tree WSNs***, IEEE 16th International Symposium on Object/Component/Service-Oriented Real-Time Distributed Computing,(ISORC), Germany, 2013.
- S. Tennina, A. Koubaa, R. Daidone, M. Alves, P. Jurcik, R. Severino, M. Tiloca, J. Hauer, N. Pereira, G. Dini, M. Bouroche and E. Tovar, ***IEEE 802.15.4 and ZigBee as enabling technologies for low-power wireless systems with QoS constraints,*** Lecture Notes in Electrical and Computer Engineering, Springer Berlin Heidelberg, Germany, 2013.
- R. Severino, N. Pereira, and E. Tovar. Technical report: ***Dynamic cluster scheduling for cluster-tree WSNs***, CISTER Technical report, CISTER-TR-130205, 2013

2011

- J. Büsch, R. Daidone, J. Hauer, R. Severino, S. Tennina and M. Tiloca, ***An Open-Source IEEE 802.15.4 MAC Implementation for TinyOS 2.1***, In Poster and Demo Session of the 8th European Conference on Wireless Sensor Networks (EWSN 2011), pp 15-16, Bonn (Germany), 2011.

2010

- R. Severino, R. Gomes, M. Alves, P. Sousa, E. Tovar, L. Ramos, R. Aguilar, P. Lourenço, ***A Wireless Sensor Network Platform for Structural Health Monitoring: enabling accurate and synchronized measurements through (COTS + custom)-based design***, 5th IFAC International Conference on Management and Control of Production and Logistics, University of Coimbra, Portugal, September, 2010.
- R. Aguilar, L. Ramos, P. Lourenço, R. Severino, R. Gomes, P. G. de Sousa, M. Alves, E. Tovar, ***Operational Modal Monitoring of Ancient Structures using Wireless Technology,*** International Modal Analysis Conference and Exposition on Structural Dynamics - IMAC-XXVIII, Jacksonville, Florida, USA, 2010.
- R. Severino, M. Batsa, M. Alves, A. Koubâa, ***A Traffic Differentiation Add-On to the IEEE 802.15.4 Protocol: implementation and experimental validation over a real-time operating system***, 13th Euromicro Conference on Digital System Design (DSD'2010), Lille, France, September 2010.

What's next

- QoS balancing framework
  - TECM brought it a little closer
- Improvements to the engineered applications (*“product development?”*)
- Look into other more recent protocols

Improving QoS for Large Scale WSNs

PhD Thesis Presentation

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