Wireless Sensor Networks A Decade of Wireless Sensing Applications

MO809 - Tópicos em Computação Distribuída

Luísa Madeira Cardoso

Agenda

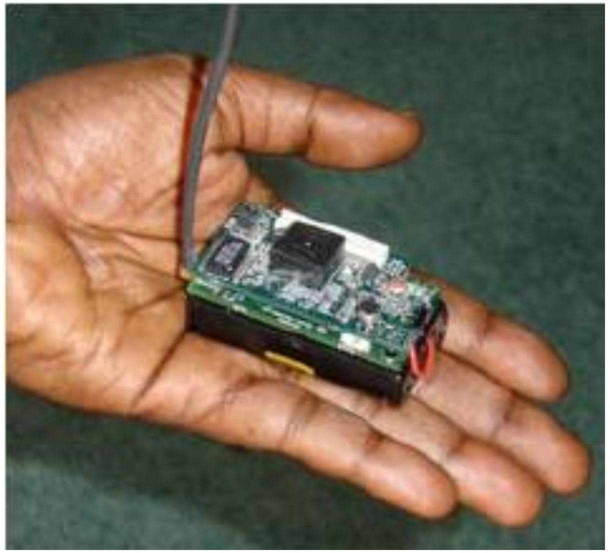
- Introduction
- Applications

1. Low-Rate Data Collection
2. High-Rate Data Collection
3. On-Demand Data Collection
4. Event detection and classification
5. Localization and Tracking
6. Actuation

A Decade of WSN

- The first prototypes of WSNs actually consisted of a small number of matchbox-sized devices, often called “motes.”
  - Small size allows a careful placement close to the phenomenon of interest
  - Low costs
  - Minimal need of human intervention
- Most WSN deployments have a strong scientific background.
  - Main purpose: demonstration of new technologies
  - Exploration of remaining limitations
  - The requirements of the actual application at hand are often secondary

- First application areas
  - Military surveillance: sensors are seen as a tool to enable reliable detection and tracking of enemy forces
  - Environment Monitoring: Great Duck Island in the year 2002 (first significant application deployment of a WSN)
- Around the year 2004: the number of reported WSN deployments increased significantly.
  - Commercialization of the first WSN platforms: Mica2, Mica2Dot, MICAz, TelosB.
  - Maturing software infrastructures (TinyOS, TinyDB)
  - Increasing robustness of networking protocols
  - In recent years: overlap of neighboring research areas (home automation, Internet of Things)



"Most deployments remain prototypical in character and are conducted by researchers working on sensor network technologies. Commercial applications tend to be conceptually simple and not to exploit the full potential of scientific innovations. For example, advanced **multi-hop routing protocols are rarely used"**

Applications Classification

1. *Low-Rate Data*
   Periodic collection using low data-rate sensors
2. *High-Rate Data*
   Periodic collection with high generated data-rate
3. *On-Demand Data Collection*
   Data collection on-demand
4. *Event Detection and Classification*
   Sensor network performs on-node processing (event detection or classification)
5. *Localization and Tracking*
   In-network event detection to localize or even track their position
6. *Actuation*
   Actively manipulate the monitored environment

1 Low-Rate Data Collection

- First application scenario for WSNs
- Still represents the majority of existing deployments
- Periodic monitoring with low-data rate sensors
  - Temperature
  - infrared sensors that usually produce a single scalar value per measurement

- Support an extensive lifetime of the network up to several years
- It is feasible to communicate the collected raw data without filtering, compression, or aggregation

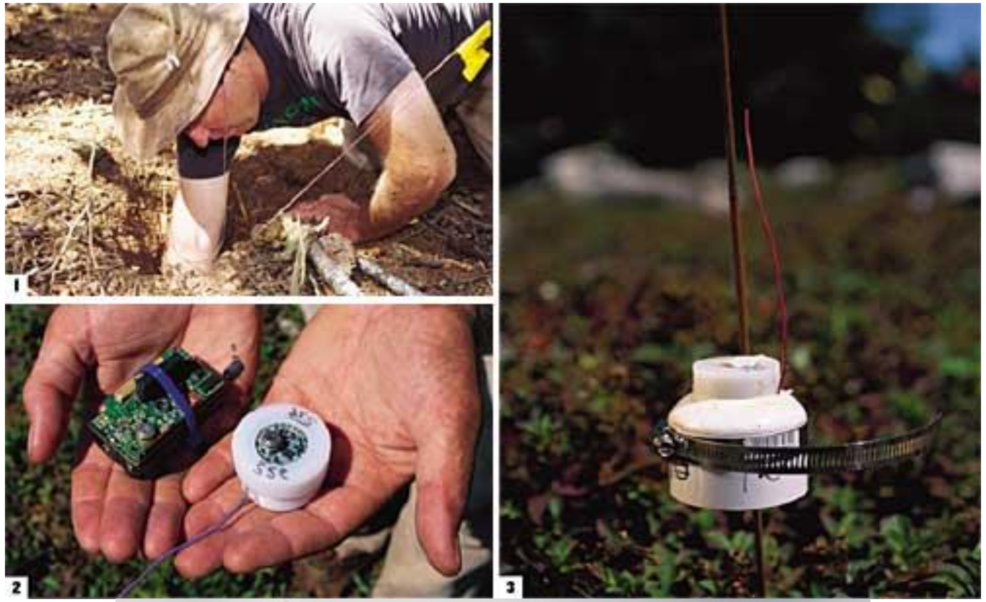
Habitat monitoring: Great Duck Island

2002-2004 - [102, 62, 72]

Mobility: static. Connectivity: connected.

Storage: persistent (server). 32 - 190 sensors.

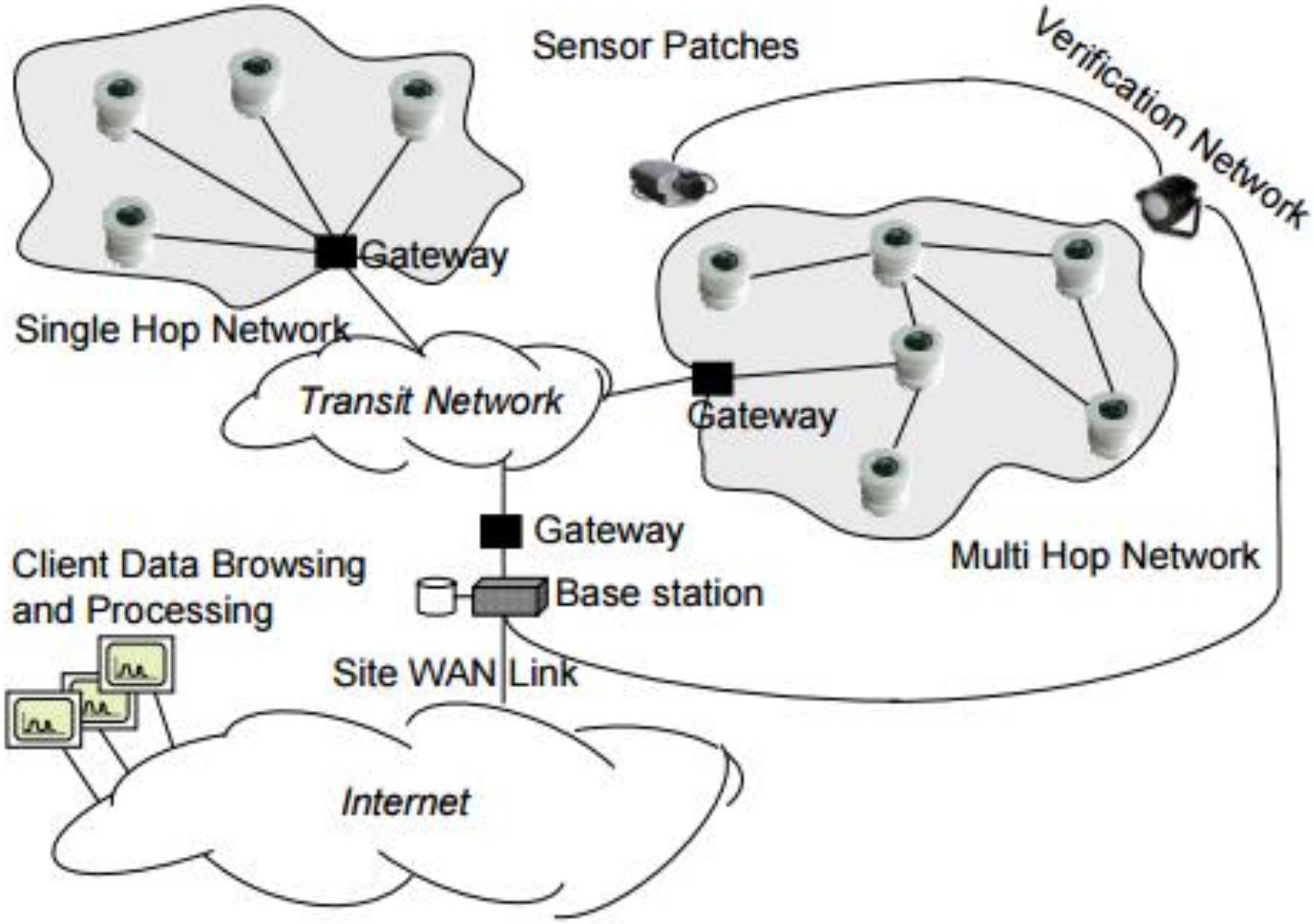
Lifetime: months



Goal: the long-term observation of the breeding behavior and nesting conditions of Leach's Storm Petrels

Sensors:

- Temperature and humidity (in the nesting burrows)
- Infrared radiation sensors were used to detect the presence of a bird



Deployment consisted of several patches of sensing nodes, connected to a transit network via dedicated more powerful gateway nodes

A single base station provided Internet connectivity and database services for the whole deployment

Environment monitoring: PODS - 2002 - [19]

- Goal: Monitor several species of plants - Hawaii Volcanoes National Park
- Sensors: temperature, humidity, rainfall, wind, and solar radiation sensors

Redwood Eco-Physiology – 2005 [32,105]

- Goal: Monitor redwood trees **-** Sonoma, CA, USA
- Sensors: air temperature, relative humidity, and photo-synthetically active solar radiation

GreenOrbs – 2009 [75]

330 sensor nodes

- Goal**:** observe the effect of different sunlight conditions in shrub thicket
- Sensors: temperature, humidity, illumination, and carbon dioxide measurements

GlacsWeb

Briksdalsbreen in Norway - **2003-2005 - [74]**

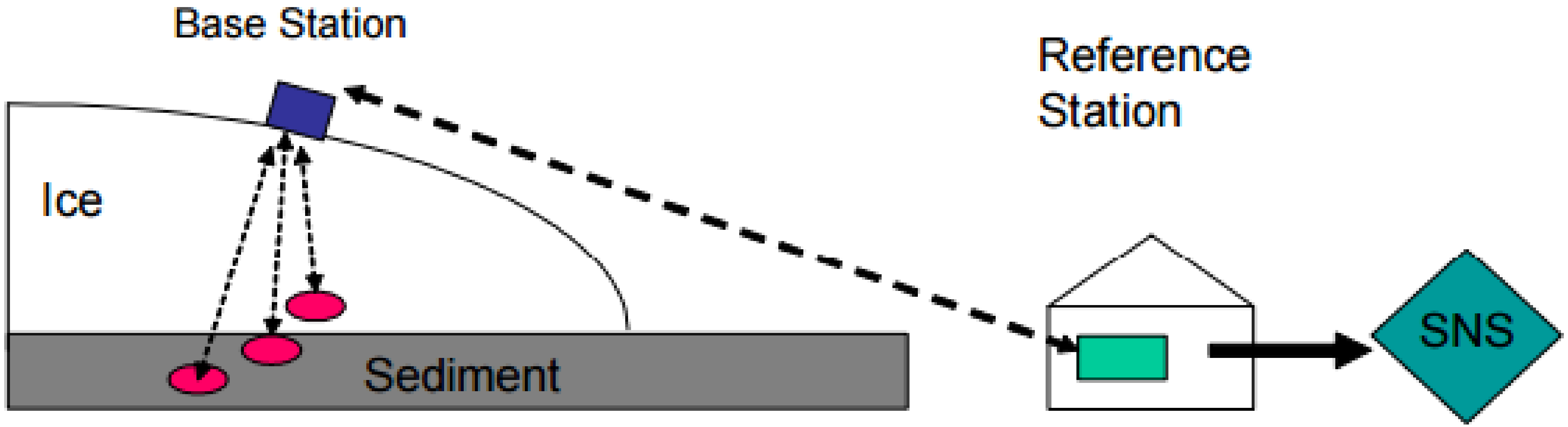
Mobility: nodes. Connectivity: intermittent. Storage: persistent (gateway). Time synchronization

Lifetime: months

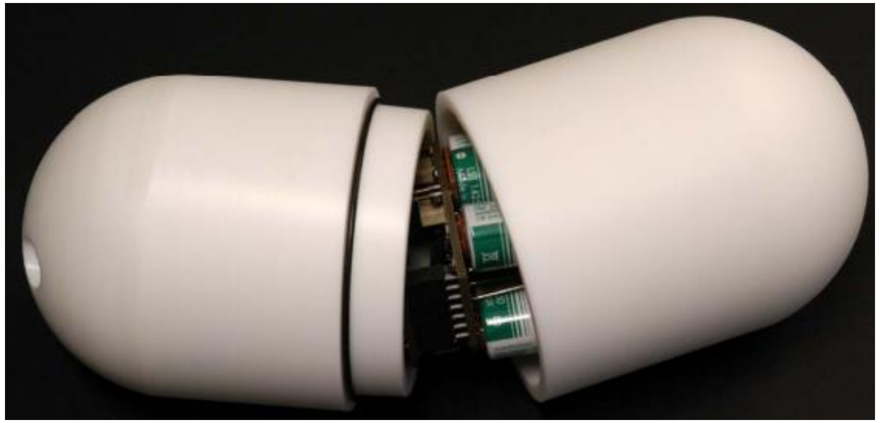
Goal: Monitor conditions inside Glaciers

Glacier environment:

- Is especially hostile to sensor nodes
- Radio communication through ice and water is known to be difficult and highly unreliable
- Remote deployment location: 2.5km distances - network had to reliably operate over long time intervals without direct interaction



Base station
- GPS
- Solar panels
- 500mW radio modem
- 2.5 km



Sensors
- PIC-based boards
- Temperature, pressure, and the orientation in the ice
- Encapsulated in robust and waterproof PVC capsules
- Probes collect data six times daily
- 50m to 80m deep

PermaSense - 2009 - [18] & **SensorScope** – 2007 [15]

- Goal: support the creation of new temperature models
- PermaSense - highly inaccessible terrain area in the Alps
- SensorScope - Le Génépi, Switzerland

Suelo - 2009 - [84]

- Goal: collect high-resolution data on soil state
- If required, the system can automatically call for human verification and assistance

SenSlide – 2005 [94,95]

- Goal: prediction of landslides through constant monitoring of ground stress

LOFAR-agro

2006- [63] - Borger-Odoorn (Drentheand, Netherlands)

Mobility: static. Connectivity: connected.

Storage: persistent (node). 109 sensors.

Lifetime: A year

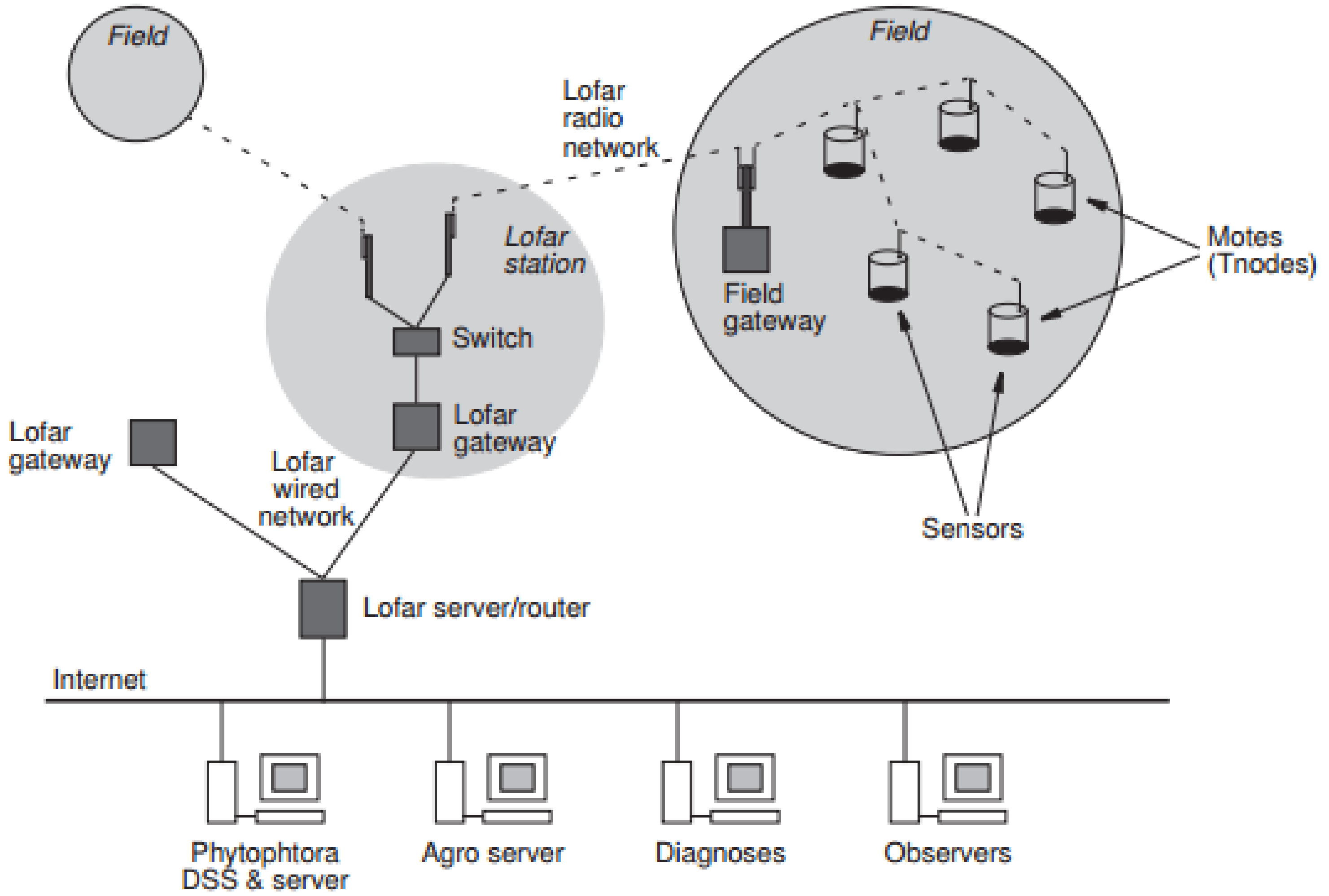
Goal: generate new insights on climate conditions favoring Phytophthora

Sensors:

- Temperature and humidity
- Waterproof PVC-based
- Once per minute

Gateway:

- Solar panel



Sensor – gateway communication:

- Directly
- Through multiple hops

Routing: **MintRoute** - multihop routing protocol to overcome possible obstructions by the growing potato plants

Gateway – LOFAR backbone network:

- Wi-fi

The Agro server: logs the data, filters out erroneous readings, and hands the accumulated data to the Phytophthora decision support system (DSS) server.

The deployed WSN never operated as intended and was hampered by a **very high packet loss rate**. According to the authors, **only 2% of the measurements** made it to the back-end system.

Vineyard Monitoring – 2004/2009 - [7, 17, 20, 78]

Lifetime: months, years

- Goal: get a more fine-grained picture of the microclimate in the proximity of the plants
- Also monitor humidity and temperature in the cellar used for wine storage

Greenhouse monitoring - 2008 - [3]

Eletronic Shepherd - Tracking of sheep – 2004 - [103]

Irrigation Control - 2005/2005/2007 - [13, 57, 81]

Soil moisture monitoring – 2004 - [23,24]

PIPENET

2004 - [101] - Boston Water and Sewer Commission

Goal: monitoring large diameter bulk-water transmission pipelines

Sensor: Bluethooth

Routing: cluster

Monitoring Road Tunnels – 2005/2007 - [26, 27, 31,78]

Substation monitoring - 2008 - [80]

Power Monitoring – 2004/2009/2010 - [4, 49,50,2]

Employed a WSN to provide information on room occupancy in order to operate a Heating, Ventilation and Air Conditioning (HVAC) system based on the actual demand

Relic protection- 2007 - [65,66]

Goal: detect unsuitable climate

Prototype deployed in the forbidden city in Beijing, China

Reliable Clinical Monitoring

2009- [29] - Barnes-Jewish Hospital (Saint Louis, MO, USA)

Mobility: node. 41 patients.

Lifetime: Months

Goal: monitor patients that do not require intensive care, but are at high risk

Sensors:

- TelosB-based wireless
- measure pulse (30s)
- blood oxygen saturation (60s)

Designed new protocol - Dynamic Relay Association Protocol

- discovers new neighbors by listening for beacons periodically broadcast by the relay node
- ssociates with the relay which has the highest Signal strength

(a) Patient node (b) Relay

2 *High-Rate Data Collection*

- Usually don’t transmit raw data to a central server for processing
- Data-rate generated by sensors
  - Usually exceeds the available communication bandwidth
  - Would quickly drain the limited energy budget if the raw sensor data is sent directly to a central unit.
- Need to implement
  - Compression
  - Filtering
  - Data processing

Four Seasons project

2004- [28,109] - abandoned four-story building in Sherman Oaks, CA, USA

Time synchronization.

Lifetime: days

Goal: monitor the health of the structure during earthquakes

Simultaneously to the sensor network experiment, a series of forced-vibration tests with conventional equipment were conducted.

Sensors:

- Vibration sensors and accelerometers
- To limit the data to a maintainable rate, the system employed silence suppression and data compression
- Synchronization: Tracked the time it took a packet to travel through the network

Monitoring Bridges

Golden Gate Bridge – 2007 - [56] – 64 nodes, sampling rate 1kHz

St. Lawrence County - 2009 - [110]

“Torre Aquila” 2009 - [25]

Trento, Italy - Medieval tower

- Contained renowned medieval fresco
- Endangered by construction of road tunnel below the building
- Sensor applied to generate a better insight into the structural behavior of the building

Underground Animal Tracking – 2010 - [73]

- Goal: Badgers tracking
- Limited radio propagation underground – Data locally stored (compression)
- When the badger was near the base station: transmission of data

Volcano Monitoring- 2006 - [108]

- Reventador, Ecuador
- Goal: collection of high fidelity data on volcano activity to enable geologists to build a clearer picture of the seismic phenomena
- 16 sensors: seismic and acoustic
- Rely on a network time synchronization protocol and a single GPS receiver (they needed precision in the order of milliseconds)
- High data rates: 1200 bytes/s per node (network: >100 Kbps)
- Each node temporarily stored the collected data locally
- Detection of predefined pattern - node signaled a detection event to the base station. Base station triggered data collection and iteratively downloaded the last 60 s of recorded data from each sensor node.

Industrial Plant Monitoring: Oil Tanker – 2005 - 61

North Sea

Goal: monitor the vibrations of industrial machinery and equipment - Predictive maintenance

150 off-the-shelf accelerometers

Data was stored persistently in a server located outside the sensor network

The oil tanker's aft engineering spaces are constructed of steel floors and bulkheads and are subdivided into three major watertight compartments with hatchways in between.
The hatches may be periodically open and shut.
The sensor network was expected to work despite the periodically disconnected nature of these watertight compartments

Health Monitor

Data obtained from cardiac or epilepsy care monitoring employing EKG (electrocardiogram), EEG (electroencephalography) also imply high data-rates.

3 *On-Demand Data Collection*

The user triggers the collection of data

Usually involves persistent data storage on the node or within the network

ZebraNet

2002- [51,115] – Sweetwaters Game Preserve, Kenya

Mobility: nodes, base. Connectivity: sporadic.

Storage: persistent (node). Lifetime: A year

Goal: to record data on migration patterns of zebras

Sensors:

- GPS – Position recorded once an hour
- Area: 100 km^2
- Nodes could only sporadically communicate - the data was replicated to other nodes in the vicinity
- Recorded data was collected by a mobile base station on a vehicle regularly driven by the end-user through the observed area
- Solar Panels

High Fidelity Motion Analysis

2009- [70] – Spaulding Rehabilitation Hospital in Boston

Mobility: nodes. Connectivity: intermittent.

Storage: persistent (node).

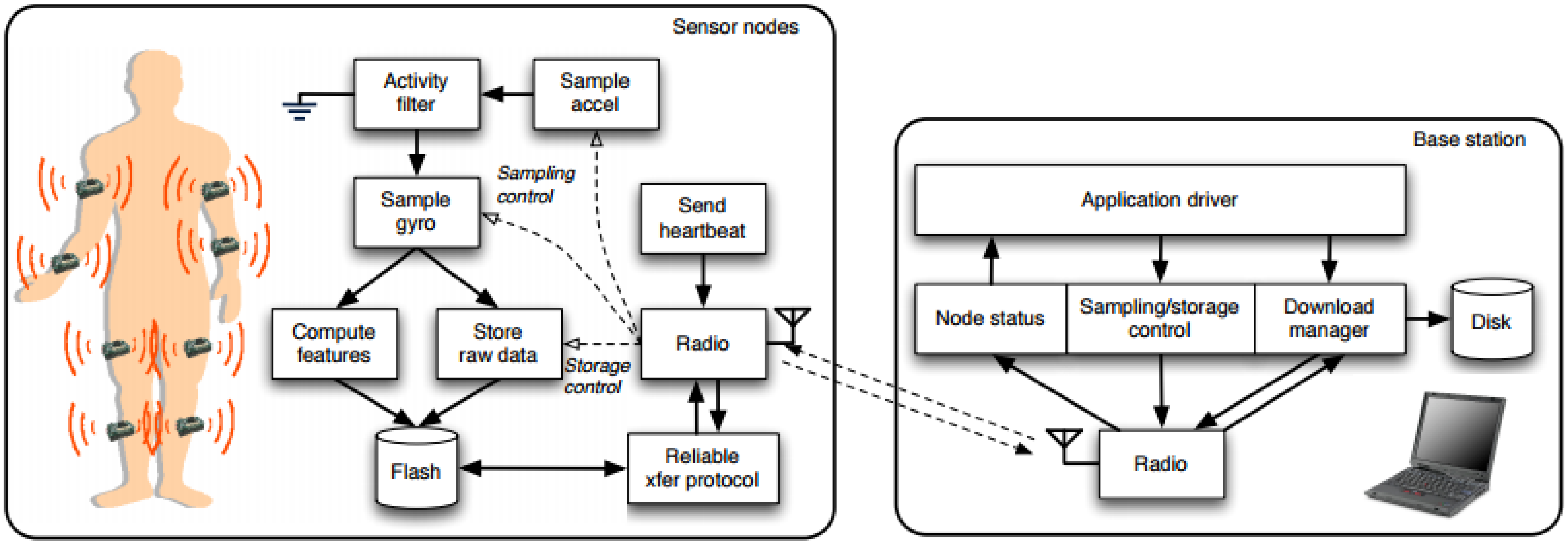
Clock synchronization

Goal: motion analysis of patients being treated for neuromotor disorders, such as Parkinson’s Disease, epilepsy, and stroke

Sensors: accelerometers and gyroscopes

Continuously sample and store sensor data in a MicroSD flash card for later retrieval

The transfer is triggered remotely by the end-user who needs to specify which specific set of data should be collected.



802.15.4
2 GB of MicroSD flash
sample block is 1200 bytes plus metadata, which is equivalent to 1 sec of sensor data sampled at 100 Hz across 6 channels

Provides a suite of custom feature-extraction algorithms such as maximum peak-to-peak amplitude, mean, and root mean square of the time series that are computed on the fly as sensor data is being acquired.

4 *Event Detection and Classification*

On-node processing to detect or classify events

Coal Mine Monitoring – 2009 - [67]

- Goal: detect collapses in coal mines - in order to ensure safer working conditions

Cane-toad Monitoring- 2007 - [46, 47, 98]

- Goal: monitoring of the increasing spread of cane toads in the North-East of Australia
- Acoustic sensors - implemented a frog vocalization recognition algorithm (autonomously classify toads)
- Hybrid devices: Mica2 + Stargate

Acoustic Monitoring: VoxNet - 2008 - [6]

- Goal: acoustically detect marmots at the Rocky Mountain Biological Laboratory

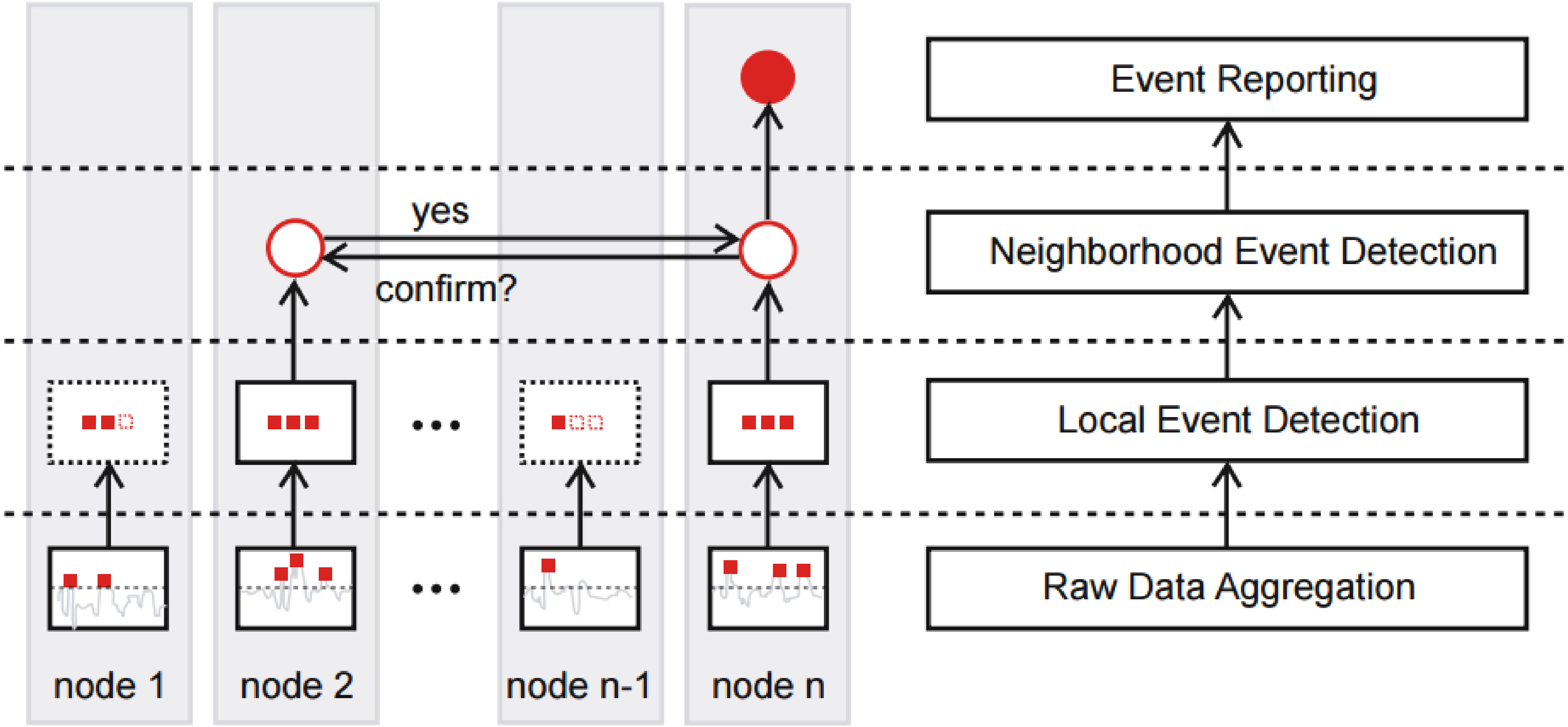
Fence Monitoring - 2007 - [111]

- Department of Mathematics and Computer Science Freie Berlin
- Civilian intrusion detection based on fence monitoring
- Goal: detect and report any incident occurring in the proximity of a fence

- 105 sensor nodes placed 3.5m apart from each other along the fence line
- ScatterWeb + FACTS middleware
    - Microcontroller : TI MSP430 16-bit
    - Radio transceiver: Chipcon CC1020 868MHz
    - Freescale Semiconductor MMA7260Q accelerometer

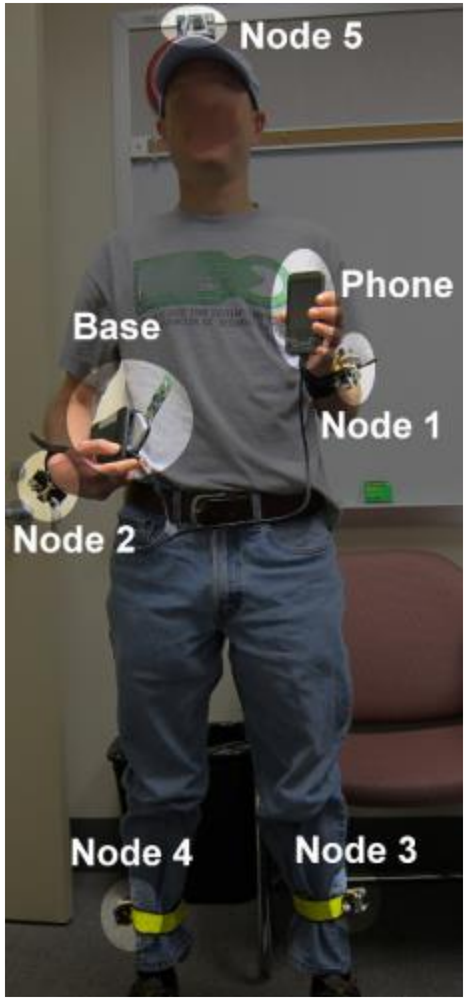
Events

- Kick
- Lean
- Shake
- Peek
- Climb



Activity recognition: PBN Practical Body Networking 2011[54]

- Goal: activity monitoring
- Combined a five node BSN with an Android smartphone in order to enable reliable activity recognition



Human Monitoring: Behavior Scope - 2008 - [71,14]

- Goal: in-house monitoring of elders
- Nodes equipped with PIR sensors were distributed in the monitored apartment
- Create a model of the daily habits of the person

Fall Detection: WeCare - 2010 - [5]

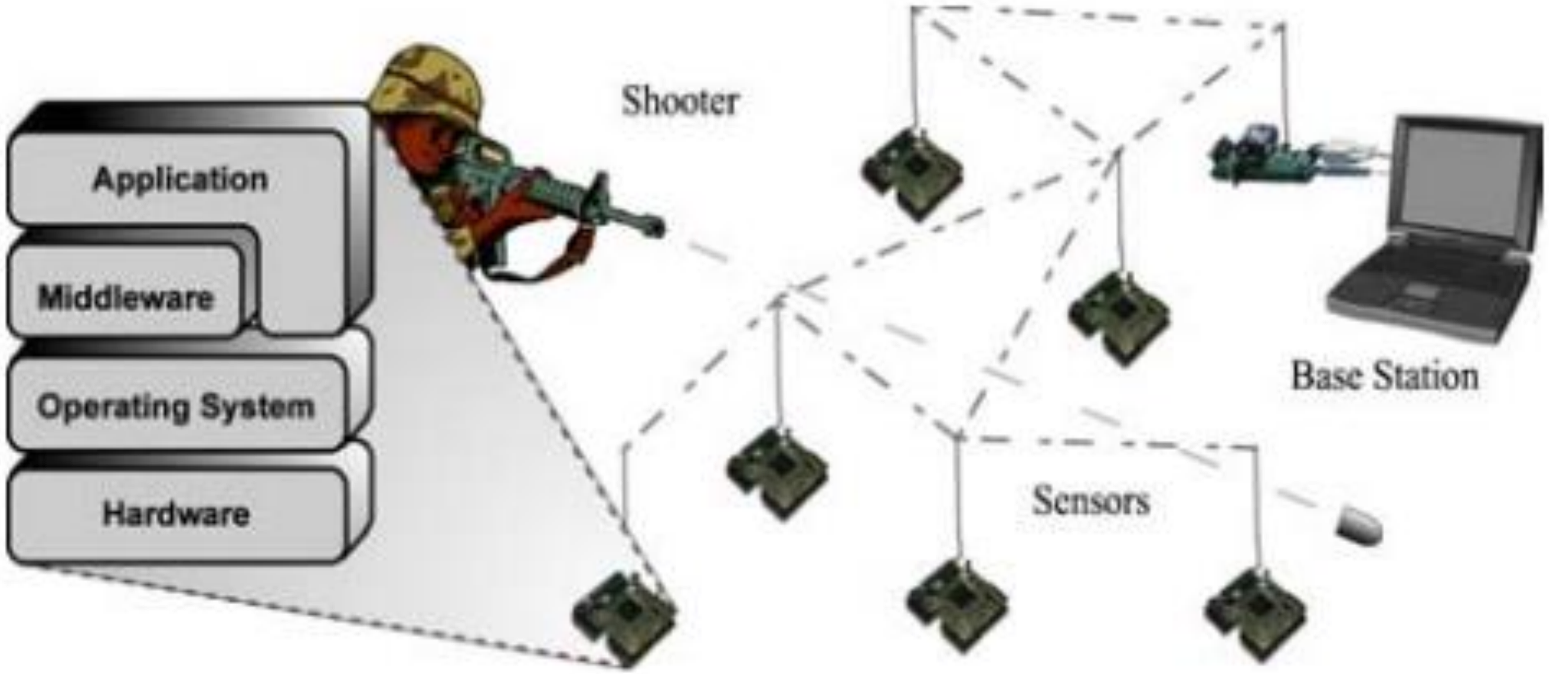
- Goal: detect falls
- Employed a combined BSN and WSN to detect falls

5 *Localization and Tracking*

Sniper Localization: PinPtr – 2004 - [99]

50 nodes - 30x15 meter area - McKenna MOUT training facility

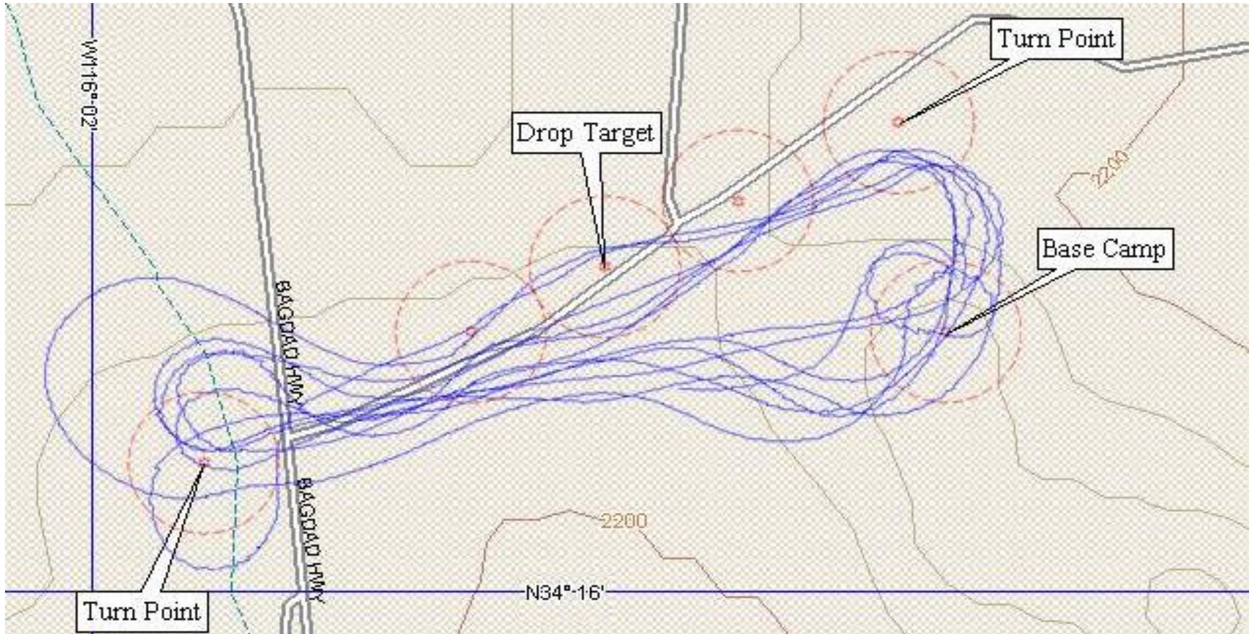
- Goal: accurately estimate the position of snipers
- Sensor nodes were equipped with microphones to detect the muzzle blast of firearms
- Performed sound-based localization using distributed data processing



- Mica, Mica 2
- Flooding Time Synchronization Protocol
- Directed Flood Routing Framework (Gradient-based with built-in data aggregation)
- Self-localization: acoustic range estimation between pairs of nodes
- Signal processing: classify acoustic events as muzzle blasts, shockwaves or none

Intrusion Detection: 29Palms – 2001 - [83]

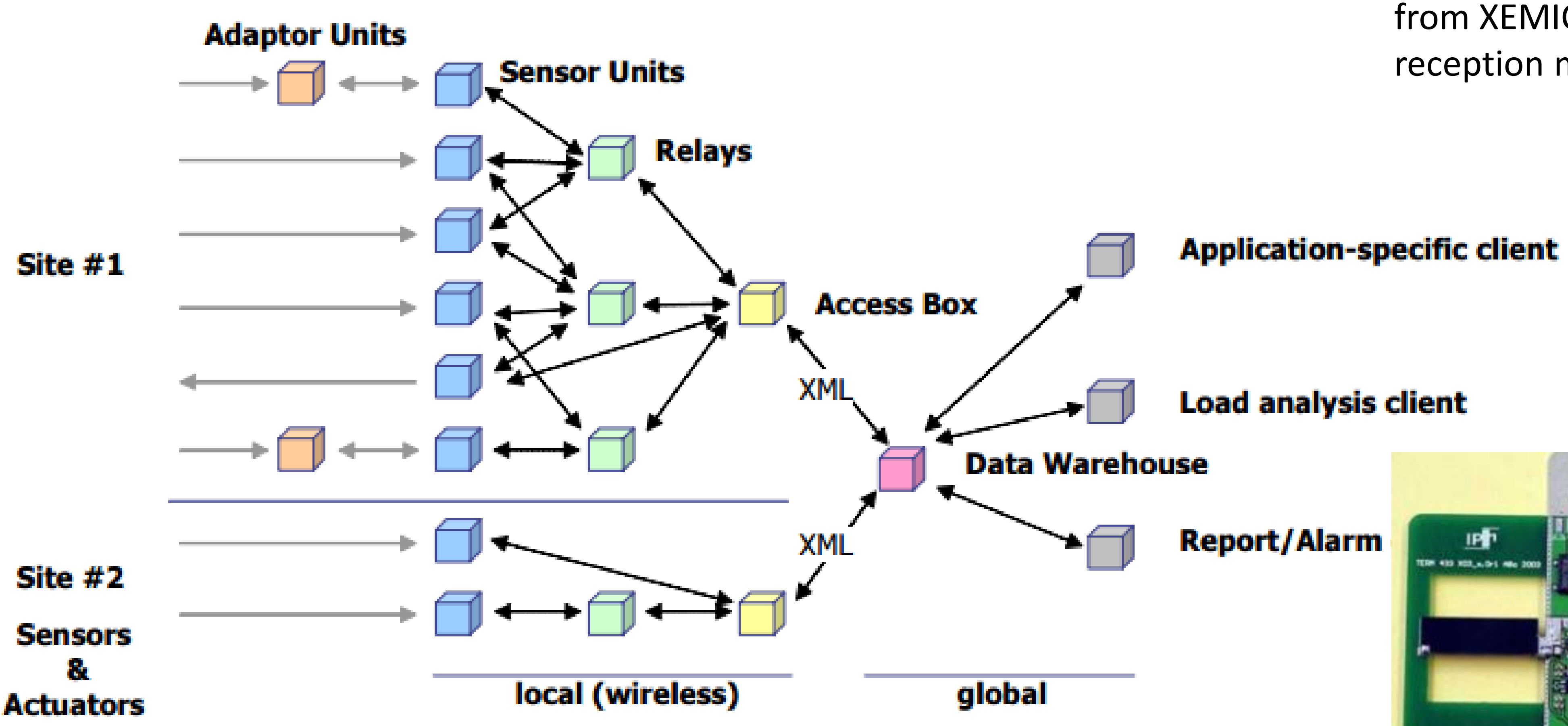
- Goal: Vehicle detection and tracking
- A WSN was dropped from an unmanned aerial vehicle (UAV) to monitor a road for vehicle movements
- Clock synchronization
- Nodes equipped with a two-axis magnetometer: allowed the detection of vehicles in a perimeter of 5–10 m
- Allowed to track vehicles once they were detected
- The information on detected vehicles was temporarily stored in the network and later collected by a second flyover of the UAV



Sensor:
916.5 MHz OOK radio.
2 axis Honeywell
HMC1002 magnetometer
(1mGauss resolution)

Cold Chain Management – 2004 - [88]

- Goal: monitor climate conditions while some goods travel through the cold chain



Radio: very low power transceiver from XEMICS - 433 MHz (6 mA in reception mode).

6 *Actuation*

Building Automation: HVAC (Heating, ventilation and Air Conditioning) – 2005 [34]

- Goal: Control temperature
- Control logic based on the current climate in various parts of the building and a set of preferred temperature levels specified by the building users

Animal Control: Bulls fighting - 2007 - [107]

- Goal: control the behavior of bulls (avoid fights)
- The bulls were equipped with sensor/actor nodes that allowed to apply unpleasant but harmless stimuli to the animal.
- Constantly monitored the distance between the bulls and their aggressiveness level

Animal Control: Networked Cows - 2004 – [22]

- Goal: Keep cows within a limited area with the help of virtual fences
- Sound stimulus - volume is proportional to the distance from the boundary

Industrial plant monitoring - GINSENG

Sines, Portugal – Oil refinery – 2013 - [85,116]

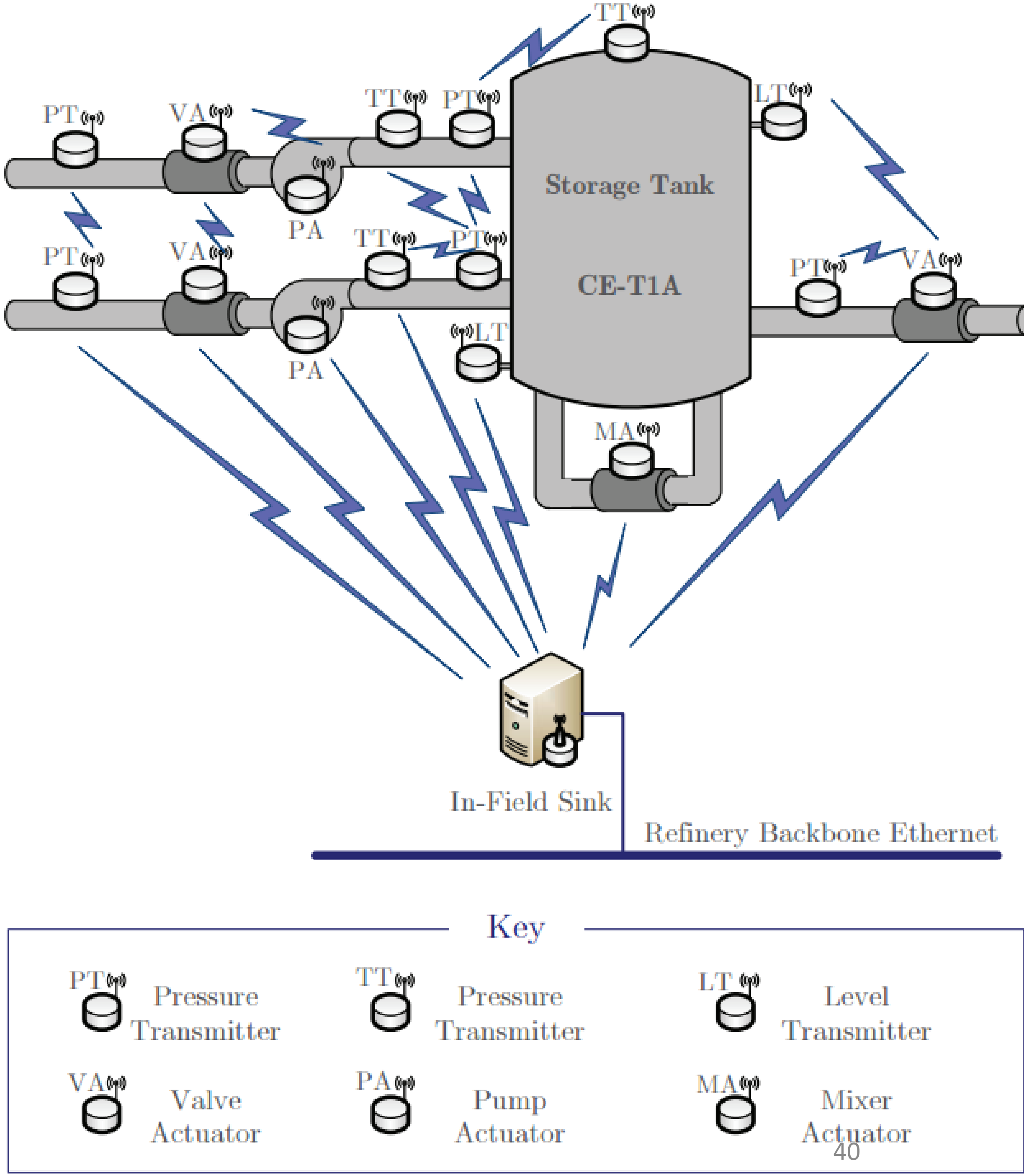
Goal: monitoring several areas through various types of sensors, but also for actuating on several devices, such as valves, in a closed loop fashion

Two networks: 12 nodes each.

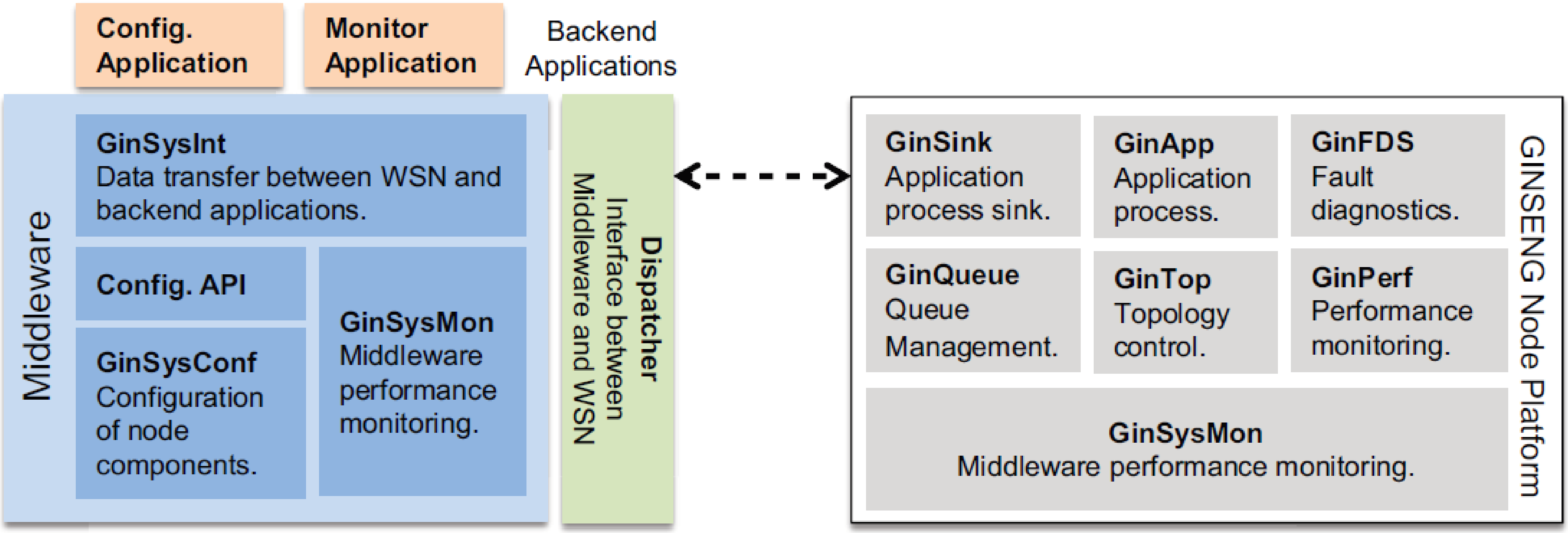
End-to-end solution: sensor + middleware + integration to other systems

Demonstrate and evaluate:

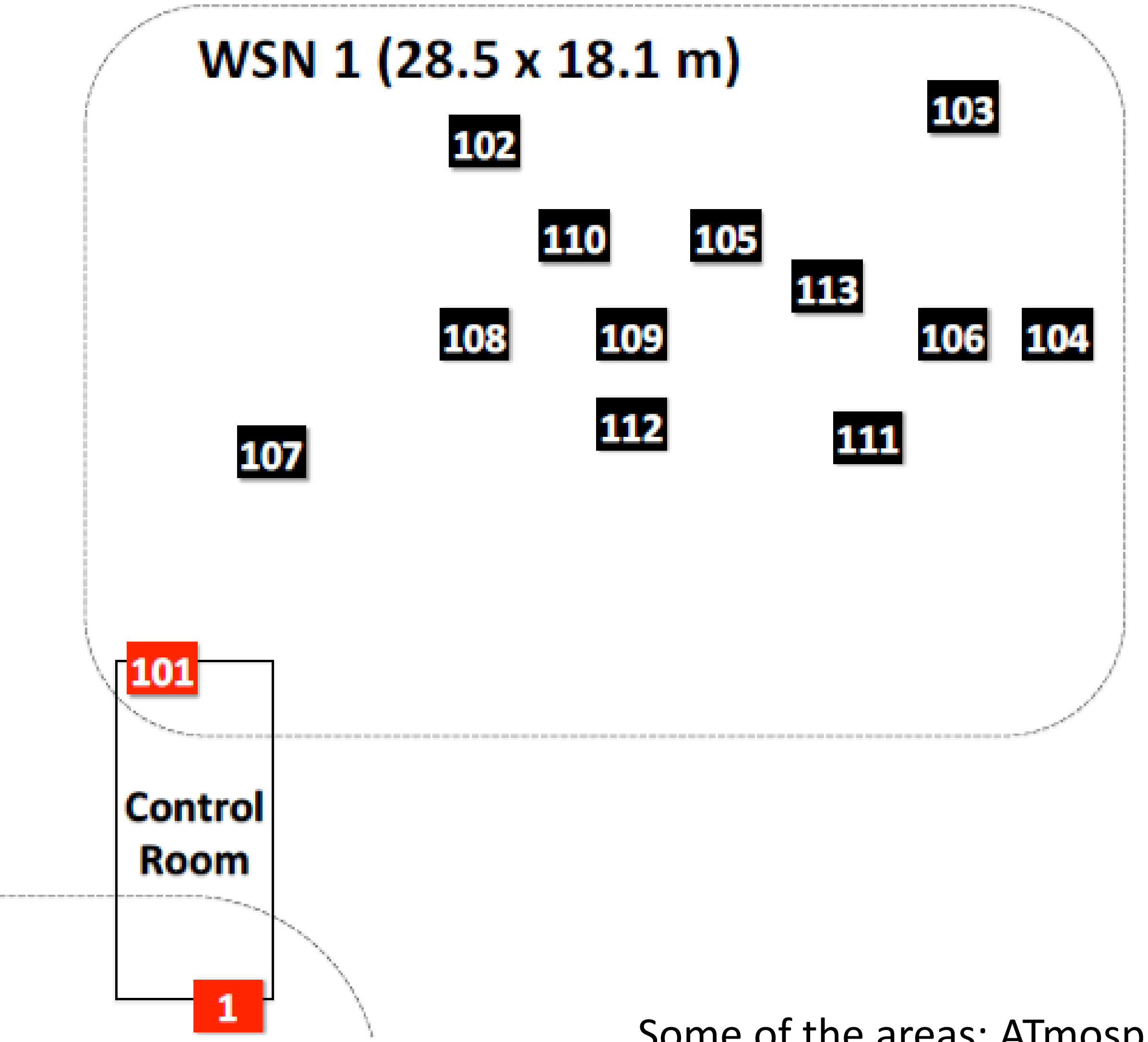
- The integration and interoperability of diferent networks
- closed-loop control between different networks

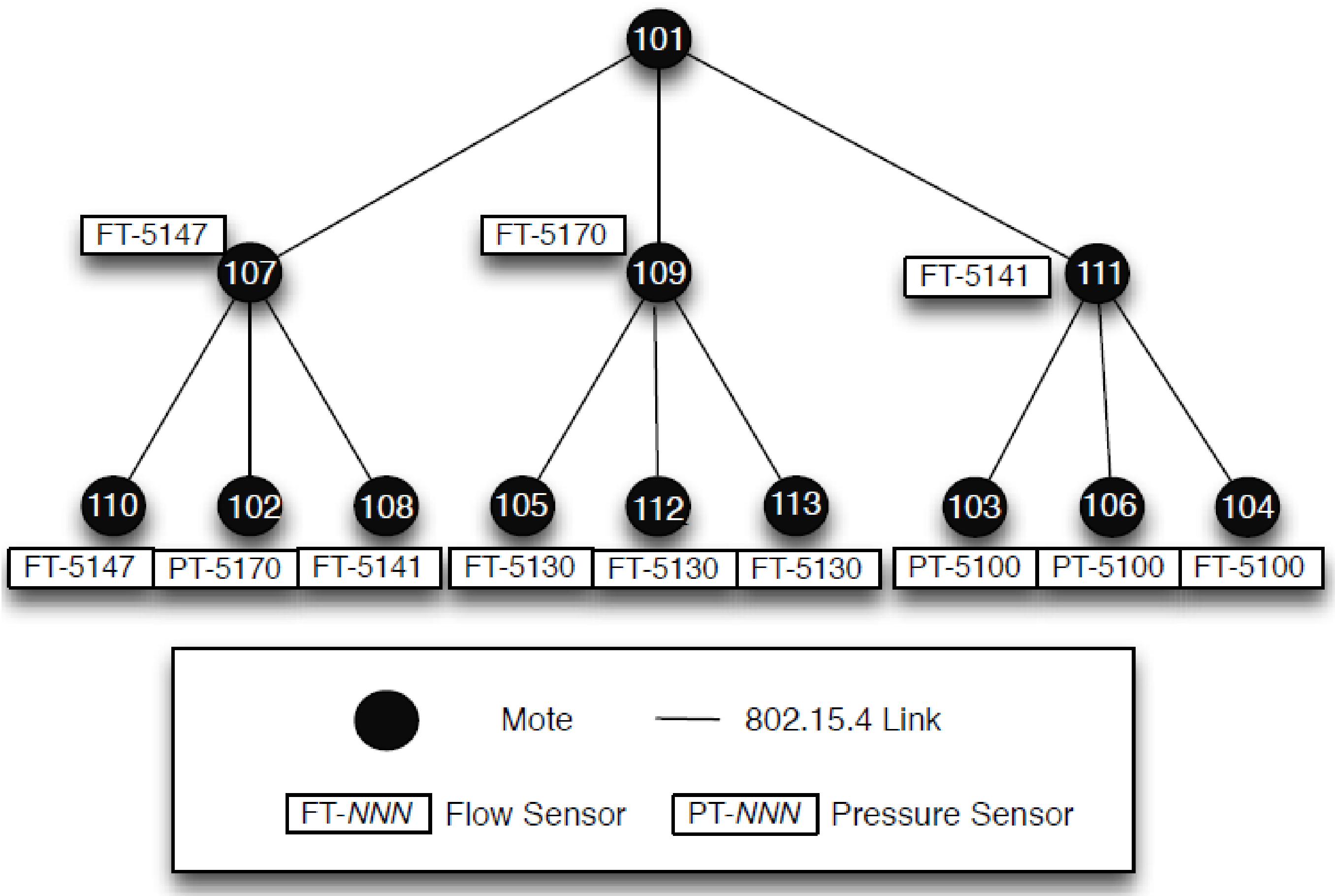


Complete solution design



- TelosB
- Contiki OS
- IEEE 802.15.4





Some of the areas: ATmosphere Explosive

- ATEX enclosures - wireless signal attenuation: €125
- External ceramic antenna – avoid corrosion: €220

References

Habib M. Ammari. 2014. *The Art of Wireless Sensor Networks: Volume 1 Fundamentals*. Springer Publishing Company, Incorporated

Chapter 2: A Decade of Wireless Sensing Applications

1. T. Abdelzaher, B. Blum, Q. Cao, Y. Chen, D. Evans, J. George, S. George, L. Gu, T. He,S. Krishnamurthy, L. Luo, S. Son, J. Stankovic, R. Stoleru, A. Wood, EnviroTrack: towardsan environmental computing paradigm for distributed sensor networks, in *Proceeding of the24th International Conference on Distributed Computing Systems (ICDCS)*, pp. 582–589 (2004)

2. Y. Agarwal, B. Balaji, S. Dutta, R.K. Gupta, T. Weng, Duty-cycling buildings aggressively: the next frontier in HVAC control, in *Proceeding of the 10th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 246–257 (2011)

3. T. Ahonen, R. Virrankoski, M. Elmusrati, Greenhouse monitoring with wireless sensor network, in *Proceeding of the 4th International Conference on Mechatronic and Embedded Systems and Applications (MESA)*, pp. 403–408 (2008)

4. I.F. Akyildiz, I.H. Kasimoglu, Wireless sensor and actor networks: research challenges. AdHoc Netw **2**(4), 351–367 (2004)

5. H.O. Alemdar, G.R. Yavuz, M.O. Özen, Y.E. Kara, O.D. Incel, L. Akarun, C. Ersoy, Multimodal fall detection within the WeCare framework, in *Proceeding of the 9th International Conference on InformationProcessing in Sensor Networks (IPSN)*, demo session, pp. 436–437(2010)

6. M. Allen, L. Girod, R. Newton, S. Madden, D.T. Blumstein, D. Estrin, VoxNet: an interactive, rapidly-deployable acoustic monitoring platform. in *Proceeding of the 7th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 371–382 (2008)

7. G. Anastasi, O. Farruggia, G. Lo Re, M. Ortolani, Monitoring high-quality wine production usingwireless sensor networks, in *Proceeding of the 42nd International Conference on System Sciences (HICSS)*, pp. 1–7 (2009)

8. T. Antoine-Santoni, J.F. Santucci, E. De Gentili, X. Silvani, F. Morandini, Performance of a protected wireless sensor network in a fire: analysis of fire spread and data transmission. Sensors **9**(8), 5878–5893 (2009)

9. A. Arora, P. Dutta, S. Bapat, V. Kulathumani, H. Zhang, V. Naik, V.Mittal, H. Cao, M. Demirbas, M. Gouda, Y. Choi, T. Herman, S. Kulkarni, U. Arumugam, M. Nesterenko, A. Vora, M. Miyashita, A line in the sand: a wireless sensor network for target detection, classification, and tracking. Comput. Netw. **46**(5), 605–634 (2004)

10. R. Bagree, V.R. Jain, A. Kumar, P. Ranjan, Tigercense: wireless image sensor network to monitor tiger movement, in *Proceeding of the 4th International Conference on Real-World Wireless Sensor Networks (REALWSN)*, pp. 13–24 (2010)

11. L. Bai, R. Dick, P. Dinda, Archetype-based design: sensor network programming for application experts, not just programming experts, in *Proceeding of the 2009 International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 85–96 (2009)

12. H. Baldus, K. Klabunde, G. Müsch, Reliable set-up of medical body-sensor networks, in *Proceeding of the 1st EuropeanWorkshop onWireless Sensor Networks (EWSN)*, pp 353–363 (2004)

13. J. Balendonck, J. Hemming, B. van Tuijl, L. Incrocci, A. Pardossi, P.Marzialetti, Sensors and wireless sensor networks for irrigation management under deficit conditions (FLOW-AID), in *Proceeding of the International Conference on Agricultural Engineering and Agricultural & Biosystems Engineering for a Sustainable World (AgEng)*, pp. 583–588 (2008)

14. A. Bamis, D. Lymberopoulos, T. Teixeira, A. Savvides, The behaviorscope framework for enabling ambient assisted living. Pers. Ubiquitous. Comput(6), 473–487 (2010)

15. G. Barrenetxea, F. Ingelrest, G. Schaefer, M. Vetterli, O. Couach, M. Parlange, Sensorscope: out-of-the-box environmental monitoring, in *Proceeding of the 7th International Conference on Information Processing in Sensor Networks (IPSN)*, pp 332–343 (2008)

16. M.A. Batalin, G.S. Sukhatme, M. Hattig, Mobile robot navigation using a sensor network,in *Proceeding of the IEEE International Conference on Robotics and Automation (ICRA)*,pp. 636–641 (2004)

17. R. Beckwith,D. Teibel, P. Bowen, Unwiredwine: sensor networks in vineyards, in *Proceeding of IEEE Sensors*, pp. 561–564 (2004)

18. J. Beutel, S. Gruber, A. Hasler, R. Lim, A. Meier, C. Plessl, I. Talzi, L. Thiele, C. Tschudin, M. Woehrle, M. Yuecel, PermaDAQ: a scientific instrument for precision sensing and data recovery in environmental extremes, in *Proceeding of the 8th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 265–276 (2009)

19. E.S. Biagioni, K.W. Bridges, The application of remote sensor technology to assist the recovery of rare and endangered species. Int. J. High Perform. Comput. Appl. **16**(3), 315–324 (2002)

20. Burrell, T. Brooke, R. Beckwith, Vineyard computing: sensor networks in agricultural production. IEEE Pervasive Comput. **3**(1), 38–45 (2004)

21. N. Burri, P. von Rickenbach, R.Wattenhofer, Dozer: ultra-low power data gathering in sensor networks, in *Proceedings of the 6th International Conference on Information Processing inSensor Networks (IPSN)*, pp. 450–459 (2007)

22. Z. Butler, P. Corke, R. Peterson, D. Rus, Networked cows: virtual fences for controlling cows, in *Proceeding of the MobiSys Workshop on Applications of Mobile Embedded Systems (WAMES)*, 2004

23. R. Cardell-Oliver, K. Smettem, M. Kranz, K. Mayer, Field testing a wireless sensor network for reactive environmental monitoring, in *Proceeding of the International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP)*, pp. 14–17 (2004)

24. R. Cardell-Oliver,M. Kranz, K. Smettem, K.Mayer, A reactive soil moisture sensor network: design and field evaluation. Int. J. Distrib. Sens. Netw. **1**(2), 149–162 (2005)

25 M. Ceriotti, L. Mottola, G.P. Picco, A.L. Murphy, C. Gunˇa, M. Corra, M. Pozzi, D. Zonta, P. Zanon, Monitoring heritage buildings with wireless sensor networks: The Torre Aquila deployment, in *Proceeding of the 8th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 277–288 (2009)

26. M. Ceriotti,M. Corra, L. D'Orazio, R. Doriguzzi, D. Facchin, ¸ S. Gunˇa, G.P. Jesi, A. Murphy, R.L. Cigno, L. Mottola, M. Pescalli, G.P. Picco, D. Prognolato, C. Torghele, Is there light at the ends of the tunnel? Wireless sensor networks for adaptive lighting in road tunnels,in *Proceeding of the 10th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 187–198 (2011)

27. S. Cheekiralla, Wireless sensor network-based tunnel monitoring, in *Proceeding of the 1st Workshop on Real-World Wireless Sensor Networks (REALWSN)*, poster session, 2005

28. K. Chintalapudi, T. Fu, J. Paek, N. Kothari, S. Rangwala, J. Caffrey, R. Govindan, E. Johnson, S. Masri, Monitoring civil structures with a wireless sensor network. IEEE Internet Comput.**10**(2), 26–34 (2006)

29. O. Chipara, C. Lu,T.C.Bailey, G.C. Roman, Reliable clinical monitoring usingwireless sensor networks: experiences in a step-down hospital unit, in *Proceeding of the 8th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 155–168 (2010)

30. P. Costa, L. Mottola, A.L. Murphy, G.P. Picco, Teeny Lime: Transiently shared tuple space middleware for wireless sensor networks, in *Proceeding of the 1st International Workshop on Middleware for Sensor Networks (MidSens)*, pp. 43–48 (2006)

31. P. Costa, G. Coulson, R. Gold, M. Lad , C. Mascolo, L. Mottola, G.P. Picco, T. Sivaharan, N. Weerasinghe, S. Zachariadis, The RUNES middleware for networked embedded systems and its application in a disaster management scenario, in *Proceeding of the 5th International Conference on Pervasive Computing and Communications (PERCOM)*, pp. 69–78 (2007)

32. D.E. Culler, Toward the sensor network macroscope, in *Proceeding of the 6th International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, pp. 1–1 (2005)

33. K. Dantu, B. Kate, J. Waterman, P. Bailis, M. Welsh, Programming micro-aerial vehicle swarms with karma, in *Proceeding of the 9th ACM Conference on Embedded Networked Sensor Systems (SenSys), ACM*, pp. 121–134 (2011)

34. A. Deshpande, C.Guestrin, S.R.Madden, Resource-awarewireless sensor-actuator networks. IEEE Data Eng. **28**(1), 40–47 (2005)

35. D.M. Doolin, N. Sitar,Wireless sensors for wildfire monitoring, in *Proceeding of SPIE Symposium on Smart. Structures and Materials*, vol. 5765, pp. 477–484 (2005)

36. A. Dunkels, J. Eriksson, L. Mottola, T. Voigt, F.J. Oppermann, K. Römer, F. Casati, F. Daniel, G.P. Picco, S. Soi, S. Tranquillini, P. Valleri, S. Karnouskos, P. Spieß, P.M. Montero, D-1.1— application and programming survey. Technical report, makeSense (2010)

37. P. Dutta, M. Grimmer, A. Arora, S. Bibyk, D. Culler,Design of a wireless sensor network platform for detecting rare, random, and ephemeral events, in *Proceeding of the 4th International Symposium on Information Processing in Sensor Networks (IPSN)*, pp. 497–502 (2005)

38. V. Dyo, S.A. Ellwood, D.W. Macdonald, A. Markham, C. Mascolo, B. Pásztor, N. Trigoni, R. Wohlers, Wildlife and environmental monitoring using RFID and WSN technology, in*Proceeding of the 7th International Conference on Embedded Networked Sensor Systems (SenSys), poster session*, pp. 371–372 (2009)

39. V. Dyo, S.A. Ellwood, D.W. Macdonald, A. Markham, C. Mascolo, B. Pásztor, S. Scellato,N. Trigoni,R.Wohlers, K.Yousef, Evolution and sustainability of awildlifemonitoring sensor network, in *Proceeding of the 8th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 127–140 (2010)

40. T. Flach, N. Mishra, L. Pedrosa, C. Riesz, R. Govindan, Carma: towards personalized automotive tuning, in *Proceeding of the 9th ACM Conference on Embedded Networked Sensor Systems (SenSys), ACM*, pp. 135–148 (2011)

41. R.K. Ganti, N. Pham, H. Ahmadi, S. Nangia, T.F. Abdelzaher, GreenGPS: a participatory sensing fuel-efficient maps application, in *Proceeding of the 8th International Conference on Mobile Systems, Applications, and Services (MobiSys)*, pp. 151–164 (2010)

42. T. Gao, T. Massey, L. Selavo, D. Crawford, B. Chen, K. Lorincz, V. Shnayder, M.Welsh, The advanced health and disaster aid network: a light-weight wireless medical system for triage. IEEE Trans. Biomed. Circuits Syst. **1**, 203–216 (2007)

43. C. Hartung, R. Han, C. Seielstad, S. Holbrook, FireWxNet: a multi-tiered portable wireless system for monitoring weather conditions in wildland fire environments, in *Proceeding of the 4th International Conference on Mobile Systems, Applications and Services (MobiSys)*, pp. 28–41 (2006)

44. T. He, S. Krishnamurthy, J.A. Stankovic, T. Abdelzaher, L. Luo, R. Stoleru, T. Yan, L. Gu, J. Hui, B. Krogh, Energy-efficient surveillance system using wireless sensor networks, in *Proceeding of the 2nd International Conference on Mobile Systems, Applications, and Services (MobiSys)*, pp. 270–283 (2004)

45. J. Hill, R. Szewczyk, A.Woo, S. Hollar, D.E. Culler, K. Pister, System architecture directions for networked sensors. ACM SIGPLAN Not. **35**(11), 93–104 (2000)

46. W. Hu, V.N. Tran, N. Bulusu, C. tung Chou, S. Jha, A. Taylor, The design and evaluation of a hybrid sensor network for cane-toad monitoring, in *Proceeding of the 4th International Symposium on Information Processing in Sensor Networks (IPSN)*, pp. 503–508 (2005)

47. W. Hu, N. Bulusu, C.T. Chou, S. Jha, A. Taylor, V.N. Tran, Design and evaluation of a hybrid sensor network for cane toad monitoring. ACM Trans.ens. Netw. (TOSN) **5**(1), 4:1–4:28 (2009)

48. J.W. Hui, D.E. Culler, IP is dead, long live IP for wireless sensor networks, in *Proceeding of the 6th ACM Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 15–28 (2008)

49. X. Jiang, S. Dawson-Haggerty, P. Dutta, D. Culler, Design and implementation of a highfidelity AC metering network, in *Proceeding of the 8th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 253–264 (2009)

50. X. Jiang, M. van Ly, J. Taneja, P. Dutta, D. Culler, Experiences with a high-fidelity wireless building energy auditing network, in *Proceeding of the 7th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 113–126 (2009)

51. P. Juang, H. Oki,Y.Wang, M. Martonosi, L.S. Peh, D. Rubenstein, Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with ZebraNet, in *Proceeding of the 10th International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS-X)*, pp. 96–107 (2002)

52. J.M. Kahn, R.H. Katz, K.S.J. Pister, Next century challenges: mobile networking for “smart dust”, in *Proceeding of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (MOBICOM), ACM, New York, NY, USA*, pp. 271–278 (1999)

53. C. Kappler, G. Riegel, A real-world, simple wireless sensor network for monitoring electrical energy consumption, in *Proceeding of the 1st European Workshop on Wireless Sensor Networks (EWSN)*, pp. 339–352 (2004)

54. M. Keally, G. Zhou, G. Xing, J. Wu, A.J. Pyles, PBN: towards practical activity recognition using smartphone-based body sensor networks, in *Proceeding of the 9th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 246–259 (2011)

55. D.H. Kim, Y. Kim, D. Estrin, M.B. Srivastava, Sensloc: sensing everyday places and paths using less energy, in *Proceeding of the 8th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 43–56 (2010)

56. S. Kim, S. Pakzad, D. Culler, J. Demmel, G. Fenves, S. Glaser, M. Turon, Health monitoring of civil infrastructures using wireless sensor networks, in *Proceeding of the 6th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 254–263 (2007)

57. Y.J. Kim, R.G. Evans,W.M. Iversen, Remote sensing and control of an irrigation system using a distributed wireless sensor network. IEEE Trans. Instrum. Meas. **57**(7), 1379–1387 (2008)

58. J. Ko, R. Musˇaloiu-Elefteri, J.H. Lim, Y. Chen, A. Terzis, T. Gao, W. Destler, L. Selavo, Medisn: medical emergency detection in sensor networks, in *Proceeding of the 6th International Conference on Embedded Networked Sensor Systems (SenSys)*, demo session, pp. 361–362 (2008)

59. J. Ko, J.H. Lim, Y. Chen, R. Musvaloiu-E, A. Terzis, G.M. Masson, T. Gao, W. Destler, L. Selavo, R.P. Dutton, MEDiSN: medical emergency detection in sensor networks. ACM Trans. Embedded Comput. Syst. (TECS) **10**(1), 11:1–11:29 (2010)

60. J. Ko, K. Klues, C. Richter, W. Hofer, B. Kusy, M. Brünig, T. Schmid, Q. Wang, P. Dutta, A. Terzis, Low power or high performance? a tradeoff whose time has come (and nearly gone), in *Proceeding of the 9th European Conference on Wireless Sensor Networks (EWSN)*, pp. 98–114 (2012)

61. L. Krishnamurthy, R. Adler, P. Buonadonna, J. Chhabra, M. Flanigan, N. Kushalnagar, L. Nachman, M. Yarvis, Design and deployment of industrial sensor networks: experiences from a semiconductor plant and the north sea, in *Proceeding of the 3rd International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 64–75 (2005)

62. J. Kumagai, The secret life of birds. IEEE Spectr. **41**(4), 42–48 (2004)

63. K.G. Langendoen, A. Baggio, O.W. Visser, Murphy loves potatoes: experiences from a pilot sensor network deployment in precision agriculture, in *Proceeding of the 14th International Workshop on Parallel and Distributed Real-Time Systems (WPDRTS)*, 2006

64. Y. Lee, G. Kim, S. Bang, Y. Kim, I. Lee, P. Dutta, D. Sylvester, D. Blaauw, A modular 1mm3 die-stacked sensing platform with optical communication and multi-modal energy harvesting, in *Proceeding of the International Solid-State Circuits Conference (ISSCC)*, pp. 402–404(2012)

65. D. Li, W. Liu, Z. Zhao, L. Cui, Demonstration of a WSN application in relic protection and an optimized system deployment tool, in *Proceedings of the 7th International Conference on Information Processing in Sensor Networks (IPSN)*, demo session, pp. 541–542 (2008)

66. D. Li, W. Liu, L. Cui, EasiDesign: an improved ant colony algorithm for sensor deployment in real sensor network system, in *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM)*, pp. 1–5 (2010)

67. M. Li, Y. Liu, Underground coal mine monitoring with wireless sensor networks. ACMTrans.Sens. Netw. (TOSN) **5**(2), 10:1–10:29 (2009)

68. C. Lombriser, N.B. Bharatula, D. Roggen, G. Tröster, On-body activity recognition in a dynamic sensor network, in *Proceedings of the 2nd International Conference on Body, Area Networks (BodyNets)* (2007)

69. K. Lorincz, D.J. Malan, T.R. Fulford-Jones, A. Nawoj, A. Clavel, V. Shnayder, G. Mainland,M. Welsh, Sensor networks for emergency response: challenges and opportunities. IEEE Pervasive Comput. **3**(4), 16–23 (2004)

70. K. Lorincz, B. rong Chen, G.W. Challen, A.R. Chowdhury, S. Patel, P. Bonato, M. Welsh,Mercury: a wearable sensor network platform for high-fidelity motion analysis, in *Proceedings of the 7th International Conference on Embedded Networked Sensor Systems (SenSys)*,pp. 183–196 (2009)

71. D. Lymberopoulos, A. Bamis, T. Teixeira, A. Savvides, BehaviorScope: real-time remote human monitoring using sensor networks, in *Proceedings of the 7th International Conference on Information Processing in Sensor Networks (IPSN)*, demo session, pp. 533–534 (2008)

72. A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, J. Anderson, Wireless sensor networks for habitat monitoring, in *Proceedings of the 1st International Workshop on Wireless Sensor Networks and Applications (WSNA)*, pp. 88–97 (2002)

73. A. Markham, N. Trigoni, S.A. Ellwood, D.W. Macdonald, Revealing the hidden lives of underground animals using magneto-inductive tracking, in *Proceedings of the 8th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 281–294 (2010)

74. K. Martinez, R. Ong, J.K. Hart, GLACSWEB: a sensor network for hostile environments, in *Proceedings of the 1st IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks (SECON)*, pp. 81–87 (2004)

75. L. Mo, Y. He, Y. Liu, J. Zhao, S.J. Tang, X.Y. Li, G. Dai, Canopy closure estimates with GreenOrbs: sustainable sensing in the forest, in *Proceedings of the 7th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 99–112 (2009)

76. P. Mohan, V.N. Padmanabhan, R. Ramjee, Nericell: rich monitoring of road and traffic conditions using mobile smartphones, in *Proceedings of the 6th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 323–336 (2008)

77. L. Mottola, G.P. Picco, Programming wireless sensor networks: fundamental concepts and state-of-the-art. ACM Comput. Surv. (CSUR) **43**(3), 19:1–19:51 (2011)

78. L. Mottola, G.P. Picco, M. Ceriotti, S. Gunˇa, A.L Murphy, Not all wireless sensor networks are created equal: a comparative study on tunnels. ACM Trans. Sens. Netw. (TOSN) **7**(2), 15:1–15:33 (2010)

79. K. Na, Y. Kim, H. Cha, Acoustic sensor network-based parking lot surveillance system, in *Proceedings of the 6th European Conference on Wireless Sensor Networks (EWSN)*, pp. 247–262 (2009)

80. A. Nasipuri, R. Cox, H. Alasti, L.V. der Zel,B.Rodriguez, R.McKosky, J.A. Grazian,Wireless sensor network for substation monitoring: Design and deployment, in *Proceedings of the 6th International Conference on Embedded Networked Sensor Systems (SenSys)*, demo session, pp. 365–366 (2008)

81. J. Panchard, S.Rao, T. Prabhakar, H. Jamadagni, J.P.Hubaux, COMMON-sense net: improved water management for resource-poor farmers via sensor networks, in *Proceedings of the 1st International Conference on Communication and Information Technologies and Development (ICTD)*, pp. 22–33 (2006)

82. S. Patel, K. Lorincz, R. Hughes, N. Huggins, J. Growden, D. Standaert, M. Akay, J. Dy, M. Welsh, P. Bonato, Monitoring motor fluctuations in patients with parkinson's disease using wearable sensors. IEEE Trans. Inf. Technol. Biomed. **13**(6), 864–873 (2009)

83. K.S. Pister, Tracking vehicles with a UAV-delivered sensor network. (2001) Tech. rep., UC Berkeley and MLB, http://robotics.eecs.berkeley.edu/pister/29Palms0103/

84. J. Polastre, R. Szewczyk, D. Culler, Telos: enabling ultra-low power wireless research, in *Proceedings of the 4th International Symposium on Information Processing in Sensor Networks (IPSN)*, pp. 364–369 (2005)

85. W.B. Pöttner, L.Wolf, J. Cecílio, P. Furtado, R. Silva, J.S. Silva, A. Santos , P.Gil,A. Cardoso, Z. Zinonos, J.M. doÓ, B.McCarthy, J. Brown, U. Roedig, T. O'Donovan, C.J. Sreenan, Z.He,T.Voigt, A. Jugel,WSNevaluation in industrial environments first results and lessons learned,in *Proceedings of the 3rd InternationalWorkshop on Performance Control inWireless SensorNetworks (PWSN)*, pp. 1–8 (2011)

86. N. Ramanathan, T. Schoellhammer, E. Kohler, K. Whitehouse, T. Harmon, D. Estrin, Suelo: human-assisted sensing for exploratory soil monitoring studies, in *Proceedings of the 7th International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 197–210(2009)

87. P. Ranjan, P.K. Saraswat, A. Kumar, S. Polana, A. Singh, wildCENSE - sensor network for wildlife monitoring. Technical report, Dhirubhai Ambani Institute of Information and Communication Technology, Gandhinagar, Gujarat (2006)

88. R. Riem-Vis, Cold chain management using an ultra low power wireless sensor network, in *Proceedings of the MobiSys Workshop on Applications of Mobile Embedded Systems (WAMES)*, pp. 21–23 (2004)

89. V. Rocha, G. Goncalves, Sensing the world: challenges on WSNs, in *Proceedings of the IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR)*, vol 1, pp. 54–59 (2008)

90. K. Römer, F. Mattern, The design space of wireless sensor networks. IEEE Wirel. Commun.**11**(6), 54–61 (2004)

91. R.M. Ruair, M.T. Keane, G. Coleman, A wireless sensor network application requirements taxonomy, in *Proceeedings of the 2nd International Conference on Sensor Technologies and Applications (SENSORCOMM)*, pp. 209–216 (2008)

92. San Francisco Municipal Transportation Agency (2011) SFpark: Putting theory into practice. Tech. rep., http://sfpark.org/wp-content/uploads/2011/09/sfpark_aug2011projsummary_print-2.pdf

93. L. Selavo, A.Wood, Q. Cao, T. Sookoor, H. Liu, A. Srinivasan, Y.Wu,W. Kang, J. Stankovic, D. Young, J. Porter, LUSTER: wireless sensor network for environmental research, in *Proceedings of the 5th International Conference on Embedded Networked Sensor Systems (Sen-Sys)*, pp. 103–116 (2007)

94. A. Sheth, K. Tejaswi, P. Mehta, C. Parekh, R. Bansal, S. Merchant, T. Singh, U.B. Desai, C.A. Thekkath, K. Toyama, SenSlide: a sensor network based landslide prediction system, in *Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems(SenSys)*, poster session, pp. 280–281 (2005)

95. A. Sheth, C.A. Thekkath, P. Mehta, K. Tejaswi, C. Parekh, T.N. Singh, U.B. Desai, Senslide:a distributed landslide prediction system. ACM SIGOPS Operating Syst. Rev. **41**(2), 75–87(2007)

96. E.I. Shih, A.H. Shoeb, J.V Guttag, Sensor selection for energy-efficient ambulatory medical monitoring, in *Proceedings of the 7th International Conference on Mobile Systems, Applications, and Services (MobiSys)*, pp. 347–358 (2009)

97. V. Shnayder, B.R. Chen, K. Lorincz, T.R. Fulford-Jones, M. Welsh, Sensor networks for medical care. Technical report TR-08-05 (Harvard University, Cambridge, 2005)

98. S. Shukla, N. Bulusu, S. Jha, Cane-toad monitoring in kakadu national park using wireless sensor networks, in *Proceedings of the 18th Asia Pacific Advanced, Network Conference (APAN)* (2004)

99. G. Simon, M. Maróti, Á Lédeczi, G. Balogh, B. Kusy, A. Nádas, G. Pap, J. Sallai, K. Frampton, Sensor network-based countersniper system, in *Proceedings of the 2nd International Conference on Embedded networked Sensor Systems (SenSys)*, pp. 1–12 (2004)

100. SmartSantander Project (2012) SmartSantander project. http://www.smartsantander.eu

101. I. Stoianov, L. Nachman, S. Madden, T. Tokmouline, PIPENET: a wireless sensor network for pipeline monitoring, in *Proceedings of the 6th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 264–273 (2007)

102. R. Szewczyk, A. Mainwaring, J. Polastre, J. Anderson, D. Culler, An analysis of a large scale habitat monitoring application, in *Proceedings of the 2nd International Conference on Embedded networked Sensor Systems (SenSys)*, pp. 214–226 (2004)

103. B. Thorstensen, T. Syversen, T.A. Bjørnvold, T. Walseth, Electronic shepherd: A low-cost, low-bandwidth, wireless network system, in *Proceedings of the 2nd International Conference on Mobile Systems, Applications, and Services (MobiSys)*, pp. 245–255 (2004)

104. S. Tilak, N.B. Abu-Ghazaleh,W. Heinzelman, A taxonomy of wireless micro-sensor network models. SIGMOBILE Mobile Comput. Commun. Rev. **6**(2), 28–36 (2002)

105. G. Tolle, J. Polastre, R. Szewczyk, D. Culler, N. Turner, K. Tu, S. Burgess, T. Dawson, P. Buonadonna, D. Gay, W. Hong, A macroscope in the redwoods, in *Proceedings of the 3rd International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 51–63 (2005)

106. K. Van Laerhoven, B.P. Lo, J.W. Ng, S. Thiemjarus, R. King, S. Kwan, H.W. Gellersen , M. Sloman, O. Wells, P. Needham, N. Peters, A. Darzi, C. Toumazou, G.Z. Yang, Medical healthcare monitoring with wearable and implantable sensors, in *Proceedings of the 3rd International Workshop on Ubiquitous Computing for Pervasive Healthcare Applications (UbiHealth)*, pp. 115–123 (2004)

107. T. Wark, C. Crossman, W. Hu, Y. Guo, P. Valencia, P. Sikka, P. Corke, C. Lee, J. Henshall, K. Prayaga, J. O'Grady, M. Reed, A. Fisher, The design and evaluation of a mobile sensor/actuator network for autonomous animal control, in *Proceedings of the 6th International Conference on Information Processing in Sensor Networks (IPSN)*, pp. 206–215 (2007

108. G. Werner-Allen, K. Lorincz, J. Johnson, J. Lees, M. Welsh, Fidelity and yield in a volcano monitoring sensor network, in *Proceedings of the 7th USENIX Symposium on Operating Systems Design and Implementation (OSDI)*, pp. 381–396 (2006)

109. D. Whang, N. Xu, S. Rangwala, K. Chintalapudi, R. Govindan, J. Wallace, Development of an embedded networked sensing system for structural health monitoring, in *Proceeedings of International Workshop on Smart Materials and Structures Technology* (2004)

110. M.J. Whelan, K.D. Janoyan, Design of a robust, high-rate wireless sensor network for static and dynamic structural monitoring. J. Intell. Mater. Syst. Struct. **20**(7), 849–864 (2009)

111. G.Wittenburg, K. Terfloth, F.L. Villafuerte, T. Naumowicz, H. Ritter, J. Schiller, Fence monitoring: experimental evaluation of a use case for wireless sensor networks, in *Proceedings of the 4th European Conference on Wireless Sensor Networks (EWSN)*, pp. 163–178 (2007)

112. A.Wood, J. Stankovic, G.Virone,L. Selavo, Z. He,Q.Cao,T.Doan,Y.Wu,L. Fang, R. Stoleru, Context-aware wireless sensor networks for assisted-living and residential monitoring. IEEE Network **22**(4), 26–33 (2008)

113. C. Xu, B. Firner, Y. Zhang, R. Howard, J. Li, X. Lin, Improving rf-based device-free passive localization in cluttered indoor environments through probabilistic classification methods, in *Proceedings of the 11th International Conference on Information Processing in SensorNetworks (IPSN)*, pp. 209–220 (2012)

114. G.Z. Yang (ed.), Body Sensor Networks, 1st edn. (Springer-Verlag, London, 2006)

115. P. Zhang, C. Sadler, S. Lyon, M. Martonosi, Hardware design experiences in ZebraNet, in *Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems (SenSys)*, pp. 227–238 (2004)

116. T. O'donovan, J. Brown, F. Büsching, A. Cardoso, J. Cecílio, J. D. Ó, P. Furtado, P. Gil, A. Jugel, W.-B. Pöttner, U. Roedig, J. S. Silva, R. Silva, C. J. Sreenan, V. Vassiliou, T. Voigt, L. Wolf, and Z. Zinonos, "The ginseng system for wireless monitoring and control: Design and deployment experiences," ACM Trans. Sen. Netw., vol. 10, no. 1, pp. 4:1–4:40, Dec. 2013. [Online]. Available: http://doi.acm.org/10.1145/2529975