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# Practical Deployments of Wireless Sensor Networks: a Survey

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***Abstract*—Sensor networks are becoming one of the most used technologies in our lives. Although there are several surveys about sensor networks, almost all of them focus on theoretical basis with little simulations. Some studies only explain where this kind of networks can be used, without details on how they can be applied. This paper classifies applications of wireless sensor networks and describes real implementations. There is not any survey like the one presented in this paper. The target is to complement the existing surveys, by presenting details on real implementations in order to understand how these networks run, and how they are designed, maintained and operated.**

***Keywords: sensor, sensor networks, sensor applications, motes.***

## I. Introduction

Latest advances in sensor technology are leading to the development of distributed mechanisms and small devices with both low cost and low energy consumption. In addition, these devices are capable of processing information locally and communicating wirelessly with other elements. These devices are called sensor nodes or motes.

In some cases, amount of sensors are necessary to sense an environment or take measurements from the surroundings. While they are sensing, they have also to communicate between them and/or with a central server. On the other hand, a monitored environment doesn't have infrastructure to supply energy for communication. So, motes must work with small batteries and use wireless channels.

Another feature of the sensor networks is their capacity of distributed processing. It is necessary because, the communication is the process that consumes more energy. A distributed system means that some sensors need to communicate through long distances. So, it is a good idea to process locally data as much as possible in order to minimize the bit rate.

Wireless Sensors Networks (WSNs) are formed dynamically because the connectivity between nodes depends on their position and their position variation over the time (if they are mobile). This kind of networks is characterized as being easy to be deployed and self-configuring. A sensor node is composed by a transmitter, a receiver, and it offers services of routing between nodes without direct vision, as well as records data from other sensors.

The following are some of the main features of WSNs:

- Dynamic topologies: In a wireless sensor network, the topology is always changing because nodes can fail or new nodes can join the network. These changes affect the communication between sensors.
- Variability channel: The radio channel is highly variable. There are several phenomena, such as the attenuation, fast fainting, slow fainting and interference that can cause data errors.
- Ad hoc networks: Generally, sensor networks do not have a wired network infrastructure. All motes are transceivers and routers simultaneously. However, the concept of sink node is important; this node collects the information and sends it to a central computer capable of processing these data.
- Failure tolerance: A sensor node should be able to continue operating despite of the existence of errors in the system.
- Multi-hop or broadcast communications: This type of networks use any routing protocol to enable communications multi-hop, although it is also very common the use of messages sent in broadcast.
- Power saving: It is one of the most important features in these networks. Currently, the motes have limited energy. A sensor node should have an ultra low consumption processor and transceiver radio. It is one of the most restrictive features.
- Limited hardware: In order to get an adjusted consumption, the hardware should be simple; this brings a limited process capacity.
- Production costs: Sensor networks are formed by high number of nodes. Motes must be economic to create a reliable network.

Since sensors can collect data from environment, a sensor network has many application areas, such as habitat monitoring, fire detection, motion tracking, reservoir water controlling, or intruders controlling. In order to control, monitor, tracking or detect, it is necessary a large quantity of sensor nodes which detect the monitored event (light, pressure, sound, heat, humidity, electro-magnetic field, proximity, location, etc.), and transmit it to a base station, where last action will be made. Sensor networks have become very useful for our lives and they have penetrated in domains such as health, home care, environment monitoring, etc [1].

The structure of the paper is as follows. The related work and our motivation are presented in Section 2. Section 3 describes the most important parts of the WSN architecture. Our classification of the applications of WSNs is shown in Section 4. This section is divided in five parts and each of them analyses an application and shows several real implementations. Then, in Section 5, we present a comparative study of different real deployments. In section 6, we show limitations and challenges of WSN. Finally, in section 7, we conclude the paper.

## II. Related work and motivation

Wireless sensor networks and their applications have been a popular research field because they provide a lot of facilities in our society.

Nowadays, the WSNs literature has large number of researches and studies. A pioneering work related to sensor networks identified the main characteristics of this type of networks. An example is the paper "A Survey on Sensor Networks" [2], which analyses the state of the art of sensor networks and describes their characteristics, architecture, and protocols. Another work is the paper presented by K. Akkaya and M. Younis [3], where only some routing protocols and types of networks are analyzed. The authors show the advances in designing WSN's new algorithms. Ning Xu, in his technical report [4], describes several installed systems of sensor networks, but only in the health and environment fields. Standards, protocols, and others important aspects about sensor networks are described in the paper "Wireless Sensor Networks and Applications: a Survey" [5].

Most of the surveys related to sensor networks describe their characteristics in great detail, but, in our case, the main contribution is that the survey is focused on analyzing and describing the fields of application. In addition, examples about real implementations will be explained in each field of application.

## III. Wireless sensor network architecture

In this section, we will present the generic architecture of sensor networks. First, we introduce the motes, their architecture, and their main features. After it, we will describe the communication protocol stack used in these networks and we will briefly analyze each layer.

### A. Motes

A network of sensors is formed by sensor nodes, also called motes. Despite of what they are measuring with their sensing unit, a mote needs to process the data, to store it, using a processing unit, and transmit the information to the network, by using the transmitter/receiver unit and taking care of how much energy is available in its power unit [2][6]. The processing unit has a processor chip, usually a microcontroller, a volatile memory, and a non-volatile memory if the data needs to be stored. In order to transmit the information, some specific protocols for sensor networks have been created. When the information of many motes is coordinated using a protocol, the environment can be measured in great detail. Its main components are shown in Fig. 1.

The main issue in today's mote development is to minimize their size for optimizing their power supply.

A sensor network is a group of motes that cooperate to do a specific task [7]. The precision of their tasks depends on the density of the scatter and on their coordination. Originally, they were formed by a small number of motes that were connected with a central station. Nowadays, WSNs allow distributed networks having more measurements and closer to the event.

### B. Embedded operating systems for sensors platforms

In order to manage the hardware of a mote, an operative system is needed. It is responsible to make the mote to carry out its operations and tasks.

A major difference between sensor networks and more traditional computing platforms, it is the extreme emphasis in sensor networks on power management. A large number of applications require battery-powered operation for extended periods of time. In order to manage power efficiently, each subsystem of the platform is powered individually.

For example, a radio should have to be turned on only during active communication, and it should be possible to shut down the CPU between processing requests. Similarly, it should be possible to power down the sensor and I/O subsystems individually when not in use.

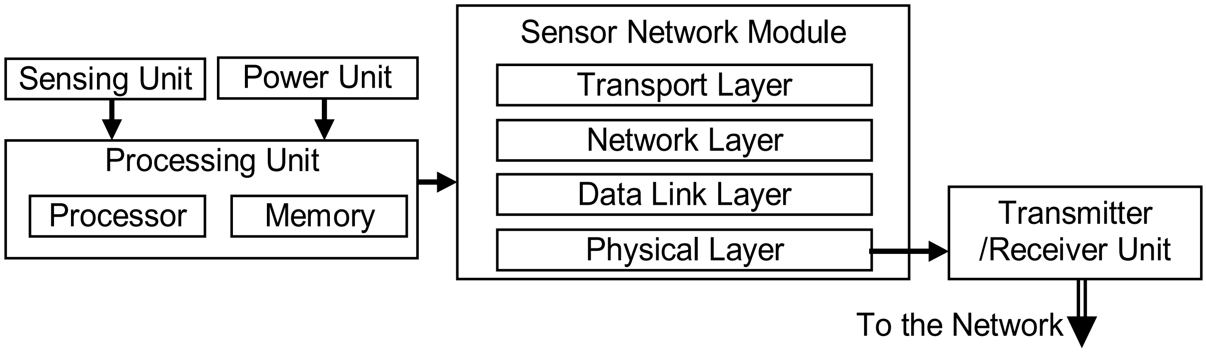


Figure 1. Components of a mote

TABLE I. COMPARATIVE OF MOTES

| | **Micaz** | **Mica2** | **Mica2dot** | **Tmote** | **TinyNode** |
|---|---|---|---|---|---|
| Distributed by | Crossbow | | | Moteiv | Shockfish |
| Clock Frequency | 7.37MHz | | 4MHz | 8MHz | |
| RAM | 4KB | | | 10KB | |
| Batteries | 2 AA | | Coin cell | 2 AA | Solar |
| Microcontroller | Atmel Atmega 128L | | | Texas Instruments – MSP 430 microcontroller | |

In spite of WSNs have a short history, there are several enterprises working in this technology. For example, Crossbow [8] is a company that develops hardware and software platforms for WSNs. Some of their products are Mica, Mica2, Micaz, Mica2dot, telos and telosb. Moteiv [9] developed the Tmote Sky and Tmote Invent platforms. Tmote Sky is a platform focused for low consumption and high collection of data applications. It has integrated sensors, radio, antenna and microcontroller. Besides it can be easily programmed. Finally, Shockfish is a Switzerland enterprise that developed TinyNode [9]. Table I summarizes the main features of these motes.

Several operative systems have been developed for the motes such as Bertha[11], MagnetOS [12], LiteOS [13], TinyOS [14], and so on. Their main features are:

- *Bertha (pushpin computing platform).* It is a software platform designed to deploy a distributed WSN with a lot of identical nodes. Their main functions are divided in the following subsystems:
  - Management of processes.
  - Management of structures of data.
  - Organization of neighbours
  - Network interface
- *MagnetOS:* It is a distributed operative system for sensor or adhoc networks. Its objective is to run network applications of low consumption devices. It is very adaptive and easy to implement.
- *LiteOS:* It is a multi-threaded operating system that provides Unix-like abstractions for wireless sensor networks. It offers a hierarchical file system and a wireless shell interface for user interaction.
- *TinyOS:* It is used for Tmote Sky. It is a reduced multi tasks core useful for small devices, like the motes. It is an "event-driven" operative system, that is, when an event happened, this calls to the corresponding functions. It has been developed for WSNs with limited resources.

The programming of sensors is quite complicated because they have a limited calculus capacity and very few resources. Several programming languages have been developed to program the motes. Some of them are nesC [15], Protothreads [16], Giotto [17], and so on.

The libraries and applications of TinyOS are written in nesC, a version of C designed to program embedded systems. In nesC, the programs are composed by linked components.

### *C. Protocol stack*

In order to enable the communication and data transfer between two sensor nodes there have to be some rules and conventions. A protocol defines the behavior of their connection and how they exchange information over a network medium. The communication process between motes and how information from a mote moves through a network medium to another mote is implemented using layers.

Each layer is reasonably self-contained so that the tasks assigned to each layer can be implemented independently. This enables the solutions offered by one layer to be updated without adversely affecting the other layers.

The sensor module shown in Fig. 1 has 4 layers. The first three layers handle data transport issues. A wide variety of communication protocols exist for each one of them. Here it is a brief description and some protocol examples:

1. Physical Layer: It is the closest to the physical network medium and tells a sensor node how to transmit to the medium and how to receive from it. Sensors transmission medium could be any wire, such as copper or fibber, or wireless (wireless sensors could use 433 MHz, 915 MHz or 2.4 GHz).
2. Data Link Layer: It provides the functional and procedural means to transfer data between network sensor nodes and to detect and possibly correct errors that may occur in the physical layer. Some data link layer protocols are mainly deployed for sensors such as S-MAC [18], IEEE 802.15.4 [19], Zigbee [20], and so on.
3. Network Layer: It provides the functional and procedural means of transferring variable length data sequences from a source to a destination through a path. Many routing protocols have been designed for ad hoc and sensor networks. They can be grouped in Pro-active Routing, Reactive Routing, Geographical Routing, and so on [3].
4. Transport Layer: This layer becomes necessary if it is wanted to access the system from Internet or other external networks. To our current knowledge, there is no any work discussing or proposing other mechanisms, different from the ones used in Internet, to be applied in sensor networks exclusively.
5. Application Layer: It offers to the applications the possibility of gaining access to the services provided by the rest of the layers. In addition, this layer defines the protocols used by the applications to exchange data.

The following section shows the main fields where wireless sensor networks can be applied.

## IV. Wireless Sensor Networks Applications

This section presents a few applications where WSNs have been usefully implemented or have a big potential to be implemented.

### A. *Real deployments for Health*

Fielding health-related deployments, WSNs can provide a better quality of life for people with physic or psychic difficulties. There are several main sub-fields, such as:

#### *1) Human body implementations and body parameter measurements*

Sensors let control important parameters of the human body like the heart rate or the blood pressure in order to diagnose the illness and identify a particular health problem. Some similar applications include Glucose level monitors [21], organ monitors [22], cancer detectors [23] and general health monitors. The idea of embedding wireless biomedical sensors inside human body is promising, although many additional challenges exist: (i) the system must be ultra-safe and reliable, (ii) it requires minimal maintenance, and (iii) must deal with the energy-harnessing from body heat. With more researches and progress in this field, better quality of life can be achieved and medical cost can be reduced. One of the examples given is the Swallowable sensor [24]. It is a wireless capsule that is ingested and can help to diagnose of stomach disorders [25]. A little medical device developed by Buffalo [26]. The intelligent pill is taken in by a patient and begins to transmit information to a receiver. This receiver is carried by same patient and gathers data from the stomach while the pill goes over it. Some of these devices include a microscopic camera. This system helps to diagnose stomach-ache and others stomach disorders that affect 20% of the humans. Sensor (pill) transmits information on levels of acidity, pressure, or time of digestion, while it is travelling in stomach. The capsule is thrown out two days after and it is recovered for its analysis and for downloading data. Another example was presented by Loren et al. in [27]. This work describes a biomedical application:, i.e., the artificial retina. Retina prosthesis chip consists on 100 microsensors that are built and implanted within human eye. This allows patients with no vision or limited vision to see at an acceptable level. The wireless communication is required to suit the need for feedback control, image identification and validation. TDMA is used for this application to serve the purpose of energy conservation because the communication pattern is deterministic and periodic.

Huan-Bang Li et al. proposed body area networks for three categories Medical and Healthcare Applications, Applications for assisting persons with disabilities, and Entertainment applications [28]. Authors proposed Zigbee and Bluetooth technology for the sensors.

Bartosz P. Jarochowski et al developed an application to rehabilitation centres [29]. In this system a personal node is located on the patient, for example on a belt clip or incorporated into an arm-band. This node stores information about the patient's session rehabilitation exercises and it is possible to obtain some statistics. Finally, the information can be sent to the medical control centre. Then, it can be analyzed by the doctors in order to improve the treatment for the next session, if it is needed.

*2) Health control, monitor, and tracking systems*

These systems have many applications. They can be used by patients who are very ill and can't go out. They can be controlled remotely by doctors. There are many proposals for monitoring elderly people and for tracking people with Alzheimer. In 2006, Bo Sun Hwang et al. developed a monitoring system which was focused on the activities of an individual daily living in a home [30]. Sensors communicate through the Bluetooth protocol [31]. The system detects the movements of a subject and then his/her activity pattern and position in a home is analyzed by a tracking algorithm. The system can be used to monitor disabled and elderly people by means of the graphical activity obtained from their system. Another work was presented by Hyung Jun Kim et al., in 2006 [32]. They proposed a home-based monitoring system that was continuously and unobtrusively monitoring a patient's condition. The system was implemented using Zigbee technology. A. Wood et al. presented ALARM-NET in [33], a wireless sensor network for assisted-living and residential monitoring. It integrates environmental and physiological sensors in a heterogeneous architecture to determine circadian activity rhythms of residents. In 2007, Yaw-Jen Lin et al. presented a ubiquitous monitor system integrated with biosensors and Radio Frequency Identification (RFID) technology [34]. The system was expected to improve the Activity of Daily Living of the disabled and elderly people, to detect the emergencies or accidents in order to enhance the quality of care.

*3) Developments to make the life easier for disabled and elderly people*

Marjorie Skubic presented in [35] a multidisciplinary project to investigate the use of sensor technology to provide early identification of problems in mobility and cognition, helping residents manage illness and impairments and stay as healthy and independent as possible. It uses an event-driven, video sensor network that hides identifying features of the residents and a reasoning component that fuses sensor and video data and analyzes patterns of behavioural activity. F. Brunetti et al. presented a system in [36] for motion caption and assessment in biomechanics using a wireless inertial sensors network using the IEEE 802.15.4 protocol. The platform expands the frontiers of movement analysis for motion caption. Many other sensor networks deployments exist for a wheelchair to avoid collisions such as the one presented by Holly A. Yanco et al in [37] and the one presented by R W. Gunderson et al. [38]. Their development consisted on a range of sensors mounted onto wheelchairs to provide navigation feedback and obstacle detection.

More sub-fields can be found but there are not so many deployments as the ones described before. One of them is to control drug administration in hospitals. Patients have sensor nodes that monitor their diseases and required medications. So, any doctor will prescribe always correctly drugs for that patient. In addition, doctors may also carry a sensor node, which allows other doctors to locate them within the hospital. The other one is the use of sensor networks to control and monitor epidemics produced in any place of the world. Maps of risk can be extracted using sensors, that is, knowing which places are infected or could be in the near future.

Paulo Bartolomeu Vasco Santos et al. have combined both health care and home automation in [39]. This modular system is formed by different subsystems and it can combine them according to the patient needs. Its most interesting contribution is the capacity of automating the house. It is a great advance for reduced mobility people. For example, the system can open a door; close a window or turn down a blind. Besides, this system can sense some vital signals.

A healthcare service for home has been presented by Nuri F.Ince et al. in [40]. It has a useful application for elderly and cognitively disabled people. This system is composed by several fixed sensors that locate a patient at home and, working together with wearable sensors, collect data to determine what bathroom activities are being done in order to know the state of the patient.

To control the main vital statistics and the intensity and duration of rehabilitation exercises that a patient has to make at home is possible with the system proposed by Chris Otto et al. [41]. However, its main advantage is its ubiquity, that is, wherever the patient is placed. It is possible thanks to the combination of ZigBee (or Bluetooth) and a personal device like a mobile phone or personal digital assistant (PDA) with GPRS/3G data network connection.

### B. Real applications for the environment

This type of applications should have a not-invasive character in order to avoid alterations to the environment. Besides, it should be a robust and precise system in order transport all the data to the control point without errors. It should also be a low cost system, because it is implemented outdoors with batteries and maybe some nodes break down and should be replaced. Applications based on the detection of natural disasters, monitoring and control of agriculture, ecosystems and geophysical studies, flood detection, precision agriculture, biological complexity mapping of the environment and forest fire detection can be also included in this field. Some real applications for the environment are the following:

At the island Great Duck, close the coasts of Maine, USA, there is a network of sensor nodes used for monitoring microclimates at refuges and surrounding areas where marine birds nest [42]. It allows investigators to supervise at-risk species and its habitats. Intel Research Laboratory in collaboration with Atlantic College (Bar Harbor) and University of California in Berkeley distributed 32 motes in the island. Each mote had a microcontroller, a low potency radio, a memory and some batteries to monitoring temperature, humidity, pressure, and infrared emissions at mid-range. Motes send their data to station bases of the island and they are connected to Internet by satellite to permit the access.

A network of little sensors was placed in the River Ribble for disasters detection [43]. They monitor the water level and the flow preventing the flooding. The system obtains more data and with bigger precision than monitoring present-day systems and they provide the opportune photos of decision to prevent imminent risks. The final network consisted of three types of sensors. One measures the pressure under the water line to determine the depth and the others take care of the velocity of the flow of water, using ultrasounds underneath the surface and cameras web above it to accomplish a follow-up of objects. All these data are sent to a control point, in order to accomplish the opportune tasks according to the received data.

A deployment of a network of sensors has been performed by the Australian agriculture departments [44]. It is intended to save great quantities of water, and to help to hold agriculture by using wireless sensor nodes. The system irrigates better than other systems, so it saves water. It has been set up in a greenhouse and in a vineyard with satisfactory results.

A system to irrigate cotton fields at arid zones of Israel and Texas is shown in [45]. These systems are based on plantation temperature. Infrared sensors are localized near the trees and when they detect temperature superior to 82ºF for more the 4 hours, water is activated. It is proved that an optimum temperature for a correct growth of cotton is between 73ºF and 90ºF.

Fire Information and Rescue Equipment (FIRE) is a project developed by Berkeley's Mechanical Engineering department and the Chicago Fire Department (CFD) [46]. Fire-fighting and catastrophes in general generate extremely chaotic environment, where it is decisive to make a fast decision. The possibility of having information about different aspects of the catastrophe in these situations becomes an inestimable value. The WSN is used to monitor the firemen, policeman, and other players in the building, sending to a central point the status of the fire, status of health, etc. Each fireman gathers data from the sensors (SmokeNet) with a small computer which has the maps of the building.

There are also implementations for fire detection and verification, such as the one presented by the same authors of this paper in [47]. The system was developed to detect and monitor any fire in rural and forest environments, while it is being used to show the rural area to the visitors. It is composed of several wireless sensors distributed on an area and some wireless IP cameras. The information is distributed in a different manner based on the type of content delivered (video steaming, sensor information or sensor alarms). When a fire is detected by some sensor node, this send a signal to the server and the nearest camera focus this zone. The system has multiple video and sensor sources and two types of users: the regular users and the firefighters. An extension of this paper has been presented by the same authors in [48].

The ALERT system [49] is the most significant example of the flood detection. In this system, there are several types of sensors that are deployed, such as rainfall, water level, and weather sensors. These sensors supply information to the centralized database system in a pre-defined way.

The COUGAR Device Database Project [50] presented a distributed data management infrastructure where sensor nodes interact with in the field to provide snapshot and long-running queries. The system resides directly on the sensor nodes and creates the abstraction of a single processing node without centralizing data.

Environmental Observations and Forecasting System (EOFS) is a large distributed system that spans large geographic areas and monitors, models and forecasts physical processes, such as environmental pollution, flooding, etc. Usually it consists of 3 components: sensor stations, a distribution network, centralized processing farm [51].

There are also wireless sensor networks developed for food monitoring. G. Manes et al. presented in [52] a user defined scenario oriented to agro-food production phase monitoring. Their results show advantages both in terms of cost and complexity reduction and experienced QoS enhancement as well. Several indoor environmental control researches can be found. The applications are focused on the control of the air conditioning in the buildings. These systems are based on sensors of temperature distributed in different plants of the building. These sensors take upon themselves to send information of the temperature to a central or distributed system and it takes the appropriate actions.

### C. *Real deployments for industry*

WSNs can improve many industrial and commercial applications for monitoring office buildings, intelligent museums, industrial sensing, product quality control, robot control and guidance, etc. These areas are very different, but WSNs can be used in all of them in order to monitor and help to manage the systems.

WSNs are also widely used for vehicle industry. They are used for a large variety of issues related with monitoring and control functions for motor management and systems of certainty and comfort (ASR, ABS, airbag, adjustment of the safety belt, air conditioning, etc.). Sensors are used to register the real status of the motor, motor's pressure of oil, temperature of motor, the number of revolutions and so on. There are other types of applications, such as to detect car thefts [53] and sensor networks for vehicle tracking [54].

An example given about the use of sensors in production is the one presented by Jenna Burrell et al in [55]. Using ethnographic research methods, the authors studied the structure of work activities and the needs and priorities of people working in a vineyard in order to understand the potential for sensor networks in agriculture. They discovered a need for localization functions to track the movement of objects, people, and equipment through the vineyard.

The application of WSNs in the household space is called smart house. We could have a system of remote metering with the networks of sensors, intelligent household appliances, a technical electric management of conditioning, illumination, water resources, home security, etc. There is a wireless sensor network deployment for light control in reference [56]. Fig. 2 shows an example of a smart house with many types of sensors placed.

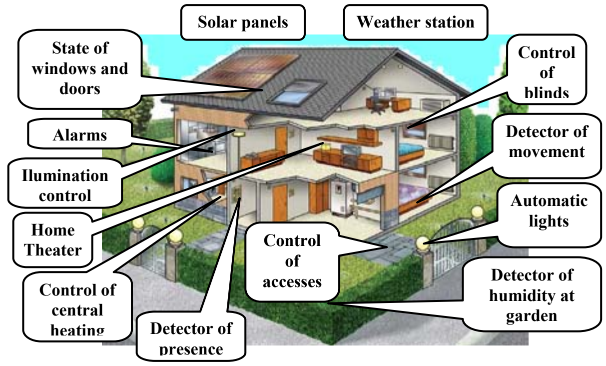


Figure 2. Smart house.

MeshNetics [57] has developed several sensor systems based on Zigbee for monitoring and control in building Automation.

The "Wireless Space Count System" is a system used for parking management [58]. This application was developed by NEDAP in January 2007. It can count the number of free places in the parking, thanks to a wireless sensor network distributed on every parking place.

In 2006, a mote network was designed, implemented, deployed and tested on the Golden Gate Bridge in San Francisco by some researchers of the Centre for Information Technology Research of the University of California [59]. Their objective was to monitor its structural condition. Sixty-four motes were distributed over the main span and southern tower, comprising the largest wireless vibration sensor network ever installed for structural health monitoring purposes. The spatially dense array resulted in an increase in effective signal-to-noise ratio compared to single, isolated, sensors. The array also allowed the values obtained from both vertical and torsional, to be analyzed easily and accurately.

Another interesting sensor application has been developed in the Loch Rannoch by BP. This project produced an efficient automated data collection system for machine monitoring and predictive maintenance that eliminated many of the manual processes by using handheld devices. It is equipped with 160 wireless motes [60].

There are applications that although they could be included in some aforementioned fields, they are also applications by themselves, e.g., intelligent nurseries personalized publicity, management of urban parking to know if there are empty places and where they are, and notification of the status of traffic at a city to know what way is the best-suited to get to a destination or to inform of the situation of the traffic at places where cameras do not cover up.

Finally, like a curious application, the interactive art is presented. Asholk Sukumaran presented the “Park View Hotel” in [61]. Using specially-built pointing devices, audiences in the park can access interior hotel spaces, by "pinging" them optically. Passers-by can emit infrared rays from several points of the street, and active sensors inside the building can illuminate rooms and change the colours. The color of the interior propagates leaking out of the building skin, jumping across the street, and entering some street-lights in the park below. The park enjoys a certain neighbourly access to the hotel, inverting the usual character of the relationship.

There are also some sensors deployments used to monitor the environment without battery that generate their energy from the environment. An example is the one developed by Enocean [62]. These sensors can produce 50 miliwatts, with variations of 3 degrees. Embedded EnOcean radios transmit around 300 meters in a free field or 30 meters in indoor (with walls and obstacles). Fig. 3 shows the schematic of free wireless sensors using ambient energy

There are other implementations published, but they appear in informative articles, so the technical depth is very low. On the other hand, there are motes developers, which products can be used in many types of applications.

### *D. Real deployments for military applications*

The need of WSNs emerged during the Cold-War, especially for submarine surveillance and battlefield monitoring. But it was not available for the public use until the 1980s, when the first commercial distributed sensor network was developed by the Defense Advanced Research Projects Agency (DARPA). This WSN is called first-generation.

We can find several applications based on WSNs for service-based C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance) [63]. They can help or can be part of a military system due to some their embedded features like their rapid deployment, self-organization, and fault tolerance [64]. Wireless sensor networks can be an integral part of defense/offensive military systems [65].

Typical military applications of sensor networks are:

- Monitoring forces: reconnaissance of opposing forces and terrain and battlefield surveillance
- Monitoring of equipment and ammunition
- Targeting
- Battle damage assessment
- Nuclear, biological and chemical attack detection and reconnaissance
- "fog of war" clearing
- Space exploration
- Undersea monitoring

Rockwell Scientific has been working with the U.S. Marine Corps and U.S. Army to test and refine WSN performance in desert, forest, and urban terrain. For the urban terrain, WSNs are expected to improve troop safety as they clear and monitor intersections, buildings, and rooftops by providing continuous vigilance for unknown troop and vehicle activity [66].

### *E. General Purpose Indoor Location and Location tracking systems*

Several position detection and location tracking systems based in wireless sensor networks exist. On the other hand, the growth of wireless networks caused multiple possibilities to calculate position. In indoor location, the main issue is that the system has to consider walls losses, interferences, multipath effect, humidity, temperature variations, etc.

One of the main applications of the Indoor Location and Location tracking systems is to locate people with Alzheimer or to locate disabled people with very little motion. An example of this kind of systems using the Zigbee technology was presented by Li-wei Chan et al. in [67].

MIT’s Cricket [68] is an indoor location system which uses ultrasounds to determinate user’s location that are moving in indoors, using mobile and fix nodes. Based on this system, interactive maps, personal location and access control to certain resources have been developed.

Jaime Lloret et al. [69] have analyzed two approaches where wireless sensors could find their position using WLAN technology inside a floor of a building. The first approach uses a training session and the position is based on a heuristic system using the training measurements. The second approach uses triangulation model with some fixed access points, but taking into account wall losses and signal variations. Both approaches are based on the Received Signal Strength Indicator (RSSI). Then, the authors compare their deployments with other deployments in [70].

Moreover, the same authors of this paper developed a new stochastic approach [71], which is based on a combination of deductive and inductive methods. In this system, wireless sensors can find their position using WLAN technology inside a floor of a building. Fundamental advantage of this system is that reduces the training phase in an indoor environment; but, without losing precision.

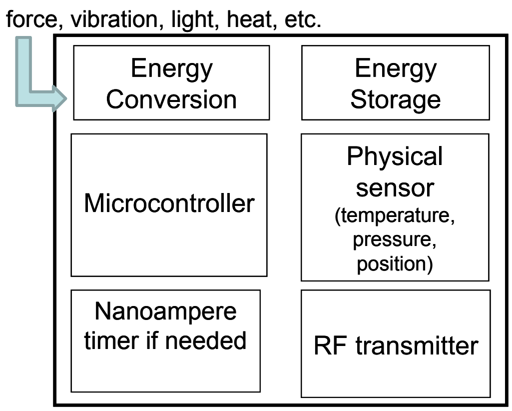


Figure 3. Schematic of free wireless sensors using ambient energy

## V. Comparative Study

A comparative of the practical deployments presented in this paper is shown in table II. Not all the works presented have been added because some of them have been published without any technical depth and some main information was missing. The S letter means that the network has a small (few meters), M means medium size (from few meters to less than 1 Km), L means large size (more than 1 Km). In the communications type column we have used C when the information is sent to a server in order to process it and D when the information is distributed in the sensors. We added the "Single use" column in order to show if the deployment could be used in other environment or only in the environment where it has been created. When some information is not provided by the authors we used a dash "-".

In order to show our conclusions from this comparative, we provide the following graphs, in order to show the global view of the state of the art of the practical deployments.

Fig. 4 shows that most of the deployments are medium, but there is not so much difference with the number of large and small size networks. Although many researchers study the scalability of the sensor networks, they are most used to cover less than 1 Km.

When wireless technologies are compared (see Fig. 5), we can observe that the most used technology has been Wi-Fi and the second one has been ZigBee. There are many implementations that use several types of technologies in their deployments.

Fig. 6 shows that there are more decentralized implementations than centralized implementations, but the difference is quite low.

Almost all the implementations have been performed for its specific purpose without the possibility of being able to be used in other implementations. Fig. 7 shows the measurements obtained.

Fig. 8 shows the comparison of the domains of the studied WSNs. We can see that WSNs are most used for health. The second domain has been agriculture and environment. This comparative gives us a view of where WSNs are most applied.

Finally, table III shows which sensor, software and hardware are used by some of the real deployments aforementioned. Not all the deployments appear because not all of them provide this information. In table III, N/A means that the information is not available.

## VI. Limitations and Challenges

Generally, wireless sensor networks are deployed to work in hostile, remote and changeable environments, so it is necessary to incorporate security mechanisms when they are being designed. However, several limitations should be taken into account.

First, nodes can't be protected physically in these environments. For example, in a battlefield any enemy can capture them and analyze the information gathered, so, fundamental information could be extracted. The challenge for researchers and developers is to design resilient protocols or others solutions to provide security to these networks, even if one or several sensor nodes are compromised. Their goal is to ensure that, if a node is captured, sensitive information stored on it cannot be taken off easily.

Another issue to be considered is the random distribution of sensor nodes. When a sensor network is deployed in a hostile environment, it is done through a random distribution. So, in this case, to gather several encryption keys on nodes, in order to establish encryption among a group of neighbours, isn't possible, because the neighbourhood cannot be known a priori. So, the challenge is to design key agreement protocols that do not require neighbourhood between nodes, and also do not require storing encryption keys on sensors before the deployment.

On the other hand, the small size of the sensor nodes and the lack of wires is another important limitation of WSNs. Although these characteristics are fundamental for many applications, it involves limited resources, such as the energy, computational power, and storage resources. Besides, a large WSN contains hundreds to thousands nodes working by batteries, so, it is difficult both to replace and recharge them in some environments.

TABLE II. A COMPARATIVE OF REAL DEPLOYMENTS PRESENTED.

| System | Network size | Technology used | Communication type | Single use | Domain |
|---|---|---|---|---|---|
| W. D. Hunt et al. [23] | S | RFID | C | No | Health (Early Cancer Detection) |
| C. Mc Caffrey, et al. [24] | S | RF (ISM-band) | D | No | Health (Gastrointestinal exploration) |
| SmartPill [26] | S | Wi-Fi | C | Yes | Health (diagnose of stomach disorders) |
| L. Schwiebert et al. [27] | S | Wi-Fi | D | Yes | Health (retina prosthesis) |
| Huan-Bang Li et al. [28] | S | Zigbee and Bluetooth | C | Yes | Health |
| B. P. Jarochowski et al. [29] | S | Zigbee | C | No | Health (Rehabilitation management system) |
| B. S. Hwang et al. [30] | M | Bluetooth | D | No | Health (monitoring system) |
| H. Kim et al. [32] | M | Zigbee | D | No | Health (monitoring system) |
| A. Wood et al. [33] | M | Zigbee | D | No | Health (Assisted-Living and Residential Monitoring) |
| Y.-J. Lin et al. [34] | M | RFID | C | No | Health (Assisted-Living and Elderly Nursing Home Monitoring) |
| M. Skubic [35] | S | Infrared | C | No | Health (In-Home Monitoring System) |
| F. Brunetti et al. [36] | M | Zigbee | D | No | Health (help for disabled or elderly people) |
| R. W. Gunderson et al. [38] | S | Ultrasonic signal | C | No | Health (wheelchair) |
| N. Firat et al. [40] | M | Wi-Fi and Zigbee | C | No | Health (monitoring system for assisting patients with cognitive impairments) |
| Chris Otto et al. [41] | S | Zigbee or Bluetooth and GPRS/3G data network connection | D | No | Health |
| A. Mainwaring et al. [42] | L | Zigbee | D | No | Environment (monitoring microclimates) |
| NICTOR [43] | M | Several | D | No | Environment (disasters detection) |
| D. Hughes et al. [44] | L | Zigbee | D | No | Agriculture (save water) |
| Irrigating When the Leaves Get Hot [45] | M | Infrared | C | Yes | Agriculture |
| S. A. Summers et al. [46] | L or M | Wi-Fi | D | No | Complicated situations (Fire-fighting and catastrophes) |
| J. Lloret et al. [47] | L | Wi-Fi | C | No | Environment (fire detection) |
| J. Lloret et al. [48] | L | Wi-Fi | C | No | Environment (fire detection) |
| ALERT [49] | L or M | Several | D | No | Environment (flood detection) |
| COUGAR [50] | M or S | Wi-Fi | C | No | Environment (snapshot and long-running queries) |
| EOFS [51] | L | Wi-Fi | D | No | Environment (forecast and pollution) |
| H. Song et al. [53] | L | GPS | D | No | Vehicle Anti-Theft System |
| C. Sharp et al. [54] | M | GPS | D | No | Vehicle Tracking and Autonomous Interception |
| Jenna Burrell et al. [55] | M | Wi-Fi | D | No | Industry (ethnographic research) |
| MESHNETICS [57] | M | Zigbee | C | No | Industry (parking) |
| Nedap's Wireless Space Count System [58] | L | Wi-Fi | C | No | Industry (parking) |
| S. Kim [59] | S | - | C | No | Industry |
| T. Kevan [60] | L | Zigbee and Wi-Fi | C | No | Industry (Shipboard Machine Monitoring) |
| A. Sukumaran [61] | S | Wi-Fi | C | Yes | Art |
| C4ISR [63] | L or M | GSM | D | No | Military (several applications) |
| M. Winkler [64] | L | GPS | C | No | Military (several applications) |
| D. N. Ngo [65] | L | Several | C | No | Military |
| K. Sohraby at al. [66] | L | - | D | No | Military |
| Li-wei Chan [67] | M | Wi-Fi | D | No | Indoor Location System |
| N. Bodhi [68] | M | RF (ISM-band) | D | No | Indoor Location System |
| M. Garcia et al. [69] | M | Wi-Fi | D | No | Indoor Location System |
| M. Garcia et al. [70] | M | Wi-Fi | D | No | Indoor Location system |
| J. Lloret et al. [71] | M | Wi-Fi | D | No | Indoor Location system |

M: medium, L: large, S: small, D: decentralized, C: centralized, -: Information not provided

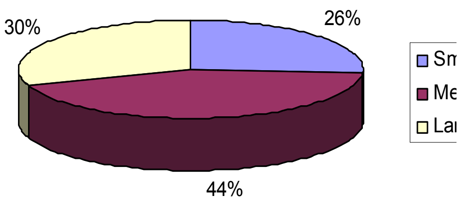


Figure 4. Network size comparison

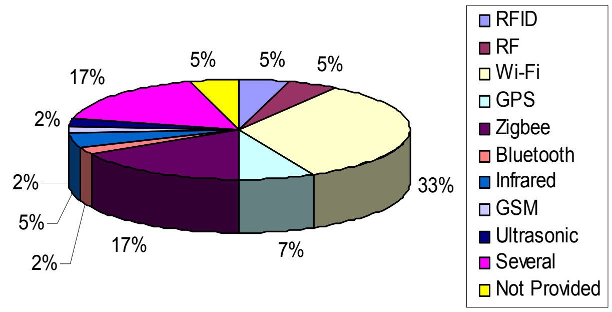


Figure 5. Technology comparison

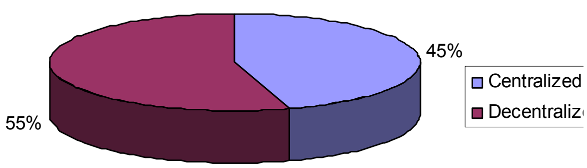


Figure 6. Communication type comparison

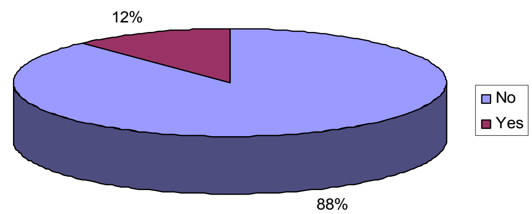


Figure 7. Single use comparison

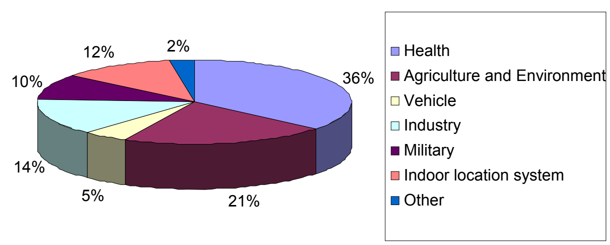


Figure 8. Domain comparison

TABLE III. SOFTWARE AND HARDWARE OF APPLICATIONS.

| System | SENSOR | Software | Hardware |
|---|---|---|---|
| W. D. Hunt et al. [23] | Surface Acoustic Wave Sensor (SAW sensor) | Their detection mechanism is a mechanical, or acoustic, wave. So, it hasn't any software. | A SAW RFID tag or sensor has an antenna for receiving and propagating an RF signal, an input/output IDT electrically connected to the antenna and a dual track reflective IDT having a first track and a second track located adjacent and acoustically coupled to the input/output IDT. |
| L. Schwiebert et al. [27] Artificial retina | Smart sensor chip | N/A | An integrated circuit and an array of sensors. The integrated circuit is a multiplexing chip, operating at 40KHz, with on-chip switches and pads to support 10x10 connections. The circuit has both transmitted and receive capabilities. |
| B. S. Hwang et al. [30] | IR sensor | N/A | N/A |
| A. Wood et al. [33] | MicaZ | TinyOS | Microcontroller: ATMEGA 128<br>Wireless Transceiver or Wireless Technology: Transceptor 802.15.4/ZigBee<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |

| | | | |
|---|---|---|---|
| Y.-J. Lin et al. [34] | Bio-sensor | N/A | Contains electronic sensing devices with output electronic signal, a process unit which partially processes digitalized data and transmits required data, and a communication unit to communicate. |
| F. Brunetti et al. [36] | Inertial sensors | N/A | N/A |
| N. Firat et al. [40] | MicaZ | TinyOS | Microcontroller: ATMEGA 128<br>Wireless Transceiver or Wireless Technology: Transceptor 802.15.4/ZigBee<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| Chris Otto et al. [41] | Wireless pulse oximeter sensors, wireless ECG sensors, and triaxial accelerometer motion sensors. | N/A | N/A |
| A. Mainwaring et al. [42] | Mica2 | TinyOS | Microcontroller: ATMEGA 128L<br>Wireless Transceiver or Wireless Technology: Chipcon 868/916 MHz<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| NICTOR [43] | Nictor | Nictor Core | Sensor and Actuation Hardware:<br>4 Digital Inputs<br>5V or 24V logic levels individually selectable<br>2 Digital Outputs<br>Switched relay outputs (0-240V, 30W)<br>2 Analog Inputs<br>Configurable as 0-5V,0-10V, 4-20mA<br>Common Mode Voltage rejection<br>(in excess of +/- 30V) |
| D. Hughes et al. [44] | Mica2 | TinyOS | Microcontroller: ATMEGA 128L<br>Wireless Transceiver or Wireless Technology: Chipcon 868/916 MHz<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| S. A. Summers et al. [46] | Mica2 | TinyOS | Microcontroller: ATMEGA 128L<br>Wireless Transceiver or Wireless Technology: Chipcon 868/916 MHz<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| J. Lloret et al. [48] | Linksys WRT54GL | Linux | Microcontroller: Broadcom BCM5352E at 200 Mhz processor<br>Wireless Transceiver or Wireless Technology: IEEE 802.11g and IEEE 802.11b<br>Internal Memory: 16MB RAM<br>External Memory: 4MB Flash |
| COUGAR [50] | Mica2 | TinyOS | Microcontroller: ATMEGA 128L<br>Wireless Transceiver or Wireless Technology: Chipcon 868/916 MHz<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| H. Song et al. [53] | Mica2 | TinyOS | Microcontroller: ATMEGA 128L<br>Wireless Transceiver or Wireless Technology: Chipcon 868/916 MHz<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| C. Sharp et al. [54] | Mica2 | TinyOS | Microcontroller: ATMEGA 128L<br>Wireless Transceiver or Wireless Technology: Chipcon 868/916 MHz<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| Jenna Burrell et al. [55] | Mica2 | TinyOS | Microcontroller: ATMEGA 128L<br>Wireless Transceiver or Wireless Technology: Chipcon 868/916 MHz<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| S. Kim [59] | Mica2 | TinyOS | Microcontroller: ATMEGA 128L<br>Wireless Transceiver or Wireless Technology: Chipcon 868/916 MHz<br>Internal Memory: 4K RAM<br>External Memory: 128K Flash |
| T. Kevan [60] | Intel motes | N/A | N/A |

N/A: Information not available, OS: Operating System

The communication between sensor nodes consumes most part of the sensor energy, much more than sensing and computation. Any encryption algorithm to guarantee a secure communication introduces a communication overhead between nodes, because it is necessary to exchange more messages, for example for authentication, initialization and encryption data. So, the adoption of strong and computationally expensive cryptographic algorithms, such as the RSA public key algorithm, is not an efficient idea. Instead, symmetric encryption algorithms are used because they don't require as computational power as asymmetric encryption. However, providing security with symmetric encryption is limited. Therefore, another challenge for researchers is to design other security solutions to cover the weaknesses of symmetric encryption and so, establishing a secure communication among the nodes participating in a communication.

The limited capability of sensor nodes for storage is another problem for security algorithms. Each sensor node needs to store as different keys as sensor nodes network has. However, when a network is composed by a large number of sensor nodes, it requires a lot of memory, which probably cannot be provided. If a single encryption key common to all nodes is used, an enemy could compromise the whole network by compromising only a single node. So, the challenge to make up for storage restrictions is to design security protocols that minimize the number of keys must be used to provide adequate protection to the network. There many theoretical works that propose security systems, but we have not found any wireless sensor network deployment with security published.

## VII. Conclusion

WSNs are needed to improve the quality of life of the disabled people. They are also a basic piece of the future medical applications. These reasons make WSNs a main research area for many research groups. WSNs help the humans to control, examine and survey places that they are not able to do because it is very difficult to achieve the place or because the human is not able to measure by itself.

Actually, more research is needed and developments of new sensors in order to get cheaper products and make them affordable. Lower prizes will help to introduce WSNs in our life.

All surveys on WSNs found in the literature show simulations and network tests in reduced and controlled environments, but this survey shows real implementations and practical deployments. There is not any survey published like the one presented in this paper.

We have compared the real deployments studied in this paper in terms of network size, technology used, the communication type, if it has being built for a single use and the domain where it is applied.

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