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Wireless Sensor Networks: A Review of Environmental Applications

Redes Inalámbricas de Sensores: Un Review de Aplicaciones Ambientales

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ABSTRACT

Air quality has been an issue of constant interest when linked to the quality of life, as confirmed by the results shown in several studies in which serious health hazards have significantly increased. One way to monitor and control the situation of air pollution is through conventional monitoring systems. However, it was necessary to have an alternative that offered greater advantages. This need was covered with the creation of wireless sensor networks, which consist of spatially distributed sensors and generally consist of five key components: the sensor, a microcontroller, a transceiver, a memory and a power source. An analysis is made of seventeen works related to WSNs oriented to environmental monitoring and classified according to the work presented by Wei Ying Yi *et. al* (2015), combining low cost portable environmental sensors and WSNs in a known system as The Next Generation Air Pollution Monitoring System (TNGAPMS). New technologies for the development of WSNs must set a precedent as an important and novel alternative. In addition, great strides have been made in the system frameworks, infrastructure and hardware.

Keywords: WSN, wireless sensor networks, environmental monitoring.

RESUMEN

La calidad del aire ha sido un tema de interés constante al vincularse con la calidad de vida, así lo confirman los resultados mostrados en diversos estudios en los que los peligros graves de salud han aumentado significativamente. Una forma de monitorear y controlar la situación de la contaminación del aire es a través de sistemas convencionales de monitoreo. Sin embargo, era necesario contar con una alternativa que ofreciera mayores ventajas. Esta necesidad fue cubierta con la creación de redes inalámbricas de sensores, conocidas como *wireless sensor networks (WSNs)*, las cuales consisten en sensores espacialmente distribuidos y generalmente constan de cinco componentes clave: el sensor, un microcontrolador, un transceptor, una memoria y una fuente de alimentación. Se hace un análisis de diecisiete trabajos referentes a *WSN*s orientadas al monitoreo ambiental y se clasifican de acuerdo al trabajo presentado por Wei Ying Yi *et. al* (2015), combinando los sensores ambientales portátiles de bajo costo y las *WSNs* en un sistema conocido como *The Next Generation Air Pollution Monitoring System(TNGAPMS)*. Las nuevas tecnologías para el desarrollo de *WSN*s deben sentar precedente como una alternativa importante y novedosa. Además, se han logrado grandes avances en los marcos del sistema, la infraestructura y el hardware.

Palabras clave: WSN, redes inalámbricas de sensores, monitoreo ambiental.

Introduction

Research in atmospheric chemistry has long been a hotbed of invention for detection technologies and methods of analysis, Lewis, A. & Edwards, P. (2016). Therefore, air quality has been a topic of constant interest when linked to quality of life, with prolonged exposure to polluted air causing permanent health problems. According to the results shown in several studies, serious health problems have increased significantly, such as heart disease, atherosclerosis, respiratory and oncological mortality, chronic obstructive pulmonary disease (COPD) and lung cancer (Wei, Y., et al. (2015), Kheirbek, I., et al. (2013), Yorifuji, T., et al. (2015), Rainham, D., (2016), Lewis, A. & Edwards, P. (2016) relate poor air quality to more than three million deaths each year, and 96% of people in large cities are exposed to levels of pollutants that are above the recommended limits. Table I mentions the most common pollutants found in some cities, the sources that originate them and their effects on the organism.

Health risks and exposure to high concentrations of gases have been informed in papers reported by Yajie, M., et al. (2008), Wen, T-H., et al. (2013), Kheirbek, I., et al. (2013), Yorifuji, T., et al. (2015) and Devarakonda, S., et al. (2013). There are also reports in cities like London (Lewis, A., Edwards, P. (2016)), Hong Kong (Wei, Y., et al. (2015)), Taiwan (Wen, TH., Et al. 2013)), Torino

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(Velasco A., et al. (2016)), Nova Scotia (Rainham, D., (2016)) and Bangkok (Pummakarncha-naa, O., et al. (2005)).

Table 1. Air pollutants and their effects on human body, Choi, S., et al. (2009).

Category	Sources	Effects
CO	Gas heaters, leaking chimneys and furnaces, woodstoves, fireplaces, gas stoves.	Impaired vision and coordination, headaches, dizziness, confusion, nausea.
NO_2	Kerosene heaters, unvented gas stoves, heaters, tobacco smoke.	Eye, nose, and throat irritation, impaired lung function, increased respiratory infections.
PM	Fireplaces, tobacco smoke, woodstoves, kerosene heaters.	Eye, nose, and throat irritation, bronchitis, lung cancer.
CO_2	Gas heaters, tobacco smoke, woodstoves, fireplaces, gas stoves, automotive products.	Stimulation of the respiratory centre, dizziness, confusion, headaches, shortness of breath.
VOC	Paints, paint strippers, aerosol sprays, air fresheners, stored fuels, automotive products, dry-cleaned clothing.	Eye, nose, and throat irritation, headaches, loss of coordination, nausea, damage to the liver, kidneys, and central nervous system.

The majority of gaseous pollutants are produced at levels of parts per billion in the air and are mixed with thousands of other compounds, Lewis, A. & Edwards, P. (2016). Undoubtedly, transportation has a significant impact on the environment in which we live (Yajie, M., et al. (2008), Rainham, D., (2016)), as mentioned by Daniel (Jian) Sun et. al (2017), referring to the World Energy Report, which predicted that carbon emissions related to urban traffic would increase at an annual rate of 1.7% from 2010 to 2030, while the annual rate of growth of carbon emissions related to traffic in developing and moderately developed countries, are projected at 3.4% and 4.2%, respectively.

This work is based on studies oriented at environmental monitoring, some of them present WSNs implemented at street level, and the classification proposal for WSNs presented by Wei Ying Yi et. al (2015) was confirmed. The components used in studied works, their characteristics and recommendations are presented. The other sections of this document are organized as follows: In section 2, wireless sensor networks, their classification and their characteristics are presented. In the same section, the seventeen WSNs oriented to environmental monitoring are classified according to what was presented by Wei Ying Yi et. al (2015). In section 3, the components that assemble the WSNs are analyzed, their classification, their characteristics and the elements used in diverse works are grouped. Finally, the conclusions show the opportunity areas that are identified in the WSNs based on the analyzed works. An annex is presented as a table with the analyzed works.

Wireless Sensor Networks (WSNs)

The development of monitoring systems based on Wireless sensor networks, has been applied in many fields with the aim of helping people in their work, reducing costs and sampling time. Such as farming monitoring, weather, forest monitoring and interiors, to name a few, Fauzi Othmana, M. & Shazalib, K., (2012).

On the other hand, necessary equipments certified by regulations for the measurements of gases have the inconvenient of high acquisition cost and maintainence, Velasco A., *et al.* (2016). These traditional approaches limit the possibility of exploring spatial-temporal variations at a fine scale for the measurement of atmospheric pollutants in the street environment ((Wen, T-H., et al. (2013), Rainham, D., (2016), Pummakarnchanaa, O., et al. (2005)).

A WSN consists in sensors spatially distributed in a defined area, called "nodes" or "motes", and generally are compound of five elements: a sensor, a microcontroller, a transceiver, a memory and a power source (Bogue, R. , 2012), and according to their communication configuration they can pass their data cooperatively through the wireless network to the coordinator node, or also called the master, and from there to a server that contains the main database or the application linked to the monitoring, Wen, T-H., et al. (2013). In **Figure 1** can see an example of a WSN presented by P. Oikonomou *et. al.* (2016).

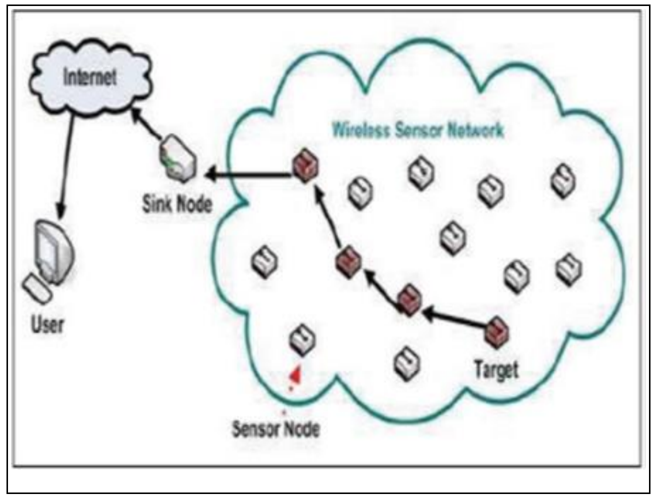

Figure 1. Example of a network topology that could be used in a WSN, presented by Oikonomou, P., et al. (2016).

The range of WSN applications is very broad and includes smart agriculture; security and surveillance of equipment, buildings and industrial processes; monitoring of health, traffic, control and industrial monitoring; as well as military actions and environmental monitoring systems (Dziadak et al (2016), Cuevas-Martinez et al (2010), Akyildiz et al (2002)). Several experiments have demonstrated the feasibility of wireless sensor networks for environmental monitoring applications, Rainham, D (2016). That is why WSNs are commonly used in air pollution monitoring and have proven to be reliable, Velasco A., et al. (2016). It is important to note that the implementation of large quantities of low cost sensors in a wireless network can increase the coverage area and the spatial distribution of the monitoring systems, especially if they are mounted on mobile platforms, Devarakonda, S., *et.* al (2013).

In some studies it is suggested that the WSN have the following properties to be able to develop applications of monitoring: a) autonomy from the point of energetic view, b) feasibility to simple management and predictable operations necessaries to avoid unexpected problems of the system, c) robustness, and d) flexibility, Fauzi Othmana, M. & Shazalib, K., (2012). Alternatively, I.F. Akyildiz *et. al.* in (2002) consider various factors, among which they mention: tolerance to fails, scalability, production costs, operative environment, network topology, hardware restrictions, means of transmission for the communication and energy consumption.

In 2015, Hasenfratz, D. in his Ph.D. thesis "Enabling Large-Scale Urban Air Quality Monitoring with Mobile Sensor Nodes" and later referenced by Wei Ying Yi *et. al* (2015), proposes a way to group the WNS according to their measurement capacity, participative detection of the devices and spatial-temporal order of the information measured on the pollution of the air, combining low cost portable environmental sensors and the WNS in a system called "The Next Generation Air Pollution Monitoring System" (TNGAPMS). As it can be appreciated in **Figure 2**, TNGAPMS classifies the monitoring networks in four categories, they are: Conventional Stationary Monitoring Network (CSMN), Static Sensor Network (SSN), Community Sensor Network (CSN) and Vehicle Sensor Network (VSN).

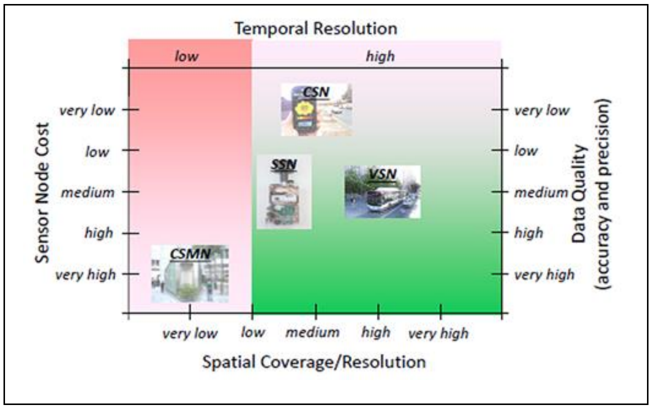

Figure 2. Balance between the sensor node cost, spatio-resolution coverage, resolution, data quality and temporal-resolution of the monitoring networks, Wei, Y., et al. (2015).

Below is a brief description of the different groups in which WSNs are classified and some reported works are mentioned, which although they are not classified in these categories by the authors themselves, in this work they are located to validate the proposed classification. In Annexed, **Table 2** shows the classification and the components used in the works that are the object of this study.

Static Sensor Network.

In this type of systems, the sensor nodes are generally mounted on lateral structures of the roads, such as poles, traffic lights or walls. The elements used are low-cost sensors, usually solid-state or electro-chemical sensors. This allows for greater spatio-temporal coverage by having authorized air pollution information available to the public through web pages, web and mobile applications. Wei Ying Yi et. al (2015) refers to seven investigations where this type of networks are used (Lewis, A., Edwards, P. (2016), Cuevas-Martinez, JC, et al. (2010), Choi, S., et al. (2009), Rainham, D., (2016), Pummakarnchanaa, O., et al. (2005), Fauzi Othmana, M. & Shazalib, K., (2012), Moreu, F., et al. (2016)). They have advantages of low energy consumption, the location of the nodes is known at all times, the weight of the elements is not considerable, several sensors can be mounted in the same node, connectivity with the network and the possibility of performing calibration tasks and maintenance periodically. On the other hand, the drawbacks that this type of networks can present are the exposure of the node to damage by external agents and complications in calibration and maintenance due to bad location.

An example of this application group can be found in reported by Tzai-Hung Wen et. al. (2013) where the WSN recolects information in real time at Street level, which each sensor node including a signal processing module, a carbon monoxide (CO) sensor and a wireless communication module. Another example is shown in the work of O. Pummakarnchana et. al. (2005), whose main objective was to remotely acquire data from continuous sensors in an urban and outdoor environment using low cost portable gas detection systems in a large area in real time through wireless Internet using geographic information systems (GIS).

Community Sensor Network.

This type of networks, also called participative networks for the developed focus, the nodes are transported by the users in bags, backpacks or objects containing them. Basically uses the same sensors than SSN. This networks allow users to acquire, analyze and share local pollution information through their mobile devices. It offers greater space-time coverage since the devices are mobile in a certain range or area. Also, usually employ usb, bluetooth or WiFi connections to establish connection with the smart devices of the users to take advantage of the WiFi or GPS modules to communicate and transmit the information, it means, open access technologies.

Wei Ying Yi *et. al* (2015) presents six works, likewise Juan Ignacio Huircán *et. al.* (2010) make a proposal with the same type of structure. Alejandro Velasco et. al. (2016) present a mobile monitoring network using community bicycles in which bring together the sensor nodes, whose objective is to complement existing systems in the metropolitan city of Torino.

Compounds of a WSN

WSNs are generally composed of some receivers that can operate in a wide range of environments and provide advantages in cost, size, power, flexibility and distributed intelligence compared to conventional cable detection solutions. These nodes can change place and configuration, they can be added or eliminated while the continuous operation of the network is still achievable, Oikonomou, P., et al. (2016).

Basically, a network of sensors consists of sensor nodes, also called "motes", which consist of three units: detection, processing and communication, Akyildiz, I.F., et al. (2002). The concept of microsensing and wireless connection of these nodes promises many new areas of application.

In the first works made it was very common to see sensor nodes that were integration of different technologies with an excluding performance between the parties, that is, there were nodes characterized by having low energy consumption, but limited in terms of storage capacity, etc. With the increasing technological advance, the new devices surpass by far the expectations of past decades. Today we can find high performance processors with low energy consumption, memories with important access speeds and capacities at a low cost, power supply modules with efficiencies or energy saving modes that can keep a device running for months.

Detecting unit: Sensors

Sensors are analytical devices in which a material sensitive to a suitable physical transducer is applied to convert a change into a property of a sensing material into a legible form of energy, Janata,

J. (2009). The most commonly used sensors for the measurement of environmental pollution can be grouped into: electrochemical, catalytic, solid state, non-dispersive infrared (NDIR) and optical by photo-ionization.

Currently a large variety of electrochemical sensors are being used extensively in many stationary and portable applications. The advantages of these sensors are: a) the pressure changes have no effect on the sensor measurement, b) they are generally very selective with the type of gas for which they were designed, c) the expected life time goes from one to three years depending on the type of gas to be measured, d) this type of sensor has the lowest energy consumption, Chou, J. (1999)

The catalytic sensors were initially used to detect combustible gases, with the passage of time and the appearance of new technologies, they were updated and have been incorporated as hydrocarbon or alcohol meters. The performance and reliability of this type of sensors varies widely depending on the manufacturer. The Wheatstone bridge is widely used in this type of sensors. On the other hand, these sensors generally present an accuracy of ± 5%, a repeatability of 2%, a response time of 10 to 15 seconds, their life expectancy is greater than 3 years according to the application, Chou, J. (1999).

Currently, solid state sensors are available to detect more than 150 different gases, each sensor has different characteristics as well as different levels of performance and quality, whixh is why they are considered the sensors of bigger versatility. They can detect low levels of gases in ppm as well as high levels. The features of the sensors are: a) the life time is higher than 10 years or more in clean applications, b) they are more susceptibles to present interference by other gases presenting false alarms, c) presents high versatily, being able to make measurements of a variety of gases and many ranges of measurements, d) has an approximately precisition of ±3% of 10% to full scale, e) have a response time from 20 to 90 seconds, f) its approximate energy consumption is 300 mW (Chou, J. , 1999). They offer an excellent opportunity for implementation in environmental monitoring due to their light weight, extremely small size, robustness, low cost and also how they can be installed anywhere to collect data that covers large areas, Pummakarnchanaa, O., *et al*. (2005).

Infrared gas analyzers are famouses to be expensive, complex and complicated. The gases used in this type of instruments are generally corrosive or reactive. The advantage of this type of sensors is that they “do not come” into direct contact with the substance to be measured, since the gas molecules interact only with the light beam, another advantage of these sensors is their minimal or no maintenance. The infrared region is more useful for gas analysis because the absorption of gas molecules is unique and selective in this region so the "footprint" is particular for each type of gas. One of the disadvantages is that they have a relatively slow response time. The most important characteristics that have: a) require 10 to 20 minutes to stabilize, b) they are affected by humidity, so they can present corrosion or contamination, c) it is necessary to couple devices that linearize the output, d) due to its low maintenance, its life expectancy is long, generally from 3 to 5 years, Chou, J. (1999).

Another problem that occurs in the sensor nodes is to mitigate the negative ecological impact of the equipment eliminated in the environment. That is why alternative energies have been considered as a way to feed these devices. Bogdan Dziadak et. al (2016) present a review of energy "harvesting" systems for WSNs.

Most of the works analyzed present the following recommendations about the measurement of gases related to environmental pollution: a) With reference to the measurement of CO, it is recommended to use solid-state or electro-chemical sensors. b) With reference to the measurement of NO2, it is recommendable to use electrochemical or solid state sensors, it is necessary to consider the interference that could occur with O3. Catalytic sensors are not recommended due to the interference they present with CO2 and H2, reported by Lewis, A. & Edwards, P. (2016). c) In reference to the measurement of O3, it can be properly detected by electrochemical or solid state sensors. Consider the reciprocal interference of NO2. d) SO2 can only be detected by solid state or electrolytic sensors.

Communication: Architecture of wireless networks.

The main wireless communication technologies used to build wireless sensor networks are in the category of personal wireless area network (Bluetooth / ZigBee), wireless local area network (Wi-Fi), wireless metropolitan area network (WiMAX), wireless wide area network (3G / 4G mobile networks) and satellite network (GPS) (Hasan Omar Al-Sakran, 2015).

Of the works analyzed in this investigation, ZigBee is identified; standard IEEE 802.15.4, as the technology most used in WSNs for offering advantages such as low power consumption when working with low data transfer and low duty cycle, P2P or P2M configuration, working frequency 2.4GHz and offer a range of distance up to 75 meters.

As an example of an application developed based on proposals for network architectures, such as ZigBee, there is the work of Juan Ignacio Huircán et al. (2010) where they present the design of a WSN localization scheme for cattle monitoring applications in grazing fields. O Velasco A. et al. (2016) in whose work, the data collected by the bicycles could be combined with the geo-reference provided by the GPS, so that the pollutants can be associated with a particular street. Robert Bogue (2012), presents diverse applications and architectures using ZigBee. Another example is Microstrain, Inc., which has installed a monitoring system that analyzes vibrations, voltage and temperature of the Goldstar Bridge in London, using an integrated ZigBee wireless transceiver (CC2420 from Texas Instruments) that transmits in the 2.4 GHz ISM band. Pummakarnchanaa et al. (2005) develop a portable application, performing a combination of ground measurements through low-cost sensors and wireless GIS, integrated into a personal digital assistant (PDA) linked through Bluetooth communication tools and global positioning system (GPS).

About the studies of wireless networks, Hasan Omar Al-Sakran (2015) mentions that there are many factors that were considered in the implementation of a WSN from the point of view of topologies and protocols: low cost, efficient energy management, scope, data fidelity, security. In I.F. Akyildiz et al. (2002) present a summary of proposed protocols and algorithms for sensor networks. Many of the sensor network routing protocols proposed also require global positioning systems (GPS).

Depending on the detection tasks, different types of application software can be built and used in the application layer, whose main functions are to collect, store and process traffic data according to Hasan Omar Al-Sakran (2015). The physical layer covers the needs of a simple but robust modulation, transmission and reception techniques. Yajie Ma et al. (2008) propose a two-layer network framework, an e-Grid P2P mesh architecture and a distributed data mining algorithm as solutions to obtain complete and real-time environmental data on air pollution emissions from traffic.

Recently, researchers shifted their attention to revolutionizing the Internet of Things paradigm (IoT), which resulted in the construction of a more convenient environment composed of several intelligent systems in different domains. IoT can be used to create a world in which all the intelligent objects of our everyday life are connected to the Internet and interact with each other with minimal human participation to achieve a common goal. On the other hand, the main problem is the interoperability between different standards, data formats, heterogeneous hardware, protocols, types of resources, software and database systems.

I.F. Akyildiz et. al. (2002) mention in their work that the IoT oriented to environmental monitoring offers a new trend for intelligent traffic development. Modern traffic management is evolving towards an IoT-based intelligent transport system. However, for sensor networks, a small-size low-cost, ultra-low power transceiver is required. Finally, mentions that there are certain hardware limitations and the trade-off between antenna efficiency and power consumption limits the choice of a carrier frequency for such transceivers to the ultra high frequency range. Due to the above, they propose the use of the ISM band of 433 MHz in Europe and the ISM band of 915 MHz in North America.

The Sub-1GHz band has been a tool that has strengthened the WSN and in which the IoT has found a means to develop their devices. This range of frequencies and their protocols offer many advantages over others, making this mode the architecture for the development of new technologies in the WSN. Some of the advantages offered by this frequency range are: a) The bands that make up the sub-1GHz spectrum are freely licensed and can be managed by the same hardware. b) Higher coverage range due to its low transmission frequency, with up to 1 km of point-to-point range. c) Reduction of energy consumption thanks to the range of working frequencies so that the same range can be obtained as 2.4GHz but at a lower consumption. d) Better coexistence with other work devices in the same medium.

Cuevas-Martinez J.C. et al. (2010) proposed the development of a new distributed system in a real network, in which each sensor node can execute a set of applications to provide routing, meshing and fragmentation through a protocol in sub-1GHz.

Conclusions: Future of WSNs

New technologies for the development of WSNs should set a precedent as an important and novel alternative, (Lewis, A. & Edwards, P. (2016)), considering minimizing the negative ecological impact of disposable devices and equipment. eliminated in the environment, Dziadak, B., et al. (2016). In this way, important efforts are being made to reduce the dependence on the duration of limited batteries and photovoltaic technology provides a means to achieve this, making the nodes self-sufficient, Bogue, R. (2012). In this sense, an extensive work on energy harvesting (EH) applied to WSN can be found in Dziadak, B., et al. (2016).

The academic community focused on air pollution must make an important effort in the laboratory and in the field in terms of calibration and testing. Providing the opportunity to become independent testers and verifiers, as is already done through committees of environmental agencies and national air pollution schemes, Lewis, A. & Edwards, P. (2016). Likewise, more creativity is needed in the experimental designs.

Great advances have been made in the frameworks of the system, the infrastructure and the hardware in the WSN; However, research on the exploration and comparison of spatio-temporal patterns of air quality at the street level using wireless geo-sensors is still limited and faces great challenges, Wen, T-H., et al. (2013).

Wireless 3D sensor networks have attracted a lot of attention because of their great potential. Uses are mainly focused on coverage, connectivity and routing problems. There is not much study of three-dimensional geometrical methods for topology control in 3D sensor networks, an exception of those studied in Li, F., et al. (2012) An attempt of this is the incorporation of new devices such as unmanned aerial vehicles (UAV) with the ultimate goal of acquiring three-dimensional information of air pollution with high spatio-temporal resolution in real time by mounting sensor nodes portable.

Another area of opportunity is the development of sensor adaptivity techniques in a network, which is necessary due to reconfigurations in the hardware and software of the sensor nodes. This would allow the node to identify the type of mounted sensor and choose the appropriate program to handle the data it detects, Wei, Y., et al. (2015).

A field that was recently incorporated into the WSN is computational science based on the concept of "intelligent networks", where artificial intelligence, distributed data mining, neural networks, fuzzy logic, system based on multiple agents, etc., are incorporated in data processing, network management, energy consumption management, etc, to develop a smart and more efficient network. On the other hand, statistics and autonomous learning methods must be further developed in order to obtain a better sampling of signals from a mixture of pollutants, Lewis, A. & Edwards, P. (2016). Examples of this are the works developed by Yajie, M., et al. (2008), Wei, Y., et al. (2015), Cuevas-Martinez, J.C., et al. (2010), Dziadak, B., et al. (2016), Al-Sakran, H.O., (2015).

All the above could be joint in the IoT field. According to the Cisco study, cities around the world will claim $ 1.9 billions in IoT value in the next decade by building smarter cities based on a smarter infrastructure, through optimal traffic management services, parking and transit (Al-Sakran, HO (2015)) which further opens the research area in WSN.

Several authors have studied sensor technologies based on lower energy consumption to extend the WSN application, such as the areas of transport and environmental management and the optimization of energy consumption of the sensors (Wen, TH., et al. (2013), Bogue, R. (2012), Baranov, A., et al. (2015)).

Thanks to this study, we visualized that in the not too distant future, wireless sensor networks will be an integral part of our lives, more than current personal computers.

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