# Wireless Sensor Networks for urban applications: evaluation and practical considerations

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**Abstract:** The Wireless Sensor Networks (WSNs) are an emerging technology for monitoring applications. WSNs are enabled by the considerable progress in fields like micro-electronics, computer science and communications. Those progresses allow to build very small and relatively cheap components, that can be deployed in the environment to monitor, where the network self-configures itself and the nodes communicate over the wireless medium.

This paper aims to illustrate the broad range of applications to urbanistic problems, where there is the need to detect relevant parameters like pollution, building strains, noise level, and video feeds. We firstly present the main features and challenges for applying WSNs to urban scenarios. Then, we provide a preliminary set of experimental results to assess the main involved parameters. Finally, we discuss the integration of a WSN with the GIS, in order to associate physical measurements with geographical information.

**Keywords:** Wireless Sensor Network; Planning Process; Distributed Systems.

## 1. Introduction

Wireless Sensor Networks (WSNs) consist of a set of nodes equipped with CPU, memory, a radio transceiver and adequate sensors. Nodes perform measurements of relevant environmental parameters, and send the data to central nodes (sinks). The sink operates as data aggregator and it forwards the information to the central station. This latter, makes the information available to the end user.

The main features of WSN nodes are to be small, consume few energy, being connected through wireless connections and to be cheap. A WSN typically provides auto-configuration and autonomy, i.e., it does not require any intervention from human operators, while it could stay active from few days to several years, depending on the adopted power supply technology. Moreover, it must properly work even in case of faulty nodes, due to malfunctioning or running out of battery. In terms of scalability, a WSN should be able to manage up to several thousands of nodes and to cover extended geographical areas.

Typical urbanistic problems that could be solved with WSNs include: coordination of specialized vehicles, like ambulances, rescue vehicles and police cars; the logistic of public transportation, for optimizing the travel and the use of available resources; traffic management, by means of real-time monitoring of urban mobility; the capillary and focused monitoring of chemical/physical environmental parameters, which determines the quality of air and water; the latter information may be correlated with the urban structure, to derive possible relationships; to monitor buildings security, both in terms of access control and structural solidity.

As a consequence of the practical problem arising from the implementation of WSN, most of the available results about WSN are theoretical studies. On the other hand, the availability of real implementations is relatively scarce, if considered the potential of this technology.

### 1.1. Contributions

In this paper, we aim to present a working implementation of a WSN, that could be used for monitoring a urban area. The technological constraints to take into account for the design will be outlined. The problems that may arise during the development will also be illustrated, as well as the technical solutions to solve such problems. Finally, an interesting set of measurements will be shown, to allow the evaluation of the proposed WSN infrastructure.

### 1.2. Paper organization

The paper is organized as follows: Section 1 introduces the WSN technology for urban applications. While Section 2 describes the requirements of WSNs, Section 3 depicts their feaures. Works related to the usage of WSNs in urbanistic applications are described in Section 4. The design of a WSN for monitoring a street is presented in Section 5, and the possibility of showing the results from a WSN is described in Section 6. In Section 7 the network organization used for experimental tests is described, and experimental results are then presented in Section 8. Finally, Section 9 concludes the paper and mentions some possible future works.

## 2. Specific requirements of a WSN

The most common applications of WSNs in urban scenarios are fire and flooding prevention, environmental monitoring, precision agriculture, traffic monitoring, inter-vehicle sensing. An example of application is shown in Figure 1, where a WSN is used to monitor a relatively long street. The acquired information are related to environmental conditions and to the vibrations of buildings. In particular, the former information are related to parameters like temperature, humidity, pollution, concentration of several types of substances, etc., while the latter are related with the measurement of accelerations.

In general, even though it is not possible to design a single network architecture for different applications, several common issues can be identified among the following:

- *Type of Service and data aggregation.* WSNs should be able to process data locally to the nodes, in order to trigger the communication of meaningful information for the specific application. Moreover, data can be collected by several different nodes and only an aggregated information is sent to the central processing site.
- *Quality of Service.* In typical scenarios the data rate originated from single or groups of nodes is very low (few short message per minute). Therefore, typical QoS metrics like delay, jitter and throughput are not adequate to measure the

network performance. Suitable parameters can be: reliability on identifying relevant events; accuracy of sensor measurements; and network lifetime.

- *Fault-tolerance.* Nodes can stop working for several reasons, like battery discharge, system crashes, or wireless link breaks. The overall network must tolerate the loss of many nodes, while still achieving the regular operation.
- *Lifetime.* In most of cases, nodes are battery powered, and it could not be possible or economically convenient to change or re-charge such batteries. A key goal for a WSN is to operate for the longest possible time (months or years in some cases). Therefore, the management of such a limited energy is mandatory. Even in case the power is supplied by solar cells or other renewable sources, power management remains a critical issue. However, this goal can only be met by imposing trade-offs with the QoS. The definition of lifetime is not unambiguous. It can be related with the time at which the first node stops working, or when the 50% of nodes stop, or even when an area is no longer under monitoring due to network partitionings.
- *Scalability*. A WSN can be made of thousands of nodes, thus protocols and technologies must be able to scale from networks of few nodes to a much larger size.
- *Non-uniform node density*. Depending on the application and environmental conditions, the node density can be highly variable, from few nodes/$km^2$ to tens nodes/$hm^2$. The network must automatically adapt to those different scenarios.
- *Programming*. It must be possible to dynamically reprogram several nodes in parallel, to update the firmware or to adapt the network behaviour. Hopefully, the node should be programmable over the wireless communication channel.
- *Maintenance*. The network must be able to self-adapt to the changing environmental conditions, re-calibrating the operational parameters without the explicit intervention of a human operator.

Beside the above mentioned issues, it is worth to remark that it is possible to design networks of sensors using trade-off approaches, such as mixing the features of WSNs with the ones from other technologies. For example, it could be possible to design a WSN where the energy issue becomes less relevant by connecting the sensor nodes to some renewable source of energy.

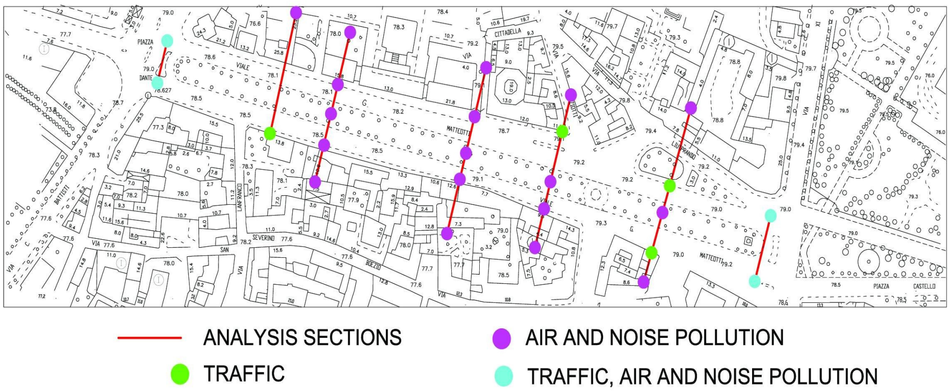


Fig. 1. Detailed map of a street to be monitored.

## 3. Features of a WSN

To face the challenges described in Section 2, new communication mechanisms, architectures and protocols have to be developed. In particular, they must provide the following functions:

- *Multi-hop wireless connectivity*. The direct communication between two any nodes is not always possible due to the presence of obstacles, high distance, noise and disturbs. Thus, the nodes must be able to forward messages received from a sender in order to deliver to the final recipient.
- *Localization*. Each single node should retain the information of neighbours only since, being the network potentially made by thousands of nodes, it is impractical to store the information about all the nodes or even a large subset of nodes.
- *Energy-aware operations*. Efficiency targeted to the management of all the operations is required to avoid hotspots, i.e., regions or groups of nodes that run out of energy quicker than other nodes.
- *Auto-configuration*. The network must be able to self-configure. Moreover, node's adds as well as removals must be properly and automatically managed.
- *In-network processing*. In some cases, a single node can not properly identify the desired events. Therefore, neighbour nodes must collaborate (i.e., exchange messages) to aggregate common data and locally computing all relevant parameters.
- *Data-centric organization*. It is not really important which is the node that detects a parameter, but the relevant information is where data has been detected. In other words, the network must be able to satisfy questions like "Shows all regions where the temperature is higher than T.", or "Show the noise level of region A."

All the mentioned features and requirements reflect directly into the design and implementation of a WSN. Therefore, trade-off design choices must be performed. The most common trade-offs are: lifetime vs. QoS, network lifetime vs. single node lifetime, node density vs. routing efficiency.

## 4. Related work

Recent advances in WSNs provide new opportunities for better environmental management of sustainable cities. In the near future, sensing and actuating nodes will be placed outdoors in urban environments to improve the people's living conditions as well as to monitor compliance with increasingly strict environmental laws. For example, these technology could advantageously be applied for the monitoring and reporting on air quality, water gas or energy infrastructures or roadways and traffic.

In [1] a WSN is integrated into a Geographical Information System (GIS) in order to create pollution maps for urban environments. In the proposed system every car could be equipped with on-board emissions sensors. These sensors would detect and transmit information regarding the presence and quantities of internal combustion derived pollution and the geographical location of vehicles in real time. Data obtained in this way should be stored by the sensor node as a historical record and also be transmitted for permanent storage and further analysis. In order to gather sensor data from vehicles, a few wireless gateways are arranged in key urban areas. Finally, once stored in a centralized database, data can be used by a Geographical Information System in order to represent pollution trends in a meaningful way.

Similarly, the Fire Information and Rescue Equipment (FIRE) project [2] applies a wireless sensor network for helping firefighters in complete critical tasks, such as building search and rescue. The project is focused toward large urban, commercial, and industrial building incidents like high-rises and warehouses. A dedicated WSN called SmokeNet tracks firefighters in large building incidents and supplies key information to all the involved parties , including location, fire and health status data. For example, the network could allow firefighters to quickly determine where the fire started in the building , how the fire is spreading and what evacuation routes are safe. The SmokeNet sensor network has been tested in a real building and results are quite promising. However, is still unknown how the system will operate in extreme conditions.

The majority of these nodes is expected to communicate wireless; therefore, given the limited radio range and the large number of nodes, the use of suitable routing protocols is required. The design of such protocols will be mainly influenced by the limited resources of the nodes and the peculiarities of the outdoor urban scenario. The IETF ROLL Working Group is focusing on routing solutions for industrial, building and urban sensor networks and it will determine the routing requirements for these scenarios. The application-specific routing requirements for Urban Low Power and Lossy Networks (U-LLNs) are presented in [3].

Liang et al. [4] present a heuristic study on fault tolerant and energy efficient routing algorithms for wireless sensor networks in street-based urban environment. Moreover, techniques for improving routing, fault tolerance and energy efficiency of an urban WSN are proposed. Results show that the proposed algorithms can significantly improve the network coverage, the average energy consumption and the packet latency in urban wireless sensor networks. Nevertheless, in is important to note that algorithms have been tested only in simulations and not in a real environment. In addition to this, researchers oversimplified the real working scenario assuming a regular grid topology for the network and ignoring noise, fade and interference in the wireless propagation model.

In [5] another routing protocol for urban WSN is proposed. The authors introduce a probabilistic epidemic-routing protocol that adapts to the network topology over time. Simulation studies show that this protocol improves the performance of the WSN in terms of data packet delivery probability. This work introduces also a detailed radio propagation model for the urban environment: although this approach should be validated on the field, it is surely a step further towards realistic simulation studies.

Looking at the big picture, Wireless Sensor Networks have received much attention in the past years and much progress has been made in designing hardware, communication standards, routing protocols and data fusion algorithms. However, the number of actually deployed sensor networks is rather small and the size of these networks is in the order of tens of nodes instead of thousands. The reason for this lies in a number of issues rising from the differences between simulations and the real-world behaviour of protocols, algorithms and hardware.

## 5. Network design

The monitoring application for the case study represented in Figure 1 requires the nodes to be equipped with proper sensors to gather information about the desired parameters. Such sensors will include: accelerometers, to register vibrations, temperature sensors, humidity sensors, and various types of chemical sensors to detect the pollution.

Since the nodes to deploy must detect heterogeneous parameters, the network design could benefit from using two different kind of nodes: simpler nodes that detect vibrations, and more complex nodes for chemical and environmental monitoring. The discrepancy of complexity arises from the type of adopted sensors. Typically, chemical sensors and similar ones are much more complex than components using the Micro Electro-Mechanical Systems technology (MEMS) [9], such as the ones for sampling vibrations and temperature, involving a more complex node architecture and, often, the impossibility of having battery-powered nodes. Nodes could be powered by solar cells or, for the most complex nodes, they could be linked to the regular energy distribution system.

The communication technology can be the based upon the ZigBee wireless protocol [10], which is designed for low-power, short range wireless communication. This is motivated by the relatively short distance among the nodes, enabling the possibility of a multi-hop transmission. In this case, however, possible network partitionings must be considered, leading the the impossibility of receiving information from some nodes. Therefore, an adequate strategy must be adopted to prevent the partitioning. Important factors that affect the wireless communication are, among the others: distance, presence of obstacles (buildings, trees, etc.), seasonal factors like presence of leaves on the trees, and weather. To assess the performance of the network under different working conditions, we provide a set of experimental results described in Section 8.

Finally, the cost of a single node can also be highly variable, since environmental sensors are much more expensive of typical micro-sensors built using MEMS.

## 6. Data visualization and interfacing

Data from the sensors out in the field is stored in a centralized DataBase Management System (DBMS) and periodic readings are related to specific sensory information (i.e. the position of the node, the sensitivity of each sensors, etc.). Once stored in a database, data can be accessed easily and can be used by different applications from almost anywhere in the Internet. For example, in Figure 2 a Geographical Information System (GIS) is used to represent the sensed data in a meaningful way. Every type of measured value, like temperature or humidity, is available as a separate layer and multiple layers can be stacked on the same map. Moreover, the use of different colors for different values provides instantaneous visibility to critical areas. Finally, it is possible to query the sensor database in order to extract historical data, thus adding the possibility to examine variations over days, months and years.

However, a database provide a high level of abstaction: many other applications and technologies could greatly benefit from the use of a centralized storage system. Using simple queries, users can extract desired information from the database in a user-friendly way, e.g. data can be saved in standard XML files or in csv/xls formats and then imported into a spreadsheet. Moreover, geocentric Web interfaces are useful for visualizing spatially and geographically related data. For example, Pachube is a web service which shares sensor data from objects, devices, buildings and environments around the world overlaying values on maps provided by Google.

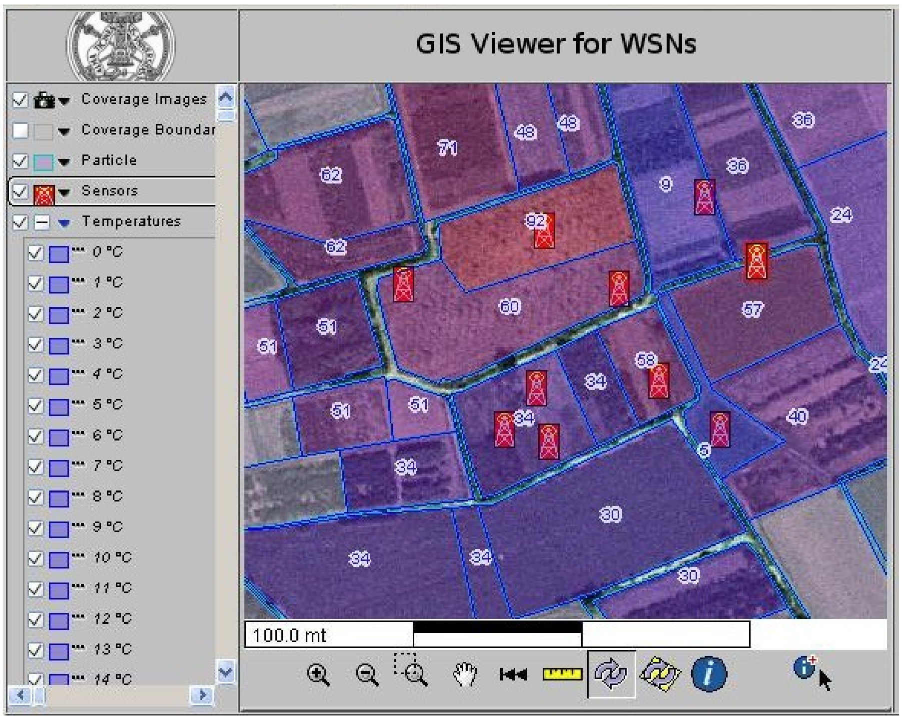


Fig. 2. Example of data integrated with the GIS visualization.

## 7. Network organization

Our WSN is composed by Squidbee wireless nodes, which are based on the Arduino development platform. The nodes use XBee RF transceiver modules operating in the 2.4 GHz ISM-band with a maximum nominal bitrate of 115.200 Kbps.

Since Squidbee lacks a complete network stack, we have developed an experimental architecture for this kind of nodes. Our network is auto-organizing and uses a simple multi-hop, hierarchical and reactive routing protocol. This enable to deploy the network without requiring any prior knowldge of the exact displacement of the nodes on the fields: devices will be able to self-configure and find the shortest path to the gateway. This approach is quite simple but effective; the resulting topology is a tree and the gateway, which collect data from all the sensors, is the root of this network tree.

In addition, nodes can enter in sleep mode to save battery: we have profiled the power consumption of every component of Squidbee motes and suitable strategies to increase energy efficiency have been identified. For example, a Scheduled-Rendezvous protocol has been implemented to organize transmissions and to synchronize sleep/wake-up cycles of nodes.

The ability to communicate between nodes faces challenges when transceivers need to communicate over obstacles. Signal transmission across trees or roofs can lead to absorption, reflection and scattering or radio waves, thus resulting in an attenuation of the signal strength and in lower link quality. Moreover, as noted also in [11], line of sight (LOS) is not sufficient to guarantee a successful radio transmission between two nodes. In fact, also the height above the ground is an important factor. Small buildings, trees and even moving vehicles are responsible for multipath fading, hence resulting in signal attenuation and fluctuations in the received signal strength. It is also important to note that these effects are non-deterministic and they exhibit seasonal trends, depending on foliage, humidity and intensity of precipitations that can heavily influence the transmission quality.

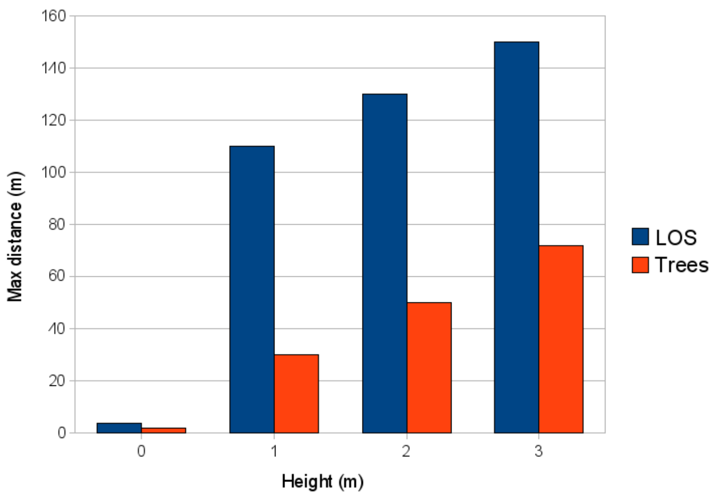


Fig. 3. Maximum covered distance as a function of the height of the node.

## 8. Experimental evaluation

We performed a number of tests on the field in order to determine the maximum achievable distance between two IEEE 802.15.4-based wireless nodes [10]. We used two Squibee devices, both battery-powered and provisioned with XBee radio modulesThe sender was located in a fixed location while we moved the receiving node. A first round of experiments have been realized on a grass plain while keeping the two nodes in line of sight. Then we moved in a large field and we put the sender next to a few large shade trees. For each of the two scenarios we repeated the tests over a range of diffent sender's heights.

Experimental results, depicted in Figure 3, show that the transmission range of a wireless node in free space is proportional to the height of the node. Moreover, as we said before, the presence of natural obstacles results in lower signal strengths, hence significantly reducing the maximum distance between two communicating devices.

## 9. Conclusion and future work

The contribution of this paper has been two-fold. On one side, we introduce the technology of Wireless Sensor Networks as an attractive solution to the several monitoring applications that could apply to urban scenarios. We present the main characteristics of WSNs and the most relevant challenges to be faced in order to implement a network. On the other hand, we show preliminary experimental results related with the most important issues that must be taken into account in the practical implementation of a network. In this context, we also illustrate the integration of the WSN into a GIS application, due to its potential relevance in urbanistic applications.

## References


[1] Cordova-Lopez L.E. et al., Online vehicle and atmospheric pollution monitoring using GIS and wireless sensor networks. In Journal of Physics: Conference Series, 2007, 76, pages. 12019-12026

[2] Wilson, J et al., A Wireless Sensor Network and Incident Command Interface for Urban Firefighting. In Proceedings of Fourth Annual International Conference on Mobile and Ubiquitous Systems: Networking & Services (MobiQuitous 2007), Philadelphia, PA, USA, August 2007.

[3] Dohler M. et al., Urban WSNs Routing Requirements in Low Power and Lossy Networks. IETF draft, IETF ROLL workgroup, January 2009.

[4] Liang C., Huang X., and Deng J., A fault tolerant and energy efficient routing protocol for urban sensor networks. In Proceedings of the 2nd international Conference on Scalable information Systems, vol. 304, Suzhou, China, June 2007.

[5] Siok Kheng Tan, Munro A., Adaptive Probabilistic Epidemic Protocol for Wireless Sensor Networks in an Urban Environment. In Proceedings of the 16th International Conference on Computer Communications and Networks (ICCCN 2007), Honolulu, Hawaii, USA, August 2007.

[6] Murty R.N. et al., CitySense: An Urban-Scale Wireless Sensor Network and Testbed. In Proceedings of 2008 IEEE International Conference on Technologies for Homeland Security, Waltham, MA, USA, May 2008.

[7] Schmid T., Dubois-Ferrière H., and Vetterli M., SensorScope: Experiences with a Wireless Building Monitoring Sensor Network. In Proceedings of 2005 Workshop on Real-World Wireless Sensor Networks (REALWSN'05), Stockholm, Sweden, June 2005.
[8] Barrenetxea G. et al., Wireless Sensor Networks for Environmental Monitoring: The SensorScope Experience. In Proceedings of 2008 IEEE International Zurich Seminar on Communications, Zurich, Switzerland, March 2008.
[9] Nadim M., An Introduction to Microelectromechanical Systems Engineering, Artech House, Boston, 2000.
[10] ZigBee Alliance, "ZigBee 2006 Specification", 2006, http://www.zigbee.org.
[11] Hebel M., Tate R., and Watson D., Results of Wireless Sensor Network Transceiver Testing for Agricultural Applications, 2007 ASAE Annual International Meeting, American Society of Agricultural and Biological Engineers, Minneapolis, Minnesota, June 2007.