Urban Air Quality Monitoring Using Vehicular Sensor Networks

Giuseppe Lo Re, Daniele Peri and Salvatore Davide Vassallo

Abstract The quality of air is a major concern in modern cities as pollutants have been demonstrated to have significant impact on human health. Networks of fixed monitoring stations have been deployed in urban areas to provide authorities with data to define and enforce dynamically policies to reduce pollutants, for instance by issuing traffic regulation measures. However, fixed networks require careful placement of monitoring stations to be effective. Moreover, changes in urban arrangement, activities, or regulations may affect considerably the monitoring model, especially when budget constraints prevent from relocating stations or adding new ones to the network. In this chapter we discuss a different approach to environmental monitoring through mobile monitoring devices implementing a Vehicular Sensor Network (VSN) to be deployed on the public transport bus fleet of Palermo.

1 Introduction

In recent years, the concept of Vehicular Ad-hoc NETwork (VANET) was introduced to refer to a wireless network in which nodes are represented by vehicles, which communicate with each other and with some fixed Access Points [1]. The primary purpose of VANETs is the development of distributed and public road safety-oriented applications, in order to save lives, improve traffic conditions and reduce the environmental impact [2]. Vehicular networks represent, in fact, the heart of the wider project of Intelligent Transportation System (ITS), that is the set of efforts and technologies that add the Information and Communications Technology to transport infrastructure and vehicles [3].

G. Lo Re (✉) · D. Peri · S. D. Vassallo
DICGIM, University of Palermo, Viale delle Scienze, ed. 6, 90128 Palermo, Italy
e-mail: giuseppe.lore@unipa.it

D. Peri
e-mail: daniele.peri@unipa.it

S. Gaglio and G. Lo Re (eds.), *Advances onto the Internet of Things*,
Advances in Intelligent Systems and Computing 260, DOI: 10.1007/978-3-319-03992-3_22,

Taking advantage of the technological progress and results obtained in vehicular networks, it is possible to build systems that detect, process and transmit some environmental features to a central server through radio links or cellular networks. This new network paradigm is called a Vehicular Sensor Network (VSN) [4]. It is a combination of communication networks based on wireless transceivers installed on vehicles and Wireless Sensor Networks (WSNs). WSNs are the sensing infrastructure of distributed systems for the control of environmental monitoring [5], habitat monitoring [6], and ambient intelligence [7], which require the perception of some physical quantities, such as temperature, humidity, ambient lighting, and so on.

A VSN has some properties [4] like:

- no energy constraints comparing to well known WSN applications, because vehicles can provide continuous power;
- high computational capabilities because vehicles can be equipped with sufficient computational resources;
- a vehicle could be equipped with a lot of sensors, so it can produce a large amounts of sensed data;
- mobile and dynamic topology.

The most important advantage of vehicular sensor networks over common static sensor networks is the possibility to carry on measurements on large areas using a small number of sensor nodes [8]. In contrast with traditional wireless sensor networks having their nodes placed in fixed locations, vehicular sensor networks are characterized by dynamic changes in network topology. This attractive feature makes VSNs a potentially cost effective solution to provide monitoring services to a broad class of applications. Vehicles may, for instance, recognize a plate and possibly may send messages to neighboring vehicles enabling the police to track the movements of a specified car [9, 10]. Another interesting application is road surface monitoring [11, 12], or urban pollution detection.

It seems thus the right time to make car an intelligent entity able to reason and cooperate with other vehicles or with environment surrounding it. To achieve this goal, the use of some formalism providing a precise structure to domain knowledge may be desirable. An ontology could fulfill this role as is an "explicit specification of a conceptualization" according to [13], that is a particular abstraction of a set of objects, concepts and relationships, that are to be represented formally for sharing and reuse of such knowledge among entities.

In this chapter, we design the prototype of a mobile system able to collect environmental data like urban air pollution. This vehicular sensor network can be considered as composed by intelligent nodes that monitor and analyze the evolution of environmental data, reporting on the occurrence of some critical issue to a supervisor entity. In order to enable reuse of air quality domain knowledge and to share the structure of such information among people or software agents, sensed data should be organized and structured in an ontology.

The remainder of the chapter is organized as follows. In Sect. 2, motivations about urban air quality and the use of vehicular sensor networks will be discussed.

Section 3 is dedicated to previous urban air quality-monitoring and diagnosis systems. In Sect. 4 we discuss our solution to the problem, describing the architecture and the implementation of the sensor network. In Sect. 5, ontological approach to the problem is described. We finally draw conclusions in Sect. 6.

2 Urban Air Quality Monitoring

In recent years researchers have begun to envision vehicular networks as systems capable of monitoring certain physical features and transmit sensed data via radio links to a server for further analysis. Observing certain environmental data, in different city spots, would in fact allow advanced support systems to detect potential alarm scenarios and suggest appropriate countermeasures. By exploiting the inherent network nodes mobility is possible, therefore, to implement a low cost environmental monitoring system with high spatial coverage.

Among the possible environmental information collectible with a vehicular sensor network, air quality plays no secondary role. This is indeed a major concern in modern cities, because air pollutants have a significant impact on human health and on the environment.

Air quality in urban areas is the result of three components: regional factors, urban term, and hot spot terms [14]. In rural areas, pollution levels depend mainly on the medium-to-long-range transport of pollutants traveling by air masses from other areas. The resulting concentration levels, are generally significantly lower in those areas. In urban areas, air pollution is linked to the set of human activities, such as closed environments heating and lighting, public and private vehicular transportation, or construction activities. Urban pollution varies spatially, as it is reasonable to expect, accordingly to human activities, topography, and local micrometeorology.

The importance of this issue is so high that is regulated by the European Commission in the Directive 96/62/EC, that establishes the basic principles of a common strategy to define and set objectives for ambient air quality in order to avoid, prevent or reduce harmful effects on human health and the environment, assess ambient air quality in the Member States, inform the public, and improve air quality where it is unsatisfactory [15].

Air pollution is usually monitored by highly reliable networks of fixed stations. A monitoring station can accurately measure a wide range of pollutants using conventional analysis tools. However, permanent monitoring stations are frequently placed so as to measure ambient background concentrations or at potential hotspot locations and they are usually several kilometers apart. Moreover, the large cost of acquisition and maintenance limits the number of such facilities, resulting in non-scalability of the system and in an extremely limited spatial resolution of the pollution maps. In fact, the effective range of spatial coverage of a static sensor is quite limited, thus it would take a large number of detectors to monitor a wide area of interest. To overcome these problems, we propose a cost-efficient and sustainable vehicular sensor network. If effectively implemented, a VSN can offer a wider spatial coverage, and a finer granularity of detected characteristics. Rather than deploying static sensors, these detectors can be installed on cars or vehicles of public transport services. Sensors attached on moving vehicles periodically monitor the air quality and transmit gathered information to a central storage system. However, there is a trade-off for this gain in spatial coverage. Temporal coverage of sensed data in a particular position will be lower compared to static sensors readings [8] as a characteristic will be measured in the same position only when the vehicle will cross again that point. This lack of temporal coverage can be handled by increasing network nodes density and so mounting sensors on more vehicles, or distributing sensors on public buses, so that environmental characteristics can be monitored continuously along their routes. Another problem that should not be underestimated concerns corrupted measurements within sensor networks. Sensor nodes may occasionally produce incorrect measurements due to battery depletion, dust on sensors, tampering and other causes. Among the several mathematical methods and algorithms in literature, suitable tools to pre-process such gathered data are Bayesian Networks [16, 17].

In the next section we discuss some existing air pollution monitoring platforms providing a brief overview of the state of the art.

3 Related Work

Monitoring air pollution using low-cost gas sensors has gained high interest in recent years. Previous research has attempted to construct networked air quality-monitoring and diagnosis systems.

CitySense [18], developed by Harvard University researchers in collaboration with BBN Technologies, consists in an approximately 100 wireless devices installed on buildings and streetlights in Cambridge. Similar to CitySense, SensorScope [19] is an example of large-scale distributed wireless environmental monitoring system.

David Hasenfratz et al. propose GasMobile [20], an air pollution smartphone-based monitoring platform. In particular, a simple and scalable system for atmospheric ozone concentration detection has been realized using a low-cost sensor connected via USB to a smartphone. A similar project, developed jointly by UC Berkeley and Intel, is called N-SMARTS [21] which shows the possibility to gather raw air pollution data by attaching sensors to GPS-enabled cell phones.

Several studies propose the use of vehicles to form an extensive air quality monitoring system. For example, OpenSense project [22], proposes to install sensors on buses to form an extensive network of mobile air quality data collection sites. A VSN architecture to measure air quality for microclimate monitoring in city areas, is proposed in [23]. These vehicular nodes roam inside the area of interest and periodically report, through short GSM messages, CO_2 concentration data to a central server for further analysis or data mining. In [24], an air pollution sensing network was tested on the public buses of Sharjah. Mobile Discovery Net (MoDisNet) [25] is a distributed infrastructure based on wireless sensors network and Grid computing technology for air pollution monitoring and mining in London. This system uses a set of vehicles such as buses, trucks, taxis, and vehicles, in which mobile sensors are installed forming a sensing network that cooperates with a grid of static sensors installed on roadside. Mobile Air Quality Monitoring Network (MAQUMON) [26] is a system composed by some car-mounted sensor nodes measuring several atmospheric pollutants. Air pollution is tagged with absolute location and time data by means of an on-board GPS. Periodically, the measurements are uploaded to a server, processed and then published on a portal. In [27], two mobile platforms for fine-grained realtime pollution measurement are presented: a mobile sensing box, deployable on public transportation infrastructure and a personal sensing device (NODE) that can be used to create a social pollution sensing.

In [28], a low power MEMS metal-oxide-sensor array is described in order to detect odor events created within the car cabin. Sensing devices have to classify the air quality level inside the car cabin with a multivariate approach closely related to the perceived AQL by human panelists. As displayed by authors, this system could be used, in combination with the the next generation of heating, ventilation, and air conditioning (HVAC) systems, in order to improve air quality inside the vehicle.

Similarly to these studies, we designed a Vehicular Sensor Network architecture for air quality monitoring to complement the fixed stations monitoring infrastructure of the city of Palermo, Italy. A few vehicles of the public transport bus fleet will be equipped with some wireless air pollution detection sensors and with the necessary components for data transmission to fixed access point acting as gateways to a central server. Vehicles, during their normal route, will sample data in a much more detailed way than is currently possible with static monitoring stations. When vehicles move close to a fixed access point installed on the roadside, for example in traffic light proximity, they may automatically transmit gathered data.

4 The Proposed System

Currently, air quality in Palermo is monitored by a network of ten fixed stations, located in some strategic spots (Fig. 1) spread on the city area. The network started to work on 1st August 1996, and it had several technical adjustments over the years in order to comply with European regulations, until March 2003, when network management activities obtained the UNI EN ISO 9001:2000 certification. All the stations are connected to a central data collection and processing facility via switched telephone lines (ISDN). Each station is equipped with a personal computer that processes data from the analysis equipment and transmits them to the central system. The network also includes four access points to the remote data center and two points for data dissemination to public.

To complement the fixed network, we designed a low-cost monitoring system using a vehicular sensor network. The proposed system will collect, process and distribute data from sensors located on vehicles belonging to the public transportation bus fleet. In the initial stage, a few vehicles will be equipped with some sensors that will measure, on their routes, the concentration of some gases like carbon monoxide,

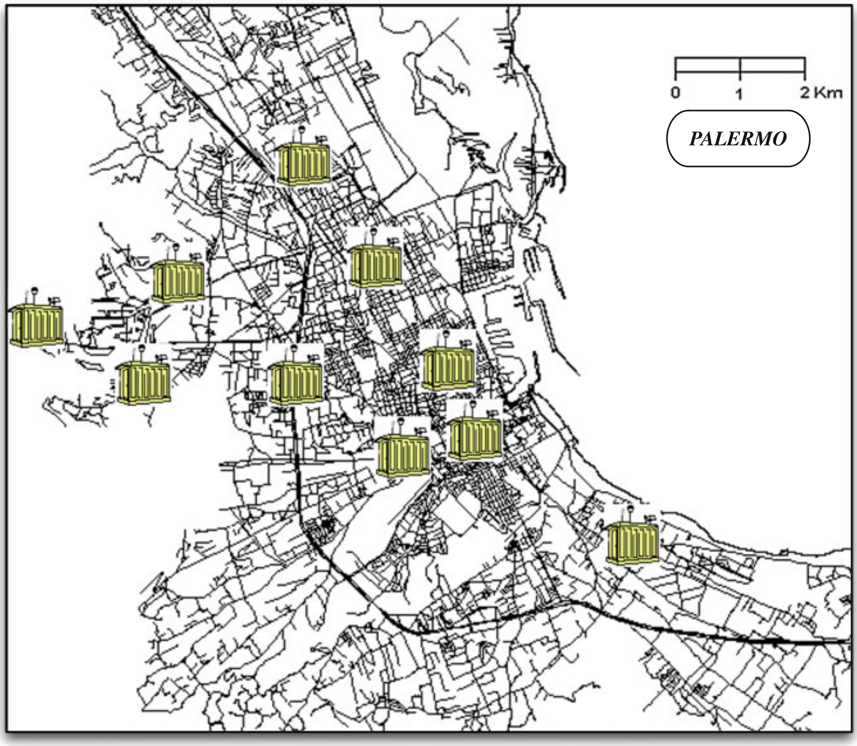

Fig. 1 Geographic positions of the fixed air quality monitoring stations in Palermo. Each station, equipped with a personal computer that processes data from the analysis equipment, is connected to a central data collection and processing facility via switched telephone lines

carbon dioxide, and ozone. Exploiting public buses mobility, even with few sensor nodes, most of the city area can be covered and detailed urban air quality data collected with fine granularity of detected characteristics. Furthermore, temporal coverage problems can also handled and overcome as buses move on fixed and established routes many times during the day.

Figure 2 shows the proposed Vehicular Sensor Network architecture for air quality monitoring. The system is composed by some vehicular sensor nodes, a monitoring server, and some access point installed on roads.

The main components are:

- In-Vechicle nodes, each provided with a microcontroller, communication devices and sensors;
- Gateways, receive data from each node and forwards them to the central server;
- Central server, store gathered data, ensuring integrity, security and availability.

Each vehicular node consists of a central unit and a sensor board. Periodically, the central unit collects the detected air pollution concentration from the sensor board

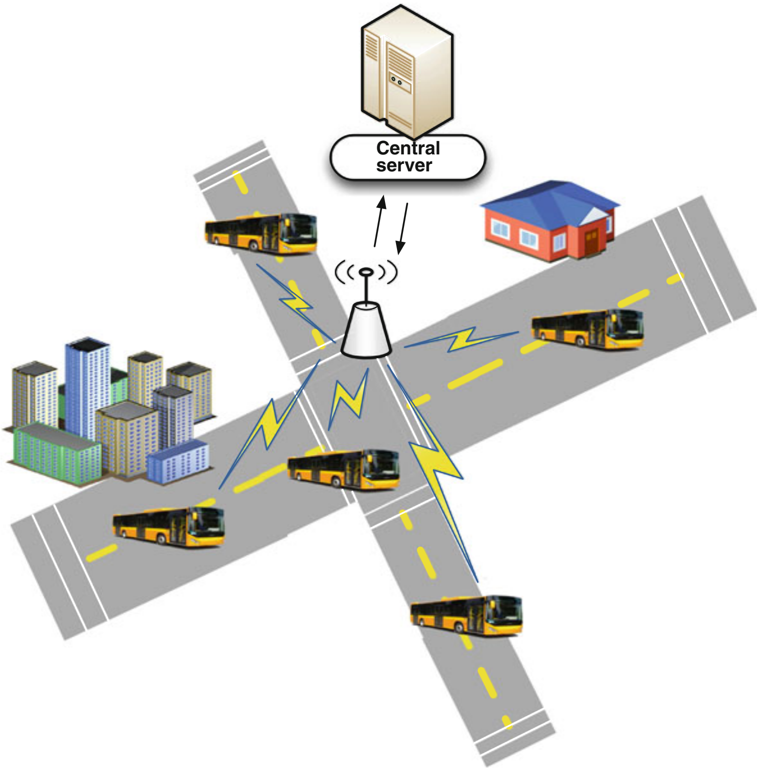

Fig. 2 Vehicular Sensor Network architecture for air quality monitoring. The system is composed by some vehicular sensor nodes that measure different pollutants in the air, some access points installed on the roads, and a monitoring server

and stores the data together with time and the current location given by the Global Position System (GPS) module. This device is so responsible for the aggregation, synchronization and transmission of sensed data to the central server for storage and further processing. Communication is granted through a centralized Vehicle-to-Infrastructure (V2I) architecture. Vehicle-to-Infrastructure concerns the connection between vehicles and fixed access points, also called Road Side Units (RSUs), requiring the placement of such communication devices in external structures, or in convenient places, such as intersections, traffic lights or buildings. A RSU acts as buffer point for the exchange of information between vehicles, so its main task is to extend the network by forwarding data coming from vehicles, to centralized servers or, eventually, to other oncoming vehicles.

The designed application is delay-tolerant and time-based, so it makes no restrictive obligation on sending real-time data to the portal. Instead, each vehicle obeys to a store and forward dissemination policy. It collects sensor data, periodically at regular intervals, and processes them locally before sending them to the central server using opportunistically encountered wireless access points in a delay-tolerant fashion. In particular, every network node keeps data in his own memory waiting for a in-range remote access point to transfer sensed data to a central server. In this way it is possible to reduce the number of connections between RSUs and vehicles, while maintaining high precision and quality monitoring. Taking advantage of the connectivity offered by the access point, the node uploads sensed data on server, where the sensory information can be structured by means of an ontology for further analysis, sharing or reuse.

4.1 Implementation

In this section we analyze the hardware components necessary to implement the system described. To realize a network node we chose to use an Arduino microcontroller, connected to a GPS receiver for global position information, a wireless module for the radio communication and a custom gas sensor board for air quality measuring.

Arduino is an open-source electronics prototyping platform, based on flexible and easy-to-use hardware and software [29]. Arduino is based on a modular architecture, in fact the idea is to easy integrate only the modules needed in each device. The development environment and the supplied libraries can be easily modified using the C/C++ language. Among the different Arduino boards, we chose the Arduino Mega 2560 microcontroller for our prototype implementation. In particular the Arduino Mega 2560 is based on the Atmel ATmega2560 microcontroller which offers 54 digital I/O pins, 16 analog inputs, 4 UART serial port, a 16 Mhz clock, a USB connection, and an ICSP header. The large number of I/O pins facilitates the inclusion of gas sensors and other communication components like the Xbee Pro shield for data transmission.

The core of the monitoring system is the gas sensor board provided with several semiconductor sensors. These sensors exploit the change of the conductivity caused by the absorption of gaseous pollutants on a semiconducting surface [30]. Their innards comprise a support in various materials such as aluminum, silicon, and ceramics, a heating resistor, and a sensing layer that is composed of a metal-oxide material such as tin dioxide (SnO_2) or zinc oxide (ZnO). At working temperature, a set of electrochemical reactions between the atmospheric oxygen and oxide granules are established. These reactions modulate and regulate the electronic flow between the grains of the sensing element, changing its resistivity, and so giving information about a precise gas concentration. These devices are particularly sensitive to temperature changes, therefore it is necessary to control the air flow directed towards the sensor head when mounted on a moving vehicle. The behavior of the sensor with respect to temperature changes is not definable by a mathematical equation, and the temperature drop of the heating element induces an error in gas concentration measures. This effect is negligible for low gas concentrations, but becomes significant for higher levels of pollution rate.

In order to validate the proposed design, in a preliminary phase, the VSN will be deployed on a single vehicle belonging to the public transportation bus fleet of Palermo and a few access points. This platform installed on the bus will monitor the following parameters:

- Temperature
- Relative humidity
- Nitrogen dioxide (NO_2)
- Carbon dioxide (CO_2)
- Carbon monoxide (CO)
- Ozone (O_3).

For data gathering, some Xbee-based Access Points will be installed on streets, and will communicate with a central server that can be implemented on a low consumption single-board computer like the Raspberry Pi board [31]. The Raspberry Pi, designed to run Linux kernel-based operating systems, is based on an ARM1176JZF-S 700 MHz processor, and includes 512 MB of RAM, two USB ports, audio and video output, and uses a Secure Digital card as boot and long-term storage. On the Pi board Lighttpd, a lightweight web server application, allow the Pi to serve dynamic HTML pages backed by a SQLite database, in which gathered information is organized in such a way as to ensure integrity, security and availability.

In the next section we propose an ontological approach to structure the domain knowledge concerning the air monitoring problem in our design.

5 Ontological Approach

Urban air pollution management requires advanced modeling and information processing techniques. Artificial intelligence provides several techniques and technologies that can solve efficiently different environmental problems. AI techniques present advantages over more traditional numeric modeling approaches, which require heavy computational resources and need as input complex data, often not easily available [32]. It is very important to make decisions in environmental protection management, so a multi-agent system (MAS) approach could be applied as a valid and robust solution. A multi-agent system is a network of software agents that interact to solve problems that are beyond the individual capacities or knowledge of each problem solver [33]. An agent can be a physical or virtual entity that can act autonomously and has skills to achieve its goals and tendencies. According to [34], the technology of intelligent agents and multi-agent systems provides the software infrastructure for the implementation of distributed environmental systems that can monitor and control the environmental quality.

In our context, the vehicular sensor network can be modeled as a multi-agent system composed by a set of intelligent entities. Each vehicle has some running software agents, which monitor and analyze the evolution of environmental data like air quality, and report to a supervisor agent if some critical problem can occur. According to Chomsky theories, information data, gathered by sensors installed on vehicles, have to be represented in a formal way so that intelligent decision agents can speak and reason on it. A way to formalize information is the definition of a correct ontology, that allow us to define messages with meaning and without ambiguity. One of the more common goals in developing ontologies is sharing common understanding of the structure of information among people or software agents [35]. The interaction between agents depends mainly on the adoption of a conceptualization, that is, a formal representation of the reality of a specific situation, so ontologic step is fundamental in our system, in order to define a common vocabulary for researchers who need to share information in this domain, but also for knowledge-based programs defining which queries and assertions are exchanged among agents.

The use of sensing devices and wireless sensor networks is raising, so an increasing volume of heterogeneous data, data formats, and measurement procedures is generated. The ontological model provides a way to manage the sensors and the accompanying volume of generated data. It can also be used to validate sensor readings and to sort out faulty sensor information as described in [36], in which the W3C Semantic Sensor Network Incubator group (SSNXG) defined an OWL 2 ontology to describe the capabilities and properties of sensors, the act of sensing and the resulting observations.

In order to formalize air quality concepts, an ontology may be used to structure air pollution domain concepts. Because one of the most important ontology features is its reusability, we considered to structure our knowledge domain according to AIR_POLLUTION_Onto. This ontology is dedicated to air pollution analysis and control, and has been actually used in MAS_AirPollution [37].

Urban air pollution structured data will be understandable and processable by agents whose goal is to monitor and mitigate pollution effects through different types of applications. For instance, combining 3D urban models, atmospheric factors and air pollution information, it is possible to estimate the quality of air in some urban areas [38]. Another interesting application could be road traffic management. Using the information provided by environmental and street ontology, it would be possible to develop some intelligent software agents that can set a recommended maximum speed for a vehicle, or manipulate traffic lights in order to manage the number of vehicles on the roads of a particular city area. This actions may contribute to disperse atmospheric pollutants thus reducing their concentration in building bordered areas.

6 Conclusions

Urban atmospheric pollution is a crucial issue for many urban areas, making it necessary to monitor and control gas pollutants concentration. Vehicular Sensor Networks are one interesting recent development in wireless and mobile networking. They are extremely multifunctional and may be useful for different applications, such as environmental monitoring. In this chapter we proposed a VSN architecture for urban air quality monitoring. The main advantage of our approach is the economy and the simplicity of the system. Using just a few vehicles belonging to a public transportation fleet, a fine-grained monitoring system able to cover all the city areas can be deployed. Moreover we propose the use of ontology as the most suitable tool to enable efficient machine-to-machine cooperation.

Acknowledgments This work has been partially supported by the PON R&C grant MI01_00091 funding the SeNSori project.

References

1. Hartenstein, H., Laberteaux, K.: VANET: Vehicular Applications and Inter-networking Technologies, vol. 1, Wiley (2010) (Online Library)
2. Da-Jie, L., Dow, C.R.: Introduction to ITS and NTCIP. Telematics Communication Technologies and Vehicular Networks: Wireless Architectures and Applications. In: Huang, C.M., Chen, Y.S. (eds.) Hershey: IGI Global, 32–57 (2010)
3. Dimitrakopoulos, G., Demestichas, P.: Intelligent transportation systems. IEEE Veh. Technol. Mag. **5**(1), 77–84 (2010)
4. Gavrilovska, L.: Application and Multidisciplinary Aspects of Wireless Sensor Networks. Springer, London (2011)
5. Anastasi, G., Lo Re, G., Ortolani, M.: Wsns for structural health monitoring of historical buildings. In: Proceedings of the 2nd Conference on Human System Interactions, HSI '09, pp. 574–579, (2009)
6. Anastasi, G., Farruggia, O., Lo Re, G., Ortolani, M.: Monitoring high-quality wine production using wireless sensor networks. In: 42nd Hawaii International Conference on, System Sciences HICSS '09, pp. 1–7, (2009)
7. De Paola, A., Gaglio, S., Lo Re, G.: Sensor9k: A testbed for designing and experimenting with WSN-based ambient intelligence applications. Pervasive Mobile Comput. **8**(3), 448–466 (2012)
8. Wong, K.J., Chua, C.C., Li, Q.: Environmental monitoring using wireless vehicular sensor networks. In: Proceedings of the 5th International Conference on Wireless Communications, Networking and Mobile Computing WiCom 09, pp. 1–4, (2009)
9. Lee, U., Zhou, B., Gerla, M., Magistretti, E., Bellavista, P., Corradi, A.: Mobeyes: smart mobs for urban monitoring with a vehicular sensor network. IEEE Wireless Commun. **13**(5), 52–57 (2006)
10. Song, H., Zhu, S., Cao, G.: Svats: A sensor-network-based vehicle anti-theft system. In: The 27th IEEE Conference on Computer Communications INFOCOM 2008, pp. 2128–2136, (2008)
11. Eriksson, J., Girod, L., Hull, B., Newton, R., Madden, S., Balakrishnan, H.: The pothole patrol: using a mobile sensor network for road surface monitoring. In: Proceedings of the 6th International Conference on Mobile Systems, Applications, and Services ACM, pp. 29–39, (2008)
12. Mednis, A., Strazdins, G., Liepins, M., Gordjusins, A., Selavo, L.: Roadmic: Road surface monitoring using vehicular sensor networks with microphones. Networked Digital Technologies, pp. 417–429. Springer, Heidelberg (2010)
13. Gruber, T.R.: Toward principles for the design of ontologies used for knowledge sharing? Int. J. Hum. Comput. Stud. **43**(5), 907–928 (1995)
14. Fenger, J.: Urban air quality. Atmos. Environ. **33**(29), 4877–4900 (1999)
15. Management and quality of ambient air. http://europa.eu/legislation_summaries/other/l28031a_en.htm. (2005). Web site consulted on 26 July 2013

16. De Paola, A., Gaglio, S.: Lo Re, G., Ortolani, M.: Multi-Sensor Fusion Through Adaptive Bayesian Networks. AI*IA 2011: Artificial Intelligence Around Man and Beyond. Lecture Notes in Computer Science, vol. 6934, pp. 360–371. Springer, Heidelberg (2011)
17. Lo Re, G., Milazzo, F., Ortolani, M.: A distributed bayesian approach to fault detection in sensor networks. In: Proceedings of the IEEE Global Communications Conference GLOBECOM, 2012, pp. 634–639, (2012)
18. Murty, R.N., Mainland, G., Rose, I., Chowdhury, A.R., Gosain, A., Bers, J., Welsh, M.: City-sense: An urban-scale wireless sensor network and testbed. In: Proceedings of the IEEE Conference on Technologies Homeland, Security, pp. 583–588, (2008)
19. Barrenetxea, G., Ingelrest, F., Schaefer, G., Vetterli, M.: Wireless sensor networks for environmental monitoring: the sensorscope experience. In: Proceedings of the IEEE International Zurich Seminar on, Communications, pp. 98–101, (2008)
20. Hasenfratz, D., Saukh, O., Sturzenegger, S., Thiele, L.: Participatory air pollution monitoring using smartphones. In: Proceedings of the 1st International Workshop on Mobile Sensing: From Smartphones and Wearables to Big Data (2012)
21. Honicky, R., Brewer, E.A., Paulos, E., White, R.: N-smarts: networked suite of mobile atmospheric real-time sensors. In: Proceedings of the Second ACM SIGCOMM Workshop on Networked Systems for Developing Regions ACM, pp. 25–30, (2008)
22. Aberer, K., Sathe, S., Chakraborty, D., Martinoli, A., Barrenetxea, G., Faltings, B., Thiele, L.: Opensense: open community driven sensing of environment. In: Proceedings of the ACM SIGSPATIAL International Workshop on GeoStreaming, pp. 39–42, (2010)
23. Hu, S.C., Wang, Y.C., Huang, C.Y., Tseng, Y.C.: Measuring air quality in city areas by vehicular wireless sensor networks. J. Syst. Softw. **84**(11), 2005–2012 (2011)
24. Al-Ali, A., Zualkernan, I., Aloul, F.: A mobile gprs-sensors array for air pollution monitoring. IEEE Sens. J. **10**(10), 1666–1671 (2010)
25. Ma, Y., Richards, M., Ghanem, M., Guo, Y., Hassard, J.: Air pollution monitoring and mining based on sensor grid in london. Sensors **8**(6), 3601–3623 (2008)
26. Völgyesi, P., Nádas, A., Koutsoukos, X., Lédeczi, Á.: Air quality monitoring with sensormap. In: Proceedings of the 7th International Conference on Information Processing in Sensor, Networks, pp. 529–530. (2008) (IEEE Computer Society)
27. Devarakonda, S., Sevusu, P., Liu, H., Liu, R., Iftode, L., Nath, B.: Real-time air quality monitoring through mobile sensing in metropolitan areas. In: Proceedings of the 12th IEEE International Conference on Peer-to-Peer, Computing (2013)
28. Blaschke, M., Tille, T., Robertson, P., Mair, S., Weimar, U., Ulmer, H.: Mems gas-sensor array for monitoring the perceived car-cabin air quality. IEEE Sens. J. **6**(5), 1298–1308 (2006)
29. Arduino web site. http://www.arduino.cc/ (2013). Web site consulted on 12 Sept 2013
30. Yamazoe, N., Sakai, G., Shimanoe, K.: Oxide semiconductor gas sensors. Catal. Surv. Asia **7**(1), 63–75 (2003)
31. Raspberry pi web site. http://www.raspberrypi.org (2013). Web site consulted on 18 Sept 2013
32. van Aalst, R.: Guidance report on preliminary assessment under EC air quality directives. European Environment Agency (1998)
33. Ferber, J.: Multi-agent systems: An Introduction to Distributed Artificial Intelligence, vol. 1. Addison-Wesley, New York (1999)
34. Weiss, G.: Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence. The MIT press, Cambridge (1999)
35. Noy, N.F., McGuinness, D.L., et al.: Ontology development 101: A guide to Creating your first Ontology. Stanford University, Stanford (2001)
36. Compton, M., Barnaghi, P., Bermudez, L., García-Castro, R., Corcho, O., Cox, S., Graybeal, J., Hauswirth, M., Henson, C., Herzog, A., et al.: The ssn ontology of the w3c semantic sensor network incubator group. Web Semant. Sci. Serv. Agents. World Wide Web **17**, 25–32 (2012)

37. Oprea, M.M.: Air_pollution_onto: an ontology for air pollution analysis and control. In: Proceedings of the Artificial Intelligence Applications and Innovations III, pp. 135–143. Springer (2009)
38. Metral, C., Falquet, G., Karatzas, K.: Ontologies for the Integration of Air Quality Models and 3D City Models. In: Teller, J., Tweed, C., Rabino, G. (eds.) Conceptual Models for Practitioners, Società Editrice Esculapio, Bologna (2008)