Padova Smart City: an Urban Internet of Things Experimentation

Angelo Cenedese, *Member, IEEE,* Andrea Zanella, *Senior Member, IEEE,* Lorenzo Vangelista, *Senior Member, IEEE,* Michele Zorzi, *Fellow, IEEE*

Abstract

"Smart City" is a powerful paradigm that applies the most advanced communication technologies to urban environments, with the final aim of enhancing the quality of life in cities and provide a wide set of value-added services to both citizens and administration. A fundamental step towards the practical realization of the Smart City concept consists in the development of a communication infrastructure capable of collecting data from a large variety of different devices in a mostly uniform and seamless manner, according to the Internet of Things (IoT) paradigm. While the scientific and commercial interest in IoT has been constantly growing in the last years, practical experimentation of IoT systems has just begun. In this paper, we present and discuss the *Padova Smart City* system, an experimental realization of an urban IoT system designed within the Smart City framework and deployed in the city of Padova, Italy. We describe the system architecture and discuss the fundamental technical choices at the base of the project. Then, we analyze the data collected by the system and show how simple data processing techniques can be used to gain insights on the functioning of the monitored system, public traffic lighting in our specific case, as well as other information concerning the urban environment.

Index Terms

Smart Cities, Test-bed and Trials, Sensor System Integration, Network Architecture, Service Functions and Management, EXI, CoAP, 6LoWPAN

I. INTRODUCTION

Generally speaking, the concept of "Smart City" consists of exploiting the modern Information and Communication Technologies (ICT) in operating the public affairs. The aim is to make a better use of the public resources, increase the quality of the services offered to the citizens and, in turn, the quality of life in the urban areas, while reducing the operational costs of the public administrations. Behind this vision, analysts foresee a potentially huge market, which is estimated at hundreds of billion dollars by 2020 [1]. To unleash the potential of such a market, however, the Smart City concept shall be adopted by various actors, as key industries, service providers, and public administrations, and applied in a synergic manner to different sectors, thus taking the flavor of Smart Governance, Smart Mobility, Smart Utilities, Smart Buildings, and Smart Environment.

In this complex scenario, public administrations may take the pivotal role of early adopter for those services that combines social utility with very clear return on investment, such as smart lighting, smart parking, smart buildings, which can then open the way for other value-added services [2]. To this end, however, these initial services need to be developed within a more general framework that allows for seamless integration of other services later.

In this respect, the Internet of Things (IoT) paradigm can become the building block to realize a unified urban-scale ICT platform, thus unleashing the potential of the Smart City vision [3], [4]. The IoT is indeed a recent communication paradigm that aims at annexing into the Internet any kind of object, provided it is equipped with a micro-controller, a communication transceiver, and a suitable protocol stack [5]. Hence, the IoT can enable easy access and interaction with a wide variety of devices such as, for instance, home appliances, surveillance cameras, monitoring sensors, actuators, displays, vehicles, and so on. The potentially enormous amount and variety of data generated by such objects will then foster the development of new services to citizens, companies, and public administrations [6]. Therefore, the adoption of the IoT paradigm in a Smart City scenario is very attractive to public administrations, which may become the promoters for the adoption of the IoT paradigm on a wider scale [7].

The objective of this paper is to describe the *Padova Smart City* (PSC) project, a practical implementation of an urban IoT realized in the city of Padova, in Italy. The project is the result of the collaboration between public and private parties, such as: the municipality of Padova, which has sponsored the project; the Department of Information Engineering and the Human Inspired Technologies research centre of the University of Padova, which have provided the feasibility analysis of the project and the data post-processing; "Patavina Technologies s.r.l."[1], a spin-off of the University of Padova specialized in the

Angelo Cenedese, Andrea Zanella,* Lorenzo Vangelista, and Michele Zorzi are with the Department of Information Engineering, University of Padova, Via Gradenigo 6/B - 35131, Padova, Italy. They are also affiliated with Human Inspired Technologies (HIT) Research Center, University of Padova, and Andrea Zanella, Lorenzo Vangelista, and Michele Zorzi are also affiliated with Consorzio Ferrara Ricerche (CFR), Via Saragat, 1 - 44122, Ferrara, Italy. Michele Zorzi and Lorenzo Vangelista are founding members of Patavina Technologies s.r.l., Via Venezia 59/8 - 35131, Padova, Italy.

*Contact author's e-mail: zanella@dei.unipd.it.

This work has been accepted for presentation at WoWMoM 2014. The International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM) is a leading event on research about networking and beyond. In its fifteenth edition, WoWMoM 2014 will take place on 16-19 June 2014 in Sydney, Australia. WoWMoM 2014 is sponsored by the IEEE Computer Society.

[1]http://patavinatech.com/

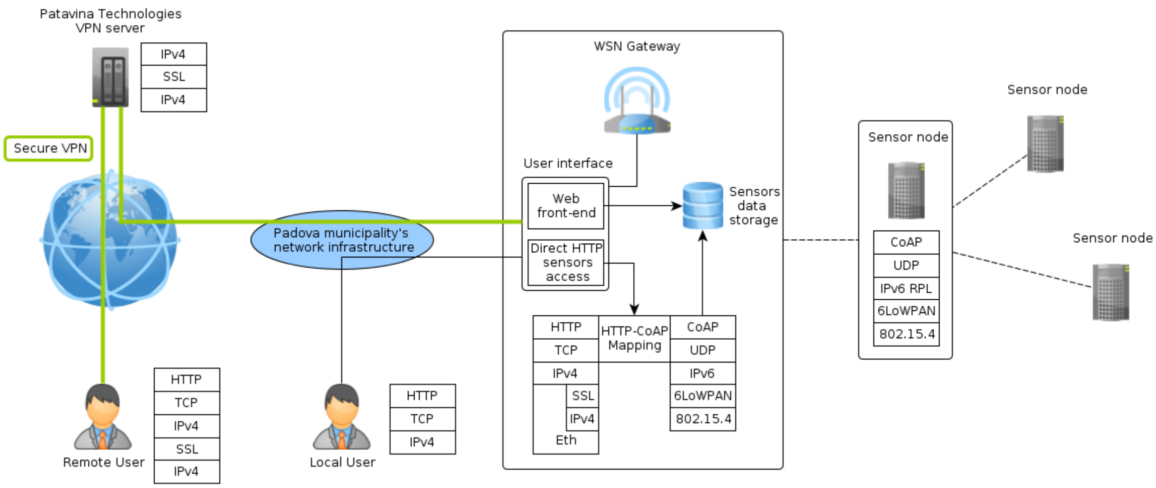


Fig. 1. System architecture of "Padova Smart City."

development of innovative IoT solutions, which has developed the control software of the employed IoT nodes manufactured by "Smart Future s.r.l.".[2]

The target application consists of a system for monitoring the public street lighting by means of wireless nodes, equipped with different kinds of sensors, placed on street light poles and connected to the Internet through a gateway unit. Besides light intensity measurements at each post, which can be used to check the correct operation of the public lighting system, this system makes it possible to collect other interesting environmental parameters, such as CO level, air temperature and humidity, vibrations, noise, and so on. Even if this system is a simple application of the IoT concept, it still involves a number of different devices and link layer technologies, thus being representative of most of the critical issues that need to be taken care of when designing an urban IoT. Furthermore, we present some experimental data collected by the PSC system and show with a couple of examples how the simple processing of raw data can provide interesting information related to the public lighting system and the level of pollution in the air.

The rest of this paper is organized as follows. Sec. II describes the PSC components and the web service architecture used to collect and export the data. Sec. III reports some selected measurements to exemplify the type of data that can be collected with the system and the kind of analysis and inference that can be performed on them. Finally, in Sec. IV we draw the conclusions.

II. PSC SYSTEM ARCHITECTURE

The conceptual architecture of the Padova Smart City system, sketched in Fig. 1, has been designed according to the web-based framework discussed in [7] and partly reported here for the reader's convenience.

The system consists of a few IoT sensor nodes placed on streetlight poles and connected to the network of the city municipality by means of a gateway. Each IoT node is geographically localized, so that IoT data can be enhanced with context information. The nodes are equipped with photometer sensors that directly measure the intensity of the light emitted by the lamps (or, actually, by any source whose light reaches the sensor) at regular time intervals or upon request. The wireless IoT nodes are also equipped with temperature and humidity sensors, which provide data concerning weather conditions, and one node is also equipped with a benzene (C_6H_6) sensor, which monitors air quality. IoT nodes are powered by small batteries, so that each unit is self-contained and can be easily placed in any location. The only exception is the node equipped with the benzene sensor that, requiring much higher power supply, has been located in the only position where a DC connector was available. The sensor nodes are packaged in a transparent plastic shield that protects the electronic parts from atmospheric phenomena, while permitting the circulation of air and light for the correct measurement of humidity, temperature, and light intensity.

The PSC project adopts IETF standards which are open and royalty-free, thus satisfying the Italian national directive that requires the use of open source software in government and in public offices. The IETF standards for IoT foresee a web service architecture for IoT services, which has been largely investigated in the literature [7]. This approach makes it possible to develop flexible IoT services that can easily interact with other web services through the adoption the *Representational State Transfer* (ReST) paradigm [8]. This paradigm, indeed, guarantees strong similarities in the structure of IoT and traditional web services, thus promoting the adoption of IoT by both end users and service developers.

The web service approach requires the deployment of suitable protocol layers in the different elements of the network, as shown in the protocol stacks depicted in Fig. 1 besides the key elements of the system architecture. In particular, we note

[2]http://www.smartfuture.eu

that the common de-facto standards for Internet communications, such as HTTP, IPv4/v6, and Ethernet, are replaced in the resource-constrained devices (as the sensor nodes) by their IoT counterparts, i.e., Constrained Application Protocol (CoAP), IPv6, and 6LoWPAN, whose role is better described in the following.

A. HTTP-CoAP Proxy

In today Internet, most of the data traffic is carried by HTTP over TCP. Therefore, HTTP seems to be the most natural choice for data transfer in IoT as well. Unfortunately, the straight application of HTTP in this context is prevented by the computational and processing constraints of some IoT nodes. Another problem is represented by the TCP transport protocol that yields poor performance in lossy environments. The CoAP protocol [9] overcomes these difficulties by proposing a binary format transported over UDP, handling only the retransmissions strictly required to provide a reliable service. Moreover, CoAP can easily interoperate with HTTP because it supports the ReST methods of HTTP (`GET`, `PUT`, `POST`, and `DELETE`), and the response codes of the two protocols are in one-to-one correspondence.

In order to enable easy interaction with the PSC system from any common Internet host, we deployed an HTTP-CoAP intermediary, also known as *cross proxy*, at the wireless sensor network (WSN) gateway. The HTTP-CoAP proxy enables transparent communication with CoAP devices. The proxy logic can be extended to better support monitoring applications and limit the amount of traffic injected into the IoT peripheral network. For instance, it is possible to specify a list of resources that need to be monitored, so that the server can autonomously update the entries in a cache related to those devices. This mechanism can be supported by two different approaches: (i) by polling the selected resource proactively, thus enabling the implementation of traffic shaping techniques at the proxy or at the gateway, and (ii) by subscribing to the selected resource using the “observe” functionality of CoAP, thus enabling the server on the node to send the updates only when the value measured by the sensor falls outside a certain range. The PSC project adopts the first option, mainly because of its implementation simplicity. Furthermore, while the gateway provides the HTTP-CoAP mapping, at the moment the peripheral nodes do not support CoAP service yet, so that data collection is performed by the WSN gateway through a dedicated application. However, the software architecture has been designed to allow for a smooth migration of the system to a full web-based framework as soon as the CoAP service will be implemented in the sensor nodes.

B. Network layer

For what concerns the network layer, the PSC system employs a mix of IPv4 and IPv6 protocols [10]. More specifically, the IoT nodes are assigned 128-bit long IPv6 addresses that guarantee global uniqueness. On the other hand, the long address field introduces overheads that are not compatible with the scarce capabilities of constrained nodes. For this reason, the IoT nodes make use of the 6LoWPAN protocol [11], [12], which is an established compression format for IPv6 and UDP headers over low-power constrained networks. The gateway transparently translates any IPv6 packet intended for a node in the 6LoWPAN network into a packet with 6LoWPAN header compression format, and operates the inverse translation in the opposite direction.

The interaction with IPv4-only hosts is obtained by means of an IPv4/IPv6 Port Address Translation (v4/v6 PAT). This method maps arbitrary pairs of IPv4 addresses and TCP/UDP ports into IPv6 addresses and TCP/UDP ports. It resembles the classical Network Address and Port Translation (NAPT) service currently supported in many LANs to provide Internet access to a number of hosts in a private network by sharing a common public IPv4 address. The same technique can be used to map multiple IPv6 addresses into a single IPv4 public address, which allows the forwarding of the datagrams in the IPv4 network and its correct management at IPv4-only hosts. We note that this approach raises a scalability problem due to the limited number of available TCP/UDP ports (65535). Nonetheless, it works perfectly to access a relatively small island of IoT nodes that can be aggregated by a single gateway, as in the case of the PSC system.

C. Link layer technology

The IoT nodes are equipped with a CC2420 transceiver, manufactured by Texas Instruments, that implements the IEEE 802.15.4 standard [13], [14]. Routing functionalities are provided by the IPv6 Routing Protocol for Low power and Lossy Networks (RPL) [15]. Nodes collectively deliver their data to the gateway, which represents the single point of contact for the external nodes. The gateway hence plays the role of 6LoWPAN border router and RPL root node. Furthermore, since sensor nodes do not support CoAP services, the gateway also operates as the sink node for the sensor cloud, collecting all the data that need to be exported to the backend services. The connection to the backend services is provided by optical fiber through a virtual private network (VPN) connection.

D. Database server

The database server is realized within the WSN Gateway, which hence represents a *plug-and-play* module that provides a transparent interface with the peripheral nodes. At the moment, the state of the resources that need to be stored in the database are collected by the WSN Gateway by means of a dedicated application. In the future, however, the WSN gateway will be replaced by the HTTP-CoAP proxy server, which will take care of retrieving the required data from the proper source. The

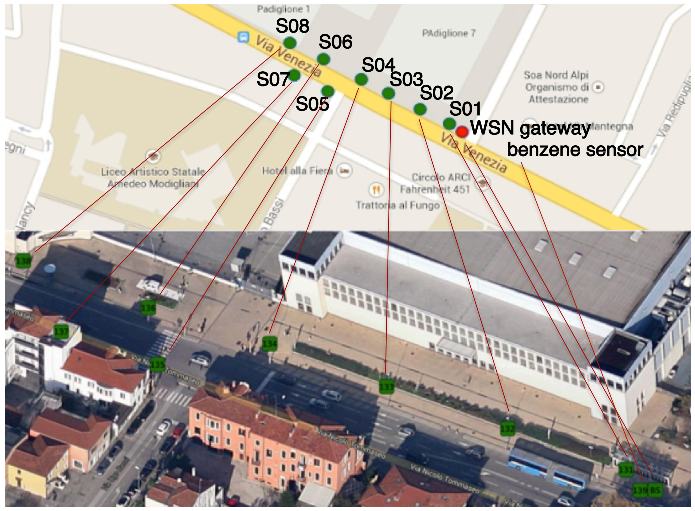


Fig. 2. Sample deployment of nodes for PSC: nodes' position is indicated by the green markers.

data stored in the database can be accessed through traditional web programming technologies and visualized in the form of a web site, or exported in any open data format using dynamic web programming languages.

Such a system can be successively extended to include other types of IoT nodes or clouds of IoT nodes, provided that each IoT peripheral system supports an HTTP-based interface, which makes it possible to interact with it in an open, standard, and technology independent manner.

III. Analysis of PSC collected data

Before being interpreted to retrieve high-level information, the data collected by the PSC system are processed by applying a moving average filter over a time window of one hour (approximately 10 readings of temperature, humidity and light, and 120 readings of the benzene sensor, whose sampling rate is larger since the node is powered by the grid). The data are then analyzed to detect anomalies and events that may occur in the monitored area, to profile the users' behaviors, and to gain insight into the use of city resources, which may serve to optimize or create services for the community.

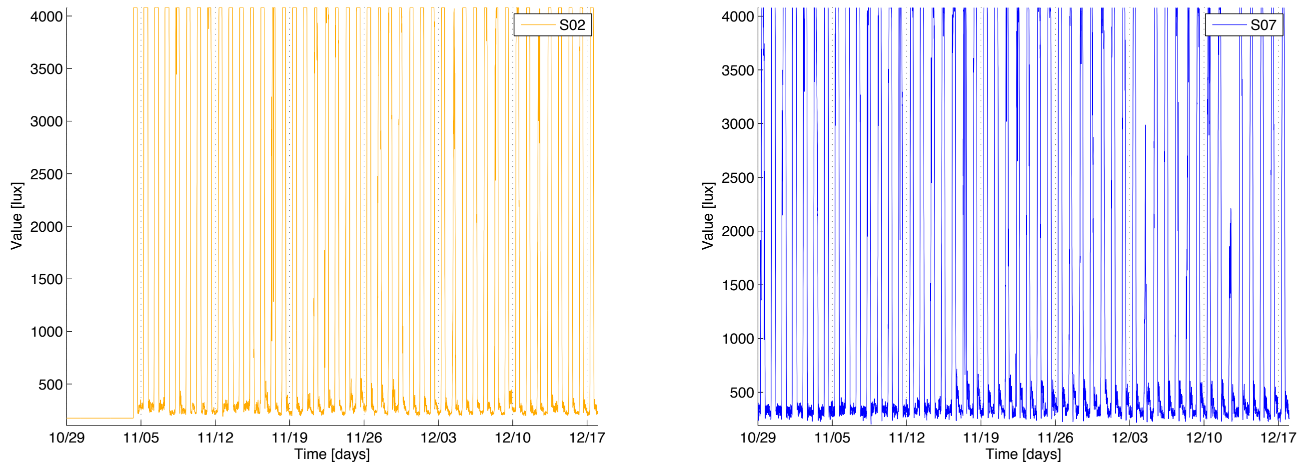
As an example, we report the data measured by the set of eight sensors positioned along the high-traffic road as shown in Fig. 2.

In Fig. 3 we show the time series of the light measurement signal collected by sensors $S02$ (Fig. 3(a)) and $S07$ (Fig. 3(b)). In general, it is possible to observe the regular pattern of the light measurements, corresponding to day and night periods. In particular, at daytime the measure reaches the saturation value, while during nighttime the values are more irregular, also due to the reflections produced by vehicle lights. The first example, in the context of anomaly detection, is summarized in Fig. 4, where the light signals collected by all sensors are processed to obtain some aggregate values. More specifically, a variance analysis of the whole time-series is shown in Fig. 4(a), which clearly highlights the presence of two clusters of measurements, respectively obtained by sensors $\{S01, S02, S03, S04, S06\}$ and $\{S05, S07, S08\}$, indicated by the red dashed circles. This result is confirmed by the time evolution of the daily variances shown in Fig. 4(b) that also shows the malfunctioning of $S02$ (dark yellow line) during the first 25 days of the experimental campaign (see also Fig. 3(a)).

A deeper understanding of the phenomena can be obtained by observing the time evolution of the variances restricted to the night hours, as reported in Fig. 4(c). The night period variance supports a further better classification: two sensors are grouped together, namely $\{S05, S08\}$ (purple and cyan lines); the four referred to $\{S01, S03, S04, S06\}$ signals have low and similar variance (red, light and dark green, light blue); finally sensor $S07$ (blue line) shows a more erratic behavior. The higher measurement stability provided by $\{S01, S03, S04, S06\}$ with respect to that of $\{S05, S08\}$ suggests a flickering illumination given by the latter set.

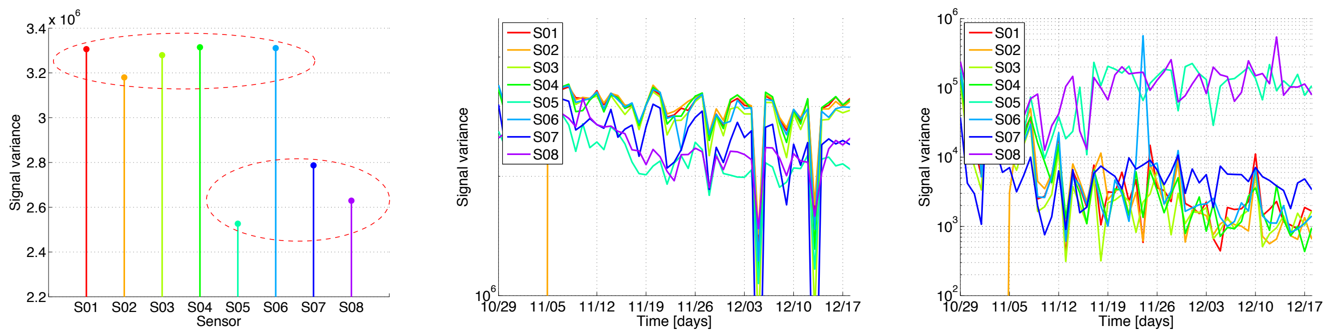
The clustering of the light sensors suggested by this last analysis is also confirmed by the visual comparison of the time series of the signals measured by the different sensors, as reported in Fig. 5 for the sensors in the first two clusters, i.e., $\{S01, S03, S04, S06\}$ and $\{S05, S08\}$.

The second example is reported in Fig. 6 (at the end of the paper) and considers the benzene measurements. In the figure, the grey bars indicate Sundays and the benzene signal is shown together with the humidity evolution. Interestingly, over a longer horizon (10 weeks), the measurement time-series shows a growing trend starting at the end of November that relates well with the weather conditions shown in the subplot Fig. 6(a) specifically with the rainfall and the average wind strength (retrieved from the local weather station database). In the absence of rainfall and in the presence of air stagnation, the pollution levels indicated by the benzene measurements tend to increase (the last three weeks reported in the plots are particularly meaningful in this sense). In addition, these values are also linked to an increment in the citizens' mobility due to Christmas shopping.



(a) (b)

Fig. 3. Example of data collected by Padova Smart City: measured light signal from sensor $S02$ (a) and sensor $S07$ (b).



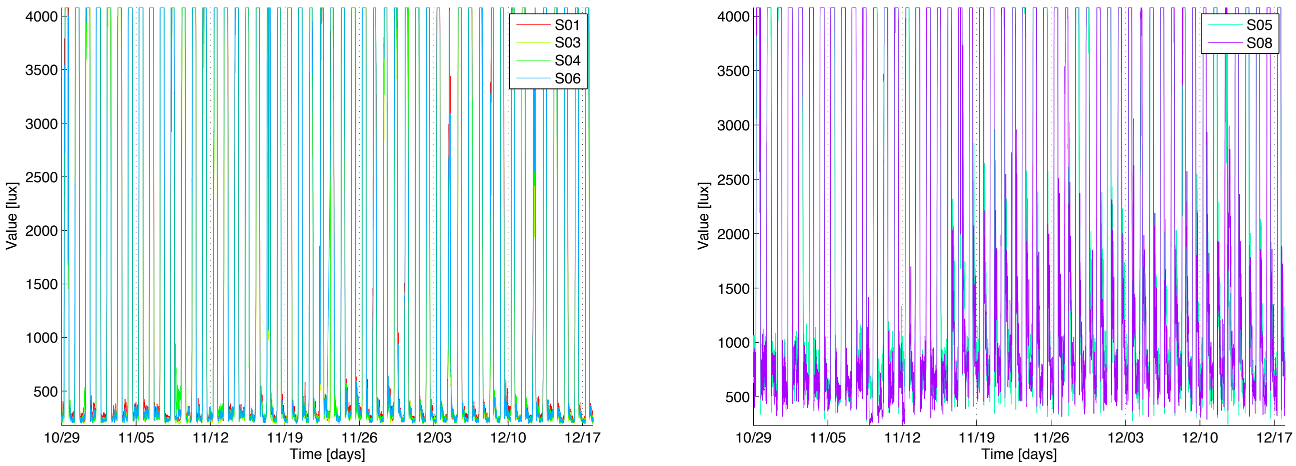
(a) (b) (c)

Fig. 4. Example of data collected by Padova Smart City: measured light signal. (a)-(b)-(c): signal variances in 70 days, 1 days, and in night period, respectively.

On a shorter timescale, it is possible to study the behavior during daytime/nighttime, which is useful to optimize the traffic flows. The two cases are presented: Fig. 6(b) remarks the difference between a vacation day (Sunday) and a working day (Monday), showing for the former a generally lower pollution level without the peak that characterizes Monday's early morning. A different situation is proposed in Fig. 6(c), where the general behavior for Sunday is similar to the previous example, but Monday signals show a completely different evolution: a peak in the humidity is followed by a rapid decrease, and correspondently the benzene signal drops and then remains limited. The scenario is consistent with an occurring storm that initially causes congestion in the road traffic and, in turn, a peak of benzene in the air, and then leaves a lower pollution level.

IV. Conclusions

In this paper we presented Padova Smart City, a pilot implementation of urban IoT within a Smart City framework. We illustrated the system architecture, which adheres to the web service paradigm, and described the adopted protocols that satisfy the requirements for standardized and open source solutions raised by the municipality that commissioned the project. The system has been designed to allow for future extension to include other types of IoT nodes or clouds of IoT nodes, provided that each IoT peripheral system supports an HTTP-based interface, which makes it possible to interact with it in an open, standard, and technology-independent manner. As an example of the possible utilizations of the data collected by such a system, we also reported some snapshots of sensor signals, namely light, humidity and benzene level in the air, and show how a several considerations and inferences can be drawn from the data through extremely simple data processing techniques. As a future work, we plan to couple the sensor data with location information provided by the GIS database and with other data that are collected by the municipality using dedicated systems (e.g., traffic intensity, parking occupancy, weather conditions, and so on) and to apply more sophisticated data analysis techniques to unravel correlations among different signals and get refined information from the raw data.



(a) (b)

Fig. 5. Example of data collected by Padova Smart City: measured light signal. Signal time-series with sensors clustering according to the variance analysis of Fig. 4(c).

ACKNOWLEDGEMENT

The authors would like to thank the municipality of Padova (Italy), and Eng. Alberto Corò in particular, for the support in the realization of the “Padova Smart City” project. The authors are also grateful to the engineers of Patavina Technologies s.r.l. (http://patavinatech.com/) for their invaluable support in deploying the system and in providing experimental data and technical documentation concerning the “Padova Smart City” project. This work has been supported in part by the European Commission through the FP7 EU project “Symbiotic Wireless Autonomous Powered system” (SWAP, G.A. no. 251557, http://www.fp7-swap.eu/).

REFERENCES

[1] Pike Research on Smart Cities. [Online]. Available: http://www.pikeresearch.com/research/smart-cities.

[2] N. Walravens, P. Ballon, “Platform business models for smart cities: from control and value to governance and public value” *IEEE Communications Magazine*, vol. 51, no. 6, pp. 72-79, Jun. 2013.

[3] J. M. Hernández-Muñoz, J. B. Vercher, L. Muñoz, J. A. Galache, M. Presser, L. A. Hernández Gómez, and J. Pettersson, “Smart Cities at the Forefront of the Future Internet,” *The Future Internet, Lecture Notes in Computer Science*, vol. 6656, pp. 447-462, 2011.

[4] C. E. A. Mulligan, M. Olsson, “Architectural implications of smart city business models: an evolutionary perspective” *IEEE Communications Magazine*, vol. 51, no. 6, pp. 80-85, Jun. 2013.

[5] L. Atzori, A. Iera, and G. Morabito, “The internet of things: A survey,” *Computer Networks,* vol. 54, no. 15, pp. 2787-2805, 2010.

[6] D. Cuff, M. Hansen, and J. Kang, “Urban sensing: out of the woods.” *Communications of the ACM* vol. 51, no. 3, pp. 24-33, Mar. 2008.

[7] A. Zanella, N. Bui, A. Castellani, L. Vangelista, M. Zorzi, “Internet of Things for Smart Cities,” *IEEE Internet of Things Journal*, vol.1, no.1, pp.22,32, Feb. 2014.

[8] R. Fielding, “Representational state transfer,” *Architectural Styles and the Design of Network-based Software Architecture*, pp. 76-85, 2000

[9] Z. Shelby, K. Hartke, C. Bormann, and B. Frank. “Constrained Application Protocol (CoAP).” *draft-ietf-core-coap-18*. s.l. : IETF, 2013.

[10] S. Deering and R. Hinden. “Internet Protocol, Version 6 (IPv6) Specification.” *RFC2460*. s.l. : IETF, 1998.

[11] G. Montenegro, N. Kushalnagar, J. Hui and D. Culler. “Transmission of IPv6 Packets over IEEE 802.15.4 Networks.” *RFC4944*: s.l. : IETF, Sep 2007.

[12] J. Hui and P. Thubert. “Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks.” *RFC6282*. s.l. : IETF, 2011.

[13] IEEE Computer Society. “IEEE Standard 802.15.4-2011.” [Online]. Available: http://standards.ieee.org/getieee802/download/802.15.4-2011.pdf

[14] IEEE Computer Society. “IEEE 802.15 WPAN Task Group 4e (TG4e). [Online]. Available: http://www.ieee802.org/15/pub/TG4e.html

[15] T. Winter, P. Thubert, A. Brandt, J. Hui, R. Kelsey, K. Pister, R. Struik, JP. Vasseur, and R. Alexander. “RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks.” *RFC6550*. s.l. : IETF, 2012.

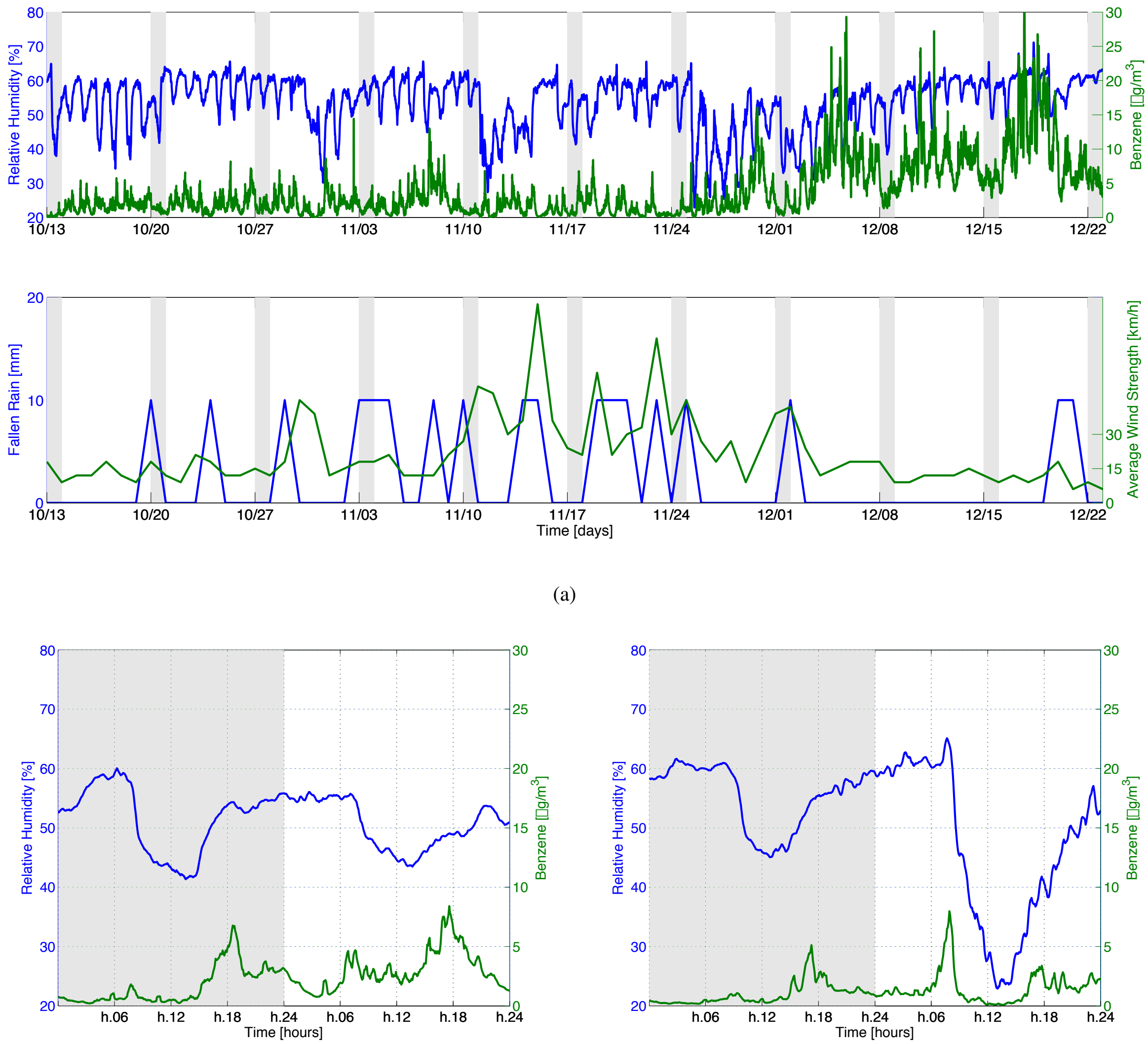


Fig. 6. Example of data collected by Padova Smart City: measured benzene signal (lower green line), plotted against the relative humidity signal (upper blue line), and compared with the weather conditions related to rainfall (discontinuous blue line) and wind (continuous green line). (a): whole time-series analysis; (b)-(c): daily analysis. The grey shadowing indicates Sundays.