Internet of Things for Smart Cities

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Abstract—The Internet of Things (IoT) shall be able to incorporate transparently and seamlessly a large number of different and heterogeneous end systems, while providing open access to selected subsets of data for the development of a plethora of digital services. Building a general architecture for the IoT is hence a very complex task, mainly because of the extremely large variety of devices, link layer technologies, and services that may be involved in such a system. In this paper, we focus specifically to an urban IoT system that, while still being quite a broad category, are characterized by their specific application domain. Urban IoTs, in fact, are designed to support the Smart City vision, which aims at exploiting the most advanced communication technologies to support added-value services for the administration of the city and for the citizens. This paper hence provides a comprehensive survey of the enabling technologies, protocols, and architecture for an urban IoT. Furthermore, the paper will present and discuss the technical solutions and best-practice guidelines adopted in the Padova Smart City project, a proof-of-concept deployment of an IoT island in the city of Padova, Italy, performed in collaboration with the city municipality.

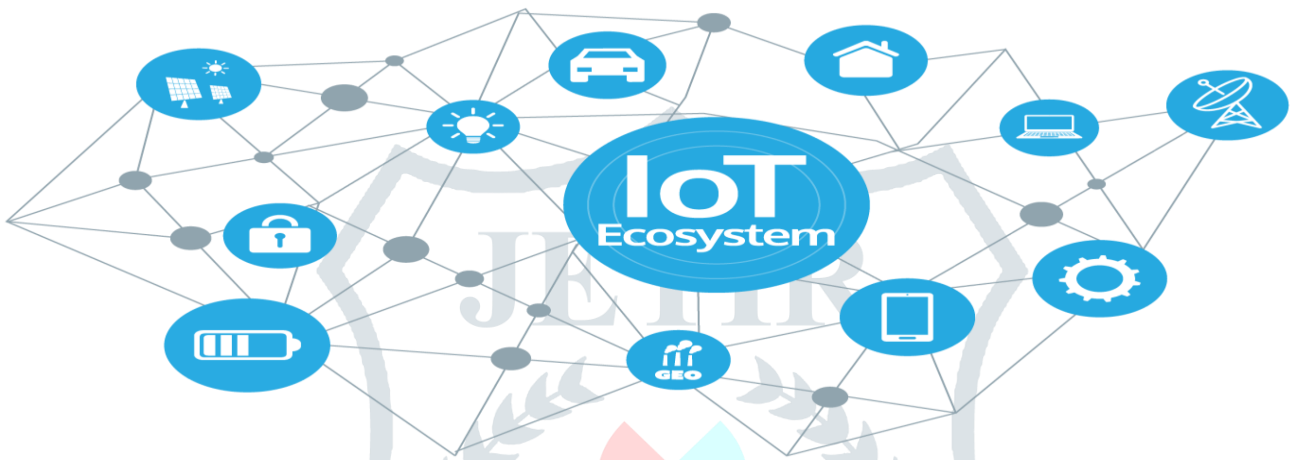
Key Terms—Constrained Application Protocol (CoAP), Efficient XML Interchange (EXI), network architecture, sensor system integration, service functions and management, Smart Cities, testbed and trials, 6lowPAN.

I. INTRODUCTION

THE Internet of Things (IoT) is a recent communication paradigm that envisions a near future, in which the objects of everyday life will be equipped with microcontrollers, transceivers for digital communication, and suitable protocol stacks that will make them able to communicate with one another and with the users, becoming an integral part of the Internet [1]. The IoT concept, hence, aims at making the Internet even more immersive and pervasive. Furthermore, by enabling 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 IoT will foster the development of a number of applications that make use of the potentially enormous amount and variety of data generated by such objects to provide new services to citizens, companies, and public administrations. This paradigm indeed finds application in many different domains, such as home automation, industrial automation, medical aids, mobile healthcare, elderly assistance, intelligent energy management and smart grids, automotive, traffic management, and many others [2].

However, such a heterogeneous field of application makes the identification of solutions capable of satisfying the requirements of all possible application scenarios a formidable challenge. This difficulty has led to the proliferation of different and, sometimes, incompatible proposals for the practical realization of IoT systems. Therefore, from a system perspective, the realization of an IoT network, together with the required backend network services and devices, still lacks an established best practice because of its novelty and complexity. In addition to the technical difficulties, the adoption of the IoT paradigm is also hindered by the lack of a clear and widely accepted business model that can attract investments to promote the deployment of these technologies [3].

In this complex scenario, the application of the IoT paradigm to an urban context is of particular interest, as it responds to the strong push of many national governments to adopt ICT solutions in the management of public affairs, thus realizing the so-called Smart City concept [4]. Although there is not yet a formal and widely accepted definition of "Smart City," the final aim is to make a better use of the public resources, increasing the quality of the services offered to the citizens, while reducing the operational costs of the public administrations. This objective can be pursued by the deployment of an urban IoT, i.e., a communication infrastructure that provides unified, simple, and economical access to a plethora of public services, thus unleashing potential synergies and increasing transparency to the citizens. An urban IoT, indeed, may bring a number of benefits in the management and optimization of traditional public services, such as transport and parking, lighting, surveillance and maintenance of public areas, preservation of cultural heritage, garbage collection, celebrity of hospitals, and school Furthermore, the availability of different types of data, collected by a pervasive urban IoT, may also be exploited to increase the transparency and promote the actions of the local government toward the citizens, enhance the awareness of people about the status of



their city, stimulate the active participation of the citizens in the management of public administration, and also stimulate the creation of new services upon those provided by the IoT [5].

Therefore, the application of the IoT paradigm to the Smart City is particularly attractive to local and regional administrations that may become the early adopters of such technologies, thus acting as catalyzers for the adoption of the IoT paradigm on a wider scale. The objective of this paper is to discuss a general reference framework for the design of an urban IoT. We describe the specific characteristics of an urban IoT, and the services that may drive the adoption of urban IoT by local governments. We then overview the web-based approach for the design of IoT services, and the related protocols and technologies, discussing their suitability for the Smart City environment. Finally, we substantiate the discussion by reporting our experience in the "Padova Smart City" project, which is a proof-of-concept deployment of an IoT is land in the city of Padova(Italy)and interconnected with the data network of the city municipality. In this regard, we describe the technical solutions adopted for the realization of the IoT island and report some of the measurements that have been collected by the system in its first operational days. The rest of the paper is organized as follows. Section II overviews the services that are commonly associated to the Smart City vision and that can be enabled by the deployment of an urban IoT. Section III provides a general overview of the system architecture for an urban IoT. More in detail, this section describes the web service approach for the realization of IoT services, with the related data formats and communication protocols, and the link layer technologies. Finally, Section IV presents the "Padova Smart City" project, which exemplifies a possible implementation of an urban IoT and provides examples of the type of data that can be collected with such a structure.

II. SMART CITY CONCEPT AND SERVICES

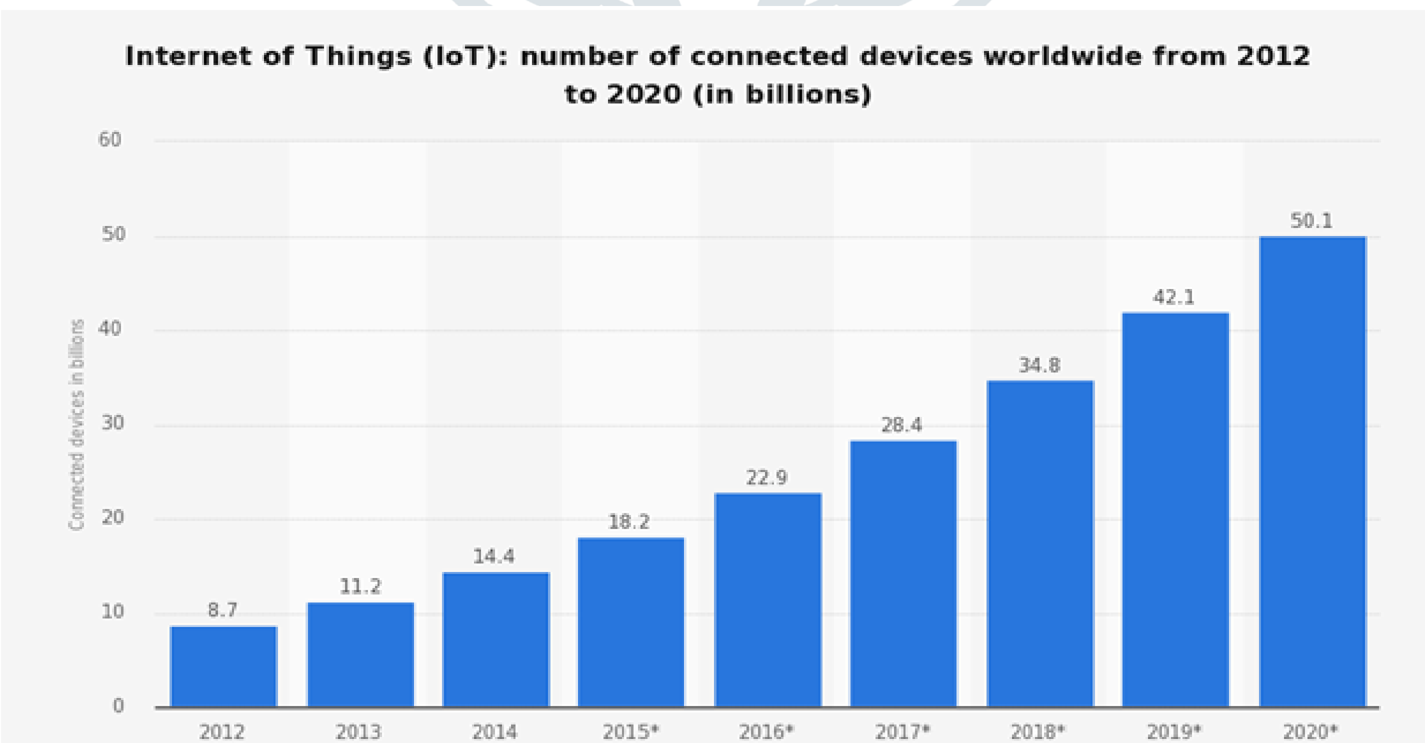
According to Pike Research on Smart Cities, the Smart City market is estimated at hundreds of billion dollars by 2020, with an annual spending reaching nearly 16 billion. This market springs from the synergic interconnection of key industry and service sectors, such as Smart Governance, Smart Mobility, Smart Utilities, Smart Buildings, and Smart Environment. These sectors have also been considered in the European Smart Cities project (http://www.smart-cities.eu) to define a ranking criterion that can be used to assess the level of "smartness" of European cities. None the less, the Smart City market has not really taken off yet, for a number of political, technical, and financial barriers [6]. Un der the political dimension, the primary obstacle is the attribution of decision-making power to the different stakeholders. A possible way to remove this roadblock is to institutionalize the entire decision and execution process, concentrating the strategic planning and management of the smart city aspects into a single, dedicated department in the city [7]. On the technical side, the most relevant issue consists in the non-interoperability of the heterogeneous technologies

currently used in city and urban developments. In this respect, the IoT vision can become the building block to realize a unified urban scale ICT platform, thus unleashing the potential of the Smart City vision [8], [9].

Finally, concerning the financial dimension, a clear business model is still lacking, although some initiative to fill this gap has been recently undertaken [10]. The situation is worsened by the adverse global economic situation, which has determined a general shrinking of investments on public services. This situation prevents the potentially huge Smart City market from becoming reality. A possible way out of this impasse is to first develop those services that conjugate social utility with very clear return on investment, such as smart parking and smart buildings, and will hence act as catalyze for the other added value services [10]. In the rest of this section, we overview some of the services that might be enabled by an urban IoT paradigm and that are of potential interest in the Smart City context because they can realize the win–win situation of increasing the quality and enhancing the services offered to the citizens while bringing an economical advantage for the city administration in terms of reduction of the operational costs [6]. To better appreciate the level of maturity of the enabling technologies for these services, we report in Table I a synoptic view of the services in terms of suggested type(s) of network to be deployed, expected traffic generated by the service, maximum tolerable delay, device powering, and an estimate of the feasibility of each service with currently available technologies. From the table, it clearly emerges that, in general, the practical realization of most of such services is not hindered by technical issues, but rather by the lack of a widely accepted communication and service architecture that can abstract from the specific features of the single technologies and provide harmonized access to the services.

Structural Health of Buildings: Proper maintenance of the historical buildings of a city requires the continuous monitoring of the actual conditions of each building and identification of the areas that are most subject to the impact of external agents. The urban IoT may provide a distributed database of building structural integrity measurements, collected by suitable sensors located in the buildings, such as vibration and deformation sensors to monitor the building stress, atmospheric agent sensors in the surrounding areas to monitor pollution levels, and temperature and humidity sensors to have a complete characterization of the environmental conditions [11]. This database should reduce the need for expensive periodic structural testing by human operators and will allow targeted and proactive maintenance and restoration actions. Finally, it will be possible to combine vibration and seismic readings in order to better study and understand the impact of light earthquakes on city buildings. This database can be made publicly accessible in order to make the citizens aware of the care taken in preserving the city historical heritage.

The practical realization of this service, however, requires the installation of sensors in the buildings and



surrounding areas and their interconnection to a control system, which may require an initial investment in order to create the needed infrastructure.

Waste Management: Waste management is a primary issue in many modern cities, due to both the cost of the service and the problem of the storage of garbage in landfills. A deeper penetration of ICT solutions in this domain, however, may result in significant savings and economical and ecological advantages. For instance, the use of intelligent waste containers, which detect the level of load and allow for an optimization of the collector trucks route, can reduce the cost of waste collection and improve the quality of recycling [12]. To realize such a smart waste management service, the IoT shall connect the end devices, i.e., intelligent waste containers, to a control center where an optimization software processes the data and determines the optimal management of the collector truck fleet.

Air Quality: The European Union officially adopted a 20-2020 Renewable Energy Directive setting climate changer education goals for the next decade. The targets call for a 20% reduction in greenhouse gas emissions by 2020 compared with 1990 levels, a 20% cut in energy consumption through improved energy efficiency by 2020, and a 20% increase in the use of renewable energy by 2020. To such an extent, an urban IoT can provide means to monitor the quality of the air in crowded areas, parks, or fitness trails [13]. In addition, communication facilities can be provided to let health applications running on joggers' devices be connected to the infrastructure. In such a way, people can always find the healthiest path for outdoor activities and can be continuously connected to their preferred personal training application. The realization of such a service requires that air quality and pollution sensors be deployed across the city and that the sensor data be made publicly available to citizens.

Noise Monitoring: Noise can be seen as a form of acoustic pollution as much as carbon oxide (CO) is for air. In that sense, the city authorities have already issued specific law stored the amount of noise in the city Centre at specific hours. An urban IoT can offer a noise monitoring service to measure the amount of noise produced at any given hour in the places that adopt the service [14]. Besides building a space-time map of the noise pollution in the area, such a service can also be used to enforce public security, by means of sound detection algorithms that can recognize, for instance, the noise of glass crashes or brawls. This service can hence improve both the quiet of the nights in the city and thidence of public establishment owners, althoue confgh the installation of sound detectors or environmental microphones is quite controversial, because of the obvious privacy concerns for this type of monitoring.

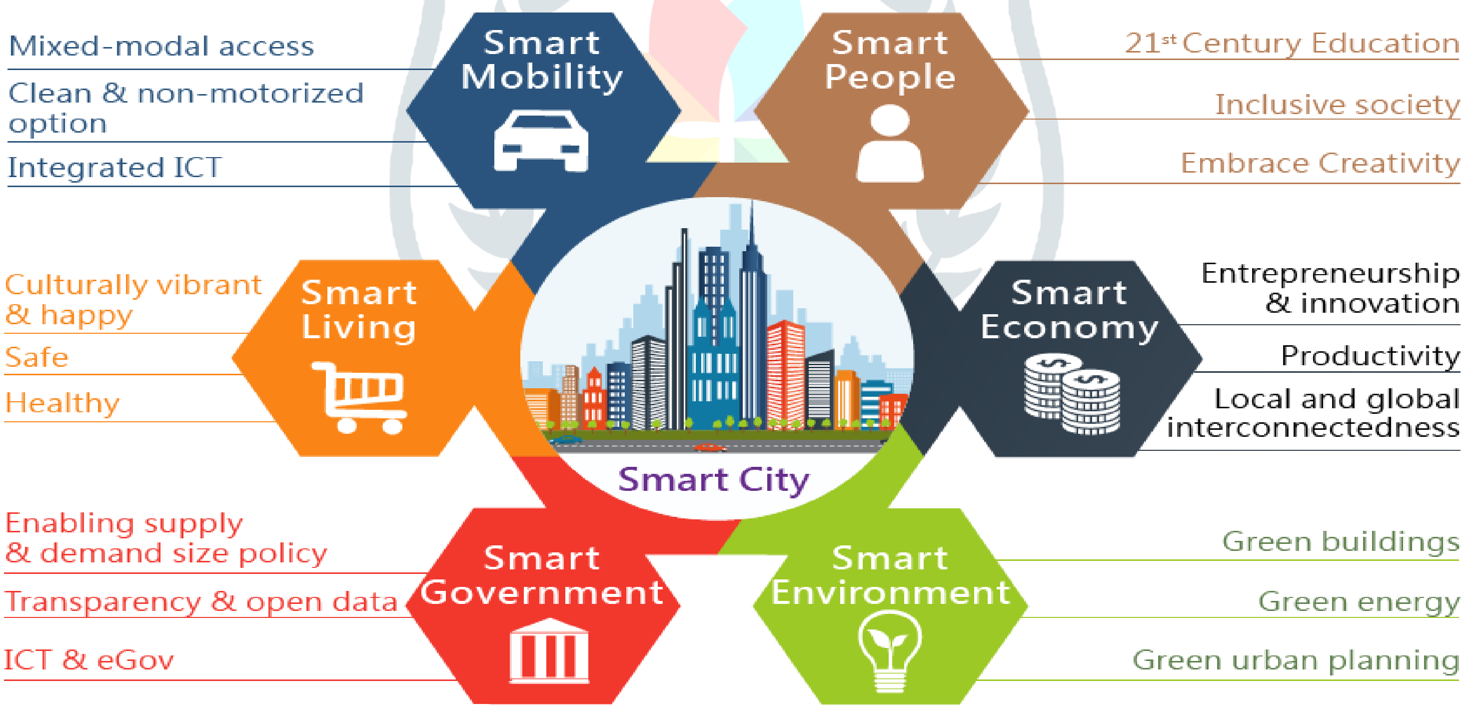
Traffic Congestion: On the same line of air quality and noise monitoring, a possible Smart City service that can be enabled by urban IoT consists in monitoring the traffic congestion in the city. Even though camera-based traffic monitoring systems are already available and deployed in many cities, low-power widespread communication can provide a denser source of information. Traffic monitoring may be realized by using the sensing capabilities and GPS installed on modern vehicles [15], and also adopting a combination of air quality and acoustic sensors along a given road. This information is of great importance for city authorities and citizens: for the former to discipline traffic and to send officers where needed and for the latter to plan in advance the route to reach the office or to better schedule a shopping trip to the city centre.

City Energy Consumption: Together with the air quality monitoring service, an urban IoT may provide a service to monitor the energy consumption of the whole city, thus enabling authorities and citizens to get a clear and detailed view of the amount of energy required by the different services (public lighting, transportation, traffic lights, control cameras, heating/cooling of public buildings, and so on). In turn, this will make it possible to identify the main energy consumption sources and to set priorities in order to optimize their behavior. This goes in the direction indicated by the European directive for energy efficiency improvement in the next years. In order to obtain such a service, power draw monitoring devices must be integrated with the power grid in the city. In addition, it will also be possible to enhance these service with active functionalities to control local power production structures (e.g., photovoltaic panels).

Smart Parking: The smart parking service is based on road sensors and intelligent displays that direct motorists along the best path for parking in the city [16]. The benefits deriving from this service are manifold: faster time to locate a parking slot means fewer CO emission from the car, lesser traffic congestion, and happier citizens. The smart parking service can be directly integrated in the urban IoT infrastructure, because many companies in Europe are providing market products for this application. Furthermore, by using short-range communication technologies, such as Radio Frequency Identifiers (RFID) or Near Field Communication (NFC), it is possible to realize an electronic verification system of parking permits in slots reserved for residents or disabled, thus offering a better service to citizens that can legitimately use those slots and an efficient tool to quickly spot violations.

Smart Lighting: In order to support the 20-20-20 directive, the optimization of the street lighting efficiency is an important feature. In particular, this service can optimize the street lamp intensity according to the time of the day, the weather condition, and the presence of people. In order to properly work, such a service needs to include the street lights into the Smart City infrastructure. It is also possible to exploit the increased number of connected spots to provide WiFi connection to citizens. In addition, a fault detection system will be easily realized on top of the street light controllers.

Automation and Salubrity of Public Buildings: Another important application of IoT technologies is the monitoring of the energy consumption and the salubrity of the environment in public buildings (schools, administration offices, and museums) by means of different types of sensors and actuators that control lights, temperature, and humidity. By controlling these parameters, indeed, it is possible to enhance the level of comfort of the persons that live in these environments, which may also have a positive return in terms of productivity, while reducing the costs for heating/cooling [17].



III. URBAN IOT ARCHITECTURE

From the analysis of the services described in Section II, it clearly emerges that most Smart City services are based on a centralized architecture, where a dense and heterogeneous set of peripheral devices deployed over the urban area generate different types of data that are then delivered through suitable communication technologies to a control center, where data storage and processing are performed.

A primary characteristic of an urban IoT infrastructure, hence, is its capability of integrating different technologies with the existing communication infrastructures in order to support a progressive evolution of the IoT, with the interconnection of other devices and the realization of novel functionalities and services. Another fundamental aspect is the necessity to make (part of) the data collected by the urban IoT easily accessible by authorities and citizens, to increase the responsiveness of authorities to city problems, and to promote the awareness and the participation of citizens in public matters [9].

In the rest of this section, we describe the different components of an urban IoT system, as sketched in Fig. 1. We start describing the web service approach for the design of IoT services, which 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 architecture. Then, we briefly overview the link layer technologies that can be used to interconnect the different parts of the IoT. Finally, we describe the heterogeneous set of devices that concur to the realization of an urban IoT.

A. Web Service Approach for IoT Service Architecture

Although in the IoT domain many different standards are still struggling to be the reference one and the most adopted, in this section we focus specifically on IETF standards because they are open and royalty-free, are based on Internet best practices, and can count on a wide community.

The IETF standards for IoT embrace a web service architecture for IoT services, which has been widely documented in the literature as a very promising and flexible approach. In fact, web services permit to realize a flexible and interoperable system that can be extended to IoT nodes, through the adoption of the web-based paradigm known as Representational State Transfer (ReST) [18]. IoT services designed in accordance with the ReST paradigm exhibit very strong similarity with traditional web services, thus greatly facilitating the adoption and use of IoT by both end users and service developers, which will be able to easily reuse much of the knowledge gained from traditional web technologies in the development of services for networks containing smart objects. The web service approach is also promoted by international standardization bodies such as IETF, ETSI, and W3C, among others, as well as European research projects on the IoT such as SENSEI,5 IoT-A,6 and SmartSantander.1

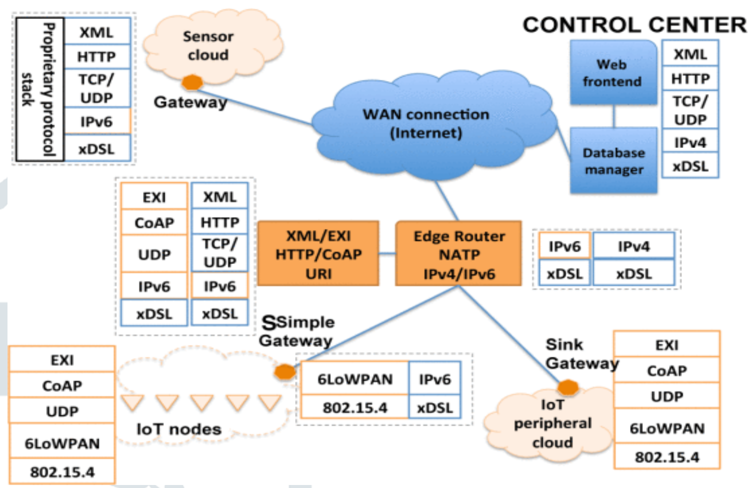
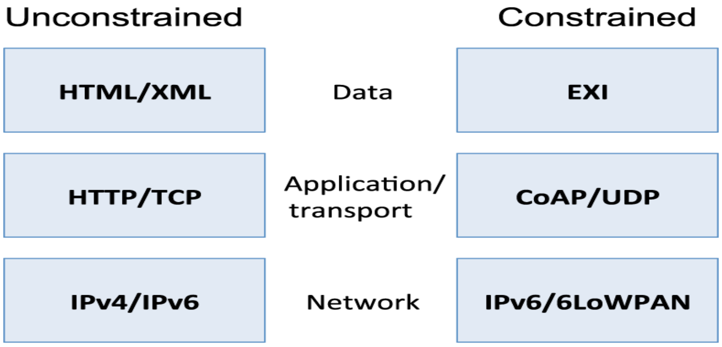


Fig. 2 shows a reference protocol architecture for the urban IoT system that entails both an unconstrained and a constrained protocol stack. The first consists of the protocols that are currently the de-facto standards for Internet communications, and are commonly used by regular Internet hosts, such as XML, HTTP, and IPv4. These protocols are mirrored in the constrained protocol stack by their low-complexity counterparts, i.e., the Efficient XML Interchange (EXI), the Constrained Application Protocol (CoAP), and 6LoWPAN, which are suitable even for very constrained devices. The transcoding operations between the protocols in the left and right stacks in Fig. 2 can be performed in a standard and low complexity manner, thus guaranteeing easy access and interoperability of the IoT nodes with the Internet. It may be worth remarking that systems that do not adopt the EXI/CoAP/6LoWPAN protocol stack can still be seamlessly included in the urban IoT system, provided that they are capable of interfacing with all the layers of the left-hand side of the protocol architecture in Fig. 2.



In the protocol architecture shown in Fig. 2, we can distinguish three distinct functional layers, namely (i) Data, (ii) Application/Transport, and (iii) Network, that may require dedicated entities to operate the transcoding between constrained and unconstrained formats and protocols. In the rest of this section, we specify in greater detail the requirements at each of the three functional layers in order to guarantee interoperability among the different parts of the system.

B. Link Layer Technologies

An urban IoT system, due to its inherently large deployment area, requires a set of link layer technologies that can easily cover a wide geographical area and, at the same time, support a possibly large amount of traffic resulting from the aggregation of an extremely high number of smaller data flows. For these reasons, link layer technologies enabling the realization of an urban IoT system are classified into unconstrained and constrained technologies. The first group includes all the traditional LAN, MAN, and WAN communication technologies, such as Ethernet, WiFi, fiber optic, broadband Power Line Communication (PLC), and cellular technologies such as UMTS and LTE. They are generally characterized by high reliability, low latency, and high transfer rates (order of Mbit/s or higher), and due to their inherent complexity and energy consumption are generally not suitable for peripheral IoT nodes.

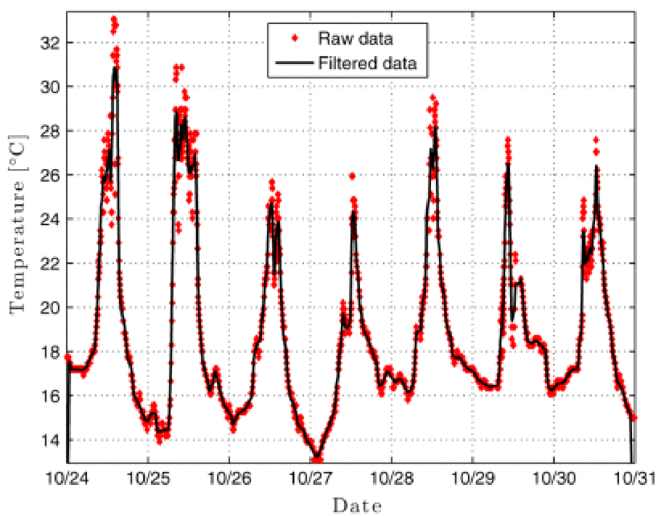
The constrained physical and link layer technologies are, instead, generally characterized by low energy consumption and relatively low transfer rates, typically smaller than 1 Mbit/s. The more prominent solutions in this category are IEEE 802.15.4 [27], [28] Bluetooth and Bluetooth Low Energy,8 IEEE 802.11 Low Power, PLC [29], NFC and RFID [30]. These links usually exhibit long latencies, mainly due to two factors: 1) the intrinsically low transmission rate at the physical layer and 2) the power-saving policies implemented by the nodes to save energy, which usually involve duty cycling with short active periods.

IV. An experimental Study: Padova Smart City

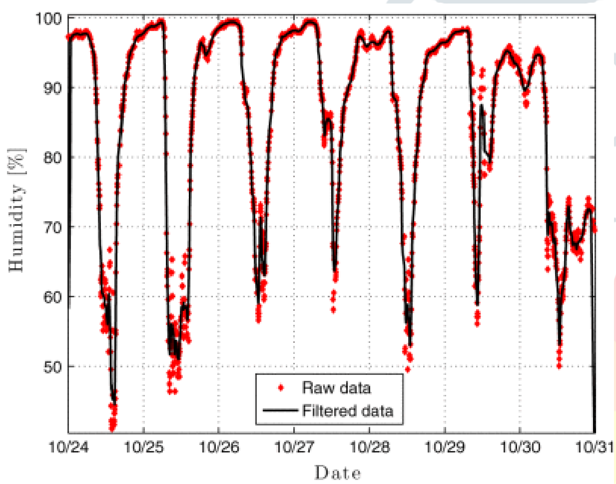
The framework discussed in this paper has already been successfully applied to a number of different use cases in the context of IoT systems. For instance, the experimental wireless sensor network testbed, with more than 300 nodes, deployed at the University of Padova [31], [32] has been designed according to these guidelines, and successfully used to realize proof-of-concept demonstrations of smart grid [33] and health care [34] services.

The primary goal of Padova Smart City is to promote the early adoption of open data and ICT solutions in the public administration. The target application consists of a system for collecting environmental data and 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. This system shall make it possible to collect interesting environmental parameters, such as CO level, air temperature and humidity, vibrations, noise, and so on, while providing a simple but accurate mechanism to check the correct operation of the public lighting system by measuring the light intensity at each post. 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. A high-level overview of the types and roles of the devices involved in the system is given hereafter.

Example of Data Collected by Padova Smart City



(a)



(b)

Figs. 4 report an example of the type of data that can be collected with the Padova Smart City system. The four plots show the temperature, humidity, light, and benzene readings over a period of 7 days. Thin lines show the actual readings, while thick lines are obtained by applying a moving average filter over a time window of 1 h (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). 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, due to the reflections produced by vehicle lights. A similar pattern is exhibited by the humidity and temperature measurements that, however, are much more noisy than those for light. The benzene measurements also reveal a decrease of the benzene levels at nighttime, as expected due to the lighter night traffic, but quite surprisingly there are no evident variations in the daytime benzene levels during the weekend (October 26–27). It is also interesting to note the peak of benzene measured in the early afternoon of October 29. Examining the readings of the other sensors in the same time interval, we can note a sharp decrease of light intensity and temperature, and an increase in humidity. These readings suggest that a quick rainstorm has temporarily obscured the sunlight, while producing congestion in the road traffic and, in turn, a peak of benzene in the air.

Conclusion

In this paper, we analyzed the solutions currently available for the implementation of urban IoTs. The discussed technologies are close to being standardized, and industry players are already active in the production of devices that take advantage of these technologies to enable the applications of interest, such as those described in Section II. In fact, while the range of design options for IoT systems is rather wide, the set of open and standardized protocols is significantly smaller. The enabling technologies, furthermore, have reached a level of maturity that allows for the practical realization of IoT solutions and services, starting from field trials that will hopefully help clear the uncertainty that still prevents a massive adoption of the IoT paradigm. A concrete proof-of-concept implementation, deployed in collaboration with the city of Padova, Italy, has also been described as a relevant example of application of the IoT paradigm to smart cities.

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