Smart cities: potential and challenges

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Abstract. This paper aims to discuss a few fundamental questions related to the smart city paradigm, such as "what is actually a smart city?", "what can we expect from a smart city?", and "which problems have to be addressed and solved in order to turn a standard (dumb) city into a smart one?" Starting from a discussion of the Smart City concept, we will illustrate some of the most popular smart services using the results of proof-of-concept experiments carried out in different cities around the world. Successively, we will describe the fundamental functions required to build a smart service and the corresponding enabling technologies. We will then describe the main research challenges that need to be addressed in order to fulfill the Smart City vision, and we will conclude with some final remarks and considerations about the possible evolution of the Smart City concept.

Keywords: smart cities, smart services, smart governance, smart mobility, smart buildings

Ciudades inteligentes: potencial y desafíos

Resumen. Este documento tiene como objetivo discutir algunas cuestiones fundamentales relacionadas con el modelo de una ciudad inteligente, tales como: ¿qué es realmente una ciudad inteligente?, ¿qué se espera de una ciudad inteligente? y ¿qué problemas tienen que ser abordados y resueltos para transformar una ciudad estándar ("*dumb*") en una ciudad inteligente? A partir de la discusión del concepto de Ciudad Inteligente, ilustraremos algunos de los servicios inteligentes más populares utilizando los resultados experimentales de pruebas de concepto llevadas a cabo en diferentes ciudades del mundo. Seguidamente, se describirán las funciones fundamentales requeridas para crear un servicio inteligente y las tecnologías que las hacen posibles. Asimismo, se expondrán los principales retos de la investigación que necesitan ser abordados para completar la visión de Ciudad Inteligente, y terminaremos con algunas observaciones y consideraciones finales sobre la posible evolución del concepto de Ciudad Inteligente.

Palabras clave: ciudades inteligentes, servicios inteligentes, gobierno inteligente, movilidad inteligente, edificios inteligentes

1. Introduction

We are undoubtedly entering into a "smart" era: we own smart phones, wear smart watches, watch smart TVs, use smart appliances, and dream to live in smart cities.

As a matter of fact, an increasing number of cities around the world (Caragliu, Del Bo, & Nijkamp, 2011), including global capitals such as Barcelona (Gascó-Hernandez, 2018), New York City, Amsterdam, and Singapore, as well as smaller towns such as Padova-Italy (Cenedese, Zanella, Vangelista, & Zorzi, 2014), have initiated what we can define as a "smartening" process.

However, despite the steady stream of scientific and technical publications, articles on magazines, and web pages dedicated to the Smart City idea, we still lack a formal and universally accepted definition of this paradigm. For example, Hall et al. (2000) offer a rather broad interpretation of the Smart City concept, which embraces services, technologies, and processes.

> The vision of Smart Cities is the urban center of the future, made safe, secure, environmentally green, and efficient because all structures–whether for power, water, transportation, etc.–are designed, constructed, and maintained making use of advanced, integrated materials, sensors, electronics, and networks which are interfaced with computerized systems comprised of databases, tracking, and decision-making algorithms. (Hall et al., 2000)

A more technical-centered vision is offered by Daniel and Doran (2013), where they associate the smartness of a city to the existence of a city-wide communication infrastructure, and the existence of software and sensors that can improve the quality of life of citizens: A city that has deployed and integrated on a large-scale advanced information and communications technology (ICT), including wireless and broadband connections, advanced analytic software, and intelligent sensors, to achieve significant improvements in efficiency and in the quality of life, and to help change the behavior among residents, businesses, and governments, so cities can grow in a more sustainable way.

A similar vision is proposed by IBM, which suggests a holistic approach, focused on integrated technologies. Again, the objectives are related to quality of life in general[1]: Cities must take greater advantage of the most advanced technologies to update service delivery. Cognitive computing [. . .] introduces fresh opportunities for government organizations to improve citizens' lives and the business environment, deliver personalized experiences, and optimize program and service outcomes.

1 IBM, Smarter Cities – Overview, Online Available: http://www.ibm.com/smarterplanet/us/en/smarter_cities/overview. Last visited on: 20 Sept. 2018.

Lombardi, Giordano, Farouh, & Yousef (2012) stress the relationship between citizens and system administration, a point of view shared by Toppeta (2010) who defines a smart city as "A city "combining ICT and Web 2.0 technology with other organizational, design and planning efforts to dematerialize and speed up bureaucratic processes and help to identify new, innovative solutions to city management complexity, in order to improve sustainability and livability".

Also, Giffinger et. al (2007) stress the role of citizens in the smart city ecosystem, remarking their ability of being self-decisive, independent, and aware.

By making an abstraction effort, we can identify three main aspects that are common in most of the definitions and visions of Smart City proposed in the literature, and that can be assumed as the actions that may turn a dumb city into a smart one, namely:

- Improving the quality of public services and of the urban environment
- Reducing the Operational Expenditure (OPEX) of such services or, at least, improving the quality/OPEX ratio
- Closing the gap between citizens and public administration

We can hence state that the ultimate objective of a smart city is to make a more efficient use of public resources, whether they are material or human.

The information and communication technologies (ICT) are definitely instrumental to achieve such an ambitious objective but are not the only enabler. Citizens indeed play an equally important role, as it will be discussed in the next sections.

In the rest of this paper, we will illustrate the potential of the Smart City concept by briefly describing some notable smart city services and applications, some of which have already been deployed in practice. We will then describe the enabling technologies, with particular attention to the communication systems, and we will finally conclude with a discussion of the open challenges that still need to be addressed in order to fully unleash the potential of the Smart City paradigm, and of the emerging trends.

2. The potential of the Smart City concept

A modern city can be seen as a complex ecosystem consisting of infrastructures, processes, and citizens. The city administration is in charge of designing, developing, and managing the infrastructures and processes of a city to guarantee sustainability, while providing for the needs of the citizens in a way that accounts for their traditions, habits, lifestyles, and expectations. Therefore, citizens should be at the center of the design of a smart city and, indeed, most of the smart services proposed so far are intended to improve the quality of life in the city, with a double return in terms of satisfaction of the citizens and reduction of the OPEX.

By considering the solutions proposed in the literature, and the services already implemented by some important cities in the world, we can identify six thrusts that should be addressed in the design of a smart city: namely, governance, citizens, mobility, utilities, buildings, and environment (see Fig. 1).

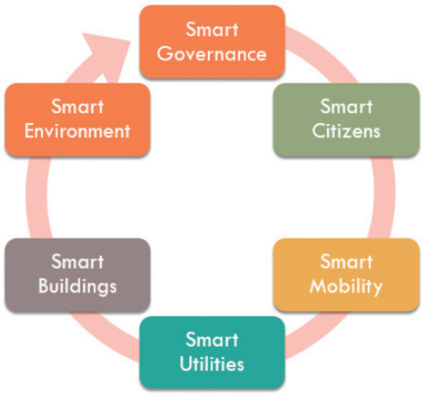

Figure 1. Smart city thrusts
Elaborated by the author

In order to exemplify and discuss the potential of the Smart City concept, we will briefly illustrate how each of the above thrusts can take form into practical services and applications.

2.1 Smart governance

The ultimate goal of Smart Governance is to (dramatically) improve the governance processes of the city by favoring the coordination of the different involved agencies, reducing the complexity of the administrative mechanisms, and improving transparency towards the citizens.

A first necessary (though not sufficient) step to achieve this ambitious goal is the harmonization and consolidation of the digital systems used by the different governance agencies into a single digital platform. Such a solution would provide dramatic advantages to both the citizens and the city administration. The citizens would indeed have one single point of access to the public administration, whether it is for residential, fiscal, education, medical, or any other matter, greatly reducing the waste of time (and frustration) of interacting with many different public offices. At the same time, the public administration would have a simple and effective way to access demographic, corporate, and other types of data, with the possibility of drawing demographic maps of the city, identifying spontaneous communities, revealing the risks of the segregation of part of the population and the creation of ghettos, tracking the demographic flows, and so on. In addition, using one single platform in place of many (heterogeneous) systems would translate in a reduction of the costs to acquire, deploy, and maintain the information infrastructure, which can then be realized by leveraging the Infrastructure/Platform/Software-as-a-Service (IaaS, PaaS, SaaS) paradigms.

Therefore, from a technical point of view, enabling the Smart Governance vision will require access to cloud services, which can either be provided autonomously by a central public office, or rented from an external service provider. The peripheral offices, in turn, will only need a good broadband connection to the governmental cloud in order to enable the PaaS and SaaS solutions.

2.2 Smart citizens

As mentioned before, smart cities should be built around their citizens, not only for philosophical or social motivations but also for a very pragmatic reason: Public administrators need to build consensus about their policy among the citizens, and the investments in smart city services may have an economical return only in the long term (likely longer than their public mandate). Therefore, in order to accept the expenses in smart city services, citizens must be informed and involved in the creation of their own smart city.

This engagement can be pursued in different ways. One possibility is to increase transparency of the administration processes by giving public access to a number of information regarding the current urban scenario as, for example, real-time maps of traffic, pollution, schools population, criminality, and so on. A second action may consist in providing tools to collect feedback from the citizens in order to realize a two-way communication channel between citizens and administrators. Although today many administrations have citizen offices to listen to the people's needs, the process will be greatly improved by dematerializing it through a digital platform that allows the citizens to express their opinions, suggestions, and requests in a simple and convenient manner. Such a platform may also be used to improve some public services with the help of the citizens that, for example, may indicate a malfunctioning of the public illumination system, broken/full trash bins, holes in streets or sideways, dangerous situations, and so on[2].

Along the same line of thinking, citizens can be deeply involved in the creation of new smart city services. An example of this type of action is provided by the annual Amsterdam Smart City Challenge, a yearly event that is aimed at collecting ideas for new services directly from the citizens. One such challenge has led to the development of the Mobypark app[3], which allows owners of parking spaces to rent them out to people for fee, while the data generated from this app can be used by the city administration to determine parking demands and traffic flows in Amsterdam.

2 See, e.g., http://www.decorourbano.org

3 https://www.mobypark.com/en

Note that all of this would be easily realizable within the Smart Government framework described before, which remarks the potential synergy among the many facets of the smart city ecosystem.

2.3 Smart mobility

Mobility is a major issue in most modern cities, with a huge impact on the life quality of the citizens and the healthiness of the environment, not to mention the economic impact that slow urban mobility can have on basically all business sectors. Many metropolises today discourage the urban use of private motor vehicles, e.g., by applying fees to enter the city, or limiting the access to most critical areas, or even increasing the taxes for cars' owners. At the same time, they promote alternative mobility through the creation of pedestrian areas and bike lanes, and offering bike- and car-sharing services. These initiatives are complemented by efficient and capillary public mobility services, which include buses and (subway) trains, with routes and time schedules designed to best suit the mobility flows in town.

Knowing such mobility flows is hence pivotal to realize smart mobility plans. For this reason, traffic monitoring systems have been widely deployed in many cities. In particular, the last generations of traffic monitoring cameras can provide a number of useful information, such as real-time traffic maps, detection of congestion and accidents, recognition of speed and traffic light violations, and even checking each single vehicle's condition (revision, insurance, taxes), by means of real-time plate identification and access to the motorist's databases.

Besides driving the public administration decisions regarding the discipline of traffic and the planning of public transportation, the data collected by the traffic monitoring services can also be used to display real-time maps of roads congestion in the city, thus making it possible for citizens to better plan their trip to the office or decide which means to take. By combining this information with a smart traffic lighting system, it is furthermore possible to realize advanced services, as done in Barcelona, where a traffic management system can track the position and direction of the public transportation and emergency vehicles, and make them find green traffic lights at intersections[4].

Smart parking is another very useful service that can contribute to the reduction of traffic and pollution in a city. Its realization requires the deployment of a grid of sensors to monitor the occupancy of the different parking spaces. The information is usually delivered to a central control station that makes it available in real-time to the drivers through digital roadside panels or web apps. The sensing can be realized either by equipping each parking slot with a very simple sensor that can detect the presence of a vehicle, or by means of cameras that,

4 https://www.barcelona-metropolitan.com/features/smart-city-Barcelona/

using advanced signal processing techniques, can recognize which parking places are available and which are occupied. The data collected by these sensors is then sent to the control station through different transmission technologies, which will be described in Section 3.2.

2.4 Smart utilities

A city is expected to provide a number of utilities to its citizens, such as electric power, water, gas, and waste collection. These services are generally offered by a number of different private or public companies that often operate in a competitive market, despite in certain cases they basically hold a monopolistic position. Clearly, the costs to realize and maintain the infrastructures required to deliver such services is reflected into the bills paid by the citizens, though sometimes the municipality covers part of such costs. Therefore, improving said services and reducing the OPEX can provide substantial advantages to both citizens and public administration.

Once again, the information and communication technologies can play an important role in this context. An example is the smart power grid which enhances the current power grid with monitoring stations that can instantaneously measure the values of active and reactive power along the lines, thus making it possible to identify the lines with a higher power dispersion caused by an imbalance between the different current phases. The smart grid can also include equalization elements to counteract the fluctuations in voltage levels due to the injection of power into the network by secondary power sources (such as small/domestic solar energy plants). In addition, it may be possible to deploy power storage units that can store the excess of power generated by such energy sources and release it when demanded by the consumers in order to minimize the costs (Erseghe, Zanella, & Codemo, 2014). In 2005, one of the main Italian power suppliers, ENEL, started deploying the first national smart grid with a cost of 2.1 billion euros. However, the investment returned 500 millions per year in OPEX reduction. Furthermore, smart grids are expected to be able to decrease CO2 emissions by 12% in the USA and 15% in India (National Energy Technology Laboratory, 2007, p.17; Webb, 2008).

Similarly, sensors can be deployed to monitor the provisioning of water and gas, thus making it possible not only to obtain a real-time view of the service demand but also to rapidly detect problems such as leakages or pipe obstructions, dramatically reducing the time and cost of repairs.

2.5 Smart buildings

Many cities around the world dedicate an important budget to the preservation of their historical heritage. For example, the Scrovegni Chapel, in the city of Padova (Italy), contains some fragile frescoes painted by Giotto in the fourteenth century that need to be protected from the risk of degradation due to air pollution and humidity, as well as the high levels of CO2 that may be generated by letting many tourists stay in the small chapel for long periods. To this end, the chapel has been equipped with an advanced heating ventilation air conditioning (HVAC) and air cleaning system, and with some sensors that monitor the quality of the air in the chapel. An algorithm then control the HVAC system in order to constantly maintain ideal environmental conditions within the chapel, irrespective of the external weather conditions and number of visitors (whose access rate is, anyway, limited and controlled). Similar monitoring systems are deployed in many historical buildings and museums with the main objective of preserving the artworks. The most advanced systems can provide a plethora of additional services, including information to the visitors (smart museum), monitoring of the affluence and permanence time of visitors in the different rooms of an exhibition center, theft prevention, and so on.

Note that the inertia of environmental conditions (temperature, humidity), particularly in large buildings, may delay the detection of variations of comfort levels, which may result in a late overreaction of the HVAC control system. This generates the typical oscillations in the comfort level of public environments (especially when occupied by a variable number of people during the day, as in school classrooms, museums, or conference rooms) with an important power consumption. Deploying a large number of (simple) environmental monitoring devices, which can provide an almost real-time map of the comfort levels in a building, and exploiting sophisticated models to predict the dynamics of the environmental conditions (possibly based on historical data through machine-learning techniques) would make it possible to realize real-time control systems that perform fine-grain proactive control of the HVAC system in order to stabilize the comfort level while reducing the power consumption of the system.

2.6 Smart environment

The preservation of the environment is another key aspect of the Smart City vision. Many metropolitan areas in the world live under a dome of pollution generated by vehicle emissions, building heating/cooling systems, and industrial activities. Furthermore, waste management is another factor with a significant impact in the urban ecosystem, both in environmental and economic terms.

The deployment of smart mobility, smart utilities, and smart building solutions can significantly contribute to alleviate the environmental footprint of cities, particularly in terms of air quality. In addition, the adoption of intelligent waste management systems can contribute to increase the amount and quality of recyclable garbage, with a positive effect on both the environment and service costs. For example, sensors can be applied to waste bins to periodically check their filling level and report this value to a control station, which can then optimize the route of the collector truck, increasing the efficiency and improving the quality of the service offered to the citizens.

2.7 The power of integration

Clearly, the service taxonomy that we used to illustrate the different lines of action and that can be followed to realize a smart city is rather artificial. In practice, a service may impact the urban tissue in many different ways. For example, a bike-sharing system can help to reduce the traffic congestion (smart mobility) and air pollution (smart environment). Furthermore, the data generated by the bike-sharing service can provide useful information of the citizens' habits (smart government) to the city administration. As an example, in Chiariotti, Pielli, Zanella, & Zorzi (2018), the data regarding the use of bikes provided by the New York City bike-sharing service[5] has been used to track the main flows in the city, revealing the most "critical" bike stations. In addition, the access to such open data has made it possible to develop a mathematical model of the bike-sharing system and propose a methodology to improve the quality of the service offered to the citizens, while reducing the OPEX. As a further example, the access to the data regarding the utilization of the bike-sharing service provided by the municipality of Padova (Italy) has enabled the identification of clear-usage patterns, namely, from the train station to the university departments and back, which has permitted to (i) propose some improvements in the bike redistribution policy and (ii) design a system to help the redistribution of the bikes by the same users through a gamification approach (smart citizens).

A few regions in Italy have understood the potential of service integration and have centralized all information technology services into a single agency. In this way, it has been possible to reduce the costs to develop new infrastructures, thanks to the economy of scale, and promote the development of cross-sector applications, thanks to the use of a common software platform (smart government). One such application cross-references road accidents to the medical reports of the people involved in them, in order to identify the most dangerous roads and plan targeted road interventions (smart mobility).

Therefore, we can conclude that the full power of the Smart City vision can be expressed only by crossing the boundary of isolated services and merging multiple services into technologies.

In the following section, we will describe which technologies can be used to support such a vision.

3. Enabling technologies

The previous section described some of the possible advanced services that collectively contribute to make a city smarter. Although the list is far from being exhaustive, it is still apparent that the support of such services will require different technologies at all levels of the protocol

5 https://www.citibikenyc.com/system-data

stack. Nonetheless, most of such services share a common (despite rather abstract) logical structure which consists of the following five phases:

- Creating data
- Collecting data
- Sharing data
- Extracting information
- Building services

In the rest of this section, we will briefly describe the purpose and technical requirements of each such phases.

3.1 Creating data

Most smart city services need to collect data from the environment, e.g., light, temperature, humidity, pollution, proximity of people/vehicle, pressure, and so on. This data is generated by sensing devices that, to simplify the deployment of the services, should ideally be low cost, easy to configure and connect to the Internet, and self-sustainable without the need for maintenance. Such requirements are actually demanding and not easy to be satisfied.

To enable the so-called place-&-play functionality, i.e., the possibility to set up the system with little (if not zero) configuration (Biral, Centenaro, Zanella, Vangelista, & Zorzi, 2015), the devices need to be able to connect to the Internet (as for the Internet-of-Things paradigm) and to self-configure (authenticate itself to the server, configure the transmission parameters, etc.), which requires some computation, storage and communication capabilities.

Furthermore, in many cases, it may not be practical, or even feasible, to connect the peripheral devices to the power grid, so that sensor nodes may have to be battery powered. In order to minimize the need for maintenance, such devices must be extremely energy efficient, reaching a lifetime of ten to twenty years without the need for battery replacement, which can represent an important cost and be even infeasible in certain scenarios. Ideally, sensor nodes should be energy neutral, i.e., capable of scavenging the required energy from renewable environmental sources (typically, using small solar panels).

Unfortunately, these requirements contrast with the need to reduce the manufacturing costs, which increase with the complexity of the hardware. To overcome this roadblock, it is hence necessary to work on the software components of the system, trying to engineer all the processes (environmental sensing, data storing, data processing, and data transmission) in order to provide the required service level while minimizing the energy expenditure (Biason et al., 2017).

3.2 Collecting data

Once data is generated by the so-called "data producers" (i.e., the sensor nodes), it requires to be made available for the services that need to use it, which are generally referred to as "data consumers." To this end, the first step consists in providing digital connectivity to the end devices, i.e., supporting what in the literature is often referred to as Machine Type Communication (MTC). Although the IoT paradigm would require that each single node supports the TCP/IP protocol stack, thus being able to talk to any other node in the Internet, in practice, the limitations of the end devices make it preferable to connect them to the Internet through an intermediate node called Gateway, which acts as proxy between the end devices and the IP world. Then, the connection between sensor nodes and gateway can be realized using dedicated transmission technologies, in many cases wireless, specifically designed to support MTC.

Today, there is a plethora of such technologies with different capabilities and characteristics. A possible classification is depicted and described in Fig. 2.

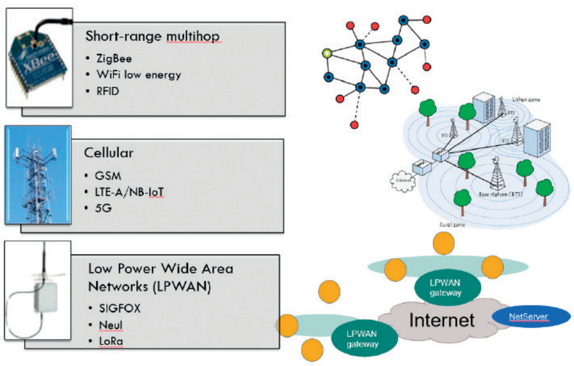

Figure 2. MTC wireless technologies classification

Elaborated by the author

3.2.1 Short-range multi-hop

Short-range wireless technologies were originally designed to interconnect electronic devices in close proximity, such as headsets and phones, or laptops and printers, as in the case of Bluetooth. Successively, they have been considered to interconnect electronic devices in office or home environments, realizing the so-called Domotic Scenario. They are characterized by low cost, low-energy consumption, and medium bitrates (from hundreds of Kbit/s to few Mbit/s).

However, their coverage range is typically limited to a few meters, and the coverage of large areas requires the adoption of multi-hop transmissions, i.e., node-to-node packet relaying, until the gateway is reached. However, the management of a multi-hop network is complex, since it requires nodes discovery, network establishment, routing, and so on. Furthermore, considering the variability of the wireless medium, the connectivity of the network can vary in time, making the multi-hop packet delivery even more challenging, and increasing the energy consumption of the nodes.

Among the most popular technologies of this class, we can mention Bluetooth, particularly in its Low Energy version (BLE), ZigBee, Z-Wave, IEEE 802.15.4, and others.

3.2.2 Cellular

Contrarily to the short-range multi-hop class, cellular technologies offer very large coverage ranges with single-hop communication between peripheral nodes and gateway (which is called Base Station, or eNB, in the cellular system terminology). Furthermore, the cellular networks of the main operators offer almost ubiquitous coverage without the need to deploy new infrastructure.

On the other hand, the cost of cellular radio transceivers is still significantly high for MTC applications due to its energy consumption. The most common cellular technologies that are used today for MTC are GSM (in particular, GPRS) and LTE-A. However, both systems have been designed to support broadband data transmissions characterized by few devices per cell that generate significant data traffic. MTC has almost dual characteristics, since it is typically generated by a massive amount of devices densely deployed in the coverage range of a cell, each of which generates a tiny amount of traffic (on the order of packets per minute or less). Therefore, traditional cellular technologies can be unsuitable to support MTC, which is affected by the so-called Massive Access Problem (Biral et al., 2015; Polese, Centenaro, Zanella, & Zorzi, 2016; Zanella et al., 2013).

Recently, the 3GPP standards organization released the specifications for the long-awaited Narrow Band IoT (NB-IoT), an amendment to the LTE standard that has explicitly been designed to support MTC, and that greatly alleviates the massive access problem. Although the standard promises very low energy consumption and good bitrates, some preliminary studies reveal that the power consumption and the cost of the devices can still be too high for some applications, thus limiting the range of applicability of this technology (Sinha, Wei, & Hwang, 2017).

3.2.3 Low Power Wide Area Networks (LPWAN)

The design of this family of technologies has been explicitly targeted to MTC. These systems are indeed characterized by an extremely long coverage range (from few kilometers in urban areas to tens of kilometers in rural areas) and a very low power consumption. Such nice features have been obtained by compromising the bitrate, which is usually very low (on the order of hundreds of bit/s), and the delay, which is instead quite long (on the order of seconds). However, many services that require MTC do not have strict requirements in terms of bitrate and delay, and can therefore fruitfully adopt LPWAN solutions.

Although there has been a proliferation of LPWAN technologies in the last years (Centenaro, Vangelista, Zanella, & Zorzi, 2016), today the most popular ones are SigFox and LoRaWAN. SigFox adopts a cellular-like business paradigm, where the infrastructures (gateways) are deployed by the SigFox providers, and the customers just buy the service, i.e., the connectivity and data collection from their end devices. LoRaWAN, instead, offers the possibility to build and manage private networks by buying end devices, gateways, and management software (NetServer), which can run in any node connected to the gateways through standard IP technologies. Both these protocols offer low bitrates in uplink, though LoRaWAN can also support a certain downlink traffic (Capuzzo, Magrin, & Zanella, 2018a), while SigFox is rather limited in this respect. Furthermore, LoRaWAN also allows for confirmed traffic (i.e., end devices may require the NetServer to acknowledge the reception of uplink packets), despite enabling this mechanism may yield to performance reduction (Capuzzo, Magrin, & Zanella, 2018b).

We can see that the different classes of MTC technologies possess rather complementary characteristics, as shown in the spider graph of Fig. 3. Therefore, it is likely that all of them will find an application in the smart city scenarios, depending on the specific application to be supported. The harmonization will then occur at a higher protocol layer, likely the IP layer, thanks to the data-sharing protocols described below.

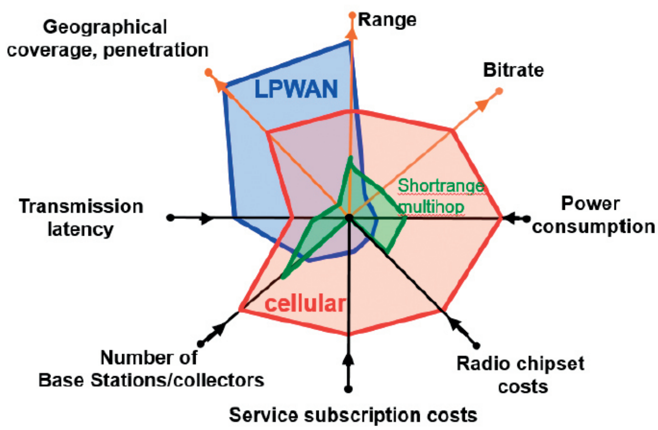

Figure 3. Comparison among MTC wireless technologies
Elaborated by the author

3.3 Sharing data

As mentioned before, the most popular approach to collect data from the peripheral nodes is by means of proxy devices (i.e., gateways) that have the role of bridging sensor nodes and Internet nodes, enabling two-way communications. Typically, gateways can receive commands from control stations or servers located somewhere in the Internet, and forward them to the peripheral nodes using the MTC technology employed in that specific system. Analogously, the gateways make the data generated by the node accessible from external (authorized) nodes.

This second functionality can be provided through different approaches, the most common of which are the request-response and publish-subscribe approaches described below (Pielli, Zucchetto, Zanella, Vangelista, & Zorzi, 2015).

3.3.1 Request-response

This approach is commonly used to access Internet resources, such as web pages, files, or others: The client sends a request for a specific resource to the server, which replies by sending back the requested element to the client, if available, or an error message if the resource is not available at the server. Each resource is hence uniquely identifiable by means of a Universal Resource Locator (URL), and the clients can use a Hyper Text Transfer Protocol (HTTP) to retrieve the data of interest. This approach requires that the gateways (or end devices) support an HTTP server. Typically, the sensor nodes are not sufficiently powerful to run a full-fledged HTTP server (or, better, a full TCP/IP protocol stack). To overcome this problem, the Internet Engineering Task Force (IETF) has designed the 6LowPAN protocol stack, a light version of the TCP/IP protocol stack that can be more easily implemented in low-end devices. The gateway, then, needs to support both the standard TCP/IP and the 6LowPAN protocol stacks, operating the translation between the two domains. In particular, the LowPAN stack includes the Constrained Application Protocol (CoAP), which is a light version of HTTP that allows for a very simple and direct mapping of the HTTP commands into the CoAP commands and vice versa. The use of this approach greatly simplifies the design of the end services that can be developed by following the standard programming practice used for any Internet application. On the other hand, the request/response paradigm is not ideal for reading dynamic data, since the request may not be synchronized with the actual availability of the data, thus possibly resulting in a waste of transmission resources and energy.

3.3.2 Publish-subscribe

This paradigm somehow mimics an exchange market, where a broker collects data from the producers and then dispatches it to the consumers depending on their specific requests. Consider, for example, an application that wants to check the temperature in a classroom.

Rather than sending a periodic request to each sensor node in the classroom to retrieve the last temperature reading as in the previous approach, with the publish-subscribe approach the sensor nodes publish (i.e., report) their new readings to a broker, which is a software module typically running in the gateway, while the consumer subscribes to this type of information at the broker. Whenever a new temperature value is published by a sensor node, the broker will send the data to all the consumers that have subscribed to said service. The most popular protocol that implements this paradigm is the Message Queue Telemetry Transport (MQTT), which is lightweight and simple. This approach is very efficient, since the communication occurs only when the data is actually available. However, the applications need to be designed by following a paradigm different from the standard Representational State Transfer (REST) approach used by most web applications. Today, however, there are a number of freely available MQTT brokers (e.g., Eclipse Mosquito) and several web services that can read data from MQTT brokers and display the values in dynamic web pages (see, e.g., https://thingspeak.com/ or http://www.sentilo.io).

3.4 Extracting information

The technologies described so far make it possible to collect a large amount of data in a simple and effective way. Such data, however, is rarely usable in its raw form and needs to be processed in order to extract useful information: a problem known in the literature as "Big Data."

There are many and variegated data analytic methodologies, ranging from very basic statistical analyses to determine the empirical mean, standard deviation, and probability distribution of the measured signal, to complex deep learning algorithms to find correlations among the most disparate types of measurements. It is interesting to mention that some useful information can be obtained even from a rather simple analysis. For example, in Cenedese et al. (2014) and Zanella, Bui, Castellani, Vangelista, & Zorzi (2014), it is shown how malfunctioning street lights can be easily identified by simply comparing the standard deviation of the values read by the light sensors applied to the different light poles during nighttime. More advanced techniques can be used to extract interesting correlations among different signals and build advanced services (Piovesan, Turi, Toigo, Martinez, & Rossi, 2016).

3.5 Building services

The last step consists in making use of the information extracted from the data to provide useful services to the citizens and the city administration. Such services are generally realized by using standard web programming frameworks but without a well-defined and globally-accepted reference model. This approach makes it rather complicated for a city to replicate the services of another smart city, which will likely differ in terms of required infrastructure, data access protocol, and so on. Furthermore, the exchange of data among services realized by different cities is also very difficult. This important roadblock has been recently recognized by a number of cities in the world, including Amsterdam, Dubai, Dublin, and Barcelona, with the latter being considered one of the top most advanced smart cities in the world according to several recent surveys. These cities decided to team up in the so-called City Protocol Society, whose aim is to define a common system view for cities, and identify or generate protocols that will help the development of such a view. The declared goal of the City Protocol Society is hence to break the boundaries of silo solutions and interconnect the different cities into an "Internet of Cities"[6].

However, other similar initiatives are being undertaken by other groups so that, once again, the risk is the proliferation of multiple, incompatible models.

4. Research challenges

The way to the realization of the Smart City concept is littered by a number of roadblocks that, in turn, generate a series of research challenges. In this section, we outline some of the most interesting points that require further research.

4.1 Access technologies

As seen before, there is a plethora of wireless transmission technologies that can be used to collect data from the peripheral nodes, each with different characteristics. However, it is not clear which technology can suit best the different requirements of smart services. Furthermore, there is still ample space for the optimization of the transmission protocols in order to reduce the energy consumption while maintaining the desired accuracy in the data collection (Biason, Pielli, Zanella, & Zorzi, 2018; Zucchetto, Pielli, Zanella, & Zorzi, 2018).

4.2 Open data

Another challenge to come up with is the common representation of the data, in order to enable the development of a standardized approach for its processing and ease the development of new applications. Furthermore, it would be essential to open the data as much as possible to involve the citizens, and foster the development of new ideas and findings. Unfortunately, the publication of data is hindered by a number of practical obstacles, including anonymity and privacy issues and, more importantly, the increasing awareness of the inner (economical) value of the data, which make it an important asset for its owners.

6 http://ityprotocol.org

4.3 Data analysis

Another open area of research is related to the processing of such data. As mentioned before, a lot of information can be obtained even using basic analytic tools. However, such methodologies only scratch the surface of what can possibly be done by applying advanced data analysis tools to the variety of data that can be collected by the different services of a smart city. Therefore, a lot remains to be done in this domain.

4.4 Security and safety

Security, privacy, and related issues are clearly fundamental to protect the sensitive information gathered and exchanged by the smart city services from its disclosure to non-authorized parties, and to shield the system against malicious attacks. On the other hand, the strong limitations on the cost of the devices and, therefore, on their hardware and software capabilities have contributed to relegating their security to a subsidiary role in the design of many IoT commercial products. This topic has gained increasing attention due to the growing awareness of the risks of entrusting simple IoT devices with sensitive information (Almuhimedi et al., 2015) or critical controls (e.g., building accesses, traffic lights, and so on) (Misbahuddin et al., 2015).

However, the vulnerability surface of a smart city is extremely wide, with aspects that differ from the standard Internet security. For example, the fact that sensors placed in public areas can be physically accessible to attackers, the limited capacities of such devices, the possibility of inferring the wealth of private information from the data collected by public sensors (e.g., road cameras), and also the possibility of injecting malicious signals into the system (e.g., triggering alarms or other type of reactions) make the security problem in IoT and smart city contexts unique and even more challenging than in standard Internet scenarios.

4.5 Digital divide and social isolation

Another aspect that needs to be accounted for is the risk of increasing the digital divide and, consequently, the social isolation of the citizens that are less acquainted with modern technologies. To mitigate this risk, aspects regarding acceptability and user friendliness should be part of the design process, which should be jointly carried out by engineers, psychologists, and sociologists.

5. Conclusions: the key to smartness

From the quick overview of the possible services that can be realized in a smart city, it is apparent that the key to smartness is integration in its widest meaning. The potential of the smart city services, indeed, can be fully unleashed only by leveraging the uncountable synergies among the different services that can be released only by adopting an integrated, systemic and holistic design of the urban system, which takes into account people, processes, and technologies.

Unfortunately, the complexity of such a design effort is likely beyond the capabilities of our modern society, and the most common approach today is a sort of best effort that targets the realization of subsets of low-hanging smart services, often without a clear long-term development plan. The risk of such an approach is the proliferation of a number of isolated, non-interoperable and non-replicable services, which would still represent an improvement over the current urban scenarios, but will eventually fail to fulfill the Smart City vision in all its potential.

The integration concept can actually be pushed forward by thinking of a symbiotic system in which not only the information and communication technologies are used to build new services, but these very same services are used to improve the performance of the communication infrastructure. This concept, which we dubbed "SymbioCity", has been exemplified in Chiariotti, Condoluci, Mahmoodi, & Zanella (2018) and Dalla Cia et al. (2018), where it is shown that, by exploiting the data collected by the road traffic monitoring service, it is possible to optimize the configuration of the cellular system, thus providing a better service to the citizens.

In conclusion, despite the several and interesting initiatives that are being undertaken by different cities in the world, the Smart City concept remains so far an ambitious vision (and, perhaps, a bit of a utopia). The full realization of such a vision requires the solution of a number of challenges, which must be addressed by adopting a multidisciplinary approach that merges engineering, psychology, and sociology. Finally, fundamental is the full support of the public administration and the deep involvement of the citizens in the whole process.

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