Environmental Sensing Testbeds for Livable Smart Cities

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ABSTRACT

The rapid development of our cities is posing new global challenges that require crucial transformations with a focus on its human dimension. This includes the needs of more lively, safe, and healthy cities, and an active community that is engaged in this transformation. In this paper we describe how the concept of smart cities and large-scale and fine-grained deployments of environmental wireless sensors can play a crucial role in addressing these challenges. We present two testbeds in the City of Antwerp, Belgium, focused on air quality and noise monitoring, and we discuss how they enable future applications for a more humanized city.

CCS CONCEPTS

• **Applied computing** → *Environmental sciences*; • **Hardware** → *Sensors and actuators*.

KEYWORDS

smart cities, testbeds, environmental sensors

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1 INTRODUCTION

The concept of smart cities, that has increasingly gained interest since 2010, refers to the idea of the so-called urban *technological utopia* [5]. It is with the deployment and integration of various technologies in the urban environment that new solutions for addressing city challenges are possible. The introduction of digital technologies such as wireless sensor networks and internet-based networked application started to work together, and by so forming a backbone of a large, intelligent infrastructure [9].

Although smart cities are often linked to this technology evolution, there is no clear or single definition on the concept. In the search of a definition Dameri [1] identified different elements that are relevant for describing the concept.

(1) A smart city is a collaborative endeavour, resulting from the interaction and collaboration among stakeholders, urban environment, and a governance structure. With regard to the stakeholders, the quadruple helix (in which government, industry, academia and citizens are working together) is the central core.
(2) The smart city is linked to a specific dimension. This can vary from a local urban dimension to a more larger national and even global dimension.
(3) The smart city needs to be focused to a specific goal. Hence, the smart city is not the goal, the means to what it can or needs to be achieved.

Based on these components, Dameri suggests the following definition: "smart city is a well defined geographical area, in which high technologies such as ICT, logistic, energy production, and so on, cooperate to create benefits for citizens in terms of well-being, inclusion and participation, environmental quality, intelligent development; it is governed by a well defined pool of subjects, able to state the rules and policy for the city government and development".

Kitchin [6] distincts two streams of what makes a city smart. On the one hand he refers to so-called *everyware*; the integration of technology in the urban environment. This enables a city to become more knowable and controllable than before. On the other hand the smart city refers more to the ecosystem, where the economy and governance is being driven by innovation and entrepreneurship. Therefore, smart cities entails two dimensions: a technological and a human one [7]. The latter can also be found in the new concept of so-called human cities, that stresses not only the more goal-oriented aspect of a smart city, but also the human potential, growing knowledge and empowerment that it can facilitate.

This paper embraces both definitions of smart cities with a focus on the following elements: (i) Smart cities need to be *goal-driven* starting from the city challenges to be addressed and identifying possible solutions; (ii) the introduction of technology is the enabler of new disruptive solutions; (iii) both the city government and the citizen need to be actively contributing to the solutions for long-term and effective transformations.

Starting from the top challenges that cities are facing nowadays (Section 2), we present possible future application scenarios that can help us in reaching the goals of the cities (Section 3). In Section 4 we present the crucial role of a large-scale IoT infrastructure for environmental monitoring and describe our testbeds in the city of Antwerp, Belgium. Section 5 concludes the paper with a look at our future work.

2 URBAN CHALLENGES

The rapid growth and development of our cities is an enabler for new economical and social opportunities for their inhabitants. However, it also poses new challenges that requires radical interventions. From Gehl [4] and the 2007 New York City Plan [8], four main goals can be identified as high priority for urban interventions. These goals bring back the human dimension to the city, and next to the optimization of the urban processes, focus on an improved livability.

(1) A *lively city*, where more people walk, bike, and stay in the city and where new social and cultural opportunities are possible. Cities need to provide "welcoming signals" where social interaction is promoted. Lively cities also needs a varied and complex city life where recreation and social activities are mixed and follow the human city flows. To address this challenge, cities need to promote common spaces for concentrating people and events. The presence of other people spontaneously attract new comers. Events do not necessarily need to be created a-priori but emerge by social aggregation and interaction.
(2) A *safe city* is a city where people experience and, equally important, perceive safety and security. Safety in cities are mainly related to traffic and criminal activities. In both cases, cities need to provide solutions for preventing and reacting to unsafe situations. Life in the street promotes safer cities. Therefore, the social dimension of this challenge needs to be considered.
(3) A *sustainable city* is a city that actively contributes in reducing energy and water consumption, waste production, carbon emissions, and pollution. Transport and traffic are key components in carbon emission in the cities. Sustainable cities need to be accessible, and attractive to all groups in the society. This includes democratic involvement in the transformation processes of all citizens.
(4) A *healthy city* with an improved well-being of citizens. A healthy city promotes active behavior of their citizens favouring physical activities such as walking, biking, or exercising as a natural part of their daily life. Moreover they need to address the two main environmental risks threatening the health of their citizens: air and noise pollution. According to the World Health Organization, ambient air pollution is a major threat for health and climate. A recent report estimates 4.2 million worldwide deaths every year are attributed to ambient air pollution mainly due to respiratory and heart diseases, and 91% of the world's population lives in places exceeding WHO air quality guidelines[1]. Excessive noise seriously harms human health. It can disturb sleep, and cause cardiovascular and psycho-physiological effects[4].

Addressing the challenges above is not easy. Multiple interventions are required at multiple levels, from long-term urban planning and policy making, to large societal transformations. Nevertheless, technological innovation in smart cities can play an important role in facilitating and accelerating transformation process. Moreover, starting from the challenges, clear roadmaps can be derived to guide current and future technological advances.

3 FUTURE SCENARIOS AND EXTENSIONS

In this section, we depict future possible scenarios where technology in smart cities can help achieving the goals described above, or at least getting a step closer towards their realization.

3.1 Lively Cities

To make a more lively city, technology need to favor social aggregation and interaction. This can be achieved by monitoring the current use of the spaces and identifying existing social aggregation points in the cities. Some of these points can be fixed, such as areas with bars and cafes, theaters, and supermarkets. However, others, the most unexpected and probably interesting ones, are dynamic, and spontaneously created. For instance, a street can become a place for street musician to play music or for kids to play.

The identification of the aggregation points, especially for the second category and in large city, cannot be achieved without a continuous monitoring of the spaces. This scenario can be enabled by analyzing geo-localized social media interactions. However, not all the categories of the population in a city would be equally represented and aggregation opportunities may be missed. A different approach, complementary to the first one, would involve a fine-grained deployment of wireless sensors aiming at listening the *sounds of the city*. These sensors, supported by data processing algorithms, can distinguish between different activities happening in the city or characteristic sounds (e.g. the bells in a tower, or the ice cream truck) and signals new opportunities for interaction.

Given this real-time data set, a second step, would enable the analytics on how lively a city is, and propose new interventions to improve its status.

3.2 Safe Cities

Safe cities need to prevent, and to respond to possible traffic accidents and criminal activities. To manage road safety, different technologies are widely available in our cities. These technologies monitor the speed of cars, signal when accidents occur (through traditional emergency response or current GPS navigation applications), and activate the proper response. The prevention of road accidents will also be improved by future autonomous vehicles, as well as the use of IoT sensoring embedded into the road pavement [3].

Responding to criminal activities requires a different type of technological solutions. From one side, users can rely on dedicated apps on their smart phones to trigger an alarm. However, this may

[1] https://www.who.int/airpollution/ambient/en/

not be always possible when in direct contact with the offender and can even put the victim at higher risk. Wearable technologies, from smart watches to smart jewelry, can mitigate this risk but they are nowadays less widespread over the population. A smart city solution is needed where no dedicated device is required by the user, especially for such critical applications. Smart cameras have been successfully deployed in the city. However, the cost of its deployment, may affect the availability in all areas of the cities. A complementary solution can involve the use of acoustic sensors, that can detect specific alarm voice signals or screams. This solution would enable a more natural, transparent interaction with the space, and resemble what people would typically do if they face such risky situations. Acoustic sensors could also be used for detecting the noise of ambulance and deriving automatic actions such as traffic re-routing.

3.3 Sustainable Cities

Sustainability requires multiple solutions to address its different constituents. Reducing the energy consumption of a city has been traditionally one of the main use cases in the first smart city deployments. Smart lighting infrastructure and smart energy systems rely on wired connected infrastructure to send usage data to the Cloud for storage, and for further analysis. These systems are able to automatically control the light and optimize its usage. This results in reduced costs for the cities.

Automatic optimization processes supported by the Internet of Things are also found in waste management. This include route optimization for garbage pickup trucks, which, by leveraging the presence of smart bins, collect the garbage only where and when it is needed. Moreover, the use of RFID and NFC tags and QR code can be used to track the waste and optimize product recycling.

A sustainable city needs to reduce carbon emissions from industries, buildings, and cars. While some of the interventions may require appropriate traditional urban policy making, such as the introduction of low-emission zones in cities, it is crucial also in this case to rely on environmental monitoring systems that can evaluate the impact of the introduced policies and support the decision maker in the creation of new ones.

3.4 Healthy Cities

Health and well-being is a personal matter involving individual choices, habits, and lifestyles. For this reason, solutions addressing this challenge need to have a full participation of both the city and the citizens. The city needs to promote healthy lifestyles and make sure the city environment is a healthy space. Citizens need to actively engage in this issue, by understanding and eventually adapt their behavior. The promotion of active lifestyle is typically addressed by traditional policy making, in the organization of sport events, in the availability of sport facilities or parks, and in making more convenient the use of public transportation, biking, or walking.

Technology and the Internet of Things play a crucial role in the second aspect of healthy cities: improving the environment by reducing air pollution and noise pollution; and therefore reducing the negative impact on people's health. To address this issue wireless environmental sensing is the basis for a reliable solution. Air quality monitoring needs to be fine-grained, real-time, and cost-effective. Air quality is very local and can rapidly change over time. The deployment of the sensors need therefore to provide accurate measurements at street level. The more sensors are deployed, the more accurate the measurements. To make the deployment economically viable, wireless sensors need to be low-cost to support the required scale. The same applies for noise pollution monitoring, aiming at measuring noise hotspot and take immediate required interventions where noise levels reach a certain level.

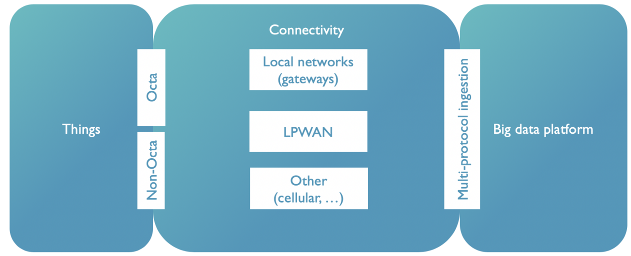

Figure 1: Testbed architecture.

Once the network and data infrastructure has been set up, new applications can be foreseen both for air quality and noise monitoring. For instance, for an engaged citizen would be important to monitor his/her own personal exposure to the air/noise pollutants, and have predictive supporting tools to take appropriate actions.

4 TESTBEDS FOR WIRELESS ENVIRONMENTAL SENSING

From the description of the outlined scenarios in the previous sections, the creation of stable and cost-effective wireless sensor networks is required to provide fine-grained, real-time, and accurate environmental measurements. These networks also need to be supported by a data platform for reliable data collection, and by a data processing layer where data analytics and actionable insights can be generated.

In this section, we describe the use of testbeds for the research and the development of environmental wireless sensor networks, and for validation and testing of new future applications. We present two testbeds covering two different geographical areas of the city of Antwerp, Belgium. The City of Things testbed, among other different applications, focuses on the state of the art advancement in air quality monitoring; and the CityLab testbed, which is the enabler of air quality and noise level monitoring.

4.1 Architecture

Both testbeds share a similar architecture and use the same hardware for the development of their sensor nodes, shown in figure 1. Data flows from *Things*, which measure phenomena, over different possible wireless networks to the big data platform.

The sensor node, called OCTA, is a multi-sensor multi-network platform that enables, with modular add-ons, the integration of different commercially available sensors to measure environmental parameters, as shown in figure 3.

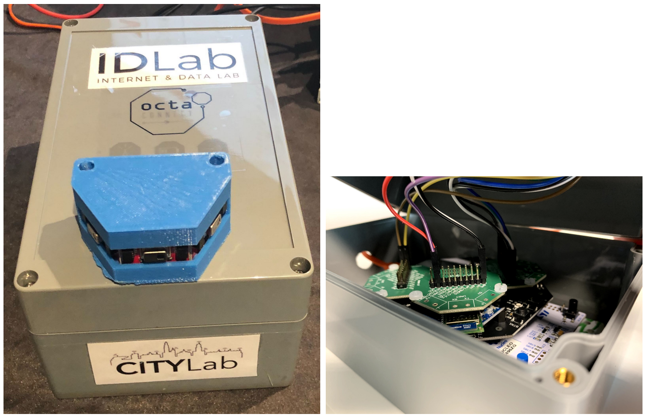

Figure 2: CityLab sensor, with visible PIR array component and inside.

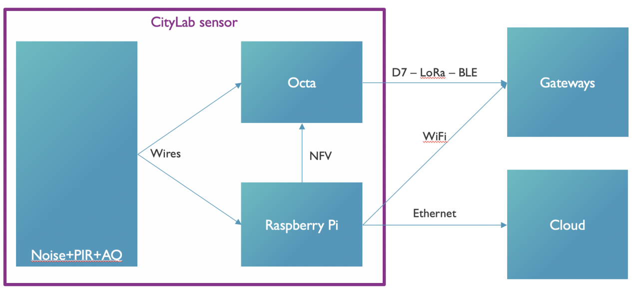

Figure 3: Sensor Node architecture.

A picture of the OCTA node is shown in figure 2. The sensor is defined to be highly versatile, with multiple connections to sensoring modules and/or communication modules.

The sensor measurements are sent to a data platform for data storage and processing. Figure 4 shows the high-level architecture of the platform. Data received from the sensors are first ingested by a cloud component supporting multiple networking protocols. The measurements are then forwarded to a message broker that send the message into two paths: the cold-path is for long-term, cost-effective storage; the warm path is used for real-time processing of the raw data into augmented, clean and calibrated data. The link between the cold-path and the warm-path is the data processing layer, which uses historical data retrieved from the cold-path data storage to compute the necessary parameters used by the real-time processing. Different algorithms are running in the data processing layer according to the specific application and use case. Finally, the real-time processed data are sent to a common API layer for the integration with the client application.

4.2 City of Things and Air Quality Monitoring

City of Things is a large initiative aiming at introducing innovative smart city solutions by testing in the field within the areas of mobility, citizen engagement, and environment. One of the main focus of the City of Things testbed is the research and development on air quality algorithms. The goal of this research is to improve

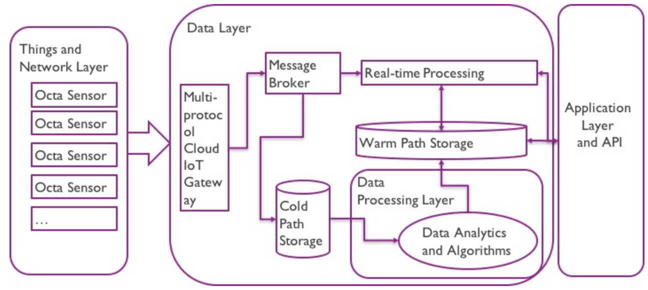

Figure 4: Data Platform Architecture.

the quality of low-cost air quality sensors by automatically calibrating raw measurements in the data platform. To achieve this, for every pollutant, and given the technical specification of the sensors used, new algorithms are developed using multiple data sources, including the official reference stations of the local environmental agency, to derive parameters that are then used to calibrate the raw measurements in real time.

A peculiarity of this deployment is the combination of 18 fixed and 20 mobile nodes. The mobile nodes are installed on top of the post office vans (BPost), so that while they are driving, it is possible to collect air quality data points in areas where typically no sensors are installed. This deployment uses both LoRA and NB-IoT. Figure 6 shows air quality insights resulting from this testbed.

4.3 CityLab

The CityLab testbed[10] is a smart cities testbed located in Antwerp, Belgium. Previously targeted only at wireless and edge cloud research, the testbed is being extended for smart cities sensor data research, as shown in Figure 7 with *gateways* in blue and sensor deployments marked in orange (first deployment) and red (second deployment). Mainly used by researchers and industry, in this paper we want to invite the broader community of citizens and citizen scientists, interested in this kind of data gathering.

To realize air quality and noise insights, the current testbed is proposed as a starting point. Currently about 50 CityLab *gateways* are deployed in the city center. An example gateway deployment is shown in figure 8. These gateways are connected to academic fiber via an Ethernet connection, and are offered to users by means of the jFed experiment management software[11], part of the European Fed4FIRE+ project[2]. The gateways offer to users the possibility to connect to other gateways or sensors via their on-board WiFi (at both 2.4GHz and 5GHz), Bluetooth, Zigbee (at 2.4GHz and 868MHz) or custom sub-GHz radios (at 868MHz and 433MHz). All of the radios are connected over dedicated antennas. In the case of the ongoing smart city sensor deployment, sensors are being connected over WiFi, Bluetooth and DASH-7 (a custom sub-GHz protocol).

The sensor measure noise levels, air quality and movement based on different measurement components. For noise, the sensors are equipped with off-the-shelf SparkFun SEN12642 sensors. These allow measuring noise levels, avoiding any recording of sounds itself. For air quality, the sensors use the SDS011 particulate matter 2.5 sensor, combined with a DHT22 sensor for temperature and humidity measurements (see Figure 5.

Figure 5: The BPost van with the sensor nodes on top

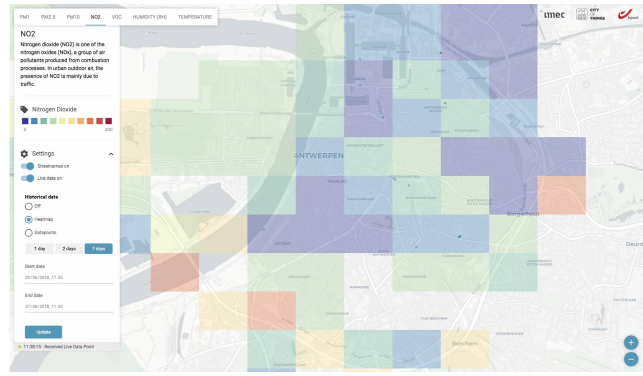

Figure 6: City of Things Map with Air Quality Visualization

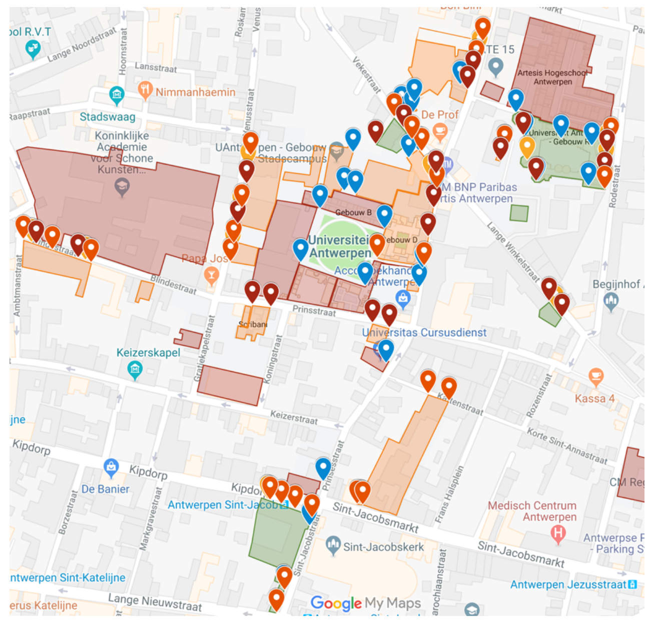

Figure 7: Map of CityLab gateway and sensor locations.

The sensor is connected over multiple wireless technologies (DASH-7, Bluetooth, WiFi and LoRa) and even a wired network. The wireless technology diversity allows users to experiment with different wireless technologies, leveraging the existing infrastructure. E.g., it allows studying the difference between the sub-GHz DASH-7 as opposed to the higher bandwidth but lower range Bluetooth, or the very low bandwidth LoRa. The wired connection allows for continuous data streaming, irrespective of the used (wireless) network technology. This way, users can experiment with the wireless network of their choice, while double checking the data and possibly missed data.

Because of the CityLab architecture, the sensor data can then be processed at the edge, i.e., in the gateway, or in the cloud. This allows for studying sensor correlation or data compression at the edge.

The experimentation with such smart city sensors should happen in close collaboration with the users, the citizens. Therefore, we propose to use in CityLab an iterative Living Lab approach to steer and support the different research projects. This Living Lab approach entails the following components:

(1) an open innovation testbed environment. The CityLab is a vendor-neutral environment in which various technologies next to each other can be tested. As an open innovation testlab it is open to anyone that is willing to test and research.
(2) a multi-stakeholder, public-private partnership. In the Citylab different actors, both from public and private sector do collaborate together, working on common goals and objectives in an open and transparent way.
(3) A need-based agile development approach. In setting up the experiments in the CityLab an iterative development process

Figure 8: CityLab gateway deployment example architecture.

is being used in which we move from paper-prototypes over lab-tested solution towards real-life texting of the solution.

CityLab does not only offer the necessary technological infrastructure as described above, but also the necessary research expertise to perform research activities on all fronts (hardware, software, applications, user experience and business modelling).

5 CONCLUSIONS

This paper proposes a framework for the definition of goal-driven smart city transformations. Starting from the main urban challenges cities are nowadays facing, we derived a set of future scenarios acting as starting point for new applications and technology that addresses what the city and the citizens need. The list of proposed scenario is not exhaustive. They are intended as a representative example of the potential of using this approach. Despite the specific applications, the development of wireless sensor networks and the supporting end-to-end system plays a key role in the city transformation. Our research focus is in the continuous extension of our testbeds both in scale and functionality.

On the basis of the presented scenarios, new technical challenges emerge that need to be addressed in the future extensions of our testbed. First, as in every currently running deployment, privacy of the data and the citizen is a top priority. This is more critical where a continuous noise monitoring is needed. To ensure privacy, we will investigate the deployment of data processing algorithms, at the edge or even at the sensor node itself, rather than in the Cloud. This would require more powerful hardware systems, and more complex network solutions. Second, our current testbeds focus only on noise level measurements The transition from this configuration to a system measuring the “sound of the city” is a not trivial task, especially if the solution still needs to be cost-effective. New hardware is needed and this may also affect the overall energy consumption of the system. Finally we will continue to involve citizen in the innovation process to make sure our extensions fit their needs.

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