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Integrated system architecture for decision-making and urban planning in smart cities

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Abstract

Research and development of applications for smart cities are extremely relevant considering the various problems that population growth will bring to large urban centers in the next few years. Although research on cyber-physical systems, cloud computing, embedded devices, sensor and actuator networks, and participatory sensing, among other paradigms, is driving the growth of solutions, there are a lot of challenges that need to be addressed. Based on these observations, in this work, we present an integrated system architecture for decision-making support and urban planning by introducing its building blocks (termed components): sensing/actuation, local processing, communication, cloud platform, and application components. In the sensing/actuation component, we present the major relevant resources for data collection, identification devices, and actuators that can be used in smart city solutions. Sensing/actuation component is followed by the local processing component, which is responsible for processing, decision-making support, and control in local scale. The communication component, as the connection element among all these components, is presented with an emphasis on the open-access metropolitan area network and cellular networks. The cloud platform is the essential component for urban planning and integration with electronic governance legacy systems, and finally, the application component, in which the government administrator and users have access to public management tools, citizen services, and other urban planning resources.

Keywords

Smart cities, decision-making, big data, urban planning

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Introduction

Globally, more than half (55%) of the world's current population resides in urban areas compared with just 30% in 1950. By 2050, it is expected that 68% of all people will be urban dwellers. The most urbanized regions include Northern America with 82% and Latin America and the Caribbean with 81% of their population living in urban areas in 2018.[1] As the world continues the process of urbanization, sustainable development depends increasingly on the successful management of urban growth. Otherwise, it may lead to exurban expansion, the formation of slums, scattered workplaces, and aging infrastructure. These may

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cause huge inefficiencies in energy use, traffic, governance, waste management, and pollution, among others. Urban growth is closely related to the three dimensions of sustainable development: economic, social, and environmental. As it is depicted in Figure 1, to achieve these three-dimension challenges, public and private sectors invest in smart city technologies to create a variety of services such as (1) smart elderly health monitoring, (2) smart metering, (3) water tank monitoring, and (4) smart traffic light, and so many other solutions.

Smart cities use information and communication technologies (ICTs) infrastructure in a flexible, reliable, secure, and scalable way, in order to improve the quality of their services. It can provide stable economic growth through higher standards of living and job opportunities, welfare, and access to better education.[2] Research in this area emerged from smart homes and smart buildings which are an essential part of smart cities, offering residents different facilities, ranging from generating a portion of the electricity to remote controlling, monitoring, and auto-adjusting different appliances.[3] As mentioned, ICTs play an important role in smart city applications, especially by interconnecting together cyber-physical devices such as radio-frequency identification (RFID)-based devices, wireless sensor and actuator nodes, and embedded appliances through the Internet. The interconnection of these devices is basically the foundation of the Internet of things (IoT), that is, the things (devices) connected to the Internet, and thing-to-thing (T2T) or machine-to-machine (M2M) communications.[4] It is worth mentioning that this "Things" interconnections scenario was described first by Mark Weiser as ubiquitous computing over two decades ago,[5] 10 years later as pervasive networks capable of connecting the physical world with the digital world.[6]

This connection between the physical (real environments) and digital (cybernetic) worlds has enabled the development of cyber-physical systems (CPSs) responsible for physical processes and computation, which may bring a lot of solutions to smart cities.[7] Typical CPS applications operate with feedback loops that consist of sensing, communication, decision-making and actuating, rather than simply collecting and sharing data.[8] While ubiquity is strongly present in CPSs with the use of cyber-physical devices, there are other important requirements that must be considered, especially in large-scale applications. Most of these requirements are related to the processing and storage capacity of the devices as well as the connectivity issue. The cloud computing paradigm represents a primary solution to reach these requirements, and it provides abundant resources for distributed systems for large-scale data processing and storage, big data analytics frameworks, and on-demand data centers, with the accounting model "pay as you go."[9]

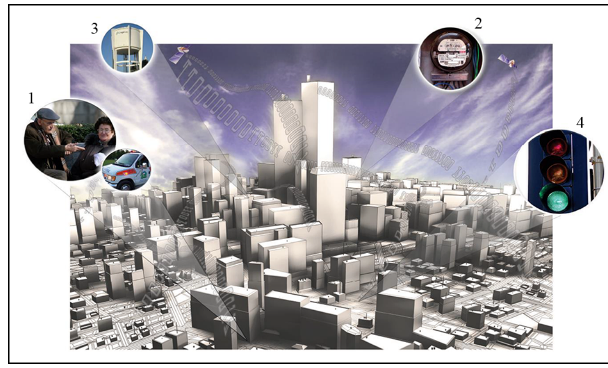

Figure 1. Application domains in smart cities.

Although CPSs are extremely effective in collecting data, situations in which there are no sensors available are the majority of cases, or even the available ones are not able to collect certain information. Therefore, a new method of capturing information using smartphones or other mobile devices has been employed in these situations. Participatory sensing is a sensor-based data collection paradigm and it is focused on the extraction of data generated by people. Initiatives based on this concept are becoming crucial for designers of intelligent urban infrastructures since they enable the collection of several types of relevant data that cannot be properly captured by traditional physical sensors.[10]

Based on the observations above, in this article, we present our proposal of an integrated system architecture for decision-making support and urban planning by introducing its building blocks (termed system components): sensing/actuation, local processing, communication, cloud platform, and application components. In the sensing/actuation component, we present the major relevant resources for data collection, identification devices, and actuators that can be used in smart city solutions. Sensing/actuation component is followed by the local processing component, which is responsible for processing, decision-making support, and control in local scale. Depending on the sensing model adopted, there may be no local processing; in this case, the devices are connected directly to the communication component. The communication component, as the connection element among these components, is presented with an emphasis on the open-access metropolitan area networks (MANs) and cellular networks. The cloud platform is an essential component for urban planning and integration with electronic Governance (e-Gov) legacy systems, and finally, the application component, in which government administrators and users can have access to public management tools, services, and urban planning dashboards. The rest of the article is organized as follows: in section "Motivation and contributions," we introduce the motivations for the research, consisting of some related works, case studies presented in the literature and contributions. In section "Proposed CPS architecture and components," we present the proposed system architecture, followed by experimental validation and results in section "Experimental validation and results." Finally, in section "Concluding remarks," we discuss the proposal and give some future directions and concluding remarks.

Motivation and contributions

The concept of a smart city has a multidisciplinary approach, which enables the study in disciplines of engineering, architecture, computer science, and several others. Our study is directed to the use of computational resources for the development of solutions and services that may bring this concept of smartness to the cities. The major objectives in this scenario are to collect information from heterogeneous sources, through different network technologies, and use machine learning or other techniques to add value to data. Aiming for the same goal, authors address important projects and implementations in environmental monitoring with the objective of reducing air pollution through active monitoring, traffic management, and better city planning,[11] urban mobility,[12] smart transportation system,[13] smart metering,[14] smart healthcare,[15] street lighting control,[16] smart parking,[17] and several other solutions available for implementation and adoption of IoT in urban areas.[4,18]

In order to guarantee the achievement of the aforementioned objectives, it is not possible to model, design, and develop isolated solutions in a large context, such as a smart city. Obviously, when designing a smart city not all services are designed and put into operation at the same time, new solutions come up according to the need of the city and its citizens and administrators. Thus, the initial plan must ensure the project flexibility, reliability, security, and especially scalability, so that future services and applications can be aggregated without harming those already in operation. Therefore, several architectures have been proposed in the literature in order to manage the communication between connected devices with the hope of establishing a standardized model for smart city and monitoring applications.[19–21] Most of these architectures have at least three common characteristics: (1) they use the IoT concept for the data collection, (2) cloud computing for data storage and processing, and (3) they are three-layered architectures. These three layers are considered to be IoT basic layers that exist in most architectures of IoT.[19,20,22] The first layer consists of all IoT objects and devices, in which the main functionality is information acquisition and perception. The second layer is the network layer responsible for the communication between devices and the Internet. Finally, the third layer is the application layer and consists of several applications for different business needs. The data processing in these architectures is most often performed on a cloud platform, and services such as data aggregation, data mining, and data analysis are managed by the application and network layers. A survey of similar architectures is presented by Ray[23] highlighting a variety of applications in different areas.

The architecture-layered model is quite interesting and widely adopted in several applications because it brings four major benefits: (1) maintainability: each layer is independent of the others, where updates and changes can be made without affecting the application as a whole; (2) scalability: the independence of layers enables the architecture to scale adding new applications; (3) flexibility: as each layer can be managed or scaled independently, flexibility is increased; and (4) availability: services can exploit the modular architecture of enabling systems using scalable components, which increases availability. The architecture proposed in this work is composed of five layers that we termed components. These five components constitute a CPS that is responsible for managing and implementing the functions of each component. The major contributions of the proposed system architecture are summarized as follows:

1. Design of a local processing component for decision-making support with the rapid response time. It is a crucial implementation to reduce the time between an event occurrence and the event being acquired and processed by the system.
2. Integration of legacy systems to improve the quality of information collected by the sensing/actuation component. This contribution has high relevance, especially for urban planning.
3. The use of open-access MANs to interconnect the components of the architecture.
4. Using different sensing techniques to provide a vast amount of data to be processed in a unique system capable of acting in the environment when necessary.

Proposed CPS architecture and components

Modeling an architecture or any solution for smart city scenario is a quite complex task and must be carefully designed. The diversity of environments (e.g. public buildings, open spaces), the number of scattered sensors, the diversity of data, the use of actuator nodes, and data security are some issues that must be addressed. In a smart city environment, most data are extracted by IoT nodes which are not secure by design, making its applications vulnerable especially to security and privacy threats. In order to address security requirements, research scholars have investigated blockchain and IoT integration.[24,25] Sharma and Park[26] proposed a hybrid architecture for a scalable smart city network extending the DistBlockNet[27] model, a distributed mesh network architecture for IoT using software-defined networking (SDN) and blockchain technology concept to improve security, scalability, and flexibility, without the need for a central controller.

Regarding the use of actuators, Longo et al.[28] proposed the Stack4Things framework for Sensing-and-Actuation-as-a-Service (SAaaS) adopting a device-centric perspective, in which architecture was constructed using the free, open-source OpenStack cloud platform.[29] In this approach, the board-side (node level) is equipped with microcontroller and microprocessor units (e.g. Arduino YUN) that can interact with sensors and actuators through a set of digital/analog I/O pins, while the connection to the Internet is assured by Ethernet and WiFi network interfaces. On the cloud-side, the Stack4Things implements as an OpenStack service the IoTronic subsystem providing the management of sensing and actuation resources. Also, the ceilometer which is traditionally used in OpenStack deployments to collect, normalize, and transform data is extended to allow the collection of metrics coming from the board-side. For both cases, the nodes interact with the cloud by connecting to specific web application messaging protocol (WAMP) routers through a WebSocket channel, which on the cloud the WAMP messages are translated to advanced message queuing protocol (AMQP) messages using specific agents. In the Stack4Things architecture, the measurements are sent to MongoDB and the standard OpenStack dashboard, Horizon, is used for data visualization.

Our objective is to propose a cloud-based CPS architecture adopting a data-centric perspective in order to integrate the ubiquitous urban sensing and big data processing in a smart city environment, enabling analyses of historical and real-time data. The model is composed of three domains: physical, cyber, and social (see Figure 2). The physical domain is equipped with mobile devices, sensors, and actuators for data extraction from the environments. The cyber domain provides network and Internet connection, cloud platform features, analytical tools, computational intelligence such as data mining, and machine learning algorithms useful in converting information into knowledge. The social domain is the interaction tool with users through services and applications.

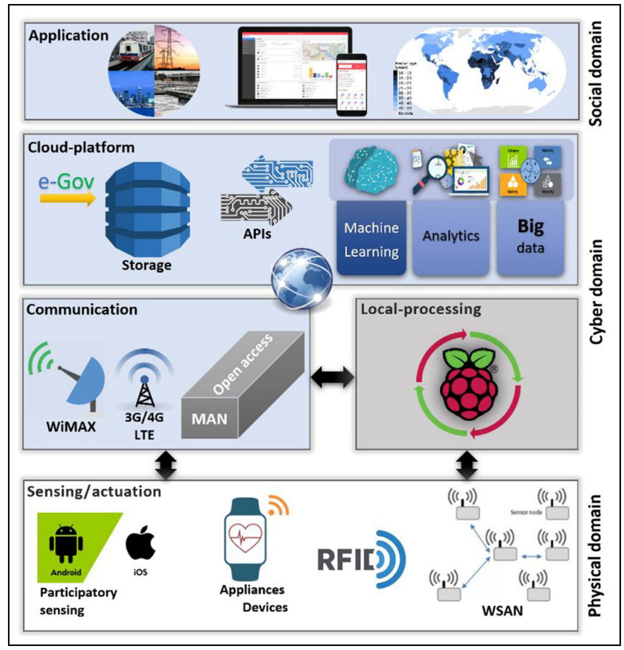

Figure 2. Integrated CPS architecture and components.

The five components of the proposed model are distributed over the three domains aforementioned. The sensing/actuation, local processing, communication, cloud platform, and application components. Although we refer to our proposal as being cloud-based, all components have equal importance, and the integration enables a closed-loop system with bidirectional communication, rather than simply collecting and sharing data, as discussed in the following section.

Sensing/actuation component

Basically, there are three main sensing paradigms: RFID, wireless/wired sensor and actuator networks (WSANs), and participatory sensing. The RFID technology provides identification of individual people and objects which have an attached tag that must be within the range of an RFID reader. Active RFID use battery-powered tags that advertise their identity to various access points or readers. However, passive RFID tags do not contain a battery and the power is supplied by the reader, even when it is surrounded by several other items.[30] In most applications, the use of passive RFID is more interesting for issues such as tag cost, battery life, and for being simple to install. In a smart city, applications can be found particularly in access control, transportation, and healthcare.[15,19,31]

WSANs enable the opportunities of instrumenting the physical world with ubiquitous networks of sensors, actuators, and embedded computation (nodes). Traditionally, sensors are embedded devices able to collect data from a set of input modalities, including heat,

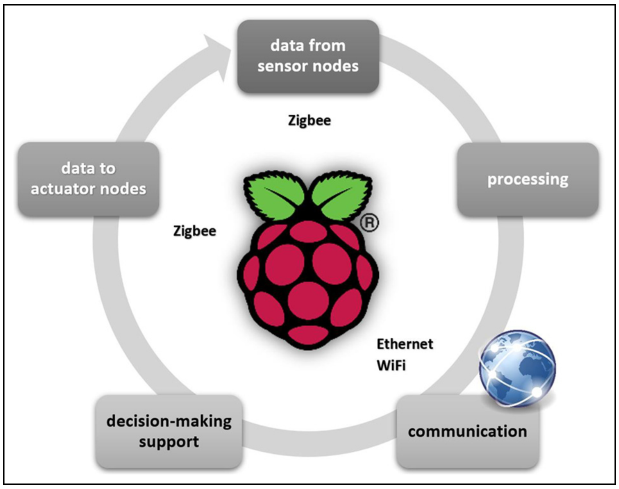

Figure 3. Local processing component with decision-making support.

image, acoustics, motion, vibration, light, pressure, ultrasound, radio, magnetic field, and many more modes.[32] The actuators can carry out actions on the environment, manipulating autonomously the physical world based on observations made by sensors, network devices, or even remotely by an administrator or qualified user. The true potential of WSANs lies on the embedded computation that brings to these networks the ability of processing, analyses, and dissemination of valuable information gathered in a variety of environments.[33,34] In our approach, the nodes are equipped with microcontroller units (e.g. PIC16F688) which can integrate sensors and relays using the I/O pins. The availability of all these resources makes the WSANs an important tool in urban sensing and control.

Participatory sensing is a new sensor-based data collection paradigm and it is focused on the extraction of data generated by people, especially in social networking.[10] Initiatives based on this concept are becoming crucial for designers of intelligent urban infrastructures since they enable the collection of several types of relevant data that cannot be properly captured by traditional physical sensors. This paradigm also is known by other names including collaborative monitoring, crowdsourcing, and citizen sensing. It has gained momentum and it has spread mainly due to the popularization of smartphones, that is, mobile devices with Internet access and integrated sensors (e.g. microphone, camera, GPS, and accelerometer, among others).[35] Taking advantage of these devices, data can be collected passively through the integrated sensors, in which case the user does not act directly in the monitoring, or the data collection can be performed through applications, where the user actively inserts information about the city.

Local processing component

Our model defines two components for collaborative data processing modes: (1) local processing with decision-making support and (2) cloud processing for urban planning. The local processing component manipulates especially the data from RFID devices and WSANs due to the number of sensors and devices operating in the same environment. Instead of all objects of the network and devices to communicate directly with the cloud platform, the data are concentrated and processed locally and then sent to the cloud platform for deeper analyses. The main goal of using local processing is to reduce the time between an event occurrence and the event being acquired and processed by the system enabling decision-making support with the rapid response time.

As it is depicted in Figure 3, the local processing component is a closed-loop system by itself, since it consists of aggregating data from sensor nodes, processing, communication, decision-making, and controlling actuator nodes. The component interacts with the cloud by connecting through a specific communication protocol. The cloud platform component receives online data for storage and analyses and also executes requests that can influence decision-making support or even interference from administrators. Some processes are performed exclusively in the cloud platform, it is the case of participatory sensing, in which the sending of information may occur from anywhere, and not necessarily from the place on which the information is concerned, but it can influence in some way the decision-making in the local processing component.

Communication component

Over the past several years, the networking research community has debated the future of the Internet architecture and protocols. Basically, there are two main design approaches for network architecture: evolutionary approach and clean-slate approach.[36] The evolutionary approach advocates the principle of making incremental changes to the current network infrastructure and reusing as much of the existing solutions as possible. However, the clean-slate approach supports the redesign of a network according to disruptive design principles without being constrained by the current architecture.[37] The proposal emphasizes the evolutionary approach, as the reuse of existing solutions operates with consolidated technologies (e.g. Internet protocol (IP), wireless technical standard, security protocols), and it reduces the time with new implementations.

In smart city solutions involving physical environments, the first elements to be deployed are sensors, and then actuators. The ubiquitous network architecture is the assurance that these elements are always available for data collection and actuation in the whole environment. Ubiquitous networks present some network devices as part of the Internet, and others can be accessed over the Internet through a gateway.

We chose to use a hierarchical network architecture, comprising both multi-access networks and wireless multi-hop networks. The majority of applications of sensor networks are implemented using a wireless multi-hop network where communication between devices is performed by direct connection or through multiple hop relays. Besides, a fixed wireless infrastructure is not required and there are a variety of specifications and protocols that can be used in applications. Another feature is the integration of different multi-access networks. It is usual to exist several radio access technologies available to connect to the Internet. These networks could be WLAN, WiMAX, cellular, and MANs. In the next section, we will give more details about our experience with open-access MANs.

Open-access MAN. The main feature of a MAN is its ability to interconnect users, computers, and other devices in a large geographic area, such as a city. It is also used for interconnection of several local area networks by bridging them with backbone lines. The latter usage is sometimes referred to as a campus network, municipal network, or open-access MANs.[38]

Open-access MANs are telecommunication networks that integrate a complete municipality in a single telecommunication environment. This type of network can boost economic and social development and have a positive effect on, among other things, a country's productivity and ability to innovate. In Brazil, municipal information highways have been used to make digital cities feasible. Open-access MANs are the telecommunications infrastructure that interconnects public buildings and provides the public with residential broadband connections, promoting digital inclusion.[39] This type of telecommunications environment favors, among other things, the development of digital, or smart cities, as open-access MANs allow the whole city, including its citizens, to be integrated into a single telecommunication environment.

Cellular network. The traditional cellular networks were mainly designed to serve human-to-human communications. However, their inherent features, such as wide coverage, easy deployment, access to the dedicated spectrum, and high-security level, have attracted many monitoring applications to exploit the cellular networks for their connectivity. Consequently, new features that facilitate M2M communications are been released, such as LTE.[40]

Wireless communication is important in the construction of sensor networks, or even in the connection of mobile devices used in participatory sensing. Besides, the cellular network offers much more interesting coverage for applications that require mobility. Even using a MAN, it is possible that some regions of the city are discovered and make it impossible to operate the system. The cellular networks complement the others, guaranteeing flexibility to the services of monitoring and control, especially when mobility is necessary.

Cloud platform component

The cloud platform component enables remote access to services as infrastructures, frameworks, and software over the Internet using the resources available. The main features of the cloud are agility, scalability, access to any location and by different devices (e.g. smartphones, laptops, smart TVs), it allows the sharing of resources by a large group of users, and easy-to-use services, not requiring necessary installation.[41] Cloud integrates all facets of ubiquitous computing by providing scalable storage, and computational resources to build smart city applications. The cloud platform for the proposed CPS architecture has communication with the local processing component and other devices directly over the Internet to execute online and batch data analyses making use of big data clusters and analytical tools, see Figure 4.

In smart city applications, in specific online data analysis, we perform decision-making support on real-time data. In urban planning, we use previous historical data generated from the same sources used on real-time smart city applications, adding or not information from the legacy system to plan for the future. For example, by analyzing electricity, water or gas consumption from previous years, we can predict the demand for the next years and take the necessary action to fulfill the demand. Both online and batch data analyses take advantage of the machine learning algorithms and other computational intelligence resources that are implemented to build the models.

Storage and e-Gov legacy systems. Storage of information in a smart city is one of the most important tasks, especially to urban planning. All applications and services depend on the processing and analyses that are performed on the data. NoSQL databases in the cloud are often used to store a large amount of unstructured data (e.g. sensor data, email, social media posts), although some applications still use relational cloud database. This cloud structure maximizes performance, reliability, and data protection.[42]

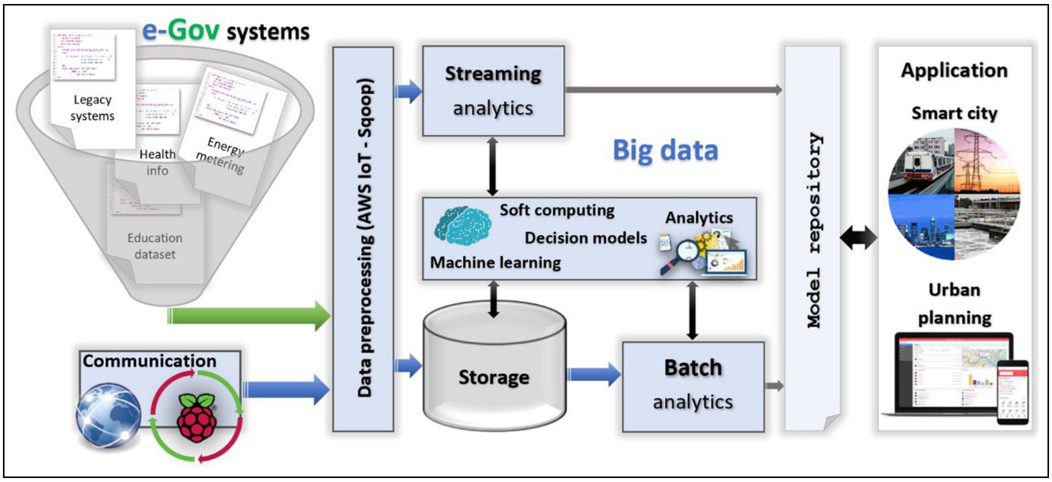

Figure 4. Cloud platform component for data processing and analysis.

In addition, when information technology is applied in public administration (e.g. federal, state, or municipal spheres), it is called e-Gov. The data contained in the databases of these e-Gov legacy systems can be aggregated to extract relevant information for efficient urban planning. Most cities use e-Gov services (e.g. people, students, and patient registration; use of public services; inventory control; and access control; among others) that can contribute to a more refined outcome of the data analysis. At first, information from e-Gov applications needs to be filtered to eliminate duplicate data, unnecessary, and irrelevant information. The choice of attributes that will be used is based on the application that will be developed and the storage of this selection will be in the same cloud environment to ensure a better performance in the data processing phase.[35]

Machine learning algorithms. Machine learning techniques are very useful in data processing in a smart city structure. These techniques transform raw data into knowledge that can assist in solving various problems. Extracting data from the environment with WSANs, participatory sensing, and other devices reconciled with these techniques makes it possible to create applications that work in the identification and recognition of activities.[43,44] One of the most important aspects of the process of identifying and recognizing activities is the task of building the activity model. Using techniques of data mining and machine learning, models of occurrences of activities are created from which new executions of such activities will be recognized.[35]

Application component

The application component is a collection of cloud-based software and application programming interfaces (APIs) which perform the data interpretation by creating services available to the smart city. These services may be for use by city managers (e.g. monitoring of public environments, intelligent transportation, and city surveillance) as well as for citizens' use (e.g. car traffic conditions on downtown, air quality information, and available services in public departments). In addition, intelligent applications must be able to perform autonomous decision-making and actions, based on the result of processing the collected data and the pre-established functions for which the app was designed.

Experimental validation and results

During the last years, we have developed specifications for several cities willing to deploy such digital city infrastructure. Also, we had a cooperation agreement with the city of Pedreira-SP localized in the southeast of Brazil, where an experimental validation was deployed. In Pedreira-SP was implemented an open-access MAN. The network consists of hybrid optical backbone gigabit Ethernet complemented by wireless-access cells. The radios are a dual-band system that provides access points and bridging interfaces. Figure 5 describes the coverage area of the MAN network, and in detail the test environment.

The network infrastructure attends both public and private sectors as well as universal access to citizens. The main goal was to develop a network to attend to digital inclusion in the less favored districts of the city and also to attend the city hall and its secretariats and departments, having as a basic rule the integration of the e-Gov systems and to monitor public environments.

We explored the existing network infrastructure and services to integrate our proposed CPS architecture. The open-access MAN became part of the CPS architecture composing the communication component. As

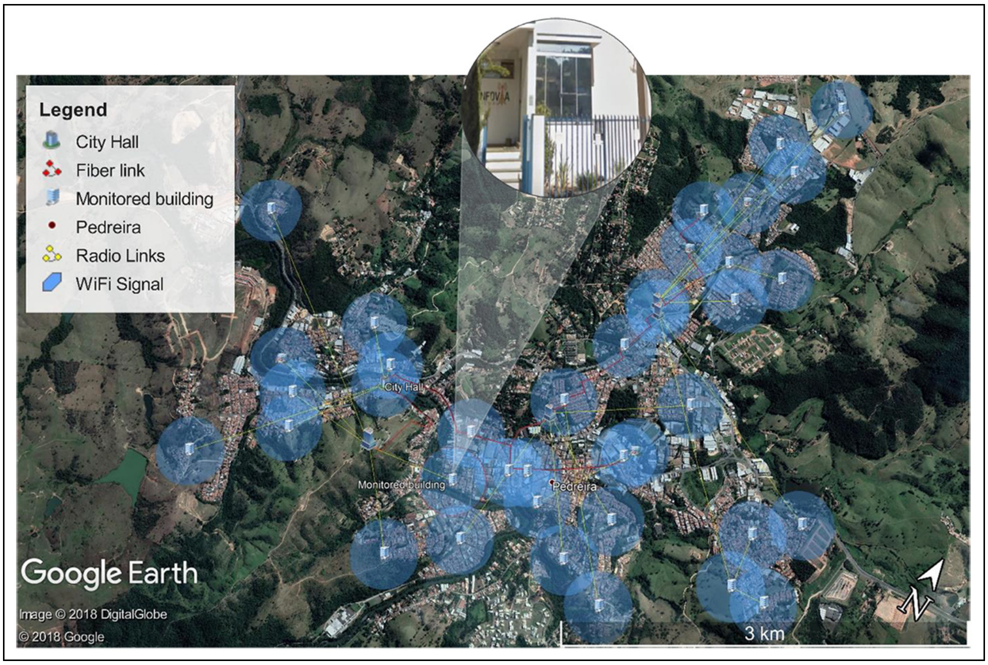

Figure 5. Google Earth visualization of Pedreira.

Table 1. Experiment configuration.

Parameter	Value
City	Pedreira-SP/Brazil
Experimentation days	120
Habitants	45,579
Area of the city	109.7 km^2
Measurements collected	10,401,511
Monitored environments	1
Number of sensors	4
Number of actuators	9 (not all used)

Table 2. Monitoring modes.

Counting-mode	Alarm-mode
People-counting	People-detection
	Alarm activation
	Message sending
AC voltage (RMS)	
Temperature (°C)	
Actuator status (ON–OFF)	

RMS: root mean square.

a way of ensuring a minimum level of security, a virtual local area network (VLAN) was created to segment the network and isolate the monitored environment information traffic from the other services available on the MAN. The experiment was realized in the IT department building (Infovia office), which hosts network devices (e.g. switches, radios, antennas, and routers), servers, and backup devices used in the maintenance of own network infrastructure. In addition, the building has a secretariat for citizen assistance. The choice of the environment was due to the need to control the entrance and exit of citizens in the building. Besides, it was supposed that the malfunction of some equipment was due to temperature and voltage fluctuations. Based on these environmental observations, the goals of the experiment were as follows: first, monitor the number of citizens assisted; second, intrusion detection alarm at non-business hours; third, monitoring the voltage and temperature of the environment to analyze the impact on the devices; fourth, actions in the environment through actuators; and finally, based on the results obtained with the experiment, evaluate the operation of the system. Table 1 synthesizes the city information and experimental details.

The system realizes the local processing with decision-making support and cloud processing to urban planning. In the experiment, the local processing component operated in two different modes, counting-mode and alarm-mode. This configuration was designed to optimize the use of the sensors, performing different functions in each mode. Basically, in counting-mode, the system reports the citizen attendance by counting the number of people that come to the secretariat on business hours. In alarm-mode, at non-business hours, especially at night and on the weekends, the same sensors were used to detect intruders and trigger the alarm. Table 2 summarizes the

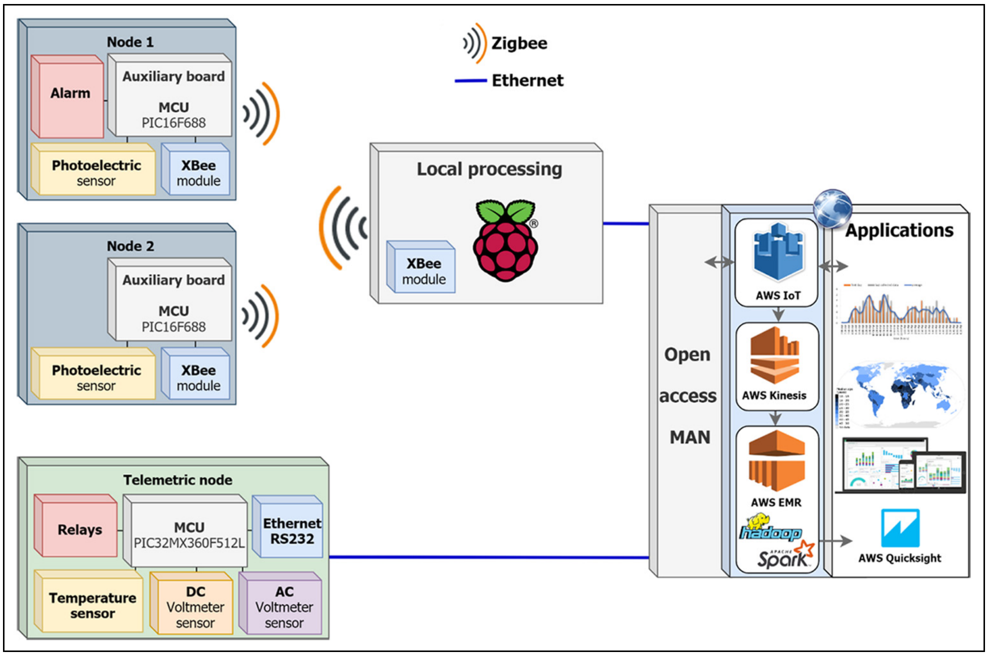

Figure 6. Systemic view of the system components.

configuration of both counting-mode and alarm-mode, and other details.

The system operated between 07:00 a.m. and 06:00 p.m. from Monday to Friday in counting-mode. Otherwise, the system automatically switches to the alarm-mode. As shown in Table 2, some monitored variables and the actuation function remains unchanged regardless of the mode of operation. Figure 6 shows a systemic view of the system components and devices used in the experiment.

The local processing component

We built our local processing component prototype using a Raspberry Pi 3 running a Python application over a Linux Raspibian distribution. The device has been equipped with Ethernet, WiFi, and Zigbee network interfaces. This component differs from conventional gateways by enabling local data processing, reducing latency, and ensuring its operation even with the failure of the Internet connection. The component interacts with the cloud by connecting to the Amazon Web Services (AWS) IoT service through the message queuing telemetry transport (MQTT) protocol over a WebSocket to publish and subscribe.[45] The AWS IoT provides secure, bidirectional communication between the local processing component and the cloud platform.

The cloud platform

As aforementioned, the local processing component establishes a connection with the AWS IoT service which is a secure and managed MQTT broker. At the core, the AWS IoT provides transport layer security (TLS) and secure sockets layer (SSL) cryptographic protocols which use a handshake mechanism to negotiate parameters to create a secure connection between the client and the server.[46] Later, the data are redirected to the AWS Kinesis that facilitates to collect, process, and analyze real-time streaming data, enabling timely insights and react quickly to new data.[47] Finally, the AWS Elastic MapReduce (EMR) clusters can read and process Kinesis streams directly using Hadoop big data ecosystem.[48] We have chosen AWS services, specifically because it has a large number of tools from data collection to results visualization. Besides, EMR Hadoop ecosystem accommodates the Apache Spark framework which integrates de MLib, Spark's machine learning library. Currently, Hadoop and Spark are the most used big data processing frameworks.[49] Even using the EMR, we have used a few resources, especially in statistical tools to analyze the data and storage.

Nodes 1 and 2

For people-counting application and intruder detection, two photoelectric sensors were used to monitor the environment. The choice of this type of sensor was made due to four characteristics: fast response time, appropriate sense range for this application, detection of all kinds of materials, and for being reliable. Auxiliary circuit boards were used to integrate the photoelectric sensors with XBee modules in order to

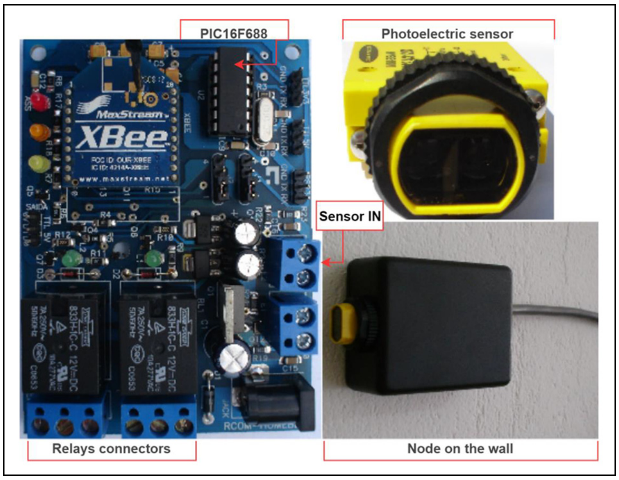

Figure 7. Auxiliary circuit board, photoelectric sensor, and node installation.

establish communication with the local processing component, see Figure 7. The XBee modules use the IEEE 802.15.4 specification and Zigbee protocols.

Photoelectric sensors. The photoelectric sensors used are model MINI-BEAM developed by Banner Engineering Corporation.[50] The sensors operated in a diffuse mode alignment, and the detection is performed by the reflection directly from the object (people). The photoelectric sensors were installed on the wall of the entrance hall due to the range of the sensor. Although the range is short (about 400 mm), other parameters were important to people-counting function such as response time (8 ms) and repeatability (2.6 ms). During the installation, some adjustments were necessary, such as the gain because of the light reflection from some background objects.

Auxiliary circuit boards. The auxiliary circuit boards are equipped with two embedded relays each that can control an external device or power electrical circuits. These relays enable the development of remote actuation and control application offering ON–OFF functions. The history of actions on the environment is stored as well. In addition, in alarm-mode, one relay was used to activate an alarm, in case of intrusion detection, with the intention of protecting the public property. At the same time, the system sends an alarm message to the responsible user. The boards can power up using a power supply of 12 V.

Results. The citizen attendance analyses results are illustrated in Figures 8 and 9. Figure 8 represents the first day of monitoring along with the latest data collected and the average of the validation period. Figure 9 shows the result of weekly analyses of this monitoring. Based on these results, the public administration can plan the best allocation of civil servants to assist the citizens. Figure 10 illustrates an operation in alarm-mode. In this case, an intrusion was detected by the sensors and the system performed the programmed actions.

Telemetric node

The Telemetric node prototype (see Figure 11) was designed to monitor server racks for networking communication equipment. It is robust and equipped with voltage sensors capable of measuring AC and DC current. The results were monitored on a web interface, or via simple network management protocol (SNMP), and stored in a database. The Telemetric is able to monitor the temperature as well, whose sensors must be coupled to the rear of the equipment. Also, external devices (e.g. audible alarms, fans, sirens, motors) can be actuated using one of the five electrical outlets. Telemetric node has been equipped with Ethernet and RS232 network interfaces.

AC voltage monitoring. Electronic devices are sensitive to disturbances in the electric power system, especially that caused by voltage fluctuations (e.g. spikes, overvoltage,

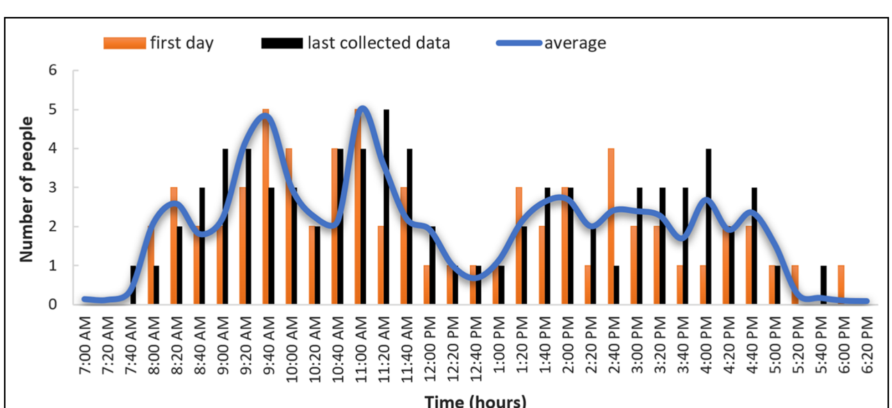

Figure 8. Citizen attendances in the monitored environment.

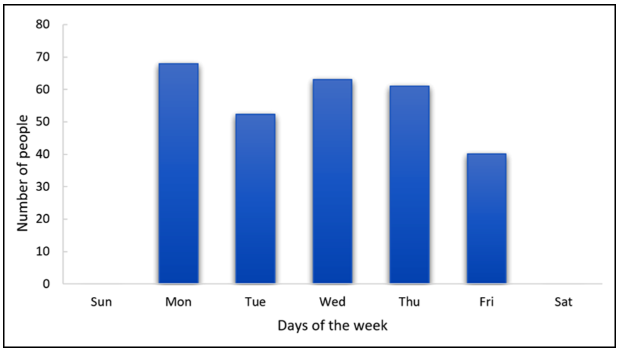

Figure 9. Average attendance weekly.

and line noise). In some cases, these effects can result in hardware damage and data loss.[51] Using the Telemetric node, we could monitor the AC voltage (root mean square (RMS)) of the power system in a networking communication equipment rack with readings in 0.5 Hz sample rate. The purpose of the monitoring was to analyze superficially the voltage fluctuations, the behavior of equipment and possible failures in their communication caused by electrical conditions. Figure 12 presents the results of three random monitoring days. Observing the results, we could notice that the voltage values varied between 115 and 128 V, and this variation did not cause a visible impact on the equipment and their communication remained in normal conditions. In the analyzed period of the experiment, we also could see that the most oscillations happened during business hours, which means that in this time the energy consumption in the region is more intense.

Temperature monitoring. The temperature is another physical variable that affects the working conditions of electronic devices.[52] Networking equipment and servers, for example, create a large amount of heat dissipation while running. If no system is monitoring the heat that is given off, it can cause a huge disruption in services, damage to the equipment and data loss. In the experiment, we monitored the temperature of the room that was the same equipment whose voltage we analyzed with the same sample rate of readings. Figure 13 presents the temperature variations of three different days. It can be observed that the greatest temperature oscillations occur during business hours, as well as the minimum temperatures. In our analyses, this behavior is due to the fact of the intense use of air conditioning in the building.

External device activation. Telemetric node enables the activation of external devices using one of its five electrical outlets. This function can be programmed to be performed autonomously according to the values of monitored variables or can be remotely triggered by users through a panel control. In addition, the system monitors all actions, storing the information (e.g. time, switching state ON or OFF, outlet number, autonomous, or human-controlled) for future analyses. Figure 14 illustrates some remote activation that we realized during the experiment to validate the data storage and simulate external device activations.

Network downtime. Network downtime monitoring is extremely important because it enables to check vulnerabilities in the communication component of the CPS architecture. The network can go through periods of downtime for a variety of reasons, including human error, system reboots, power issues, routing problems, lack of Internet connectivity, and others. Telemetric node supports the SNMP which allowed us to monitor the communication component (open-access MAN) during the whole period of the experimental validation. As it is depicted in Figure 15, in 24 h of continuous

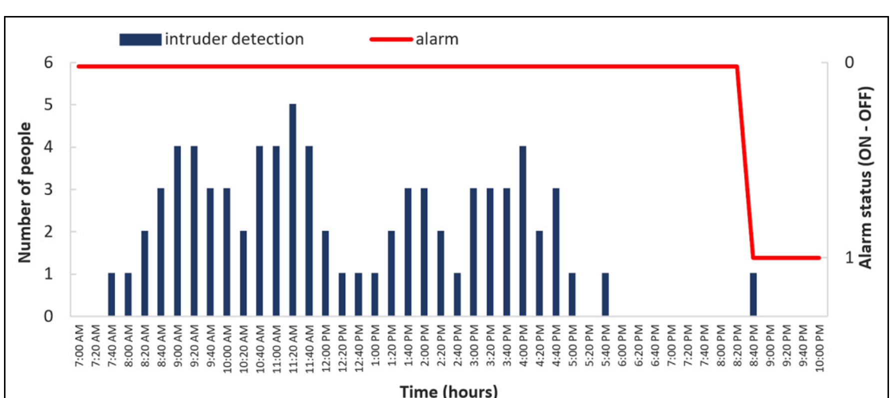

Figure 10. Intruder detection and alarm status.

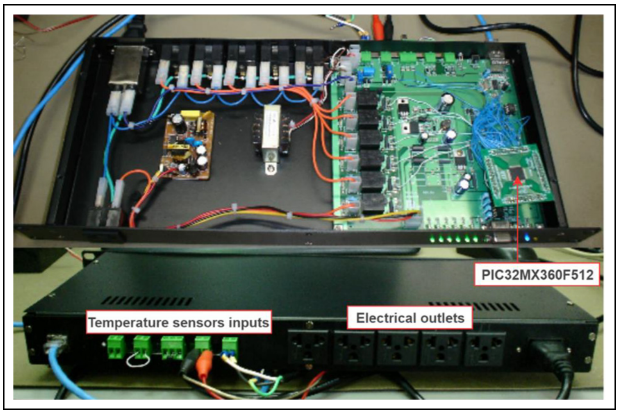

Figure 11. Telemetric device with sensors and electrical outlets.

monitoring were detected two moments of short downtime, however, the information still being collected in both moments.

Concluding remarks

The deployment of smart city solutions in the global scenario is still very timid and new proposals are very welcome. The population growth, rural–urban migration, the need for municipal management tools, the growth of vehicles on the streets, better use of public resources, and more efficient services to citizens are examples to show how important is the design of technological applications in the cities. Our proposal was focused on presenting an integrated CPS architecture capable of implementing smart city solutions, applying the principle of making incremental changes to the current network infrastructure, and reusing as much of existing solutions as possible (e.g. e-Gov applications, legacy system database, and surveillance cameras).

Based on the results obtained in the experimental validation, we could assume that the first goal was achieved by reusing the open-access MAN infrastructure as the communication component, which presented a great performance in terms of uptime, monitored by SNMP. The CPS is based on building blocks, which we termed as components, and shown to be a flexible alternative to share functionalities. As an example, the local processing component operated in two different modes, which were transparent to the cloud platform component, even the data being collected and processed by the local processing component and stored in the cloud database.

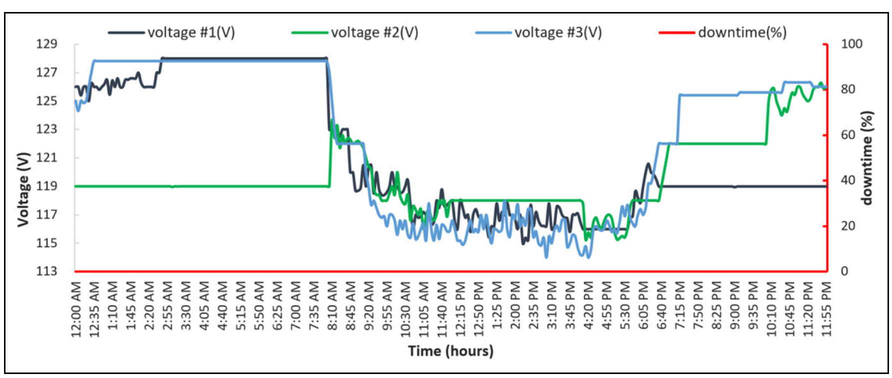

Figure 12. Three random days of voltage monitoring.

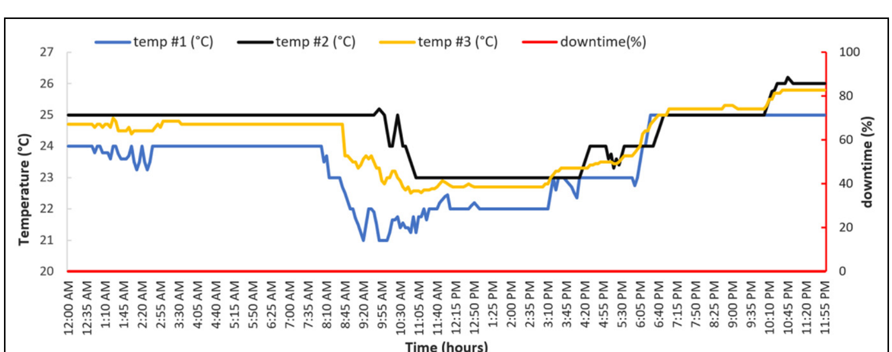

Figure 13. Temperature monitored on the experiment.

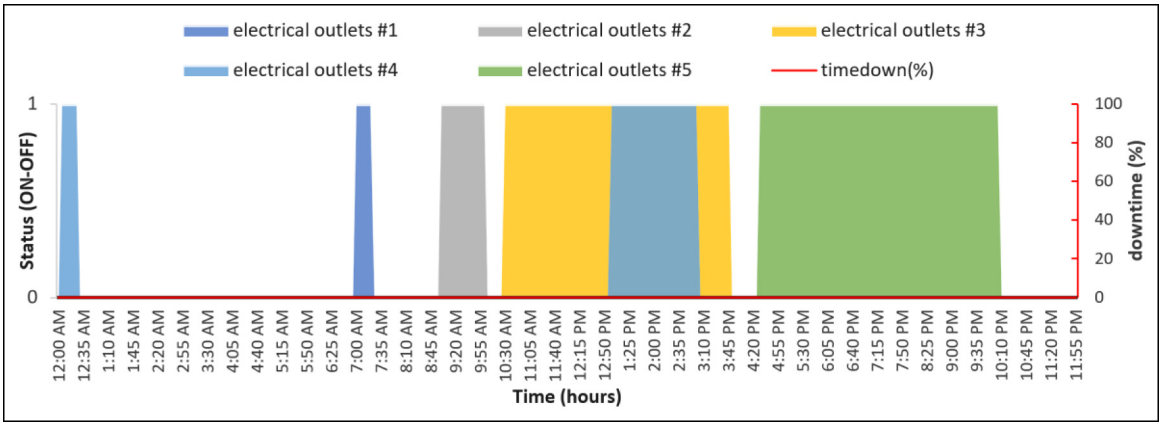

Figure 14. Remote activation of electrical outlets.

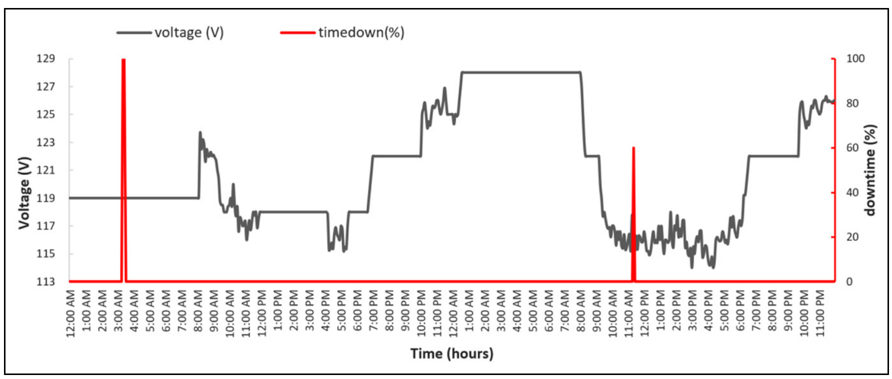

Figure 15. Network downtime occurrences in two consecutive days of monitoring.

Future directions

We intend to evaluate the integration of e-Gov systems so that it can bring more information about the monitored environment. The next step is to perform more sophisticated data processing in the cloud platform component using the EMR tools with machine learning algorithms and develop participatory sensing applications, making it possible for the citizen to contribute to the development of the city.

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