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A Social Internet of Things Smart City Solution for Traffic and Pollution Monitoring in Cagliari

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***Abstract*—In the last years, the smart city paradigm has been deeply studied to support sustainable mobility and to improve human living conditions. In this context, a new smart city based on Social Internet of Things paradigm is presented in this article. Starting from the tracking of all vehicles (that is, private and public) and pedestrians, integrated with air quality measurements (that is, in real time by mobile and fixed sensors), the system aims to improve the viability of the city, both for pedestrian and vehicular users. A monitoring network based on sensors and devices hosted on board in local public transport allows real time monitoring of the most sensitive areas both from traffic congestion and from an environmental point of view. The proposed solution is equipped with an appropriate intelligence that takes into account instantaneous speed, type of traffic, and instantaneous pollution data, allowing to evaluate the congestion and pollution condition in a specific moment. Moreover, specific tools support the decisions of public administration facilitating the identification of the most appropriate actions for the implementation of effective policies relating to mobility. All collected data are elaborated in real time to improve traffic viability suggesting new directions and information to citizens to better organize how to live in the city.**

***Index Terms*—Smart City, Social IoT, Heterogeneous Networks, Devices Tracking, Environment Monitoring, Data Protection.**

I. Introduction

The smart city (SC) is a paradigm that adopts mobile computing systems through practical data management networks amongst all components and layers of the city itself [1]. These data management systems can provide improvements in different aspects of operations and organizations, such as traffic control, sustainable resource management, quality of life, and infrastructure. Nowadays, Internet of Things (IoT) is emerging as a valid technology to develop smart solutions in order to improve everyday life of people and the way of life, acting on habits, helping in choices, limiting wasted time, or simply helping to manage it better [2]. IoT-based techniques allow to manage heterogeneous and massive data for real time monitoring and decision making and can be used for SC solutions [3]. This article presents a system that leverages the Social IoT (SIoT) paradigm [4], according to which objects are capable of establishing social relationships in an autonomous way [5]. Thanks to the resulting social network, sensors, cameras, smartphones, and other devices located in the metropolitan area of Cagliari can cooperate by discovering, exchanging, and collecting information to optimize the use and the way of living the city system, with great potential for the addition of a number of functions, from safety through biometric access controls [6], to digital support for the fruition of Cultural Heritage sites [7].

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The proposed SC system aims to carried out a project supported by the Italian Minister and proposed by a partnership of entities and companies in Southern Sardinia, Italy, for the development of ICT technologies aimed at optimizing the use of the city system and improving the life quality of people who live and work in the metropolitan area of Cagliari. The primary objective of this project was the development of innovative mobility solutions for urban and metropolitan area with low environmental impact, in order to improve the energy and environmental performance of the city, and is based on the research and testing of a sensor network consisting of:

1) fixed devices for tracking vehicles entering/exiting urban areas that allow real time analysis and historical archiving such as to provide the information necessary for the management of traffic light systems and the sending of contextualized information to the user for route optimization;
2) mobile devices for the acquisition of parameters relating to mobility and the environment in order to provide input data to the action planning models for improving both mobility and environment.

The integration of specific models in systems for intelligent transport management allows the optimization of public and private traffic flows in urban area as well as the control and reduction of polluting emissions. The innovation of the project stands on the application of a ”net-centric” paradigm through a dynamic and pervasive network (that is, Urban Information Grid) whose nodes can be both fixed and mobile, public transport, and equipped operators who are thus transformed into “mobile platforms” through the continuous acquisition of data relating to traffic, atmospheric, sound, and electromagnetic emissions.

The proposed SC system aims to:

- model system of citizen mobility by monitoring the position data of personal mobile devices. The anonymization sub-system of the collected information allows to guarantee the respect for privacy of users. This system also contribute to a significant improvement in the tailoring of the public transport offer allowing to concentrate it where

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(that is, both in time and space) there is greater demand;

- carry out a monitoring network based on sensors and devices hosted on board (that is, in local public transport - LPT). This network, insisting on routes with greater anthropogenic load, allows real time monitoring of the most sensitive areas from an environmental point of view;
- develop an integration model for mobility and environmental data useful both for assessing the levels of energy and environmental sustainability and for planning interventions aimed at containing atmospheric, acoustic, and electromagnetic pollutants;
- provide tools to support the decisions of public administration facilitating the identification of the most appropriate actions for the implementation of effective policies relating to mobility.

The SC solution has been tested in a real scenario in the metropolitan area of Cagliari.

The paper is structured as follows: in section II, an overview of previous IoT-based SC projects is presented. Key requirements forIoT-based SC environments are illustrated in Section III. The architecture and design of the proposed SIoT SC are described in section IV, while a short discussion on the privacy management of data is presented in section V. The real scenario to evaluate the performance of the carried out demonstrator and the obtained results are discussed in section VI. Finally, the conclusions are drown in section VII.

II. Background

The provision of SC applications, on the one hand, allows city authorities to monitor, manage and deliver plans for the use of public infrastructure and related smart services in cities. On the other hand, such applications raise various problems such as the reliability of data sources and the extraction of updated information in real time from large-scale dynamic data streams. In this section, previous solutions proposed to improve traffic flow management within a SC (subsection II-A) and to monitor and mitigate environment pollution (subsection II-B) due to the big amount of vehicles are presented. The objective is to highlight points of strength and weakness compared to the proposed solution. Finally, table I summarizes the main characteristics.

A. *Smart city and traffic monitoring*

One of the first objectives for the regularization of traffic flow within a SC has always been to regularize traffic light intersections by adapting them to traffic conditions instead of keeping the same timing throughout the day. L. F. P. de Oliveira et al., [8], contribute developing a centralized traffic light control system, using a unique wireless communication network. In order to prove the system's effectiveness, the most common types of urban intersections were analyzed. Direct control routines were implemented for network traffic lights, providing a complete control system for extraordinary events, such as closing roads due to accidents or public events. Finally, safety routines were formulated to report the operating status of the traffic light system lamps to a central management. With the aid of a logic analyzer connected to the outputs for each focal group, it was possible to set up an operating stages timing diagram of each traffic light. Thus, the system validation was achieved based on theoretical and practical timing diagrams similarities. Comparing this solution with the one proposed in the article, it does not perform real time acquisition of information on the traffic, as well as it is not able to instantly intervene in case of excessive congestion.

S. Kolozali et al., [9] proposed a framework that enables efficient semantic integration of data streams, and complex event processing on top of real time data aggregation and quality analysis in a semantic Web environment. To evaluate the system, has been used a real time sensor observations published via an open platform called Open Data Aarhus by the City of Aarhus. The framework has been examined using symbolic aggregate approximation to reduce the size of data streams, and performs quality analysis taking into account both single and multiple data streams. The authors also investigated the optimization of the semantic data discovery and integration based on the proposed stream quality analysis and data aggregation techniques.

Given the very high amount of data and their different sources, it must be considered that it is not realistic to expect full convergence towards a single IoT platform in the near future. Therefore, it is mandatory to allow interaction between different platforms based on multiple standards, coexisting in emerging SCs. For instance, J. An et al., [10] take the example of two global IoT standards, FIWARE and oneM2M, which are actively used in many SC projects, and analyze them to show the feasibility of IoT platforms interworking. Based on the analysis, a design and implementation of a novel IoT interworking architecture has been proposed providing a semantic driven integration framework suitable for SC. The core idea behind the proposed approach is to introduce interworking proxies that conduct a static mapping of sensor information between IoT platforms. The results demonstrate that it is able to discover and manage IoT sensors connected to both oneM2M and FIWARE.

Accurately obtaining road vehicle information is important in intelligent traffic surveillance systems for SCs. Especially smart vehicle detection is recognized as the critical research issue of intelligent traffic surveillance systems. For this purpose, a robust real time vehicle detection method for the system is proposed by Z. Wang et al., [11]. The method combines background subtraction model MOG2 (Mixture of Gaussians) with a modified SqueezeNet model (H-SqueezeNet). The MOG2 model is utilized to create scale-insensitive Region of Interest (RoIs) from video frames. H-SqueezeNet is then proposed to accurately identify vehicle category. The effectiveness of the method was verified in CDnet2014 dataset, UA-DETRAC dataset and video data from a traffic intersection in Suzhou, China. The experiment results show that the method can achieves excellent detection accuracy in traffic surveillance systems, and achieve an average detection speed of 39.1 FPS. This solution is limited by the unique acquisition of information using traffic cameras.

O. Younis et al., [12] propose a novel framework dynamic traffic lights TLs control (DTLC) at road intersections, based on a sensor network in charge of collecting traffic data and

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including novel protocols to handle congestion and facilitate more efficient traffic flow. The proposed low-overhead algorithms are practical to employ in live traffic flow scenarios. A realistic simulations using traffic data in a real-world network were performed to control the traffic signal for emergency vehicles in order to ensure an expeditious emergency response alleviating the negative influence on the traffic efficiency of conflicting directions [13]. A collaborative edge computing (CEC) in vehicles is proposed by T. Wang et al., [14] to improve traffic efficiency. The social features and connections among vehicles to reduce the average waiting time using multiagent-based deep reinforcement learning (DRL) for the servers that interact with Internet of Vehicles (IoV) and traffic lights to generate dynamic green waves at congested intersections. These solutions involve traffic light management not directly interacting with people and public administration to improve traffic flows in real time, only considering information collected by vehicles without considering other fixed devices to improve the real time analysis.

Y. Wang et al., [15] propose a deep learning-based method that uses social media data for traffic information in order to prevent jams, illegal behaviors, and emergency recourses on roads. A multichannel network with a Long Short-Term Memory layer (LSTM-layer) and a Convolution layer (Conv-layer) (termed as MC-LSTM-Conv) is proposed, to extract abstract features from input text. Moreover, a series of matching rules are constructed based on the keywords that are related to traffic-jam scenes. This solution only considers data collected by social network without matching information with real monitoring systems.

B. Smart city and pollution

In last years the number of of public (that is, bus) and private vehicles (that is, motorcycle, car, or truck) is rapidly increasing leading to traffic congestion and to environmental and noise pollution worsening. In this context, technological solutions typical of the SCs were developed and standardized to solve these kind of problems, especially in large cities where these concepts are stressed.

Driven by the increasingly serious air pollution problem, nowadays different systems can be used to achieve the monitoring task of air quality index (AQI) in urban areas. J. Gao et al., [16] outline a novel unmanned aerial vehicle-aided (UAV-aided) AQI monitoring system, called AQ 360, has been introduced, able to detect the air quality level from the 360-degree aerial panoramic images taken by the onboard camera. The proposed system has been implemented and evaluated in real-world scenarios showing that the system can provide a lower AQI recognition error compared with existing vision-based monitoring approaches, and energy consumption is also reduced when applying for large-area tasks.

Hu et al., [17] present the architecture, implementation, and optimization of an air quality sensing system, which provides real time and fine-grained air quality map of the monitored area. As the major component, the optimization problem of the system is studied in detail minimizing the average joint error of the established real time air quality map, which involves data inference for the unmeasured data values. A deep Q -learning solution has been proposed by the authors for the power control problem to reasonably plan the sensing tasks of the power-limited sensing devices online. A genetic algorithm has been designed for the location selection problem to efficiently find the suitable locations to deploy limited number of sensing devices.

M. S. Wong., [18] present an improved Integrated Environmental Monitoring System (IIEMS) able to monitor nine environmental parameters (that is, temperature, relative humidity, PM2.5, PM10, CO, SO2, volatile organic compounds (VOCs), UV index, and noise). This system was comprised of a mobile unit and a server-based platform with nine highly accurate micro-sensors in-coupling into the mobile unit for estimating these environmental exposures. A calibration test using existing monitoring station data was conducted in order to evaluate the systematic errors.

To overcome the problems of existing systems (that is, low precision, low sensitivity, and require laboratory analysis), S. Dhingra et al., [19] a three-phase air pollution monitoring system. An IoT kit was prepared using gas sensors, Arduino integrated development environment (IDE), and a Wi-Fi module. This kit can be physically placed in various cities to monitor air pollution. The gas sensors gather data from air and forward the data to the Arduino IDE. The Arduino IDE transmits the data to the cloud via the Wi-Fi module. Also an Android application termed IoT-Mobair was developed, so that users can access relevant air quality data from the cloud. If a user is traveling to a destination, the pollution level of the entire route is predicted, and a warning is displayed if pollution level is too high. The proposed system is analogous to Google traffic or the navigation application of Google Maps. Furthermore, air quality data can be used to predict future AQI levels.

The design of a low-cost air pollution monitoring system able to perform meteorological measurements on dense air quality has been presented by T. Becnel et al., [20]: PM1, PM2.5, and PM10 concentrations, temperature, humidity. The sensors are hosted and maintained by participating members of the community, which not only supplements community engagement, but eases a time-consuming burden of maintaining hundreds of sensors by a small team across a large geographical region. B. Montrucchio et al., [21] developed a low-cost monitoring system for particulate matter; it was based on special-purpose acquisition boards, deployed for monitoring air quality on both stationary and mobile sensor platforms. S. Ali et al., [22] proposed a low-cost sensor node that utilizes cost-effective electrochemical sensors to measure carbon monoxide (CO) and nitrogen dioxide (NO2) concentrations and an infrared sensor to measure particulate matter (PM) levels. All the solutions presented in these subsections only aim to assess the level of pollution in urban and sub-urban environments without integrating with smart traffic monitoring systems. Table I is a comparative table to summarize differences between previous solutions presented in this section and the proposed SIoT SC system in term of eight key aspects:

- Off-Line Traffic Lights management;

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- Real Time Traffic Lights management;
- Vehicles Monitoring;
- Global Traffic Flow Monitoring;
- Real Time Sensors Acquisition;
- Camera Acquisition;
- Environment Monitoring;
- General Data Protection Regulation 2016/679 - GDPR;
- Social Features.

From the best of our knowledge and in accordance with the state of the art, the stringent requirements of the project as innovative and research solutions, did not allow us to take advantage of commercial solutions. Therefore, it was necessary to develop a hardware/software system that met the project constraints with innovative and research solutions. The proposed solution showed a practical, highly scalable and innovative character, overcoming the limitation of existing solutions and converged the needs of municipal police, port authority and control of a large metropolitan area.

III. Key Requirements for IoT-based Smart City Environments

Nowadays, when the European Union talks about SCs it includes six main dimensions [23]:

- Smart People: people (citizens) must be involved and made involved. There is talk of bottom-up decision-making (from bottom to top) and participatory policy.
- Smart Governance: the administration must give centrality to human capital, environmental resources, relationships, and community assets.
- Smart Economy: the economy and urban commerce must be aimed at increasing productivity and employment within the city through technological innovation. An economy based on participation and collaboration and which focuses on research and innovation.
- Smart Living: the level of comfort and well-being that must be guaranteed to citizens linked to aspects such as health, education, safety, culture, etc. they are also of priority importance.
- Smart Mobility: intelligent mobility solutions, from e-mobility to sharing mobility to other forms of mobility management, must look at how to reduce costs, reduce environmental impact and optimize energy savings.
- Smart Environment: sustainable development, low environmental impact and energy efficiency are priority aspects of the city of the future.

In this work we propose a study that particularly involves ”Smart People” and ”Smart mobility” with impactful effects also in the field of ”Smart Environment”. Next three subsections shortly describe the main key aspects took into account for the development of the presented SC system.

A. Vehicular traffic monitoring

Intelligent Transportation Systems (ITS) represent a series of technologies and solutions adopted by now on a global scale aimed at adding information and communication means and tools to transport and transport infrastructures vehicles. ITS arises from the need to monitor, supervise, and manage the problems related to traffic congestion through the wise and synergistic use of new technologies of measurement, detection, processing, analysis, and information technology for simulation, real time control, and new networks and communication technologies. Traffic is constantly increasing around the world, mainly due to motorization, urbanization, and population growth, as well as a substantial change in population density, habits and the economy and logistics of city centers. To be correctly governed, this phenomenon must be measured in a precise and rigorous way and its dynamics must be understood and studied as a function of heterogeneous, endogenous, and exogenous factors, such as the temporal context (that is, hour, day, month, year), economic, social (e.g., population), environmental (e.g., sources of pollution, meteorological conditions, etc.). Traffic, in its various forms and with different degrees of incidence, reduces the use of transport infrastructures, increases travel time, pollution and fuel consumption, and the risk of accidents, even serious ones, on the roads. The new generation of traffic monitoring systems is based on impulsive cameras and radar. Initially, adopted as part of the active surveillance of Motorways and Tunnels, this new generation of sensors proved to be increasingly effective, convenient and appropriate [24]. These ”smart cameras” within the same shooting device can host different coexisting analysis software to ensure the following functions, both on an urban and extra-urban scale:

- precise speed control of vehicles;
- checking the average speed of vehicles;
- classification of the type of vehicles in circulation;
- control of travel times;
- detection of queues or absence of traffic;
- detection of accidents;
- detection of delays.

The benefits produced by the use of technological equipment are tangible, compared to traditional cameras without intelligence on board. The information produced by these ”intelligent sensors” allows real time publication of traffic information to all communication channels available, starting from satellite navigation systems, mobile phones of users, and variable message panels placed along the main city roads. These characteristics are essential to have a tool that guarantees punctual real time monitoring of vehicle flows in a given road corridor and its branches.

B. Pedestrian traffic monitoring

Traffic flow monitoring is no longer limited to road users counting and speed measurement. New techniques and measurement methods allow to acquire data in a more differentiated way. Just as the users and their behavior on the road vary, in this case fall our proposal. In addition to traditional data on volumes, speed, and direction of travel, the proposed system observes the behavior of every single person (that is, also pedestrian, cyclist, and biker). In order to formulate a reliable indication of traffic flows, parking, waiting, travel, and traffic congestion times are considered. Currently, there are several solutions for measuring and monitoring the flow

TABLE I: Related Works - Comparison

KEY ASPECTS	SIoT SC	[8]	[9]-[10]	[11]	[12]	[13]	[14]	[15]	[16]	[17]-[22]
Off-Line Traffic Lights		●								
Real Time Traffic Lights	●	●			●	●	●			
Vehicles Monitoring	●			●			●			
Global Traffic Flow	●									
Real Time Sensors	●		●		●					●
Camera Acquisition	●				●				●	
Environment Monitoring	●								●	●
Social Features	●						●	●		

of people. For example, there are meters for bicycles, scooters, and pedestrians that use piezoelectric strips for continuous data collection. The most reliable solution for timed monitoring of shared routes and cycle paths on the road [25]. Nowadays, various mobile phone apps are able to record and store users' movement trajectories, which provide a valuable data source for pedestrian network construction. B. Zhou et al., [26] propose a crowdsourcing-based system for generating pedestrian network that encompasses three key components of crowdsourced walking trajectory: data filtering, pedestrian network construction, and evaluation of pedestrian network. Experimental results demonstrate that the proposed method can accurately and completely extract pedestrian network. Moreover, the pedestrian network can be updated in a timely manner and the data collection application and the relative collected data are available to the public. Another important aspect concerns the mobility and pedestrian safety through pedestrian sensors that allow to adjust the traffic light control at intersections in favor of pedestrians or to increase the visibility of pedestrian traffic. The dynamic traffic light control and the activation of warning signs make intersections or pedestrian crossings safer and, at the same time, avoid unnecessary delays for both pedestrians and motorists. Current automatic traffic surveys make use of a technology that provides for video recording of the flows to be analyzed and subsequent automatic counting through dedicated software. Therefore, pedestrian flow monitoring systems are based on the use of cameras with data analysis and counting after video acquisition or by means of hardware to be installed as loops and radar under the road surface. The proposed approach overcomes these limitations as it is much less invasive from the hardware point of view and allows the detection of people by analyzing radio signal produced by their smartphone, allowing intelligent monitoring and real time tracking less expensive and with lower computational burden.

C. Integration and interoperability in large deployments

In SC scenarios, complex challenges relating to the integration and interoperability of different solutions must be addressed. Many IoT protocols and standards have been established as a result of the adoption of IoT devices. Unlike traditional devices, IoT devices are typically limited in terms of memory and computing power. Additionally, IoT devices may be deployed in areas where there is limited or no access to continuous power, with essential use of batteries or tiny solar panels to power them. As a result, IoT devices now have energy-efficient communication protocols with smaller memory footprints and processing needs.

The acquisition, storage, and management of vehicular and pedestrian monitoring data requires advanced tools that work on the relationships and correlations between the data collected. From this point of view, Internet of Things platforms represent a basic but insufficient tool for migration and interoperability in large deployments. Lysis platform is a SIoT platform carried out for distributed IoT applications involving socially connected objects [27]. Objects are capable of establishing social relationships in an autonomous way with respect to their owners with the benefits of improving the network scalability and information discovery efficiency. The overall architecture of the Lysis platform through four functional levels:

1) the lower level is made up of the "things" in the real world;
2) the virtualization level, which interfaces directly with the real world and is made up of Social Virtual Objects (SVOs);
3) the level of aggregation is responsible for composing different SVOs to set up entities with augmented functionalities called micro engines (MEs);
4) the last level is the application level in which user-oriented macro services are deployed.

IV. System Architecture and Design

This section presents the main architectural elements and the design of the proposed SIoT SC solution. The key components of the architecture, shortly described in next sub-sections, are:

- sensors for mobility IV-A: cameras equipped with built-in intelligence, Wi-Fi Access Points;
- crowding and environmental control units IV-A: installation on public transport and close to bus stops and traffic lights;
- Lysis-compliant integration modules IV-B: several heterogeneous hardware components have been developed, differing for communication protocols and interfaces, as well as for data format. The Lysis virtualization layer allowed to integrate all these devices;

- Lysis-compliant interoperability modules IV-B: SIoT social relationships allow to ensure interoperability between heterogeneous devices;
- data analysis platform.

A. Mobility, crowding, and environment monitoring devices

The fixed multi-sensor stations are placed in specific points of the city and interconnected to Lysis platform via 4G Long Term Evolution (LTE) transmission system. The received information can then be related to the other measurements coming from the environmental detection devices. The data collection part is performed by positioning the fixed/mobile stations in determined points of the urban area of Cagliari, mainly road crossings with traffic lights, near particularly interesting areas, such as university areas and on public transport. The stations are equipped with components for the detection and transmission of data taking advantage of the power supply present at traffic light intersections. The collection of information is performed simultaneously by the different stations, which retrieve environmental data in the area and periodically generate a json file with all the measurements captured. Measurements and transmission take place at one minute intervals. This is to preserve a possible use with combined battery/solar panel power supply. These files are then sent through the 4G LTE transmission system to the central gateway (that is, the ME of the SIoT platform), which will transmit the received data to the upper layer of the SIoT platform that is in charge of classify and cross process them.

A single spatial database (SDB) is dedicated to each installed device presented in sub-section IV-C1 in charge of collecting information. A SDB is a database optimized for storing and querying data related to objects in space, including points, lines, and polygons, integrating functionalities for processing spatial data types. A processing unit is in charge of analyzing data of the various SDBs to find relationships and to reconstruct the traffic map. A dataset related to 12 consecutive months of acquisition was used for training this unit. The SDBs collected data were subsequently processed through Lysis platform. Thus, unlike what is reported in the state of the art, the proposed architecture carries out a real time analysis. The collected data also allow the provision of services to the citizen, for the optimization of the urban mobility network or the level of vehicular traffic. A further feature concerns the optimization of the use of public transport by citizens. The level of traffic necessarily affects bus routes with obvious repercussions on waiting times at bus stops. Therefore, the analysis of the traffic level combined with the real-time position knowing of the bus, its level of occupancy, and the position of the user, allows the system to optimize the reaching of bus stops, guaranteeing an additional service.

B. Lysis-compliant modules

In order to exploit the Lysis architecture advantages, the virtualization layer elements (SVOs) were designed and implemented, representing buses, traffic lights, traffic cameras, and smart bus stops. Each bus has its own SVO with which it communicates to send and record information relating to position and internal crowding (BUS-SVO in Fig.1). This last bit of data consists of three values detected by the sniffer placed inside the vehicle: a hashed ID to maintain the anonymization of the detected smartphone; the strength of the corresponding signal received; and the manufacturer of the smartphone. The traffic light SVO (TL-SVO) provides the API to control the lighting management actuator.

The Bus-SVO and the TL-SVO, establish a Social Object Relationship (SOR) as a consequence of the encounters that take place during the bus journey (green arrow between TL-SVO and BUS-SVO in Fig. 1). This relationship is exploited at the application level (that is, by the line management platform) to set actions when buses approach traffic lights along the route. In practice, the Bus-SVO, when the bus enters the geofence set on the traffic light, sends a command requesting the green light to be turned on to the approaching TL-SVO.

The Cam-SVO exhibits two sensors: a vehicle detector that produces as output the vehicle license plate (hashed) and the type of vehicle, and a traffic jam detector (CAM-SVO in Fig.1).

The Cam-SVO and the Tl-SVO positioned at the same intersection establish a Co-location Object Relationship (CLOR) since they are installed in the same place (red arrow in Fig.1). They also have a Ownership Object Relationship (OOR) as they belong to the public body that manages the roads (black arrow between CAM-SVO and TL-SVO in Fig.1). The CLOR relationship is used at the application level to set the management actions of the lights on the traffic light in correspondence with events detected by the Cam-SVO (traffic jam, ambulance or police approaching, etc.).

At the bus stop, we have smart shelters managed by smart bus stop SVO (SBS-SVO in Fig.1). This SVO exhibits sensors for monitoring air quality (i.e, temperature, humidity, barometer, and PM10) and a sniffer for assessing crowding like inside the bus. There is also an actuator that controls the screen that shows information to waiting passengers.

The SBS-SVO creates a SOR relationship with the Bus-SVO of the buses passing along the route (green arrow in between SBS-SVO and BUS-SVO in Fig. 1). In this case, the SOR relationship is used at the application level to set actions on both SVOs.

When a bus enters the geofence of a stop, the Bus-SVO notifies the SBS-SVO that the bus is arriving and sends the internal crowding information, shown on the screen to the waiting passengers. Likewise, the SBS-SVO sends the information about the air and the waiting crowding to the Bus-SVO which, shown on the on board screen.

C. System design

Traffic and pollution data has been collected by various devices located in established points previously selected in a planning phase to accordingly cover a specific are in the city of Cagliari. All these information are transmitted using existing infrastructures, to be able to archive, process, and make them available by different services. Some of these devices ,used to capture pollution and traffic data, have been prototyped by the authors, as shortly described in next subsections IV-C1,

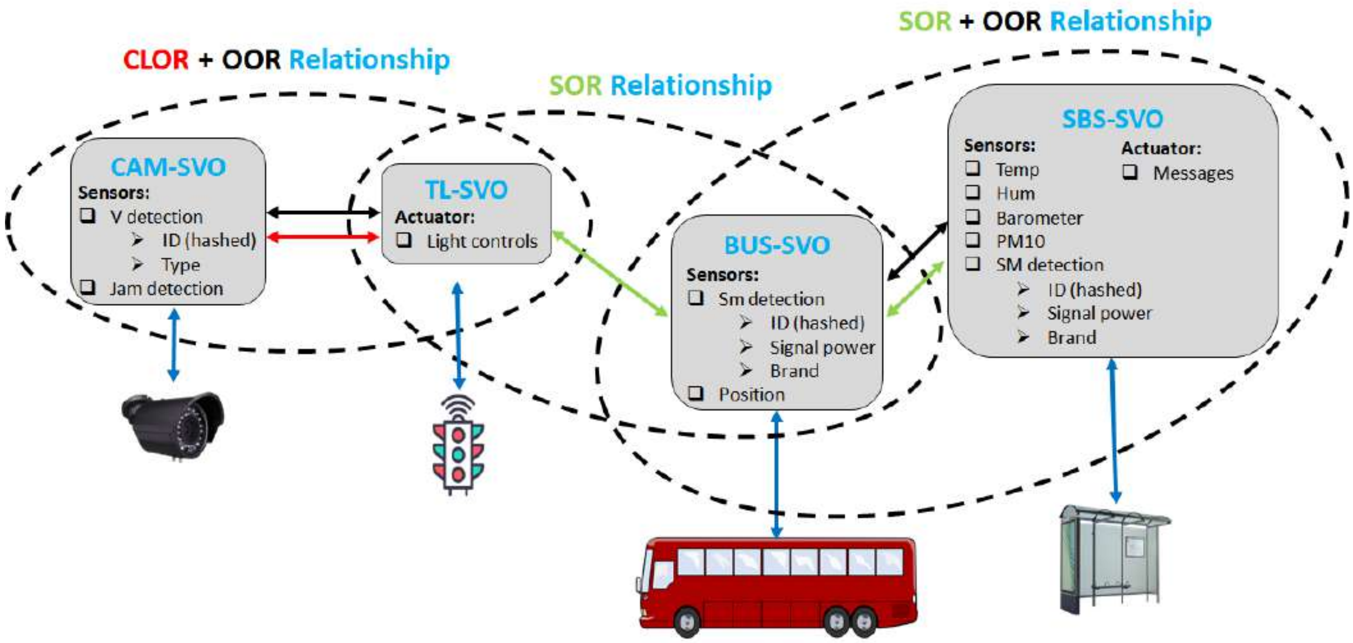

Fig. 1: Social connections between the SVOs of the elements of the system.

IV-C2, and IV-C3. Other data are extrapolated from different detection devices for tracking city mobility located in a specific geographic area:

- cameras;
- various types of sensors;
- mobile devices such as smartphones and tablets.

The proposed SIoT SC system is composed of three main levels:

1) **Level 1: the acquisition level** consists of a system composed of sensors that acquire the data to be processed. The crowding monitoring sub-system is presented in subsection IV-C1, while the mobility and the environment monitoring sub-systems are shortly described in subsections IV-C2 and IV-C3, respectively.
2) **Level 2: the elaboration and transmission level** represents the heart of the designed systems. The acquired data is anonymized and sent over the 4G LTE network to the cloud. Also in this case, the main components for the three sub-systems are shortly described in next subsections.
3) **Level 3: the data storage and management** collects revenue data from the data processing and transmission layer and stores it on the cloud where it can be processed appropriately for real-time statistics and application of certain actions in order to reduce vehicular traffic saturation.

The complete system is shown in Fig. 2.

The proposed system does not present critical issues in case of changing scale for a larger city, thanks to the social architecture on which it is based. The only implementation criticality, to be analyzed in the design phase, could be due to infrastructures which could determine a different choice on the devices to be deployed as well as their position. Moreover, the three sub-systems are protected against tampering and unauthorized access through the use of a virtual private network (VPN) used to transmit anonymized data over public 4G LTE networks anonymously and securely.

1) Crowding monitoring Sub-System: From the technical point of view, an 802.11 WiFi infrastructure capable of capturing a series of frames of the MAC sub-level has been implemented. MAC address are used by network interfaces to establish the physical connection between devices. A prototype for crowding evaluation in a specific area has been implemented (Crowding Monitoring Sub-System in Fig. 4). The tracking method is not based on the counting of individual vehicles but on the number of passengers using APC (Automatic Passenger Counting) techniques that are commonly divided into indirect and direct. Through an external network card connected to a Raspberry Pi device, the Wi-Fi traffic of mobile devices is carried out by ”sniffing” the MAC addresses. The system ensures that the redundant MACs will be not counted several times for a more accurate estimation of devices within the area of interest. It has a maximum operating range of about 50 meters and can be used both in indoor (that is, inside a bus or room) and outdoor (that is, close to traffic light) environment. The typical use case is the smartphone detection of pedestrians on board vehicles (that is, buses) moving with speeds of up to 50 Kmph (that is, urban environment). The block diagram of the developed MAC address counting prototype is presented in Fig. 3.

The Raspberry Pi 4 Model B is a device based on a Broadcom BCM2711 manufacturing system-on-a-chip, incorporating an ARM processor, VideoCore IV GPU, and 2 GB memory. The project includes neither hard disk nor solid state drive, relying instead on an SD card for booting and non-volatile memory. The prototype has been designed using the

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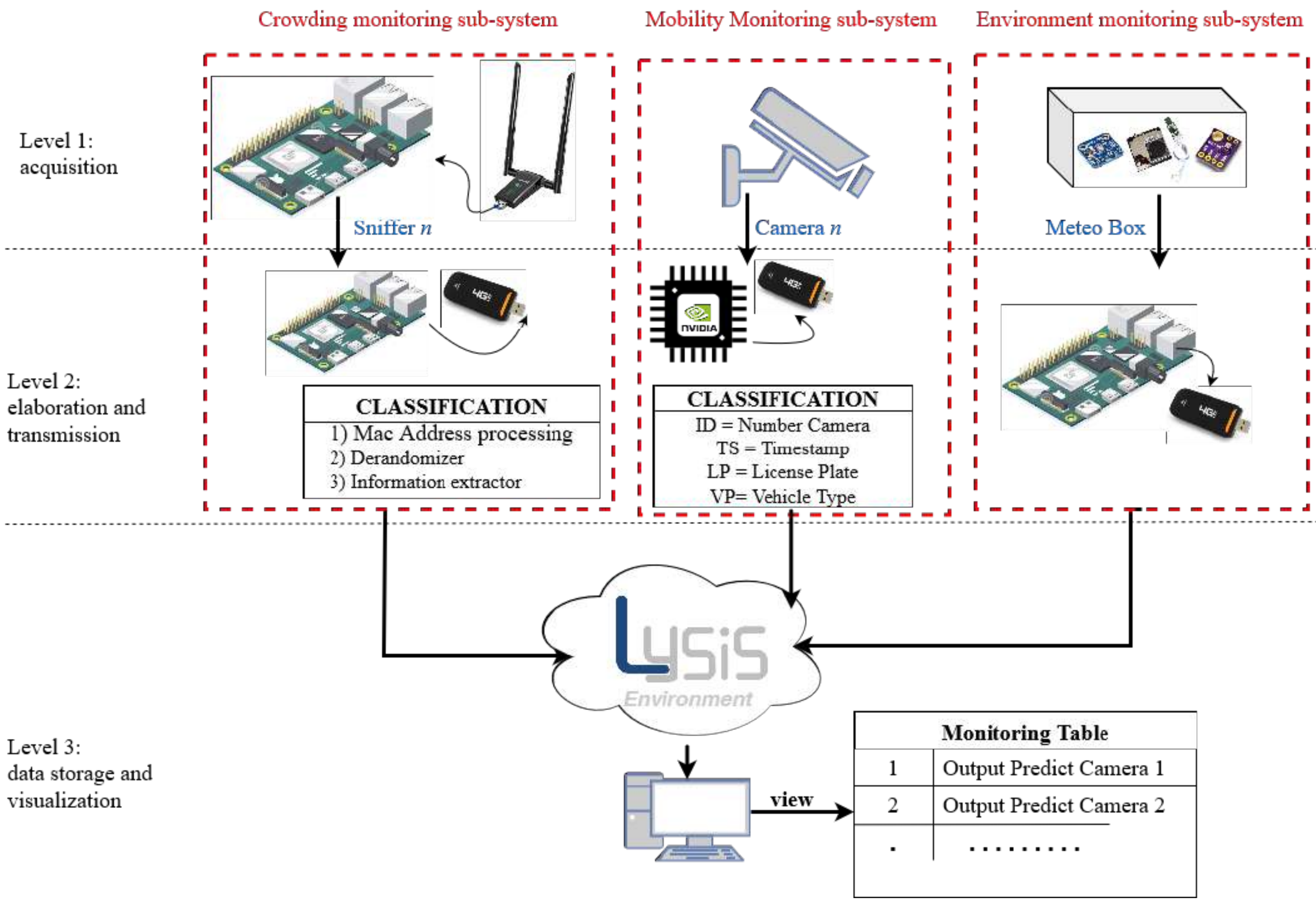

Fig. 2: General view of the monitoring system.

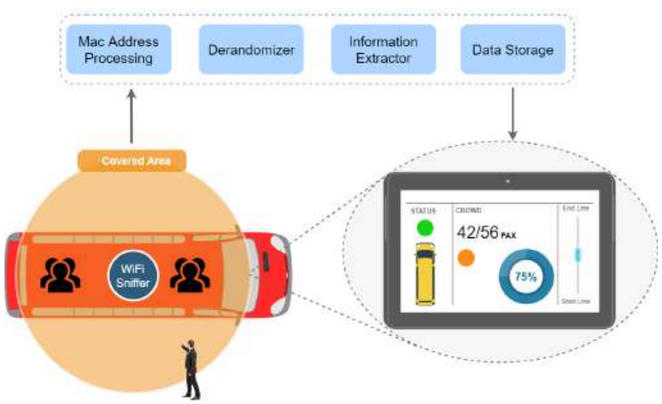

Fig. 3: Block Diagram of the crowding monitoring sub-system.

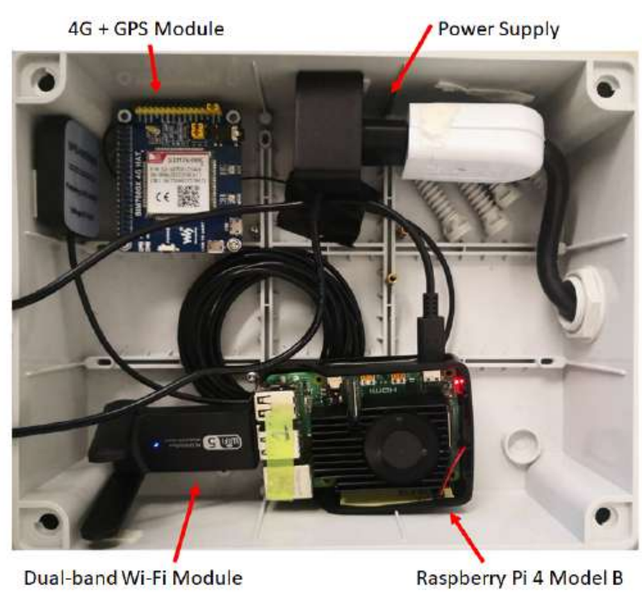

Fig. 4: Prototype of the crowding monitoring sub-system.

Python programming language and using appropriate additional modules linked to both the WiFi technology of public or private networks and LTE technology to transmit traffic data. A prototype of the Crowding Monitoring sub-system is shown in Fig. 4.

In order to effectively announce their presence to each other, mobile devices and access points (APs), need to use an active or passive mechanism for association. These mechanisms have been defined by IEEE 802.11. In the passive mechanism, the APs periodically advertise their presence to mobile devices by sending bacon frames, while in the active scanning mechanism, it is the mobile devices that actively search for the APs, transmitting probe requests, to which the APs neighbors will

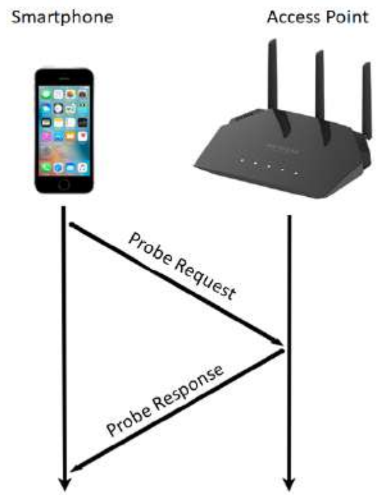

Fig. 5: Smartphone-Access Point communication.

respond with so-called probe response as shown in Fig. 5.

Probe requests are a particularly vulnerable component of WiFi traffic with regard to the identification of devices. Since each device transmits both single and burst probe requests with certain time and frequency intervals, this makes locating relatively simple. The probe requests include the MAC address and can be addressed in unicast mode to a specific AP (that is, indicating its SSID), or in broadcast mode to all APs within a specific range. Devices that are not associated with a particular AP periodically send probes requests that contain the unique identifier of the interface (the MAC address) in their header. More sniffing stations have been positioned in each intersection to improve localization accuracy and to conduct statistic evaluation on traffic flows. The probe request frames provide additional information thus display filters were used to extract only the contents of our interest from the scans, such as the MAC address of the resource, the timestamp, date and time of acquisition, and number sequence (that is, SEQ). A python script is in charge of retrieving the information from prob requests, reporting and encapsulating them in JSON format. Pandas library is useful for transforming received JSON files into dataframes. In each dataframes, the data is grouped by MAC address in HASH format, to comply with the protection of personal data, and finally sorted by SEQ number.

2) Mobility monitoring Sub-System: The camera has the task of shooting the scenes in a specific area, understanding and discriminating the vehicles (that is, object detection) in order to extrapolate its associated license plate from a frame through pre-processing techniques, such as cropping, resize, and zoom. Once the image relating to the plate is obtained, it is sent as input to a neural network opportunely trained to recognize the characters of the plates and this data is converted into a string (Mobility Monitoring Sub-System in Fig. 2). Image processing algorithms are implemented at each shooting point. The software performs a series of algorithms for the identification of the license plate:

- License plate location: this algorithm is responsible for searching and isolating the license plate on the photo.
- Orientation and sizing of the plate: this algorithm compensates for the inclination of the plate and adjusts the dimensions according to the required dimension.
- Conversion: using some image processing techniques it can be converted into a desired format, an instance to have a simpler image processing by converting it from RGB to grayscale.
- Normalization: this algorithm adjusts the contrast and brightness of the image.
- Edge detection: applied to increase the difference between the letters and the license plate holder. A median filter can also be used to reduce visual noise on the image.
- Character Segmentation: This algorithm finds individual characters on the plate and segments them for further improvement.
- Optical character recognition: is the electronic conversion of images or printed text into machine-coded text.
- Syntactic and Geometric Analysis: Checks characters and positions against country specific rules. Averages the recognized value over multiple fields to produce a more reliable and safe result. Especially since every single image can contain some reflected light or can be partially obscured.

Fig. 6: Prototype of the mobility monitoring sub-system.

At this point, the data, collected in string format, are processed by an appropriate software for the security of privacy, converting it into Hash format immediately before the transmission to the network [28]. It is a mathematical algorithm that maps arbitrary length data into a fixed size binary string called Hash value. This Hash function is designed to be unidirectional, that is hard to invert: the only way to recreate the input data from the output of an ideal Hash function is to attempt a brute-force search for possible inputs to see if there is correspondence. By means of the Gigabit Ethernet interface, the data is sent to the platform where it will be cataloged and a history of the associated hash string will be mapped, uniquely corresponding to a real plate. For a good measure of the data, the hash string is also associated with the shooting point to be able to report where the tracked vehicle has been identified. The data will be transmitted as soon as the hash string is played, so the device is expected to continuously transmit to the database. The SHA-256 [29] ”double” algorithm was used in this work, being attributable to something that is inherently special or sensitive to people. In this specific case, the MAC address of a smartphone and the license plate of a vehicle are information that can be traced to specific people. In SHA-256 ”double” the message is processed twice with the same technique of anonymization, then once produced the first code it is re-processed giving rise to a new code.

The system is composed of various strictly interconnected elements, both hardware and software. Cameras have been used to detect vehicle license plates 24 hours a day. Professional license plate reading cameras were used: IP 3.0 MPX CMOS 1920*1080 outdoor video surveillance for security systems, with variable focal length 5-50mm for high speeds 200 Kmh Max. The camera is connected to the Nvidia Jetson AGX Xavier Developer Kit with the following features: GPU 512-core Volta GPU with Tensor Cores, CPU 8-core ARM v8.2 64-bit CPU, 8MB L2 + 4MB L3, Memory 32GB 256-LPDDR4x bit — 137GB / s, and Storage 32GB eMMC 5.1. A prototype of the mobility monitoring sub-system is shown in Fig. 6.
The processing unit is equipped with a Linux operating system, where the video stream is processed into images. Filters are then applied to the images to extract features such as license plate and vehicle type. These data are then subjected to anonymization algorithms in accordance with the current regulations in force which will be discussed in section V. It is important to specify that sensitive data is not stored in any storage or storage media, but the information is processed and only anonymized data are transmitted on the wireless channel.

The data can be sent in two different ways:

- in the first case, each transmission takes place with a predetermined amount of information in terms of mega bytes (MB) in order to previously collect a certain amount of data before sending. This configuration is more suitable for limiting the number of transmissions during the hours when the traffic of vehicles and people is drastically reduced.Only when a certain amount of information is reached, it will be sent to the server;
- the second sending method provides for timed transmission at a certain frequency so that the number of messages is constant over time, regardless of the amount of data to be sent.

Both methods involve criticalities but, on the other hand, have advantages depending on the amount of data acquired. The used algorithm allows the adoption of a hybrid configuration in which both the cases described above are adopted depending on the traffic conditions. In case of high traffic which corresponds to a large amount of acquired data, the data is sent at a predetermined time interval. During the time intervals characterized by traffic reduction (e.g., night), the sending of data is bound to the filling of a buffer in order to avoid many transmissions with very low information content. The acquisition and processing of data takes place in real time, allowing traffic operators and the network of traffic lights to take a smart approach from a SCs perspective. In fact, a processing of the data in real time allows at the same time an instant modification of the traffic management with considerable advantages compared to static traffic configurations. As for the architectural system concerning the vehicle monitoring system, it is based on the concept of object detection and tracking algorithms for vehicle counting which is processed by the intelligence system on board the cameras. The cameras identify the concentration of traffic flow and the average speed of vehicles. The combination of these parameters allows the traffic classification into three classes: low, medium, and high. In case of high traffic, the system switches in real time allowing a longer duration of the green in the busiest directions. In case of homogeneous traffic, the system keeps the situation of equilibrium giving fairness of service to all directions.

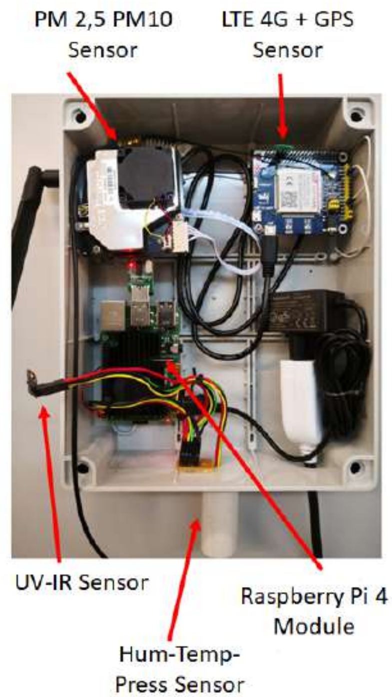

Fig. 7: Prototype of the environment monitoring sub-system.

3) Environment monitoring Sub-System: A prototype of the environment monitoring sub-system is shown in Fig. 7. The main devices which compose the Environment Monitoring Sub-Systems are shown on the right side in Fig. 2. The sensor node consists of 3 basic units:

- A sensory unit composed by 5 sub-units sensors as shown and shortly summarized in Table II. The sensors measure

the main parameters that determine the level of air quality, particularly PM2.5 and PM10 levels. Parameters such as UV radiation, IR infrared and other environmental parameters such as humidity, temperature and atmospheric pressure are also monitored. The output signals are sent to a transceiver capable of carrying out communications using the cellular network.
- A computational unit is associated with a programmable board (that is, Raspberry Pi 4 Model B) connected to a small data storage unit and manages the procedures that allow the node to collaborate with the other nodes in the network to complete the analysis of the monitored area.
- A transceiver unit connects the node to the network. A 4G LTE communication module has been employed to connect fixed and mobile nodes to the network.

The sensor nodes are installed near the bus stops where they detect the greatest concentration of CO2, PM2.5, and PM10 particles. Other sensor nodes are located along Marconi Street, far from intersections, and measure an average concentration not affected by bus stop or traffic lights. The archiving, historical data, and processing were carried out through the Lysis platform [27].

V. Data Protection Analysis

Data protection is defined as ”the protection of individuals against inadequate and unwanted use of their personal data” [30]. This aspect is growing increasingly important and needs to be taken into account in software development where many decisions are taken about how (personal) data are processed. In the European Union, the expectations about data protection are mostly defined in the General Data Protection Regulation (**GDPR**), which became applicable law in May 2018. The main goal of this regulation is to define and ensure a largely uniform level of protection across the European Union. Similar laws and regulations apply in many other countries. General Data Protection Regulation contains a set of demands on organisations and other entities that process any form of personal data, leading to organisational as well as technical measures that need to be taken. Many of these demands lead to requirements on any software used to process personal information. However, GDPR does not express these demands as software requirements. Instead, the software requirements need to be derived from the general demands on the handling of personal data, which can be a challenging task for software developers without relevant legal training.

As well as shown by N. Gruschka et al., [31], ”big data has increased access to sensitive information that when processed can directly jeopardize the privacy of individuals and violate data protection laws”. This is the reason why in this work they discuss the current state [2018] of the legal regulations and analyse different data protection and privacy-preserving techniques in the context of big data analysis. This paper gives us an important contribution as it creates the existing and close link between the application of the Regulation (GDPR), mentioning among others the most important techniques of anonymization such as: k-anonymity [32], l-diversity [33], t-closeness [34] and differential privacy [35], and the technical application of protection techniques to software and hardware. Another important operation that must be protected is the sharing of data itself. As we see at the state of the art discussed by H. Zhang et al., [36], how to share user data safely and efficiently has become one of the most challenging problems in cloud computing. This work is very important because ”it provides a data protection model, and provides a data access detection algorithm, forms a closed-loop control, provides timely feedback evidence for continuous optimization of data access control strategies, and improves data protection's integrity”.

As previously introduced in subsection IV-C, the SHA-256 ”double” algorithm was used for the anonymitazion procedure. The choice is due to the specific type of data to be anonymized, that is the MAC addresses of mobile devices and license plates of a vehicles. In SHA-256 ”double” the message is processed twice with the same technique of anonymization, then once produced the first code it is re-processed giving rise to a new code.

VI. Performance Evaluation in Real Scenario

In this section, the real scenario considered to evaluate the performance of the proposed SIoT SC solution is detailed and the corresponding obtained results are discussed together with an in deep analysis. Finally, the application carried out to help both citizens to take better decisions considering the real time traffic status and the municipal authority to manage urban and sub-urban traffic flows also considering pollution levels is described.

A. Real scenario

The proposed infrastructure, through the passive capture of the signals transmitted by devices with Wi-Fi interfaces and information collected by cameras close to traffic lights is able to determine the number of travelers (that is, pedestrian, public, and private vehicles) in real time. Using these data in the long term it is possible to obtain statistics on travel habits. To do this, it is necessary to discriminate all the devices respecting users privacy.

The basic criteria for identifying areas suitable for installation were defined as follows:
- accessibility and availability of already existing infrastructures (that is, the optic fiber network of the municipality);
- possibility to install the system and to operate without interfering in city activities;
- availability of public transport vehicles;
- logistical / operational conditions suitable for testing the functionality of the system (e.g., number of vehicles, viability, different in and out access roads).

A preliminary study was conducted to identify the best area in compliance with the presented basic criteria. The metropolitan area of Cagliari, which includes Monserrato, Selargius, Quartucciu, and Quartu Sant'Elena in addition to the capital, represents a reference basin for the whole territory of Sardinia, in which, in addition to important residential settlements, all the main services, production activities, and

TABLE II: Sensory Unit

MODEL	TYPE	DESCRIPTION
SHINEY PPD45NS	Particulate Sensor	Solid particles analysis
SDS011	Particulate Sensor	Solid particles analysis
ARCELY GY-1145	UV Sensor	Ultraviolet rays concentration monitoring
CJMCU-4541	NO2 and CO Sensor	Nitrogen dioxide and carbon monoxide analysis
BME280	T/H/P Sensor	Temperature, humidity, and pressure analysis

poles of attraction and generation of transport demand are placed. The concentration of these activities and settlements, combined with the variation in the distribution of the population in the territory, means that the road system of access to the area is busy every day by substantial vehicular flows, which in peak hours cause phenomena of vehicular congestion, with consequent dilation of travel times and conditioning of accessibility to Cagliari. Due to the geographic conformation of the metropolitan area, which sees the city of Cagliari located in a south-western position and the municipalities most closely linked to the capital concentrated in the north-eastern area, east and south-west represent a very substantial portion of the demand for mobility that moves daily to the city of Cagliari. Marconi Street is undoubtedly the shortest route to reach the city center, although characterized by flow conditions that negatively affect travel times and speeds along the route. The road, in addition to being affected by the crossing traffic between Cagliari and the municipalities of the eastern side of the area, must satisfy the local traffic which has as its origin and destination the activities located along its development. This condition generates throughout the day and in particular peak hours a further concentration of light, commercial, and heavy-vehicular traffic with different functions and needs, which makes vehicular outflow even more critical. The geometric characteristics of Marconi Street are those of an urban road with four lanes (that is, two in each direction) spanning from the intersection with Cavaro Street and San Benedetto Street (that is, in the territory of Cagliari) and extends to the town of Quartu Sant'Elena, that is the second center in the sprawling urban area of Cagliari considering its population. Fig. 8 (a) shows the map of the considered area were the system has been installed. Currently, Marconi Street is traveled by approximately 68000 vehicles per day in both directions. The distribution in the two directions is not balanced but is distributed mainly in the direction of entry to the city. This is due to the fact that the outflow exploits the presence of the embankment road that runs along the Terramaini canal. This infrastructure is characterized by two dedicated one-way lanes leaving the city and therefore represents a preferable alternative for private traffic. A preliminary traffic analysis conducted by the University of Cagliari during a transport study showed that Marconi Street towards Cagliari records a maximum traffic flow just over 2500 vehicles per hour (vph) around 7:30 in the morning, while the flow tends to decrease until 15:00 reaching a traffic volume of about 1600 vph. Subsequently, the flows rise, stabilizing around a value of 2200 vph until 19:00 and then decrease again. The monthly trend over the twelve months considered in the study shows a traffic trend in constant slight decline. Considering the opposite direction (that is, Marconi Street to Quartu direction) the traffic volume is decidedly less than for Cagliari direction. This also depends on the fact that, towards Quartu, vehicles can travel along the embankment road. The highest peaks are reached at 14:00 with a flow of about 1400 vph and at 21:30 with a volume of about 1300 vph. From the latest traffic surveys it is possible to evaluate the daily volume of traffic entering Cagliari on Marconi Street as 33300 vehicles, 19600 vehicles per day those that use the other two lanes towards Quartu Sant'Elena and 18510 those that leave Cagliari on the embankment road. Figures 8 (b) and 8 (c) are zoom views of Fig. 8 (a) left side, showing were the devices composing the proposed system have been physically placed. The Marconi street scenario shows great interest due to the high number of daily passages that allow entry to the city of Cagliari. This road corridor has lanes both for the transit of private vehicles and for public transport in both directions. As regards pedestrian mobility, we have equipped two buses with an Wi-Fi sniffer end-point both on the Cagliari-Quartu Sant'Elena route and vice versa. The system detects data about passengers inside the buses by identifying the number of users going up and down at the various bus stops. Close to each bus stops additional Wi-Fi sniffer end-points were placed to identify people waiting and to detect people getting off the buses. Five Wi-Fi sniffer end-points were placed at fixed locations along the bus stops. The data is collected and anonymized in real time before being sent to the network. Considering the traffic monitoring subsystem, cameras were installed for each direction of travel close to pre-determined strategic traffic light systems. In particular, these points concern the traffic light system that from Marconi Street allows entry to the circular road axes (CRA) of Cagliari, in north-west direction of the metropolitan area that is one of the corridors that allow to quickly cross the city. The second point of interest is the intersection between Marconi Street and the north-west direction towards Cagliari center (that is, Sarpi street), while the last intersection is the one which leads to San Benedetto district (that is, between Marconi street, Cavaro Street, and San Benedetto Street) which hosts the main commercial activities and is one of the busiest district in the city. This subsystem allows to make a double evaluation of the traffic levels: on the one hand the traffic towards Cagliari, on the other hand the traffic leaving the city towards Quartu Sant'Elena. The first road intersection involves Marconi Street and the CRA representing an important road junction for entering the city of Cagliari and the destination can be the center of the city or the northwestern metropolitan area. Through an appropriate installation is composed by two cameras to

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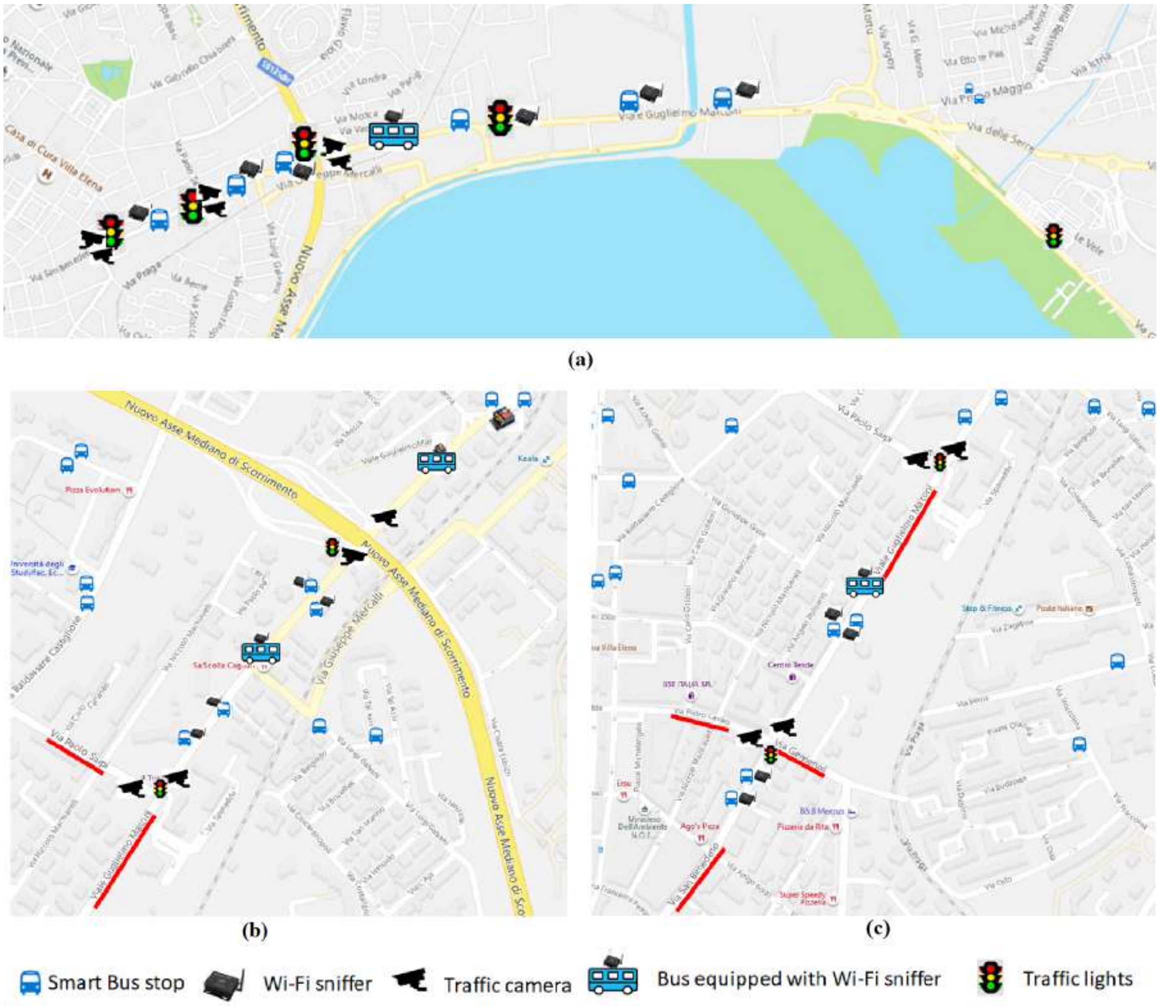

Fig. 8: The Marconi Street scenario

identify directions of traffic flows and to quantify the habits and numbers of people entering the central districts of Cagliari. These information allow to regulate the timing of traffic light system. Hourly, daily, weekly and monthly data were collected and statistically analyzed during the experimentation carried for 12 months. The second intersection (Fig. 8 (b)) is an important junction for vehicles heading towards a district named Fonsarda where there are important hotels and a city park. The third intersection (Fig. 8 (c)) involves vehicles heading towards the San Benedetto and Genneruxi residential districts with high density of population and commercial activities.

The proposed system has a twofold objective:

- providing operators with city traffic management and pedestrian flow monitoring. Events such as slowdowns, traffic jams, vehicle breakdowns, dangerous driving, accidents and falling loads are events that must be managed to able to promptly intervene and to prevent fatal consequences;
- collecting data to provide a service to the citizen, capable of receiving real time information on traffic conditions. This service is both for vehicular and pedestrian users, also taking advantage of data about harmful emissions.

Therefore, the proposed system is not a simple vehicle counter, but is equipped with an appropriate intelligence that takes into account instantaneous speed, average speed, type of traffic, instantaneous pollution data and is able to determine the directions and flows undertaken by the vehicles or the pedestrians in a given day including the weekly, monthly, and annual occurrences for each of them.

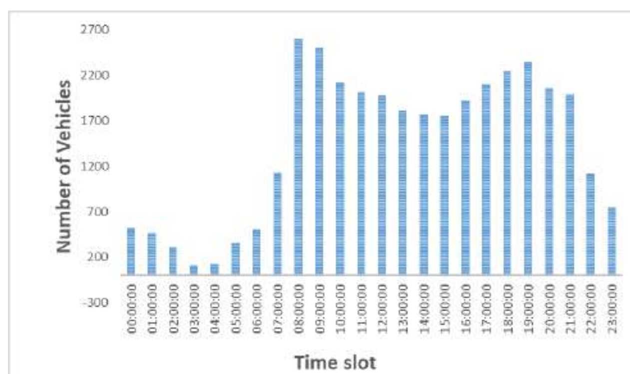

Fig. 9: Daily Traffic Flow on Marconi Street to Cagliari

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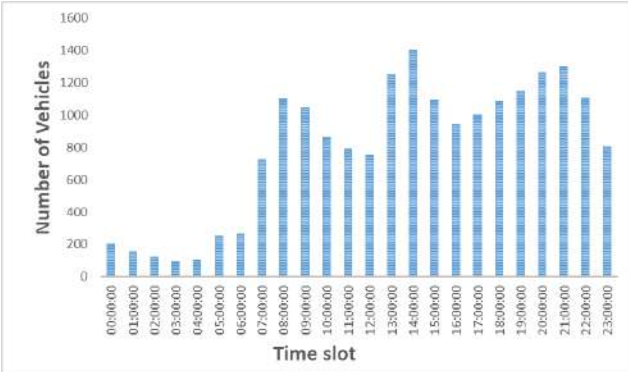

Fig. 10: Daily Traffic Flow on Marconi Street to Quartu Sant'Elena

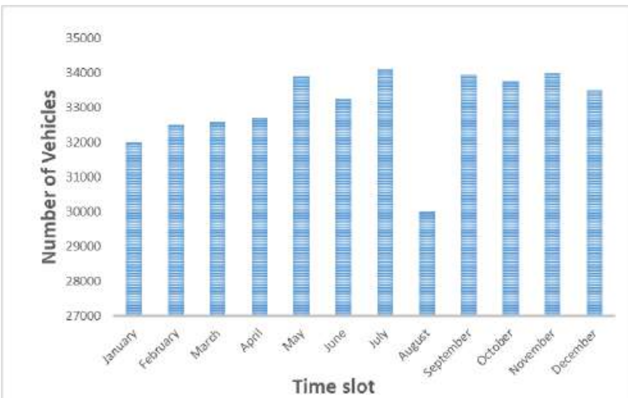

Fig. 11: Year Traffic Flow on Marconi Street to Cagliari

B. Daily monitoring data analysis

Fig. 9 represents the average daily flow of vehicles (that is, private and public) traveling on Marconi Street to Cagliari. This trend has been obtained collecting data during the six working days (that is, from Monday to Saturday) for two consecutive months. The first peak (that is, from 8:00 a.m. to 9:00 a.m.) is justified by the simultaneous entrances to public schools (that is, nursery, primary, and secondary) and to public and private offices. Fig. 10 shows the trend of vehicles traveling on Marconi Street in the opposite direction, showing two peaks, one corresponding to students coming out from schools and lunch break (that is, from 14:00 to 15:00), and the other when workers come back home (that is, 21:00 to 22:00). Fig. 11 summarizes the mean flow of vehicles travelling on Marconi Street each month. The reported data are the results of the acquisition campaign to monitor Marconi Street and its intersections performed for a year. As shown by this figure, August is the less congested month corresponding to the typical holiday period for the majority of citizens.

Table III shows the traffic flows affecting Marconi street towards the WEST (that is, towards the city center). In this direction, a flow of 34.626 vehicle was detecteds, 13.824 turn towards CRA, while the remaining 20.802 do not change direction continuing on Marconi Street. Monitoring the intersection with Sarpi Street, 3.933 vehicles turn right while the remaining 15.754 do not change direction staying on Marconi Street.

TABLE III: Vehicles at traffic intersection on WEST Way Marconi Street

TOTAL	TO	TO
34.626	CRA 13.824	No Change 20.802
19.687	Sarpi Street 3.933	No Change 15.754
15.754	Cavaro Street 7.212	San Benedetto Street 8.542

TABLE IV: Vehicles at traffic intersection on EAST Way Marconi Street

TOTAL	TO	TO
31.564	Cavaro Street 3.118	No Change 28.446
26.847	Sarpi Street 2.061	No Change 24.786
24.786	CRA 3.865	No Change18.921

At the next intersection, 7.212 vehicles turn right towards Cavaro Street, while the remaining 8.542 vehicles continue on to San Benedetto Street which introduces the same district. Similarly, Table IV shows the flows of Marconi Street in the EAST direction, that is, out of the city center of Cagliari. First of all, it can be noted that the number of occurrences detected in the EAST direction (that is, 31.564 vehicles) is lower than in the WEST directions (that is, 34.626 vehicles). In this case, 3.118 turn left towards Cavaro Street while the remaining 28.446 continue towards Marconi Street. At the next intersection, 2.061 vehicles turn left towards Sarpi Street, while the remaining 24.786 vehicles continue towards Marconi Street. Finally, at the last considered intersection, 3.865 vehicles were detected heading towards the CRA while the remaining 18.921 vehicles contribute to the flow towards Marconi Street leaving Cagliari city center.

Fig.12 shows the trend of the flow of passengers on lines 30 and 31 (that is, the main public transport lines) on WEST way Marconi Street. The trend of the two lines is largely overlapping as the two routes are generally complementary and for 95% their overall section is identical. The on board devices detected a total of 5.908 and 5.680 passengers for the two lines, respectively. The hours of greatest daily use are linked to peak hours, in correspondence with the entry to offices and schools (that is, time slot 08:00-09:00 am), at lunchtime (that is, time slot 1:00-02:00 pm), and the exit from work in the afternoon (that is, 7:00 pm).

Finally, in Fig. 13 the hourly trend of the use of lines 30 and 31 along Marconi Street is represented. The number of passengers recorded has been 4.195 and 3.718, respectively. As in the WEST way case, there is a substantially overlapping behavior of the two curves. There are three peaks that correspond to the time bands in which more users were detected, specifically between 08:00 and 09:00 am in correspondence of the movements to schools and offices, from 1:00 to 3:00 pm corresponding to school exit and lunch breaks, and finally around 6:00 pm at work exits.

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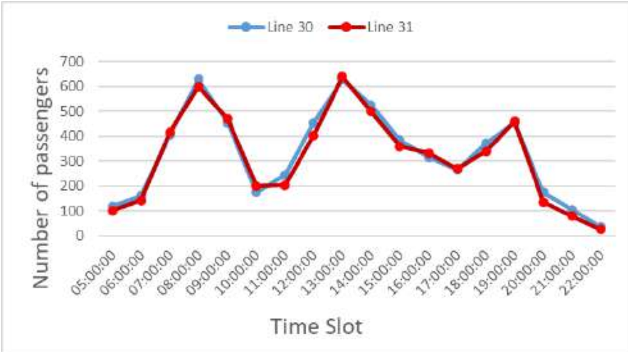

Fig. 12: Daily travelers on lines 30 and 31 of the urban transport on WEST way Marconi Street.

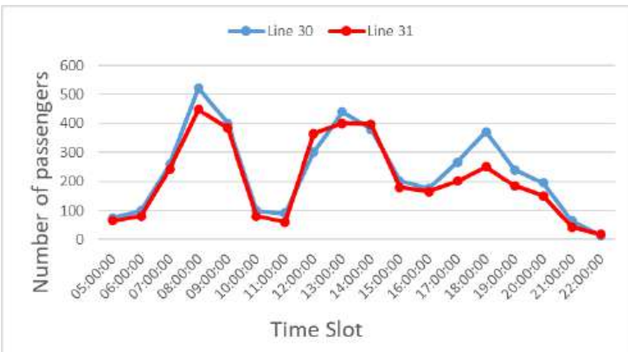

Fig. 13: Daily travelers on lines 30 and 31 of the urban transport on EST way Marconi Street.

C. Urban mobility - comparative analysis

This section shows a comparison of data processed in different methodologies, before and after the proposed system. Currently, data monitoring and control is done with manual methods that involve more human personnel working in the control rooms. Traffic intensity levels are analyzed by human staff viewing video recordings of sites of interest. Traffic light timer setting actions also occur manually through the intervention of teams of technicians who manually change the duration in seconds of green, yellow, and red, respectively. Therefore, it must be stressed that these operations do not take place in real time, but with decisions that are then implemented in the following days, in which traffic conditions may have further changed. The introduction of real-time monitoring and control has allowed to overcome these limitations, providing both the minucipalities and the citizens with flexible updates and modifications of the entire traffic light network.

Fig. 14 and Fig. 15 show the comparison between the average traffic measured and the vehicular flow due to the application of real-time policies on the management of road intersections and alternative routes taken by motorists, both in the direction of Viale Marconi to Cagliari, and in the direction of Viale Marconi to Quartu Sant'Elena, respectively. As can be observed, the proposed system acts positively by reducing the traffic flow especially in the rush hours where traffic is more intense. Up to 20% average gain in terms of traffic saving was performed. This value can also be incremented mapping

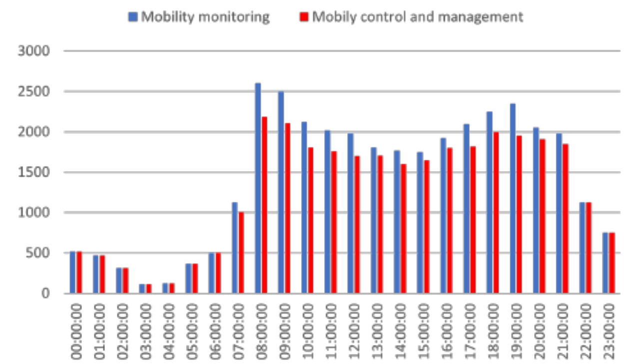

Fig. 14: Comparison between daily traffic flow (Marconi Street to Cagliari) and the impact of real-time traffic monitoring and control.

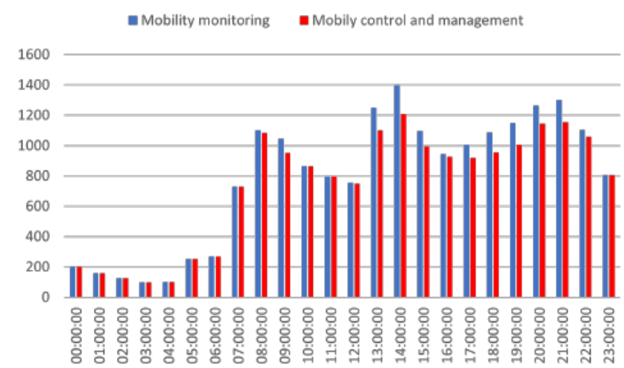

Fig. 15: Comparison between daily traffic flow (Marconi Street to Quartu Sant'Elena) and the impact of real-time traffic monitoring and control.

a large scale distribution of the system in order to cover all the metropolitan area. The high scalability of the system would allow a homogeneous management of very large areas in the city.

D. The mobile application

The application presented in this paper has been developed to be used by:

- citizens to take better decisions considering the effective punctual traffic status and to improve their way to cross the city;
- municipal authority to manage urban and sub-urban traffic flows also considering pollution levels;
- both of the above, for timely monitoring of air quality levels, choosing green routes or easing traffic congestion in areas of low air quality.

Different programming languages have been used:

- the front-end is developed using HTML, CSS, and JavaScript on top of the Bootstrap framework;
- the back-end part was developed in Python with the use of the FASTAPI library;
- interfaces were carried out for reading data from the sensors;

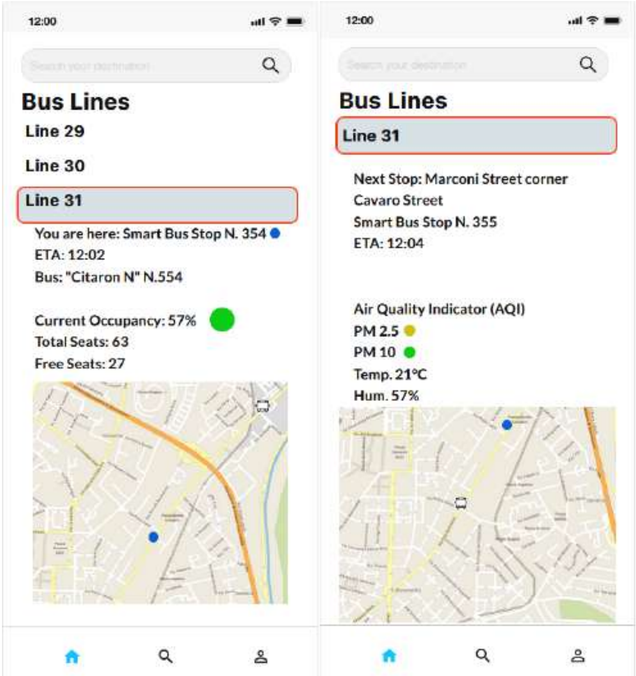

Fig. 16: The Smart Bus Stop Mobility application for bus occupancy monitoring and Air Quality Indicator (AQI).

The best performance and the typical use of it (that is, taking advantage of all its potential features) can be potentially reached covering the entire city of Cagliari and the corresponding metropolitan area with the cameras and devices previously presented and actually installed in Marconi Street area. First of all, the login procedure allows the application to individuate the type of user and the corresponding information to be displayed:

- a citizen needing the best path to rapidly reach a desired destination (that is, for vehicular or pedestrian user);
- a citizen needing the best path to be reached by using public transport;
- public administration to support the decisions facilitating the identification of the most appropriate actions for the implementation of effective policies relating to mobility.

After the login procedure, the application finds the current location of the smartphone via GPS and starts to collect information on traffic and pollution level querying the SDBs corresponding to devices and cameras all over the city. Users have the possibility to train the app saving the main destinations typically reached each day during an ordinary week (e.g., daily path to reach the office, Wednesday path to reach gym in the afternoon, etc.) or, alternatively allowing the app to automatically learn about them observing and saving their movements.

For the first two type of users, once the destination is added (that is, manually or automatically) the app displays different information. For the first type of user, a map displaying the best path and, with little red and orange circles the congested areas to be avoided in case of travelling on alternative paths. Moreover, an evaluation on travelling time is given in real time according to the speed. For the second type of users, for each useful bus to reach the destination the main information displayed are:

- real time position of each interested bus;
- the nearest bus stops;
- estimated travelling time considering the real time traffic level path, which is fixed;
- number of on board passengers up to total for each bus;
- number of people waiting close each bus stop;
- pollution level in the proximity of each bus stop.

Fig. 16 shows two screenshots of the developed application. The left screen depicts a configuration displayed by the user when is close to a smart bus stop: based on the selected line (that is, 31 in the example), an indication of the user's geolocation, estimated time of arrival (ETA), and vehicle type is provided. Finally, information is provided for crowding monitoring and control: the percentage of occupancy and free seats inside the bus before it arrives at the stop of interest is estimated. Once the bus is in motion, a new analysis is carried out after ieach stop and the data is updated in the SIoT platform. The right screen in Fig 16 shows a representation that can be traced back to the user on board the bus in the direction of the next stop. The information provided is about the ETA, the stop number and the street directions near the stops. In addition, the bus smart stop interactions also offer indications of air quality (that is, PM 2.5 and PM10) and other environmental indications (that is, temperature and humidity) that will be encountered in the vicinity of the next stop. For municipal authority, the app shows a general view of the city indicating, if present, circle areas pointed out with colours differing according to the level of critical issues (that is, yellow, orange, and red).

VII. Conclusions

This paper presents a new SIoT-based system for better managing the SC of Cagliari, based on the tracking of all vehicles (that is, private and public) and pedestrians, integrated with air quality measurements (that is, in real time by cameras, mobile and fixed sensors). The proposed system models citizenship mobility flows by monitoring the position of personal mobile devices and vehicles with the use of dedicated devices, carried out by the authors, and cameras. Privacy of users is guaranteed by the developed anonymization sub-system. A real time monitoring network based on sensors and devices hosted on board aims to improve the public transport offer and services allowing to concentrate it where (that is, both in time and space) there is greater demand and helping users in their daily choices. The integration model for mobility and environmental data is useful both for assessing the levels of energy and environmental sustainability and for planning interventions aimed at containing atmospheric, acoustic, and electromagnetic pollutants. The proposed SIoT SC solution has the objective of providing operators with city traffic management and pedestrian flow monitoring, and to collect data to provide a service to the citizen, capable of receiving real time information on traffic conditions. This service is both for vehicular and pedestrian users, also taking advantage of data about harmful emissions. Therefore, the proposed system is not a simple vehicle counter, but is equipped with an appropriate intelligence that takes into account instantaneous speed, average speed, type of traffic, instantaneous pollution data and is able to determine the directions and flows undertaken by the vehicles or the pedestrians in a given day including the weekly, monthly, and annual occurrences for each of them. Finally, an application has been developed by the authors to be used both by citizens to take better decisions considering the effective punctual traffic status and to improve their way to cross the city, and by municipal authority to manage urban and sub-urban traffic flows also considering pollution levels. Up to 20% average gain in terms of traffic saving was performed, comparing the daily traffic flows observed in a specific area of Cagliari before and after the installation of the proposed system.

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