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IoT-based air quality monitoring systems for smart cities: A systematic mapping study

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ABSTRACT

The increased level of air pollution in big cities has become a major concern for several organizations and authorities because of the risk it represents to human health. In this context, the technology has become a very useful tool in the contamination monitoring and the possible mitigation of its impact. Particularly, there are different proposals using the internet of things (IoT) paradigm that use interconnected sensors in order to measure different pollutants. In this paper, we develop a systematic mapping study defined by a five-step methodology to identify and analyze the research status in terms of IoT-based air pollution monitoring systems for smart cities. The study includes 55 proposals, some of which have been implemented in a real environment. We analyze and compare these proposals in terms of different parameters defined in the mapping and highlight some challenges for air quality monitoring systems implementation into the smart city context.

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1. INTRODUCTION

In a recent report about air quality, the World Health Organization (WHO) warns that air pollution sources represent the greatest environmental risk to human health, evidenced in more than over 6 million premature deaths caused by exposure to contaminated air sources [1]. Several studies ([2, 3]) have shown that exposure to air pollution at an early age can impair lung function, and increase the risk of respiratory diseases as well as the probability of premature mortality. Pollution problems are more prevalent in large cities with high population density due to the fact that the sources of pollution are more abundant (i.e., a greater number of cars and industries burning fossil fuels, which are a major source of pollution) and their population is often constantly exposed to high levels of air pollution.

Using technology to measure and manage air pollution in cities is key in the path to mitigate the problem, and hence, it has been a topic of study for several researchers worldwide. In particular, the internet of things (IoT) has been deemed as one of the most promising technologies to achieve these tasks. IoT refers to the network of everyday objects (also called "things") connecting intelligent sensors that exchange information about themselves and their surroundings. There are many systems based on IoT technologies for the management of environmental pollution in cities to develop smart solutions, which constitute a mandatory component of smart cities.

IoT has emerged as a solution for the pollution challenges imposed by increasing population. The main goal is to fight against the climate change and gas emissions, as well as to improve energy efficiency in cities [4]. In this context, several proposals have come to light targeting different aspects of the problem. For instance, air pollution monitoring in a smart city helps to improve health in citizens when alerts are created if the contamination overpasses a specific threshold [5]. Smart devices constitute a key component of the IoT technology, thus allowing the connection of objects over existing networks [6]. They aim at enhancing city operations (such as transport, healthcare, education, water, communication, and energy) and competitiveness, in order to improve the quality of life and wellbeing of citizens [4]. Smart cities use IoT technology to connect a city in an intelligible way with minimal human intervention, while assuring that present and future generations have resource availability, where cities' resources have to be optimally managed [6].

In this context, it is important to study the different solutions that have been proposed to monitor and mitigate the pollution problem in large cities. Hence, we have developed a systematic mapping study based on the guidelines proposed by [7]. The main contribution of this paper is to provide an overview of IoT-based air quality monitoring systems for smart cities, by addressing a visual summary of the research status in this area worldwide, as well as to identify its technology trends. We have defined a five-step methodology to identify and analyze the studies about IoT-based air pollution monitoring systems for smart cities. By considering the relevance of IoT technologies to measure pollution, this work summarizes recent publications in this area.

The remainder of this paper is organized as follows: Section 2 describes background information about air pollution measurement and IoT technology. Section 3 presents the methodology of the systematic mapping study, followed by the presentation of the results and discussion in section 4. Section 5 identifies some research challenges for air-quality monitoring systems. Finally, section 6 discusses the main conclusions of our systematic mapping.

2. BACKGROUND

2.1. IoT technology

Internet of things (IoT) refers to the collection of pervasive "things" or objects, that can interact by exchanging information with neighbors to reach common goals [8]. IoT can be defined as a networking infrastructure that connects uniquely identifiable objects to the Internet. These objects are usually sensors/actuators with smart capabilities. Information about these objects can be collected, whereas their state can be changed from anywhere, anytime, by anything [9]. IoT is considered as the internet of the future, with the potential to communicate billions of smart devices without human intervention. IoT paradigm has increased the interest in monitoring and study of air pollution and its consequences on human health, thus evaluating its impact in life forms as well as environmental damage. Modern air quality monitoring systems are based on electronic sensors, microprocessor/micro-controller chips for signal acquisition and processing. These systems usually acquire data to be processed on cloud platforms and presented through mobile or web applications. In order to extract useful information from the raw sensors' measurements, big data strategies are normally utilized in the analysis.

IoT has been widely used in different domains such as transportation, agriculture, healthcare, energy production and distribution, environmental or infrastructure monitoring, to name a few. Even though there are different approaches to the architecture of IoT systems, the most commonly used is a four-layer architecture [10] as shown in Figure 1. The lower layer, also called the perception layer, is responsible for gathering the data through a set of sensors. These sensors are part of the end-point devices, which are usually based on embedded systems that have pre-processing capabilities and communicate with the upper layers. The network layer interconnects the devices, and hence the selection of the communication protocols in this layer will have an impact on the overall performance of the system. The upper layers (namely service and application layers) provide further processing of the data and end-user interfaces. The choice of technologies, platforms and protocols for each of the layers highly depends on the application, and will also determine the cost, complexity and performance of the IoT deployment.

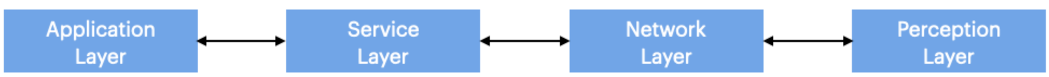

Figure 1. IoT multi-layer architecture

2.2. Air contaminants

Air pollution consists in the introduction of particles or substances in the air that can cause damage to human health and other life forms. It also damages ecological systems by degrading atmospheric conditions [11]. There are a lot of compounds that can be considered as pollution in the air. However, according to [12], the main air contaminants are: i) particulate matter (PM), which are micro-metrical solid particles in the air due to human activity (studies have shown that most dangerous PM is between 1 micrometers (μm) and 2.5 μm [12]), ii) carbon monoxide is a sub-product of incomplete combustion and is very dangerous for living beings, iii) carbon dioxide is a product of fossil fuels combustion, iv) nitrogen oxides are products of fossil combustion, which generate acid rain that causes serious negative ecological damages, v) methane is a "greenhouse" gas, mainly produced in the decomposition of organic matter, vi) ozone in the high atmosphere is a protection against the most energetic solar radiation, but in the low atmosphere, it is considered as pollution because it affects human health.

3. METHOD

A systematic mapping study is a well-organized method to summarize the state-of-the-art around a particular research area. It involves a classification and counting process for the contributions in the literature in order to analyze the topics that have been covered and those that remain as open issues [7, 13]. In this study, we have developed a systematic mapping study based on the guidelines proposed by [7]. Five steps were defined to identify and analyze studies related to IoT-based air pollution monitoring systems for smart cities. The first step is to *plan the research questions*, where a set of questions are defined to be solved according to the main topic of research. The second step is *to define the search strategy*, which specifies the used methodology to gather information. In this step, the "search query" to use on the academic databases is defined. The third step is *to define the selection criteria*, which consists in defining a set of rules to include/exclude the found studies on the search process. The fourth step is *to synthesize data*, where we deeply analyze the included articles in the study, by extracting data to answer the research questions. Finally, the fifth step is *to analyze the results* by presenting figures and making conclusions about the obtained information. In order to update the results of the study and maintain current information, the search process and the corresponding analysis should be repeated with an annual periodicity. A detailed description of the defined steps is presented in the following sections.

3.1. Research questions

The primary goal of this study is to understand and classify the related research in IoT-based air quality monitoring systems. We aim to survey research literature regarding software and hardware architectures in air quality solutions, the most commonly used environmental variables and sensors, communication technologies, data processing analysis, and interaction with other applications (e.g., smart cities). Table 1 presents the defined research questions for this study. To simplify the analysis of this kind of systems, we linked each research question to the corresponding IoT layer in the general IoT architecture mentioned in section 2.1.

Table 1. Research questions of the systematic mapping review

RQ1:	(Application layer) What are the monitored environmental variables?
RQ2:	(Application layer) Where has the solution been deployed?
RQ3:	(Service Layer) What are the main provided services to the applications?
RQ4:	(Network Layer) Which communication protocols and network infrastructure are used to transfer messages?
RQ5:	(Perception Layer) If the objects communicate with each other, what type of network is used?
RQ6:	(Perception Layer) What are the hardware platforms used to implement the "things" in the IoT-based air quality monitoring solutions?
RQ7:	(Perception Layer) What type of access networks are used to transfer the data to the upper layer?
RQ8:	(Context Information) How is the environmental data processed?
RQ9:	(Context Information) How do IoT AQ systems interact with other applications into smart cities?

3.2. Search strategy

Based on the research questions, we identified the following four main keywords: *internet of things*, *air pollution*, *monitoring*, and *smart cities*. Then, we built the search query strings, considering the variations of these terms, i.e., singular/plural forms and synonyms. Table 2 presents the resulting search queries, where we highlight the main keywords (in bold) and connect with their corresponding variations by using the OR logical operator. We used the AND logical operator to connect the resulting keyword groups.

This search was implemented in January 2020 in five of the most important electronic databases such as IEEEXplore, ACM Digital Library, Science Direct, SCOPUS, and ISI Web of Science. Those databases were selected based on the experience reported by Chen *et al.* [14]. We conducted the search considering the concordance of search query in the title, abstract and keywords of the published studies. In total, 152 studies were obtained from this search.

Table 2. Search query used in the systematic mapping study

Keywords group 1:	internet of things, iot
Keywords group 2:	air pollution, air quality, environmental variables
Keywords group 3:	monitoring, sensing, detecting
Keywords group 4:	smart cities, smart city

3.3. Inclusion/exclusion criteria

We defined selection criteria to evaluate the relevance of the retrieved papers on the previous stage. The idea is to exclude those papers that comply to the search query but do not contribute to answer the research questions. In the same way, we expect to include the relevant studies to answer them. At this stage, each reviewer inspects the title, abstract, introduction and conclusions of the paper, thus aiming to identify if the paper must be included or excluded.

The following inclusion criterion (IC1) was defined: the study includes publications with a clear description of IoT-based air quality monitoring systems and their application in smart cities. In the same manner, the following exclusion criteria were defined: (EC1:) The study excludes papers that are not solutions for IoT-based air quality monitoring systems such as those oriented to signal processing instead of sensing; (EC2:) The study excludes papers that are not written in proper English; (EC3:) The study excludes papers that are duplicated or are a previous version of a more complete study about the same research; (EC4:) The study excludes papers such as systematic reviews, mapping studies, editorials, prefaces, article summaries, interviews, news, correspondence, discussions, comments, readers' letters, tutorial summaries, panel discussions, poster sessions, abstracts, and PowerPoint presentations; (EC5:) The study excludes papers that do not specify a direct relationship between the IoT system and smart cities applications.

Each reviewer developed an individual selection process to filter studies based on the above selection criteria, thus using the web application Rayyan [15]. Afterwards, a meeting was conducted to compare the results and solve existing conflicts, thus resulting in a consensual preliminary selection. Thereby, a total of 55 papers were selected.

3.4. Data extraction and mapping study process

During this step, we divided the selected papers in four subsets. We assigned each subset to a reviewer in order to extract the information for answering the research questions related to this work. To reduce the bias, we used a technique reported in [16], where each reviewer assessed all extractions made by another reviewer in the group. We carried out an agreement meeting out to compare results and solve conflicts.

4. RESULTS AND DISCUSSION

In this section, we present the results of the systematic mapping study, considering the research questions and the extracted data. First, we present an overview of the selected studies. Then, we answer the research questions regarding each layer of the reference IoT architecture, namely perception layer, network layer, service layer, and application layer. Finally, we present an analysis of the research questions about context information.

4.1. Overview of selected studies

The academic interest in IoT-based air quality monitoring systems is recent, as shown in Figure 2. Two works were published in 2014, and from that date, the number of publications has grown to eighteen papers in 2019. Figure 3 provides the distribution of the articles between the considered venues in this study (i.e., journal and peer-reviewed conferences). Most of the articles were published in conferences (54.6%), from which eight articles (14.5%) were published in conferences indexed by SCImago. Around 13% of publications correspond to Q3 and other journals. It is worth to mention that around 33% of the articles were published in high quality journals (Q1-Q2).

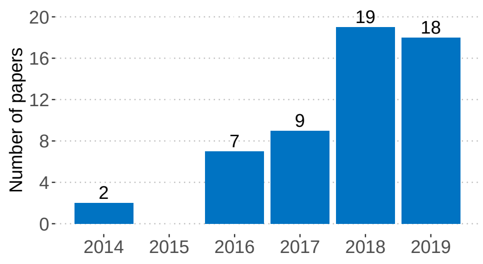

Figure 2. Histogram of paper publications per year

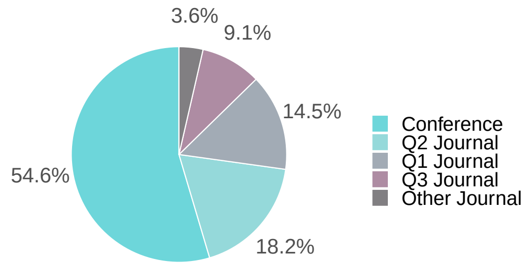

Figure 3. Pie chart of venue types

According to the classification proposed by [7], we analyzed the type of research for each work. Most of the articles (27) fit on the *evaluation research* category, 11 articles were classified as *solution proposals*, 14 as *validation research*, and only 3 as *experience reports*. These results are consistent with the type of developed search, since we excluded papers that are not solutions for IoT-based air quality monitoring systems (see exclusion criteria in section 3.3).

4.2. Application and service layers

Regarding the application layer, we posed two research questions (RQ1 and RQ2), related to the monitored environmental variables and the location of the solution deployment. Figure 4 shows the used variables in the analyzed monitoring systems in this study. Particulate matter (PM) (2.5 μm and 10 μm), nitrogen oxides (NOx), carbon monoxide (CO), ozone (O3), and carbon dioxide (CO2) are the most commonly measured pollutants. Temperature and humidity are often related to sensors calibration, which could be the reason for their frequent usage. Ammonia, hydrocarbons, solar radiation, and volatile organic compounds are useful in other specific applications. Usually, the decision of which variables to include depends on the particular conditions of the city to be monitored, i.e., the main air pollutants present in the city area.

The service layer, which is responsible of providing services to "things" or applications, is between the network and the application layer. The implementation of the service layer usually involves cloud development. The systems analyzed in this study describe mainly the two first layers of the IoT architecture (i.e., perception and network layers), which resulted in a poor description of the service layer, thus not providing enough implementation details in this layer. Most of the processing is carried out on cloud platforms, where fog/edge computing is still little explored in this context. We did not find a detailed description of its implementation, thus complicating to answer the research question RQ3 stated as, what are the main provided services to the applications?

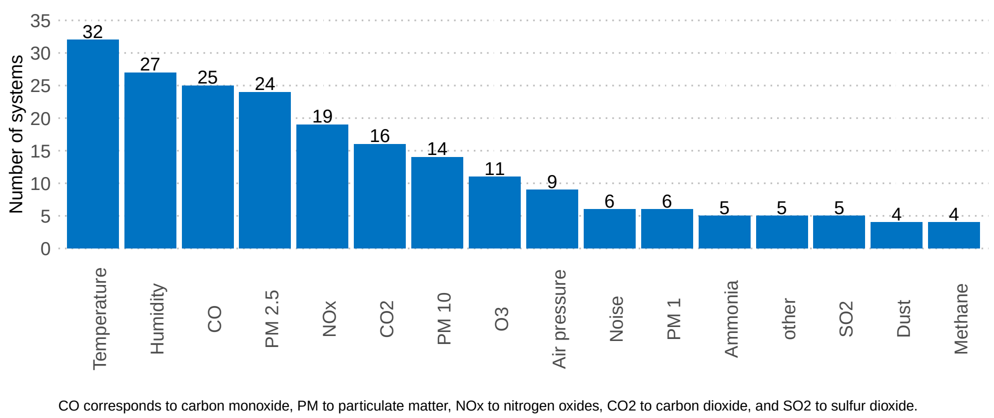

Figure 4. Histogram of environmental measured variables by the reviewed systems

As can be seen from Figure 5, an increasing number of IoT-based air quality monitoring systems for smart cities have been deployed around the world. The figure presents systems' location, highlighting in red the countries where the solutions have been deployed. For this study, solutions were implemented on 22 different countries where India, USA and Italy, are the countries with the most reported solutions (11, 6 and 5, respectively).

4.3. Network layer

In this section, we discuss the RQ4 related to the network layer. Figure 6 shows the frequency of the used network infrastructure in the screened papers. The most used type of network was private networks (twenty-three papers) and the least used was vehicular to infrastructure (V2I) networks (two papers). Fifteen papers used cellular networks, six papers public infrastructure, and nine do not specify the used network. Private networks are highly used since the experiments were performed by using a sensor network with different access technologies. Regarding network protocols, there was not enough details in the screened papers to depict on this study. It is worth to note that the innovative V2I infrastructure has been little used for air monitoring, although it is an interesting option in a smart city environment. Classical communication technologies such as Wi-Fi and cellular are the most used for communicating sensed data. However, the relatively new LoRaWAN emerges as an alternative with long-range and low-cost implementation in an urban environment. Most of the papers reported prototype works, where around 55% of the systems use hardware development kits (e.g., raspberry Pi or Arduino).

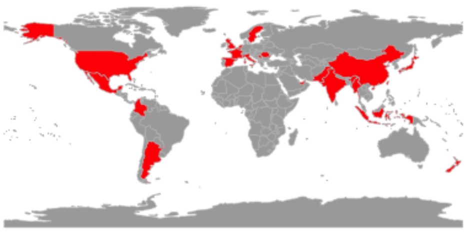

Figure 5. Countries where air-quality monitoring solutions have been implemented

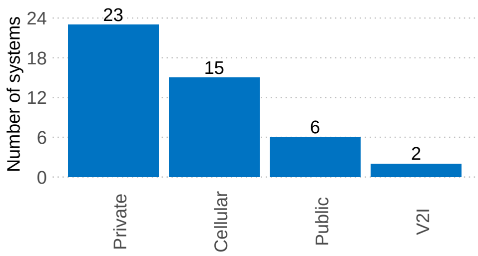

Figure 6. Histogram for network infrastructure (nine studies provide no information)

4.4. Perception layer

In the perception layer, we analyzed the hardware nature of the prototypes implementing air quality monitoring systems (RQ6). Figure 7 presents a bubble plot that shows the information related to the hardware platform. We gathered information related to the portability of the air quality monitoring systems, defining using three categories: *fixed*, *mobile*, and *mobile+fixed*. We also analyzed the type of hardware used to implement the monitoring system, by defining two types of categories: *DK-based* for implemented prototypes with hardware development kits (e.g., arduino, raspberry, and similar), and *specific purpose* for developed prototypes that use a hardware platform specifically designed for the proposed application.

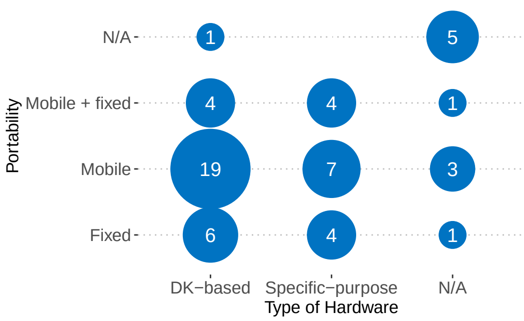

Figure 7. Bubble plot for hardware platforms

As shown in Figure 7, in 30 of the 55 analyzed works, researchers used DK-based prototypes, while in 15 works a specific-purpose prototype was used. This may suggest researchers report results using early-stage prototypes instead of commercial or pre-commercial systems. Using mobile technologies is a good strategy to cover extensive areas with few acquisition nodes, which may explain that mobile systems are used frequently for air quality monitoring. Only 11 out of 55 systems use the traditional fixed systems to gather air quality information.

Regarding the RQ7, “What type of access networks are used to transfer the data to the upper layer?”, Figure 8 shows the most frequently used technologies in the implementation of the monitoring systems. Wi-Fi technology and cellular networks are the most commonly employed, together with LoRaWAN. Other technologies such as Bluetooth and ZigBee are less used. This may be explained by their short-range, which makes difficult to implement air quality monitoring applications due to they are usually deployed in big urban areas.

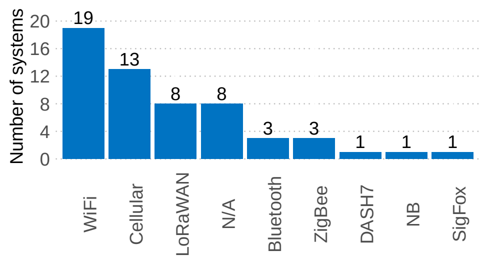

Figure 8. Histogram of access technologies in the perception layer (notice some studies implement several access technologies)

4.5. Context information

About the context information, we are interested in how the environmental data is processed (RQ8), in terms of time (i.e., real-time or off-line) and place (i.e., node, cloud, and edge). Figure 9 suggests that real-time systems are preferred in air-quality monitoring applications. Latest updated values of environmental variables are useful to take timely decisions. It is even more important if we take into account the interaction of these platforms with users e.g., through mobile applications.

The place where processing is carried out for these systems usually depends on several factors, such as processors computing capacity, energy source, amount of data, sensors conditioning, among others. Figure 10 presents the processing location of the analyzed systems in this study. Cloud computing is remarkably preferred over the other options, such as node and edge. Node processing is challenging because the processing units (i.e., typically micro-controllers) have very limited processing capacity. Edge computing is a relatively new strategy, but it has been little explored on this kind of applications. It is necessary to define a model for determining which components are processed locally and which ones should be sent to the cloud.

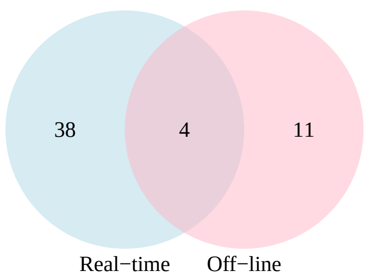

Figure 9. Venn diagram for data processing timing (two studies provide no information)

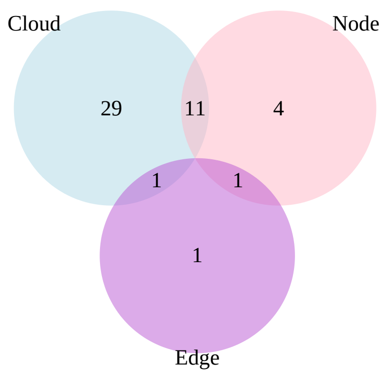

Figure 10. Venn diagram for data processing location (eight studies provide no information)

Finally, we analyzed the interaction between air quality monitoring systems and smart-city applications (RQ9) as depicted in Figure 11. Most of the systems interact with a smart-city warning platform, which usually sends warning messages to interested or vulnerable users. Other systems interact with traffic monitoring in order to reduce pollutant emissions in automotive. Other interactions are presented but little explored (e.g., health systems, open-data platforms, news services, and policy-making platforms). Since most of the works mention an interaction with smart-city applications, 28 systems present a proposal, and only 7 works really implement or simulate this interaction see Figure 12.

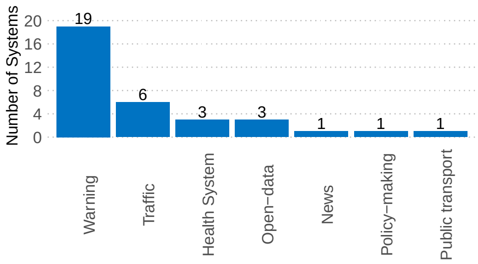

Figure 11. Histogram for interaction between air-quality monitoring systems and smart-city applications (twenty-one studies provide no information)

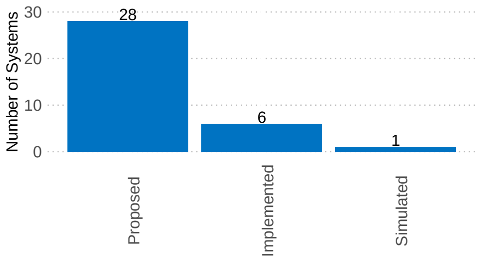

Figure 12. Histogram for the type of smart city interaction (twenty studies provide no information)

4.6. Citations

The following works were included in this systematic mapping study: [17–71].

5. CHALLENGES

Throughout the article, we have presented the main conclusions related to the different topics included in the analysis. We have, however, found some challenges that we discuss in the following paragraphs.

Massive deployments of IoT Air Quality monitoring systems: According to [72], the top five countries with the worst air quality index are Mexico, China, India, USA and Mongolia. Most of the IoT-based air quality systems were found to be located in highly polluted countries (e.g., India and USA), as an action to control and prevent pollution. However, there are still some highly polluted countries that have not deployed an important number of IoT-based air quality monitoring systems. We expect these systems to be massively deployed in the near future, and hence, more research is needed to decrease the costs for granting low-income countries to have an easier access to this technology.

IoT Protocols in air-quality monitoring systems: New communication technologies have emerged for IoT applications, providing new interesting features (e.g., machine-to-machine interaction). Efficient network protocols such as MQTT or CoAP, and new communication technologies, namely LoRaWAN, Sigfox or Narrow-Band, are now available. However, according to our study, very few deployments make use of the IoT-specific technologies. The implementation of these technologies can enhance the performance of the IoT-based air quality monitoring systems while decreasing implementation costs.

Mobile networks and V2I technology: We have identified the growing utilization of mobile nodes for air-quality monitoring in smart cities. However, technologies like Wi-Fi or Cellular networks can have a limited utilization due to coverage problems or deployment costs in mobile nodes. Emerging technologies like V2I networks, or more widely V2X (i.e., Vehicular-to-Everything) systems, can improve the air-quality monitoring systems by providing large-coverage infrastructure and efficient communications for acquiring data in a city context [73]. New vehicular applications can emerge with the advent of air-quality monitoring to vehicular networks.

Smart cities interaction: A smart city can be achieved through the integration of information communication technology (ICT) into cities to develop smart solutions. One of the main goals of this study was to identify the application of IoT-based air quality monitoring systems in the context of a smart-city. Even though most of the works propose some interaction with smart cities, only a few of them actually implement it. The development of a smart city goes beyond the implementation of a specific application and demands the support of the local government through the definition of policies that aim at the integration of multiple systems. Hence, it is necessary for cities to provide platforms to access non-critical city applications (i.e., that do not affect citizens' security), where researchers can develop and test new smart city solutions.

6. CONCLUSION

In this systematic mapping study, we presented results from mapping 55 IoT-based air quality monitoring systems for smart cities. Nine research questions were defined to characterize these systems using a four-tier architecture of an IoT system. We gathered the main information of the systems, in order to identify technology trends, which can be useful in the design of new systems. We have identified the main variables being sensed and hardware types utilized, as well as other relevant information of each layer of the IoT system. Regarding to the network protocols, only few works discuss their details, and hence, we did not find any trends in this topic. We highlighted some research challenges, by analyzing the obtained results, and identified interesting research directions for future work.

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