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A Survey on Concepts, Frameworks, and Key Technologies for IoT-enabled Smart Cities

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ABSTRACT

Smart cities have progressed substantially in recent years, by dramatically increasing their potential. In fact, rapid innovations in the Internet of Things (IoT) have opened up new possibilities, serving as a collection of essential technological solutions for smart cities and allowing the creation and automation of innovative features and advanced applications for numerous local stakeholders. The focus of this research is to highlight the main trends and open issues of implementing IoT technologies for the development of effective and resilient smart cities by reviewing the research literatures on IoT-enabled smart cities. This paper begins with a survey of the key technologies proposed in the literature for the implementation of IoT frameworks, followed by a review of the main smart city approaches and frameworks, based on an eight-domain classification that expands on the traditional six-domain classification used in most related works.

Keywords: Smart Cities, Internet of Things, Big Data.

1 Introduction

The ongoing development and use of Internet of things (IoT) and Internet of everything (IoE) technologies is a necessary precondition in today's smart city environment, accelerating the smart city paradigm into the big data domain. According to [1,] a project study by Ericson predicted that by 2022, 29 billion devices would be connected. According to a report released by Statista Research in 2019, the total number of connected IoT devices worldwide is expected to reach 75 billion by 2025 [2], culminating in a potential IoT economic impact of USD 11 trillion per year by 2025 [3]. These figures show that the Internet of Things will be one of the most valuable disruptive technologies, opening up new horizons, opportunities, and difficulties in the development of smart applications and services. The Internet of Things is becoming increasingly important in the formation of smart cities, where IoT is one of the biggest factors for smart technology and protracted development. Smart cities are complex socio-technical infrastructures made up of human actors (such as citizens, city operators, administrative institutions, public and private businesses, and so on) and digital devices.

The wide range of diverse approaches, contexts, application domains, and technological solutions offered in the literature for the creation and management of smart cities illustrates this complexity. The major

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purpose of deploying and integrating IoT solutions is to enable smart cities to evolve further, potentially giving capabilities and features while minimizing human interaction substantially [4]. Furthermore, it is necessary to emphasize on the social issues addressed and the societal benefits eventually realised as a consequence of the adoption of these technologies, such as determining how they can contribute to the United Nations' Sustainable Development Goals (SDGs) developed within the context of the 2030 Agenda [5].

The focus of this research is to integrate IoT and smart city solutions using a classification strategy that focuses on identifying eight relevant domains: governance, living and infrastructures, mobility and transportation, economy, industry and production, energy, environment, and healthcare. The remaining part of the paper is structured as follows. A survey of the main technologies used in IoT frameworks is presented in Section 2. A survey of IoT-enabled smart city domains and components is described in Chapter 3. Section 4 examines some recent trends and open challenges, as well as the societal issues involved and potential future approaches for IoT-powered smart cities. Section 5 is reserved for the conclusion.

2 IoT Architecture and Technologies

The Internet of Things has resulted a profound fundamental change in how digital devices communicate with one another, as well as how they link to the external reality [1] and interact with humans. Through the integration of cloud, fog, and edge computing, services, and applications, IoT architectures integrate and consolidate all processes of data sensing/actuating from/to devices, transmitting/receiving messages, data storage, processing, analysis, and ultimate exploitation. The implementation of IoT frameworks involves a wide range of technologies. However, general functional architectures based on a simplified version of the Open Systems Interconnection (OSI) concept, but with different techniques, have been proposed in the literature. The perception/sensing layer, the network layer, and the application layer are all defined in certain studies [1,6] as three layers (from the lowest physical level to the highest levels of abstraction) in a typical IoT framework. The previous concept is expanded into five layers of architecture in other publications [7, 8, 9, 10, 11, 12], including the perception/sensing layer, transportation/network layer, middleware/processing layer, application layer, and business layer.

Edge computing, fog computing, and cloud computing are three different computing paradigms that are characterized depending on which level of the stack is being evaluated, from bottom to top [13]. The following sections provide a description of the various layers in terms of capabilities and technology involved. Because the five-layer architecture can be viewed as a more detailed variant of the three-layer architecture, it was considered.

2.1 Perception/Sensing Layer

The perception or sensing layer is connected to the physical level, which consists of devices such as sensors and actuators that communicate with one another and with the real world by transmitting and receiving data over wireless networks [8]. Sensors, actuators, and mobile device technology are all involved in this scenario. Sensors for detecting temperature, humidity, pressure, distance and geographical coordinates, speed, acceleration, voltage, weight, pollution particles, brightness level, biometrical signals, and other physical quantities and variables are available commercially. Actuators are used to physically or virtually control/move other devices or systems, and they are often categorized as electrical, pneumatic, or hydraulic [14].

Low-level IoT applications are deployed using a variety of software tools and technologies. Visual programming languages (VPLs) are used in the following examples: Scratch is a visual programming tool developed at MIT for IoT code generation and communication with Arduino-based IoT products [15]. NetLab is an open source environment for developing embedded systems; Ardublock is an open source visual block programming tool for Arduino systems; and Ardublock is an open source visual block programming tool for Arduino systems.

2.2 Transportation/Network Layer

The transportation layer, often known as the network layer, is responsible for data routing and transmission. Network gateways can be used as mediators to connect various IoT nodes, allowing them to send and receive data from various sensors for M2M communication. Different technologies and protocols are utilized for data transmission. Bluetooth, radio-frequency identification (RFID) tag technology, and near-field communication are examples of proximity communication protocols (NFC). Wireless technologies such as Wi-Fi, Zigbee, long-range wide-area network (LoRaWAN), Sigfox, and 5G are used in larger coverage networks.

The network layer stack's final component is in charge of properly preparing data for presentation. The subscription mechanism between IoT devices and brokers represents the client/server architecture, which includes push and pull modalities for sending or receiving data. REST calls, web services, FTP, and HTTP/HTTPS are common pull protocols. WebSocket (WS), Constrained Application Protocol (CoAP), Message Queue Telemetry Transport (MQTT), Advanced Message Queuing Protocol (AMQP), and FIWARE NGSI and NGSI-V2 [20] are the most used push protocols for receiving data via data-driven subscriptions. Furthermore, distributed publish–subscribe messaging systems (such as Apache Kafka, RabbitMQ, and FIWARE's Orion Broker) for managing various data streams in an efficient and scalable manner should be enabled in order to allow data interchange among multiple devices and applications [13]. In this regard, data persistence of queues is a key feature to boost fault tolerance when processing data that should not be lost in the event of a failure (e.g., Apache Kafka).

2.3 Middleware/Processing Layer

The processing layer, often known as the middleware, can perform a variety of tasks. It can, for example, operate as a data aggregator module, because data may be acquired from heterogeneous devices that use different protocols and weren't designed to communicate and interact with one another in the first place. As a result, the middleware layer must facilitate interoperability among connected devices by executing programming and/or model abstractions as needed. At various levels, interoperability must be ensured:

•Technical level [21], in order to efficiently achieve and maintain end-to-end connectivity with devices, gateways, brokers, servers, and other components;

•Syntactical level, to manage the many protocols and formats;

•Semantic level, semantic web technologies such as XML, RDF, OWL Ontology, and linked data (LD) are used to ensure unambiguous data representation and data semantic enrichment, hence increasing the system's expressiveness [22].

2.4 Application Layer

The application layer provides the final users with the output formats, applications, and services they require. The communications protocols management is usually included in this layer in publications in the literature that are based on the three-layer IoT design.

As IoT devices and systems are becoming more widely available, event-driven applications are becoming more popular (exploiting push protocols). This is a considerable departure from the previous generation of smart city apps, which focused on vertical applications and were frequently built on extract, transform, load/extract, load, transform (ETL/ELT) procedures and languages, which only supported pull protocols. On the other hand, multiple frameworks and ecosystems, such as VPL tools [23], are used to build and implement event-driven IoT applications. One of the most popular is Node-RED, which is built on the Node.js engine and allows the composition of visual nodes or blocks to create application processes in a graphic environment [24].

2.5 Business Layer

The business layer was invented to define all operations and front-end tools that consume data from the application layer in order to produce advanced big data analytics and visualization services for building business models, supporting decision-making processes, and performing simulations and what-if analysis. Predictive models based on machine learning, deep learning, and artificial intelligence (AI) approaches [25], as well as advanced and interactive visual analytic tools [26], can help achieve this. Furthermore, the business layer encompasses all actions carried out by system administrators in order to assess, control, and maintain the platform/overall framework's functionality.

3 Components and Solutions for IoT-enabled Smart Cities

There is indeed a substantial amount of research on IoT applications in smart city environments. A search of the Web of Science (WoS) database for papers with the keywords "smart city" OR "smart cities" AND "IoT" OR "Internet of things" in their topic (i.e., the union of the "title," "abstract," and "keywords" search fields) yielded 5285 articles, published between 2010 and 2021, which is a large number of resources to be reviewed extensively and systematically, or even filtered in a supervised way.

On the other hand, several alternative techniques to classify smart city frameworks and solutions in a number of application domains have been offered in the literature. As a result, we centered our research on reviews and surveys as a starting point. The following criteria were used to conduct the literature review:

- The WoS database was used to find reviews and survey articles that included the keywords "smart city" OR "smart cities" AND "IoT" OR "Internet of things" in at least one of the following fields: title, abstract, or paper keywords. Then, to ensure that each paper topic genuinely fit the subject of this review, a supervised overview and filter was performed.
- The current study focused on recent literature, therefore articles published between 2018 and 2021 were chosen from the first search;
- Papers from Q1 and Q2 journals (as ranked in the SCImago index) were given priority over those from Q3 and Q4 journals.

The following eight domains, which are typically used to classify smart city components and application areas, were identified in order to describe the vast landscape that we discovered by reviewing the selected literature in the most comprehensive way: governance; living and infrastructures; mobility and transportation; economy; industry and production; energy; environment; and healthcare.

Each of the above-mentioned smart city domains is addressed in detail in the following subsections, including general situations, features and services supplied, IoT technologies used, frameworks or solutions adopted, and real-world case studies of smart cities implementing solutions for that area.

3.1 Smart Governance

Smart governance is concerned with the incorporation of information and communication technology (ICT) into city governance practices in order to improve decision-making and streamline bureaucratic and administrative processes through smarter collaboration among various stakeholders and social actors [28], such as public administrations, city officers, private companies, and citizens. This can be accomplished by offering citizens with novel city services, dedicated channels, and network integration. Citizens, for example, can be involved in city governance activities and decision-making processes using ICT-based tools and social media [29], as evidenced by the mobile crowdsourcing paradigm [30], in which citizens can use their smartphones and mobile devices to act as "users as sensors," participating as individuals and in groups in the acquisition of data of interest for smart cities.

3.2 Smart Environment

Environmental data gathering, monitoring, and analysis for pollution reduction, water quality and supply monitoring, and weather and climate event management are all part of the smart environment area [32]. In this sense, air quality monitoring is critical for tracking levels of air pollutants (such as NOx, O3, CO2, N2O, PM10, PM2.5, and others) that are a severe health concern (caused by transportation, heating and industrial emissions). Because it has so many negative effects on the environment, smart waste management is also included in this category. Smart garbage bins, which are equipped with sensors and capable of giving real-time analysis of the capacity that is now available, are used to manage waste production strategies [42]. In the case of smart water, sensing equipment used to monitor water quantity and quality often detect pH, conductivity, turbidity, total dissolved solids, and other characteristics [44].

3.3 Smart Healthcare

Remote monitoring, telemedicine and telenursing, adverse medication reactions, community healthcare, and other components of IoT and ubiquitous computing have been widely applied to mobile healthcare, and these aspects are even more relevant in this recent period of the COVID-19 pandemic. Wearable or implanted devices (e.g., cardiac devices, airflow monitors, blood glucometers, etc.) that are connected in the cloud utilizing WSN technologies can be used for remote patient monitoring (RPM) [18]. This has resulted in the creation of body sensor networks (BSNs) or wireless body area networks (WBANs), in which the integration of several heterogeneous data sources enables the capture of biometric and physiological data for IoT healthcare applications [46].

3.4 Smart Mobility and Transportation

The notion of smart mobility and transportation entails a move from traditional transportation systems to Mobility-as-a-Service (MaaS), in which a smart IoT infrastructure connects various actors (people, government agencies, private businesses) and institutions (vehicles, personal devices, city sensors, actuators, etc.) [33]. IoT and intelligent transportation systems (ITSs) [34] provide smart applications and services to manage private and public traffic flows, dynamic traffic routing, smart parking, vehicle sharing and sustainable mobility, linked driving, and other issues. Predictive models are frequently used in intelligent traffic solutions for early warnings, accident avoidance, and real-time traffic congestion management.

3.5 Smart Economy

The innovative integration of local and worldwide markets through ICT, delivering e-business and e-commerce services to boost production and delivery, is the foundation of a smart economy [36]. This sector also includes the concept of a sharing economy, in which individuals or private organizations sell services using their own assets as well as peer-to-peer marketplaces. Peer-to-peer labor services are also available, in which individuals and stakeholders contribute their skills and experience for specific tasks [37]. For e-commerce and retail shopping, artificial intelligence and machine learning approaches have been used to construct prediction models and improve recommendation systems [38]. Payment and transaction processes have been made easier thanks to the usage of NFC and wireless sensor technologies.

3.6 Smart Industry and Production

Smart industry IoT technologies, cyber-physical systems (CPS), M2M communication systems, and cloud-based manufacturing [39] are all part of the 4.0 transformation process, which allows for a more innovative and less human-dependent productive environment [40]. When it comes to the automation of products supply chains, sensor technologies like RFID and NFC can be used to trace them from the manufacturing process through ultimate delivery. For shipment tracking, as well as assessing the quality and usability of products, real-time data can be collected and analyzed [14]. Smart agriculture and farming, which addresses the difficulty of sustainable food production, is included in the smart industry and production domain, as are all domains in which ICT leads to the automation of the productive workflow.

3.7 Smart Energy

Smart energy systems aim to optimize power usage by intelligently integrating decentralized renewable and sustainable energy sources and their effective delivery [41]. Smart grids use ICT and IoT technologies to improve power generation and distribution management, utilizing, for example, prediction models (derived from collected consumption data) and frequently ensuring energy network supply self-healing [43]. Smart grids assist in balancing energy load based on usage and availability. This allows for automatic switching to alternate energy sources, as well as forecasting future energy consumption and calculating power availability and price.

4 Recent Trends, Open Challenges, and Future Directions

Smart city IoT technology and applications are fast gaining traction, as seen by an increasing number of real-world examples. However, based on the analysis and assessment conducted in the preceding sections, this integration process is not yet complete, as it still faces several open difficulties that may be handled in future advancements.

Because there are so many different IoT protocols, formats, and frameworks, there are interoperability issues [3,20,42,46,47], and this is exacerbated by the fact that many smart city applications were originally developed as vertical silos applications [3,18], each with its own data ingestion, storage, and exploitation solutions. Resolving interoperability concerns could result in financial gains. In fact, achieving a higher level of interoperability among devices, applications, and services necessitates lowering the costs of developing completely new and different deployments of the solutions [47], allowing for backward compatibility via the use of older systems as well as incremental deployment and integration. On the other hand, the adoption of event-driven and push protocols [23] as part of the IoT/IoE paradigm has paved the way for not only sensing the city but also acting through actuators and creating event-driven applications. However, the majority of solutions described in the literature still focus on narrow areas, solving specific problems with little or no software reuse [3].

Furthermore, IoT-enabled smart city platforms are moving toward multitenancy and cross-organizational IoT platforms and applications. Because the infrastructures are shared by several operators, this permits the development of vast infrastructures that can support multiple enterprises, increase scalability, and lower infrastructure costs [27]. This feature is directly related to the reuse of components in smart city frameworks, and it aims to harmonize and overcome the inefficient effort required to construct custom-made platforms for each city or special scenario [3]. The introduction and distribution of novel network technologies, such as 5G [19, 31, 35, 45], are other potential future approaches. The importance of technological advancements in network and device solutions cannot be underestimated.

Finally, in order to analyze the social difficulties that IoT and smart city technologies address, we concentrated on evaluating each application area and domain in terms of their contribution to the SDGs, as stated in Section 3. To that purpose, we have identified the 17 indicators that make up the Sustainable Development Goals: (1) no poverty; (2) no hunger; (3) good health and well-being; (4) good education; (5) gender equality; (6) clean water and sanitation; (7) affordable and clean energy; (8) decent work and economic growth; 9) industry, innovation, and infrastructure; 10) reduced inequalities; (11) sustainable cities and communities; (12) responsible consumption and production; (13) climate action; (14) life below water; (15) life on land; (16) peace, justice, and strong institutions

5 Conclusions

A survey of recent research literature on IoT-enabled smart cities framework was conducted in this paper. The need to comprehend and classify the most recent trends in the use of IoT technology as a vital driver for the effective and sustainable development of smart cities was the impetus for this research. The goal was also to draw attention to the major open issues that must be addressed and resolved in the future. The analysis was carried out for both significant IoT technologies, which were evaluated from an architectural standpoint, and smart city methods and frameworks, which were classified into eight domains that described the primary application areas. To that aim, the next generation of smart apps will be able to handle and optimize larger sets of heterogeneous data, systems, sensors, and devices. This process, however, is not yet complete because it must address a number of unresolved technical and social difficulties (regarding the efforts to harmonize the many different standards for IoT formats and protocols, interoperability and scalability issues and the achievement of sustainability goals).

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