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Review

A Thorough Review and Comparison of Commercial and Open-Source IoT Platforms for Smart City Applications

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Abstract: In this paper, we conducted a state-of-the-art survey on the current state of IoT platforms suitable for the development of smart city (SC) applications. Both commercial and open-source IoT platforms are presented and compared, addressing various significant aspects and characteristics of SC applications, such as connectivity, communication protocols, dashboards/analytics availability, security, etc. The characteristics of all the investigated platforms were aggregated so that useful outcomes regarding the technological trends of the IoT platforms could be derived. Furthermore, an attempt was made to identify any discrepancies between the needs of smart cities and the capabilities provided by the relevant platforms. Moreover, IoT platforms referring to the domains of industry, agriculture, and asset tracking were also included, alongside platforms that purely target smart cities, as parts of them are also applicable to smart city applications. The results of the comparison proved that there is a lack of open-source IoT platforms targeted at smart cities, which impedes the development and testing of connected smart city applications for researchers.

Keywords: IoT; smart cities; platform; hybrid cloud; MQTT; microservices

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1. Introduction

A smart city (SC) is a city that uses data and technology to tackle urban problems and provide its denizens with higher living standards, given the new problems that arise from rapid urbanization [1]. As of November 2022, the world population grew to 8 billion persons [2], with more than 55% of them already living in urban areas and having to face poor transport systems, polluted air, increased noise levels, and higher disease transmission rates [3], amongst other issues. As a result, a sharp increment in interest in smart cities has been noticed over the last decade in both academia and industry.

In [4], Chourabi et al. present different interpretations of the SC that have been provided bya variety of sources and authors. For example, one way to define a city as being smart is the range of consideration of issues such as flexibility, individuality, synergy, self-decisiveness, awareness, transformability, and strategic behavior taken into account. Another definition presented argues that the SC must be instrumented (aggregation of real-world data from multiple sources), interconnected (facilitation of integrating and distributing the aggregated data to stakeholders), and intelligent (presence of data analytics, optimization processes, visualization, etc.). Continuing in this direction, there are arguments that a city is considered smart merely when real-time computational technologies are applied to the infrastructure and the city services. On the other hand, some interpretations define cities as smart when they are viable, efficient, unbiased, and habitable for their citizens. Additionally, if we consider a city as an integration of subsystems, an SC facilitates the networking and linking of these subsystems.

The European Commission defines the SC as a place in which traditional services and networks become more efficient by integrating digital solutions for the sake of the wellness of its citizens and business; an SC emits less CO_2, manages its resources better, offers smart urban transportation networks and efficient ways to light and heat its buildings, provides upgraded waste disposal and water supply facilities, and offers a sense of security for its inhabitants [5]. As can be seen from the above, as well as from the works of Concilio et al. [6] and Lnenicka et al. [7], the SC is an ambiguous subject with no clear meaning. The research of Abadía et al. [8] defines an SC as an urban area that fosters transparency and creates an ideal environment for the growth of its residents, economy, and surroundings. It achieves this by effectively integrating information and communication technologies with governance, infrastructure, natural resources, and human talent.

In [1], Yin et al. discuss the definition of an SC and its application domains. They first present the origin and the basic issues that an SC project faces, and then they focus on the smart city's fundamentals by analyzing its definition and application domains. Secondly, they introduce data-centric solution SCs using key-enabling technologies. Therefore, the authors present four basic pillars that constitute an SC: the technical infrastructure, the application domain, the system integration, and the data processing.

Moreover, in [9], Bastidas et al. consider the SC to be an enterprise and apply an enterprise architecture (EA) approach, which essentially models architecture components and enacts relations between business, information, and technology domains. In their work, they first inspect the SC frameworks to propose a complete definition. They also compare some types of architecture, focussing on the core requirements. Finally, they focus on the completeness of SC frameworks concerning the EA core requirements.

In [10], Mallapuram et al. suggest that SCs are segregated into three layers: in the bottom layer, the infrastructure of the city is included alongside all sensors and actuators; in the middle layer (cyber-infrastructure), computers and devices that interconnect the devices of the bottom layer are included; and the top layer includes data processing and services. They start with a review of existing research and tools and develop a method for extracting real-time SC-related data. Finally, they use simulation tools conducting evaluations in smart energy to conclude with a Java-designed application for SCs.

According to Google Trends (Figure 1), there has been a sharp increase in the topic of "Smart Cities" over the last decade, which peaked around late 2015–early 2016 and continues its upward trend steadily. Furthermore, during the "Horizon 2020" (H2020) program from the European Union, between 2014 and 2020, around 1.4 billion euros were granted to academic institutions, municipalities, and enterprises for smart cities R&D projects [11], amounting to more than 300 unique projects in total (Figure 2). As of 2021, the EU has launched a new program called "Horizon Europe", which will end in 2027 and has a budget of 95.5 billion euros of which at least 15.5 billion euros will be granted to smart cities projects that will target civil security, climate, energy, and mobility [12].

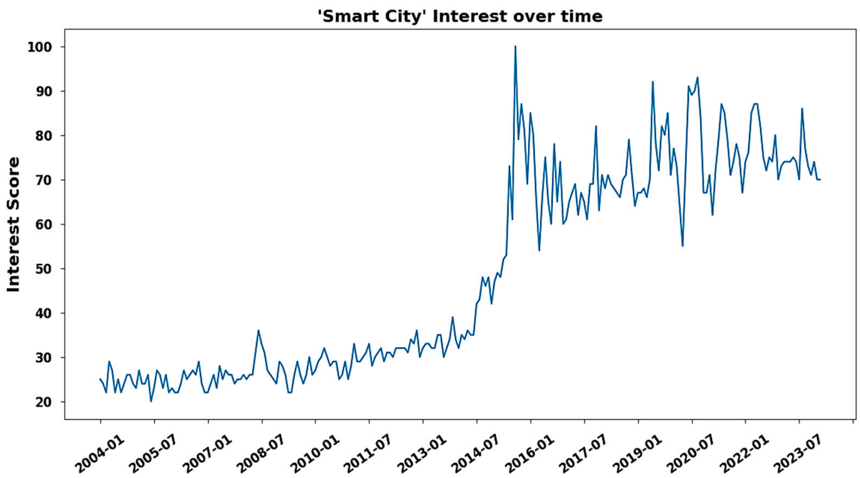

Figure 1. "Smart Cities" interest trend in internet search engines from January 2004 to February 2024. Source: [13].

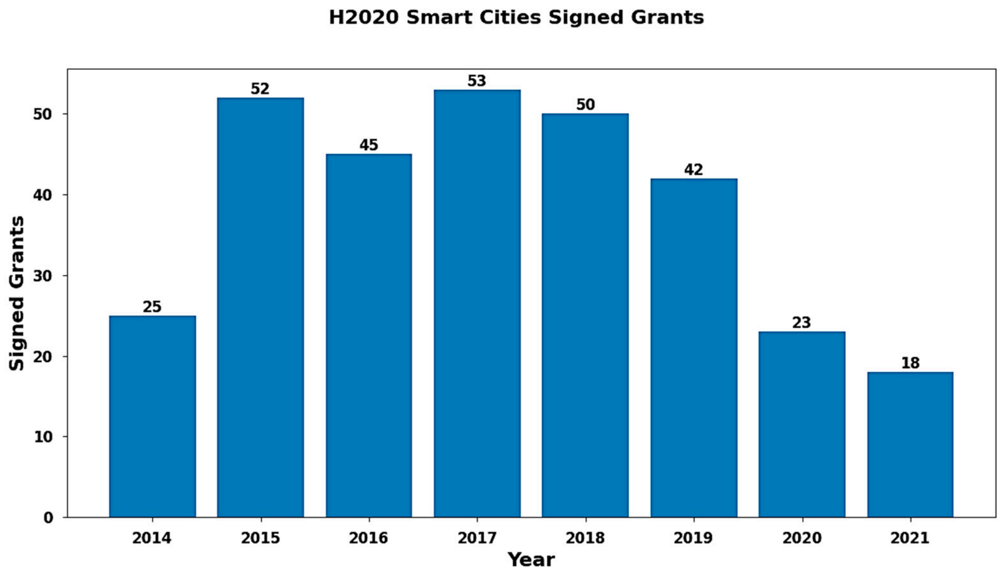

Figure 2. Annual signed grants for smart cities R&D projects for EU's H2020 program. Source: [14].

Some common SC applications include, but are not limited to, omnipresence wireless connectivity, smart homes/smart buildings, smart public services/smart governance, smart urban management, green cities/air quality monitoring, smart transportation, smart parking, smart medical treatment/intelligent healthcare, smart tourism [15], smart grid/smart energy, smart recycling/smart waste management, smart surveillance, smart traffic control, etc. [16]. In the case of smart traffic control, we see that the state of the art includes the use of artificial intelligence (AI) and deep learning (DL) algorithms [17]. In [16], the authors present the relationship between SC and the "digital city", including a brief statement on the influence of the development of SCs in China, while in [16], the authors investigate security and privacy in SC applications, pointing out some related issues for future research. In [18], Yu et al. performed a study on the cyber security aspects of popular IoT platforms and determined that a lack of interoperability between the IoT platforms causes vulnerabilities.

Lately, there has been a trend linking smart cities with the Metaverse, a digital twin of the city where the user's avatar could explore new places and historical sites, attend meetings with other avatars, vote, spend virtual currency, etc. [19]. To stimulate the topic's prospective research and further critical perspectives, the aforementioned study offers thoughts relevant to the statement that the Metaverse has disruptive and significant effects on various forms of reconstructing reality in the increasingly urban society.

In [20], Hejazi et al., in their survey, investigated and compared popular IoT platforms in terms of their device management, integration, security, communication protocols, type of analytics, and visualization support capabilities.

To begin with some examples of smart cities projects, the STARDUST project aims to reduce greenhouse gas emissions in seven European cities (Pamplona, ES; Tampere, FI; Treno, IT; Cluj-Napoca, RO; Derry, UK; Kozani, GR; Litoměřice, CZ) by 63%, therefore increasing the quality of life of their citizens and the energy efficiency of existing buildings and thus saving up to 58% energy consumption by combining state-of-the-art information and communication technologies (ICT) and renewable energy sources [21–23]. This project aims to create new business models and urban solutions that integrate the domains of buildings, mobility, and efficient energy through information and communication technologies, paving the way for low-carbon, highly efficient, and intelligent cities and remaining citizen-oriented. In this project, the researchers built their own IoT platform using open-source software, like Apache Kafka v 2.7, Apache NiFi v 1.15.3, and Grafana v 7.2.

The Ideal-Cities project utilized Internet of Things (IoT) technologies, cyber security techniques, cloud computing, and big data for resilient data acquisition and distribution in an SC environment to optimize resource utilization, smart asset management, smart mobility, and the wellness of the city's inhabitants [24,25]. In [24], the authors refer to adopting the "Circular Economy" model in urban environments. They first provide an overview of circular economy activities, and then they refer to the European policy and implementation frameworks, focusing on key technological enablers. Then, they present the Ideal-Cities Platform (ICP), which was built from scratch by the developers and researchers of the program and was deployed in a Kubernetes cluster using containerized applications (Docker).

In the FED4IoT project, digital twins, IoT, cloud computing, microservices, and containerization were used for their smart parking and smart waste management use-cases [26,27]. The authors in [27] provide useful background on how IoT applications and their supporting infrastructure are tightly coupled. Then, they present how their Cloud of Things implementation develops this fact, decoupling the application developers from their infrastructure providers. Their implementation was built by utilizing open-source software like Orion Context Broker v 3.1.

In the GrowSmarter project, 12 SC solutions covering three action areas (low-energy city districts, integrated infrastructures, and sustainable urban mobility) for three EU cities (Stockholm, SE; Bologna, IT; Barcelona, ES) used IoT technologies, extensive simulations, sensors, big data, and data platforms on the cloud [28–30]. The open-source Sentilo platform was used to interact with sensors and devices.

In the case of the Triangulum project, IoT; low-power, wide-area networks (LPWANs); containerization; cyber security techniques; and cloud computing were used, aiming to achieve sustainable energy supply, smart mobility, and a smart grid solution for the cities of Manchester (UK), Eindhoven (NL), and Stavanger (NO) [31–33]. In this project, researchers utilized Fraunhofer's FOKUS Open Data Platform and the Socrata Open Data Platform.

For the REMOURBAN project, IoT, big data, AI, microservices, and ICT were used in the cities of Valladolid (ES), Nottingham (UK), and Eskisehir (TR) for sustainable smart mobility that aims to drastically reduce gas emissions in urban environments, the integration of the infrastructure with services, and sustainable districts through maximizing energy efficiency by combining renewable energy and building energy management systems (BEMS) [34–36]. In this project, the researchers created their own IoT platform, which integrates solutions offered by third-party proprietary platforms such as Smarkia Platform.

In the aforementioned projects, IoT proved to be an important part of implementing SC solutions. The International Telecommunication Union (ITU) defines the IoT as "a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies" [37]. Given this definition, it is easy to understand why IoT has played such a pivotal role in the development of SC projects.

An IoT platform is a multi-layered set of technologies that enables the provisioning and management of the deployed devices, facilitates data aggregation from various sources, enables data distribution to heterogeneous agents inside and outside the network, and offers security mechanisms for the involved stakeholders. Often, IoT platforms feature data analytics, data visualization, data persistence, reporting/logging, and alerts for their users.

The structure of this study proceeds as follows: In Section 2, we present the IoT platforms that we investigated, which we will later compare, offering the reader a brief summary of their key features and use-cases where are applied. In Section 3, we briefly present the technologies that are mostly used by these platforms in order to interact with devices, giving some of their key characteristics as well as a brief presentation of the communication protocols that are mostly used and a brief presentation of some of the basic cyber security aspects that were found in the SC platforms. In Section 4, the results of the survey are presented and analyzed. Finally, in Section 5, we offer the conclusion of this research and identify possible future research directions.

2. Smart City Platforms

Here, we aim to compare various IoT platforms, both open-source and proprietary, and present their strengths and weaknesses. Open-source platforms are available for free on public repositories for users to download and modify according to their needs, whereas a proprietary platform has its source code closed to the public and the users can only use them, not modify them. Although the focus of these platforms will revolve around smart cities, the survey will also include platforms from areas like smart agriculture, industrial IoT, and asset-monitoring/asset tracking, as the main functionalities of a platform remain more or less the same in all these areas, i.e., ETL (extract, transform, load) data pipelines, data visualization, data analytics.

This survey was carried out by utilizing popular search engines, both web search engines, such as Google, Bing, DuckDuckGo, and Brave Search, and academic search engines, such as Google Scholar and Scopus, as well as various social media platforms such as X, LinkedIn, Facebook, and ResearchGate, over 1 year extending from October 2022 to November 2023. We used more than one search engine and more than one social media platform to avoid any bias in the results.

Although there are no official metrics for deciding which SC IoT platforms have the greatest share of the global market, various sources ([38–42]) generally agree that the key players include companies like Amazon Web Services (AWS), PTC, SAP, Microsoft Azure, IBM, Siemens, Oracle, and Software AG (randomly ordered), amongst others. In this survey, we included companies that offer both free and open-source versions of their platform, as well as a subscription-based proprietary version; the latter unlock all offered capabilities so it was decided to segregate them into the "Proprietary" category since the free version would simply be insufficient for SC applications. In the following sections, we present some basic information about each of the platforms that we investigated in a random order.

Apart from including the key players, we decided to also investigate platforms from small and medium enterprises (SMEs) as well as research institutes, as it is common for them to create innovative products.

2.1. Open-Source Platforms

2.1.1. OpenMTC

OpenMTC [43] is an open-source reference implementation of the oneM2M Machine-to-Machine (M2M) standard, offering a versatile platform for the development and deployment of M2M applications. It supports various M2M protocols such as MQTT, HTTP, CoAP, and XMPP, making it adaptable to a wide range of devices and networks. Designed for scalability, OpenMTC can handle large numbers of devices, and it incorporates robust security features to prevent unauthorized access. The platform emphasizes interoperability, enabling communication with devices and applications from different vendors. Widely adopted globally, OpenMTC is favored for its scalability, security, and interoperability. Key features include device management, application development tools, data management capabilities, and comprehensive security measures such as authentication, authorization, and encryption.

2.1.2. FIWARE N-Smart

FIWARE N-Smart [44] is an open-source initiative focused on establishing an open and sustainable ecosystem centered on public, royalty-free, and implementation-driven software platform standards, simplifying the development of smart solutions across various sectors. It offers foundational components for crafting intelligent applications in areas like smart cities, industries, and agriculture. In particular, as stated in [45], FIWARE components serve as a promising platform for applications in agriculture addressing irrigation tasks, offering advantages over the use of traditional systems. Key features of FIWARE ([46,47]) include its modular architecture, facilitating the seamless integration of new functionalities; its adherence to open standards, ensuring interoperability with other IoT platforms and devices; a broad developer and partner ecosystem for ample support; and robust security measures to safeguard IoT applications against unauthorized access. It provides essential elements such as APIs for connecting software components and data sources, context management for sharing crucial context information, data management tools for storage, processing, and analytics, and device management capabilities for ensuring interoperability and secure device connections, alongside additional services encompassing security, user management, and service orchestration.

2.1.3. EdgeX Foundry Platform

EdgeX Foundry, a Linux Foundation-hosted open-source project, spearheads the development of the EdgeX Platform [48], a versatile framework for IoT edge computing. This platform aims to streamline the creation, deployment, and operation of IoT solutions across diverse industries by offering a flexible, scalable, and secure software foundation. Key features and objectives include interoperability through a microservices architecture; modularity, allowing for easy integration of custom components; scalability to accommodate varying deployment sizes; built-in security features, community-driven development ensuring adaptability; and edge-to-cloud integration for enhanced processing capabilities. The EdgeX Platform comprises core, supporting, and security services alongside device and application services. With widespread adoption and contributions, EdgeX Foundry aims to offer developers and companies an efficient and collaborative ecosystem to build and deploy IoT solutions.

2.2. Proprietary Platforms

2.2.1. PwC Smart City Platform

PwC offers a software-as-a-service (SaaS) [49] subscription-based cloud solution for smart cities. Their web application hosts a dashboard for the end-user in which the incoming data streams from the nodes are visualized. As a node, PwC assumes that the SC already possesses a smartphone application that citizens or visitors use and transmits data to the platform. The data uploading follows the EU's GDPR. The web application also offers real-time data analytics and the ability to directly communicate with a node or a set of nodes within the SC environment. Furthermore, their platform offers scalability functionalities, meaning that it can scale up or down depending on the number of nodes and expandability functionalities by accepting data from any IoT sensor. Finally, the platform can send push notifications to the nodes.

2.2.2. UniSystem City4Life Platform

City4Life [50] is an open-architecture platform developed by UniSystems to facilitate the vision of an SC. It enables interconnection, interoperability, and communication between SC applications and systems, creating a framework for managing and optimizing urban operations. The platform is based on European standards' open-source software and leverages the benefits of IoT technologies to integrate and manage various data sources and devices. City4Life adopts an open-source approach, allowing cities to customize and adapt the platform to their specific needs and requirements. The platform enables real-time data collection, analysis, and visualization, providing city officials with actionable insights to make informed decisions. The platform can work either on-premises or on the cloud, and it claims to be compatible with every sensor.

2.2.3. IBI Group Smart City Platform

IBI Group's Smart City Platform [51] serves as an all-encompassing open technology framework, facilitating the integration of cities' existing systems with IBI's onboard tools and insight-driven applications. Through the fusion of big data and predictive analytics, the platform enhances decision-making processes, streamlining the management and optimization of city operations. Built upon open standards and protocols, the platform offers easy integration with existing systems and applications, showcasing flexibility and scalability. IBI Group asserts that security is a paramount consideration in the platform's construction, instilling confidence in cities regarding the safety of their data.

2.2.4. thethings.iO IoT Smart City Platform

thethings.iO's IoT Smart City Platform [52] is a comprehensive solution designed for the development and management of SC applications. Offering diverse functionalities, the platform supports the connection and management of various IoT devices, real-time data ingestion and analytics, data visualization tools, and a development environment for custom applications. Emphasizing security with features like encryption and access control, the cloud-based platform is adaptable for on-premises or hybrid deployment, ensuring scalability for cities of all sizes.

2.2.5. Vodafone Smart Cities Platform

Vodafone's Smart Cities Platform [53] is a comprehensive solution facilitating the collection, analysis, and utilization of data from diverse IoT devices to enhance city services. With key features including device management, data ingestion, processing, visualization tools, application development, and robust security measures, the platform serves various use-cases. It can optimize traffic flow, enhance public safety through monitoring and crime trend analysis, address environmental concerns by monitoring air and water quality, offer smart parking solutions, and control outdoor lighting for energy savings.

2.2.6. Nokia IMPACT IoT Platform

Nokia's IMPACT IoT Platform [54] serves as a comprehensive solution for cities, facilitating the collection, management, and analysis of data from diverse IoT devices. With key features such as device management, real-time data ingestion and analytics, data visualization tools, application development environment, and robust security measures, the platform addresses various aspects of urban services. Its applications span across traffic management, enabling monitoring, flow optimization, and congestion reduction, enhancing public safety through crime trend tracking and emergency notifications, monitoring environmental factors like air and water quality, managing parking spaces with real-time availability information, and controlling outdoor lighting for energy efficiency and improved safety. The platform is designed with a focus on security, incorporating encryption, access control, and intrusion detection features.

2.2.7. Huawei Smart City Solution Service

Huawei's Smart City Solution Service [55] offers a comprehensive suite designed to enhance urban functionality through the collection, management, and analysis of data from a diverse range of IoT devices. Key features include robust device management capabilities for various IoT devices, real-time data ingestion and analytics, data visualization tools, a development environment for custom SC applications, and a security-focused framework encompassing encryption, access control, and intrusion detection. The platform caters to multiple use-cases, such as optimizing traffic flow and providing real-time updates, enhancing public safety through crime trend monitoring and emergency notifications, conducting environmental monitoring for air and water quality, managing parking spaces with real-time availability information, and controlling outdoor lighting for energy efficiency and safety improvement.

2.2.8. Invipo Integration Platform

Invipo's platform [56] serves as a centralized system that aggregates data from diverse sources including traffic lights, air quality sensors, and public transport, among others. This data are then analyzed to offer actionable insights aimed at enhancing urban functionality. Features of Invipo include real-time traffic management, enabling adjustments to traffic lights, and provision of alternative routes to alleviate congestion. Additionally, it facilitates parking management by identifying high-demand areas and implementing dynamic pricing, while also assisting drivers in locating available parking spaces. The platform aids in public transport management by tracking vehicle locations and providing passengers with timely arrival and departure information. Furthermore, Invipo conducts environmental monitoring, gathering data on air quality and noise levels to support the development of policies aimed at mitigating pollution and improving urban livability.

2.2.9. ASTRI Smart City Platform

ASTRI, the Hong Kong Applied Science and Technology Research Institute, has developed key tools and platforms in support of SC initiatives. The Smart City Platform [57], a scalable cloud-based solution, serves as a central hub for connecting diverse devices utilized in SC deployments. By integrating indoor and outdoor geographical information alongside time-stamped device data, real-time data capture, monitoring and analysis are facilitated, while enhancing smart navigation capabilities. Additionally, ASTRI's Internet-of-Things (IoT) Management and Application Platform (IMAP) focuses on effectively managing and leveraging data from IoT devices within SC environments.

2.2.10. TIBCO Platform

The TIBCO Platform [58] offers a comprehensive suite of products and services aimed at enhancing integration, analytics, and data management across various business operations. Its key components include integration solutions like TIBCO BusinessWorks and cloud integration for connecting applications, data, and devices; data management tools such as TIBCO Data Virtualization and EBX for managing data across multiple sources; and analytics platforms like TIBCO Spotfire for data visualization and insights. Additionally, it features event processing capabilities with TIBCO BusinessEvents and Streaming for real-time event analysis, messaging solutions like TIBCO Messaging for reliable communication, and API management with TIBCO Mashery to secure and manage APIs. TIBCO's cloud services further support the development and deployment of applications in a scalable, secure cloud environment. The TIBCO Platform aims to facilitate system integration, manage complex data, and derive real-time insights.

2.2.11. Orchestra Cities by Martel Innovate

Orchestra Cities [59], an initiative by Martel Innovate, aims to transform urban areas into smart cities through a collaborative platform that promotes the sharing of data and digital solutions. By leveraging technologies such as IoT, big data, and artificial intelligence, the platform addresses various urban challenges, including transportation, energy management, environmental monitoring, and public services. Its open and modular architecture allows for easy adoption and customization by cities to meet their unique needs. The platform fosters a community where cities can exchange ideas, solutions, and data, enhancing innovation and enabling the scaling of successful initiatives across different locales.

2.2.12. LG INFioT

INFioT [60], developed by LG, is an IoT platform designed to streamline the management and development of IoT services across various sectors. It excels in data management, efficiently collecting, sorting, and storing vast quantities of data from IoT devices for easy analysis. The platform supports a wide range of communication protocols, enhancing device connectivity across different domains, from consumer appliances to industrial equipment. Integration with LG CNS's AI and big data platforms facilitates advanced data analysis and the deployment of intelligent services, such as predictive maintenance. INFioT also prioritizes security, featuring a robust system tailored for IoT applications. Its versatility is showcased in applications across smart cities, factories, buildings, and homes, where it enables traffic monitoring, energy optimization, production efficiency, and personalized smart home experiences.

2.2.13. ONEX Dimos

Dimos [61] is an SC platform by ONEX, designed to enhance urban living through advanced technology. It offers a comprehensive suite of features, including dynamic parking management with smart labels and mobile apps for parking and violation reporting, traffic flow monitoring for up-to-the-minute congestion and accident data, and noise mapping to identify and mitigate high noise pollution areas. Additionally, Dimos facilitates infrastructure monitoring, ensuring the preservation and maintenance of historical sites and critical structures, and collects environmental data to monitor air and water quality. It enhances citizen engagement by providing easy access to important information and services, improves public transport with real-time updates, and increases public access to Wi-Fi. Smart street lighting that adapts to environmental conditions for energy efficiency and a centralized control center for cohesive city management are also key components. Since its debut in 2017, Dimos has seen adoption in various Greek cities, tailoring its offerings to meet local urban needs effectively.

2.2.14. LTIMindtree Advanced Smart City Operating Platform

The "Advanced Smart City Operating Platform", developed by LTIMindtree [62], is a comprehensive software solution designed to enhance the efficiency of city operations and management through centralized data handling and improved civic function integration, ranging from traffic management to waste collection. Leveraging a leading software stack, the platform excels in aggregating and analyzing data from various city sensors and systems, offering actionable insights for better decision-making. It facilitates effective event management and emergency responses, performance tracking of city services, and fosters citizen engagement by providing a user-friendly interface for interaction and information access. The platform promises significant benefits including enhanced efficiency and decision-making for city officials, improved citizen services, cost reductions through optimized resource use, and increased sustainability by monitoring and supporting environmentally friendly practices.

2.2.15. Lucy Zodion Ki. City Platform

The Ki City Platform [63], by Lucy Zodion offers SC solutions, focusses on transforming existing street lighting into a comprehensive, interconnected IoT ecosystem. This platform stands out by leveraging the ubiquitous presence of streetlights to establish a mesh network of sensors and communication devices, thereby circumventing the need for substantial new infrastructure investments. Ki is meticulously designed to ensure security and scalability, meeting the expanding needs of modern urban environments. It gathers and analyzes data from a wide array of sensors, such as environmental, traffic, and noise sensors, providing actionable insights to enhance city operations, sustainability efforts, and citizen engagement. The platform boasts a user-friendly interface, simplifying the process for city officials and authorized personnel in accessing data, managing devices, and producing insightful reports. With potential benefits including improved operational efficiency, reduced energy consumption and emissions through intelligent lighting control, and elevated citizen engagement by offering real-time information and facilitating communication with city authorities, Ki aims to make cities more efficient, sustainable, and responsive to their inhabitants' needs.

2.2.16. Siemens Mindsphere

Mindsphere [64], Siemens' cloud-based IoT operating system, bridges the physical and digital worlds by connecting real objects with digital services, leveraging IoT-generated data through advanced analytics to drive business success. It enables the collection and real-time analysis of data from devices, machines, and infrastructure, helping businesses across the manufacturing, energy, infrastructure, and healthcare sectors enhance efficiency, productivity, and sustainability. Mindsphere's key features include versatile connectivity options, powerful data analytics, a development environment for custom applications, stringent data security measures, and a supportive ecosystem for partners and developers. This initiative is central to Siemens' digitalization strategy, aiming to optimize operations, foster innovation, and transform business models for the digital era.

2.2.17. Bosch IoT Suite

The Bosch IoT Suite [65], developed by Bosch, a prominent technology and services provider, is a comprehensive software platform tailored for IoT applications, offering efficient device connectivity and management capabilities. It equips businesses and developers with tools for data collection, analysis, and processing from connected devices, facilitating informed decision-making, automation, and operational efficiency enhancements. Key components encompass device management, ensuring devices are up-to-date and functional, secure connectivity protocols, robust data management and analytics tools for insights and process optimization, support for edge computing to reduce latency and enhance responsiveness, flexible integration options, and stringent security measures to safeguard data and devices from cyber threats.

2.2.18. ABB Ability

The ABB Ability platform [66], developed by ABB, a leading global provider in electrification, robotics, automation, and motion, epitomizes digital transformation across industries. Combining ABB's expertise with cutting-edge technologies, it delivers solutions for enhanced performance, productivity, and energy efficiency. Key features include a diverse array of digital solutions like predictive maintenance and advanced automation, leveraging connectivity and cloud infrastructure for real-time insights and decision-making. Tailored industry-specific applications address unique challenges, while robust cyber security measures ensure data integrity.

2.2.19. Schneider Electric EcoStruxure

EcoStruxure [67], developed by Schneider Electric, stands as a pioneering IoT-enabled architecture and platform, fostering digital transformation across diverse sectors. It harnesses IoT, mobility, cloud, and cyber security technologies to innovate at every level, from connected products to edge control and analytics. Structured around connected products, edge control, and apps, analytics, and services layers, EcoStruxure enables data collection, local decision-making, and actionable insights. With a focus on scalability and sustainability, it caters to various industries, offering holistic solutions to drive efficiency and resilience. Emphasizing cyber security, EcoStruxure safeguards systems and data in an era of heightened connectivity. Deployed globally, it showcases its efficacy in enhancing operational performance and energy efficiency across multiple applications.

2.2.20. Cumulocity IoT by Software AG

Cumulocity IoT [68], developed by Software AG, offers a cloud-based solution for IoT deployment, simplifying device connectivity, data management, and integration with enterprise systems. Its robust device management tools support a variety of devices and protocols, facilitating seamless integration into operations. The platform enables secure data collection, storage, and analysis for informed decision-making and service enhancement. With application enablement features, developers can create custom IoT applications tailored to specific business needs, while seamless integration capabilities enrich existing IT landscapes. Emphasizing security and scalability, Cumulocity IoT ensures data and device protection while accommodating growth. Positioned within Software AG's Digital Business Platform, Cumulocity IoT aids digital transformation across industries, fostering innovation, efficiency, and new business models through IoT adoption.

2.2.21. Kaa IoT Platform Enterprise Edition

The Kaa IoT Platform Enterprise Edition [69] is a renowned solution in IoT development, offering an end-to-end suite of tools catering to a wide range of applications, from simple consumer-oriented scenarios to complex industrial scenarios. With options for both cloud-based and on-premises deployments, Kaa excels in ease of use, flexibility, and scalability, supporting various protocols and languages and boasting numerous successful implementations across industries. Key features include device management for onboarding and provisioning, robust data collection and processing capabilities, customizable application development tools, and prioritized security measures like device authentication and data encryption. Its scalability allows it to handle large-scale deployments with thousands of connected devices. Kaa finds applications in diverse sectors such as smart home, SC, industrial IoT, and connected healthcare, powering solutions from connected appliances and traffic management to predictive maintenance and patient monitoring.

2.2.22. Altair IoT Studio

Altair IoT Studio [70], a cloud-native platform, simplifies the development, deployment, and management of IoT applications and services as part of Altair's suite targeting designers, engineers, and IT professionals for informed decision-making. Renowned for its user-friendly interface and data integration prowess, Altair IoT Studio enables creation without deep programming knowledge. It expedites IoT application development through drag-and-drop workflows, pre-built templates, and diverse connectors. Key features include a visual development environment, robust data connectivity, real-time processing and analytics, application deployment and management tools, security measures, and scalability. Tailored for the manufacturing, automotive, and aerospace industries and smart buildings, it enhances operational efficiency, cost reduction, and innovation, thereby accelerating digital transformation initiatives.

2.2.23. PTC ThingWorx

ThingWorx [71], an Industrial Internet of Things (IIoT) platform by PTC, empowers businesses to develop, deploy, and manage applications for connected devices swiftly. Its comprehensive toolset facilitates rapid application development with a visual environment, minimizing the need for extensive coding. With support for diverse industrial connectivity protocols and seamless integration with enterprise systems like ERP and CRM, ThingWorx ensures smooth data flow across the organization. Advanced analytics and machine learning capabilities enable data-driven decision-making, while integration with PTC's Vuforia AR platform enhances immersive experiences for training and maintenance. Scalable from small implementations to enterprise-wide solutions, ThingWorx prioritizes security with robust features for data protection and solution integrity. It is widely adopted across the manufacturing, healthcare, energy, and smart cities sectors.

2.2.24. Davra IIoT Platform

Davra specializes in delivering an IoT platform [72] that empowers businesses to leverage connected devices effectively. Their comprehensive IoT solution facilitates data collection, analysis, and visualization from diverse sources, including sensors and devices across multiple locations. Key features encompass data collection and integration from various IoT devices, real-time analytics for immediate insights, customizable visualization tools, remote device management capabilities, robust security measures, and scalability to accommodate growing IoT infrastructures. Widely adopted across transportation, utilities, manufacturing, and smart cities, Davra's platform drives efficiency, enhances operational performance, and fosters new business models by providing valuable insights, process optimization, and informed decision-making through IoT technologies.

2.2.25. AWS IoT

AWS IoT [73] is a cloud-based platform designed to facilitate secure and scalable device connectivity to the internet, enabling interaction with cloud applications and other devices. It offers a suite of services supporting different aspects of IoT solutions, including device connectivity, data collection, storage, analysis, and application development. Key components include AWS IoT Core, the central hub for secure device interaction with cloud applications; AWS IoT Device Management for onboarding and managing IoT devices at scale; AWS IoT Analytics for advanced data analysis; AWS IoT Greengrass for extending AWS to edge devices; AWS IoT Events for event detection and response; AWS IoT SiteWise for industrial equipment data management; and AWS IoT Things Graph for visually connecting devices and services to build IoT applications. Supporting various communication protocols and emphasizing security, AWS IoT enables compatibility with a wide range of devices while ensuring data protection through features like authentication, encryption, and authorization.

2.2.26. Azure IoT Central

Azure IoT Central [74] stands as a fully managed global IoT software-as-a-service (SaaS) solution, streamlining the connection, monitoring, and management of IoT assets at scale. Serving as a centralized IoT development hub, it simplifies both the initial setup and ongoing device management, requiring no deep expertise in cloud solutions or IoT. Key features and benefits encompass simplified setup and management, scalability to accommodate projects of any size, versatile device connectivity and management supporting various protocols, built-in analytics and visualization tools for data understanding, seamless integration with other Azure services for extended functionality, robust security measures, pre-built templates, industry-specific solutions to accelerate development, and customization and extensibility options for tailored experiences.

2.2.27. NoTraffic Platform

The NoTraffic platform [75], developed by NoTraffic, is an innovative traffic management solution that aims to revolutionize traffic flow and safety at intersections and crucial points within urban and suburban areas. Key features include AI and edge computing, utilizing AI algorithms and edge processing for real-time decision-making, reducing latency and dependency on constant cloud connectivity for swift responses to changing traffic conditions. Adaptive traffic signal control dynamically adjusts signals based on real-time traffic conditions, minimizing wait times, enhancing traffic flow, and reducing emissions. Safety improvements are achieved through real-time intersection monitoring, understanding the movements of all road users to prevent accidents by detecting potential conflicts and adjusting signals accordingly. The platform collects extensive data for data-driven insights into traffic patterns and congestion, aiding urban planners and engineers in infrastructure improvements and policy changes. Integration and scalability ensure seamless integration with existing systems, enabling deployment from small towns to large cities. Sustainability is promoted through optimized traffic flow, reducing idle times, and lowering vehicle emissions.

2.2.28. Pycom Pybytes

Pybytes [76], a cloud-based middleware platform by Pycom, streamlines the deployment and management of Pycom's IoT devices renowned for their support of various wireless protocols like Wi-Fi, LoRa, Sigfox, and LTE-M. Designed to simplify connecting Pycom devices to the cloud, Pybytes facilitates efficient monitoring and management post-deployment. Key features encompass device management through a user-friendly dashboard for remote device monitoring, including status checks, battery levels, and activity logs. Data visualization tools aid in understanding collected data with graphs and charts, crucial for analysis. Integration with popular cloud services extends flexibility in data processing and storage, supporting platforms like AWS, Google Cloud, and Microsoft Azure. Firmware updates over the air (OTA) allow for remote updates for bug fixes, security enhancements, and feature additions. Multi-network support accommodates devices operating across various protocols, reflecting Pycom's hardware versatility. Security features secure device registration and encrypted communication for data protection.

2.2.29. ThingsBoard

The ThingsBoard IoT platform [77] provides a comprehensive suite of tools for connecting, managing, and visualizing IoT devices and data, catering to diverse applications across industries. Key features include efficient device management, supporting multiple device types with provisioning and credentials management, alongside data collection and processing capabilities supporting popular IoT protocols like MQTT, CoAP, and HTTP(S). Telemetry data handling enables real-time monitoring and historical analysis, while customizable dashboards offer rich visual representations of IoT data. Emphasizing security, ThingsBoard provides authentication, encryption, and secure data transmission channels, with integration and API support enhancing interoperability. Scalability is ensured through horizontal scaling, accommodating millions of devices and billions of data points. Available in community, professional, and cloud editions, ThingsBoard meets various needs, from core IoT features to advanced capabilities, widely used across industries like smart agriculture and industrial IoT. Customization options and user-friendly interfaces make ThingsBoard accessible to beginners and experienced IoT developers alike, facilitating the prototyping and deployment of IoT solutions.

2.2.30. Ubidots

Ubidots is a cloud-based IoT platform [78] that simplifies IoT application development for developers and businesses, requiring no extensive hardware programming or networking knowledge. It facilitates data collection, analysis, and visualization from connected devices, offering features such as secure and scalable data storage, real-time customizable dashboards, event triggers and alerts, remote device management, integration with REST and MQTT APIs, and multi-user collaboration. Ubidots offers an educational version, Ubidots STEM, for learning purposes.

2.2.31. IBM Watson IoT Platform

The IBM Watson IoT Platform [79], part of IBM's Watson suite, simplifies the process of deriving value from IoT devices through its managed, cloud-based service. Offering connectivity and control tools, it securely connects and manages IoT devices, supporting various communication protocols. With robust data management and analysis capabilities, including integration with IBM's Watson AI, it enables real-time insights and predictive analytics. Security features protect devices and data, while cognitive capabilities allow for complex data analysis and autonomous applications. Flexible integration options and scalability accommodate diverse use-cases across industries, from manufacturing to healthcare and smart cities, making it a versatile solution for IoT applications.

2.2.32. Oracle IoT

Oracle [80] offers a suite of solutions tailored for the energy and water utilities sector, aiming to improve operational efficiency, customer service, and adaptability to the evolving energy landscape. These solutions, part of the Oracle Utilities suite, utilize cloud technologies, advanced analytics, and data management tools to address industry-specific challenges. Key components include customer information systems (CIS) for billing and service management, meter data management (MDM) for smart meter data handling, grid and asset management for optimizing distribution networks, energy efficiency and customer engagement platforms for promoting energy-saving practices, water utilities management for water conservation and supply management, and various cloud and SaaS offerings for scalability and security. Oracle's approach supports digital transformation in utilities, leveraging big data, IoT, AI, and cloud technologies to enhance operational efficiency, customer experiences, and sustainability efforts.

2.2.33. General Electric (GE) Predix

Predix [81], developed by General Electric Digital, is a cloud-based platform-as-a-service (PaaS) tailored for industrial data and analytics, serving as the backbone for GE's

IIoT applications. It facilitates the development, deployment, and operation of applications harnessing big data from industrial machinery and processes, enhancing operational efficiency, performance, and reliability. Key features include its industrial focus across sectors like aviation and energy, advanced analytics capabilities with machine learning tools for predictive maintenance, edge-to-cloud integration supporting real-time decision-making, robust security measures, a thriving developer ecosystem, and strategic partnerships to expand its capabilities and reach. Predix enables industrial organizations to leverage data-driven insights for optimized operations and improved outcomes.

2.2.34. SAP IoT

The SAP IoT solution [82], integral to SAP's digital transformation strategy, streamlines IoT device integration and management within organizational workflows. Engineered to handle vast real-time data volumes from sensors and devices, it furnishes actionable insights for optimizing operations, enhancing customer experiences, and fostering new business models. Key features include robust data management and integration capabilities, advanced real-time analytics tools, scalability for diverse IoT scenarios, stringent security measures, support for edge computing, seamless integration with SAP's portfolio, and industry-specific solutions tailored for various sectors like manufacturing, logistics, and energy. This comprehensive platform empowers businesses to harness the potential of connected devices effectively and achieve their digital transformation objectives.

2.2.35. Hitachi Lumada

Hitachi Lumada [83] is an IoT platform designed to catalyze digital innovation for businesses through the utilization of data and digital technologies. It offers a versatile array of features and capabilities, including the seamless connection and management of data from diverse sources, integration with external platforms for enhanced flexibility, and a suite of tools for data analysis and AI-driven insights. Lumada extends its solutions across various industries, underscoring its adaptability and applicability. Emphasizing collaborative co-creation, Hitachi partners with clients to develop tailored solutions. The platform promises a range of potential benefits, such as heightened productivity, reduced operational costs, informed decision-making, enriched customer experiences, and sustainable growth. Real-world applications of Lumada include optimizing urban transportation networks, automating equipment defect detection through AI image analysis, and implementing predictive maintenance strategies to avert downtime by analyzing sensor data.

2.2.36. Litmus Edge

Litmus Edge [84], an industrial edge computing platform developed by Litmus Automation, is designed to revolutionize data management and analysis in industrial environments. It operates by collecting, analyzing, and responding to real-time data from a variety of industrial assets at the edge of the network, eliminating the need for data transmission to the cloud for processing. Key features include robust connectivity with support for diverse industrial devices and protocols, data collection, normalization, and real-time analytics. Litmus Edge also has the capability to deploy custom applications on edge devices for specific tasks such as anomaly detection or predictive maintenance. Scalability and security are paramount, ensuring seamless integration with large deployments while safeguarding sensitive data through encryption and access control. The platform delivers numerous benefits, including reduced latency, improved operational efficiency, and cost savings by minimizing cloud computing expenses, heightened security, and data privacy through its air-gapped architecture.

2.2.37. Akenza

Akenza offers a self-service IoT platform [85] aimed at simplifying the creation and management of IoT solutions across various industries. It facilitates device connectivity through support for diverse protocols like LoRaWAN, Sigfox, NB-IoT, cellular networks, Wi-Fi, and Bluetooth. The platform enables real-time data collection, storage, and visualization, alongside tools for data analysis, including dashboards, reports, and alerts. Additionally, Akenza provides capabilities for application development and integration, bolstered by robust security measures. Scalability is a core feature, ensuring that the platform can accommodate extensive device networks and data streams efficiently.

2.2.38. AVSystem Coiote IoT Device Management

Coiote IoT Device Management [86], developed by AVSystems, serves as a comprehensive platform aimed at efficiently managing and securing connected devices across a multitude of industries such as smart cities, manufacturing, and healthcare. It simplifies crucial tasks, including device onboarding, configuration, maintenance, and updates, while ensuring secure communication and data management for all connected devices. Key features encompass diverse device connectivity through support for protocols like LwM2M, CoAP, and HTTP, facilitating seamless integration with various devices and sensors. The platform excels in data management, enabling the collection, storage, and analysis of device data to provide actionable insights for informed decision-making. Additionally, Coiote IoT Device Management offers robust device management capabilities, including remote provisioning, configuration, firmware updates, and diagnostics, all fortified by stringent security measures such as encryption, access control, and vulnerability management. Designed with scalability in mind, the platform efficiently handles large volumes of connected devices and data streams, ensuring its adaptability to evolving business needs and technological advancements.

2.2.39. Ayla IoT Platform

The Ayla IoT Platform [87] is a cloud-based solution designed to streamline the development and management of connected products for manufacturers and retailers across diverse industries such as the smart homes, consumer electronics, healthcare, and industrial sectors. Its primary objective is to facilitate the rapid creation and launch of connected products by offering a comprehensive suite of tools for device connectivity, data management, application development, and security. Key features include broad device connectivity support for protocols like Wi-Fi, Bluetooth, and ZigBee, alongside robust data management capabilities for collecting, storing, and analyzing device data to derive actionable insights. The platform also provides resources for application development, including tools and APIs for building custom applications and user interfaces tailored to connected products. Security is prioritized through encryption, access control, and vulnerability management measures, ensuring data integrity and user privacy. Moreover, the Ayla IoT Platform is built to scale, capable of accommodating large deployments and increasing data volumes as businesses expand their IoT initiatives.

2.2.40. Simetric IoT platform

Simetric's IoT platform [88] specializes in Industrial IoT (IIoT) applications, emphasizing data collection, analysis, and management for industrial settings. While primarily deployed on-premises, hybrid options may be available. Key features include robust data management capabilities, prioritized security measures including encryption and access control, and scalability to accommodate large deployments and growing data streams. Moreover, the platform offers customization through APIs and tools for building tailored applications and integrations to meet specific industrial needs, though on-premises deployment requires more setup and maintenance compared to cloud-based solutions.

2.2.41. Actility ThingPark

Actility's ThingPark platform [89] is a versatile and comprehensive solution for building and managing IoT networks, supporting multiple communication technologies such as LoRaWAN, LTE-M, NB-IoT, and satellite radio. Its openness and hardware agnosticism allow for its seamless integration with diverse devices and gateways, ensuring flexibility in network deployment. ThingPark's scalability and robust security features make it suitable for both small-scale proof-of-concepts and large-scale deployments. Key functionalities include network deployment and management, device connectivity, data management, and application enablement. Specific offerings like ThingPark Enterprise and ThingPark Wireless cater to different user groups, from businesses setting up internal LoRaWAN networks to mobile network operators establishing public networks. ThingPark finds applications across various sectors, including smart cities, industry, manufacturing, and utilities, enabling data-driven decision-making and improving operational efficiency and service reliability.

3. Technologies

3.1. Communication Capabilities

Our investigation identified some of the technologies that are commonly used to enable communication and interaction with the devices via the IoT platforms. These technologies, randomly ordered, are ZigBee/Z-Wave, NB-IoT, LTE-M, cellular networks, Bluetooth/Bluetooth Low Energy (BLE), Wi-Fi/Ethernet, LoRaWAN, and Sigfox.

ZigBee and Z-Wave are both wireless communication protocols commonly used in smart home devices. ZigBee operates on the IEEE 802.15.4 standard, utilizing low-power, low-data-rate wireless connections for devices like lights, sensors, and thermostats. It forms mesh networks wherein each device can act as a router, extending the network's range and reliability. Z-Wave, on the other hand, is a proprietary protocol developed by Z-Wave Alliance, optimized for home automation. It operates on the sub-1 GHz band, providing a longer range compared to ZigBee. Z-Wave devices also form mesh networks, enabling communication between devices and centralized controllers for the seamless integration of various smart home components. Both ZigBee and Z-Wave offer interoperability and flexibility, catering to different needs within the realm of home automation.

Narrowband Internet of Things (NB-IoT) is a low-power, wide-area network (LPWAN) technology designed to enable efficient communication between a wide range of devices and sensors in the IoT ecosystem. It operates on licensed spectrum bands, offering improved coverage, better penetration through walls and underground, and extended battery life for connected devices. NB-IoT is optimized for applications requiring low data rates, intermittent transmission, and long battery life, making it suitable for various IoT deployments such as in smart cities, industrial monitoring, agriculture, and asset tracking. Its standardized approach ensures interoperability across different networks and devices, facilitating seamless integration and scalability within IoT ecosystems.

LTE-M, short for long-term evolution for machines, is an LPWAN cellular technology designed to support IoT devices with extended battery life and enhanced coverage. It operates within the LTE spectrum, providing efficient data transmission for devices that require intermittent or low-bandwidth connectivity, such as sensors, meters, and other IoT applications. LTE-M offers improved penetration through buildings and underground areas, making it suitable for various industries, including agriculture, utilities, and asset tracking.

Cellular networks, encompassing 2G, 3G, 4G, and 5G technologies, form the backbone of modern telecommunications infrastructure. These networks enable wireless communication between mobile devices and base stations, facilitating voice calls, messaging, and data transfer. The capabilities of each generation are as follows: 2G, introduced in the 1990s, primarily focused on digital voice transmission; 3G, which emerged in the early 2000s, brought faster data transfer, enabling internet access and multimedia services; 4G, deployed around 2010, significantly enhanced data speeds, supporting high-definition video streaming and advanced mobile applications; the latest generation, 5G, promises even greater speed, capacity, and reduced latency, enabling innovations such as augmented reality, autonomous vehicles, and the IoT. Each generation represents a significant leap in connectivity, revolutionizing how people communicate, work, and interact with technology.

Bluetooth is a wireless technology standard used for exchanging data over short distances between devices. It enables devices such as smartphones, laptops, tablets, and peripherals like headphones and keyboards to communicate with each other without the need for cables. Bluetooth Low Energy (BLE), also known as Bluetooth Smart, is a variant of Bluetooth technology designed for low-power consumption. It is optimized for devices that need to operate with minimal energy usage, making it ideal for applications like wearable devices, smart sensors, and other IoT devices. BLE maintains the core functionality of traditional Bluetooth while consuming significantly less power, extending battery life, and enabling devices to operate for extended periods without frequent recharging or battery replacement.

Wi-Fi, short for wireless fidelity, is a technology that allows electronic devices to connect to a WLAN using radio waves, providing internet access and network connectivity without the need for physical cables. It enables users to access the internet and communicate with other devices within a certain range, typically within a home, office, or public hotspot, whereas Ethernet is a wired networking technology commonly used to connect devices within a local area network (LAN) using cables. It provides reliable and high-speed data transmission by establishing a physical connection between devices, offering stability and consistent performance, particularly in environments where wireless signals may be unreliable or congested.

LoRaWAN, short for long-range, wide-area network, is a wireless communication protocol designed for long-range, low-power communication between IoT devices and gateways. It operates on unlicensed radio frequencies, enabling cost-effective and energy-efficient connectivity over large geographic areas. LoRaWAN utilizes chirp spread spectrum modulation to achieve long-range communication while consuming minimal power, making it suitable for a wide range of applications such as smart agriculture, smart cities, asset tracking, and industrial monitoring. The protocol enables devices to transmit small packets of data intermittently, facilitating the deployment of battery-operated sensors in remote locations with minimal maintenance requirements.

Sigfox is a global communication service provider that offers LPWAN connectivity for IoT devices. It operates by utilizing ultra-narrowband technology to enable long-range, low-data-rate communications efficiently. Sigfox's network architecture is designed to facilitate the transmission of small packets of data over long distances, making it ideal for IoT applications where devices need to transmit small amounts of information sporadically. This technology is particularly suited for use-cases such as asset tracking, environmental monitoring, and SC infrastructure, where low-power consumption and long-range connectivity are essential.

3.2. Communication Protocols

Similarly to Section 3.1, here, we present the most common communication protocols that are used by IoT platforms. Randomly ordered, these protocols are MQTT, REST APIs, AMQP, WebSockets, OPC UA, Modbus, HTTPS, XMPP, CoAP, and LWM2M. We decided to include the most popular ones and exclude protocols that are rarely supported (e.g., DNP3, BACnet, WirelessHART, etc.).

MQTT (message queuing telemetry transport) is a lightweight messaging protocol designed for efficient communication between devices in IoT and other resource-constrained environments. It operates on a publish/subscribe model, where clients can publish messages to topics or subscribe to topics to receive messages. MQTT's simplicity, low bandwidth usage, and support for intermittent network connections make it ideal for scenarios where devices need to exchange small packets of data reliably and with minimal overhead. It has gained widespread adoption in IoT applications due to its flexibility, scalability, and ability to handle diverse communication patterns.

A RESTful API, or representational state transfer API, is a standardized architectural style for designing networked applications and not an actual protocol; on the contrary, it operates over the HTTP and HTTPS protocols and adheres to a set of principles that prioritize simplicity, scalability, and flexibility. RESTful APIs utilize a client–server communication model where resources are identified by unique URIs (uniform resource identifiers) and manipulated using standard HTTP methods such as GET, POST, PUT, DELETE, etc. These APIs emphasize statelessness, meaning each request from a client contains all the information necessary for the server to fulfill it, without requiring context from previous interactions. Data are typically exchanged in formats like JSON or XML, enabling interoperability across different systems. The design of RESTful APIs fosters decoupling between client and server, promoting modular, maintainable, and scalable systems.

AMQP, or advanced message queuing protocol, is a standardized communication protocol designed for message-oriented middleware, facilitating the reliable exchange of messages between applications or services. It defines a system where message brokers, queues, and clients interact in a distributed architecture, enabling asynchronous communication while ensuring messages are delivered reliably and efficiently. AMQP supports various messaging patterns, including point-to-point, publish/subscribe, and request/reply, making it versatile for diverse use-cases in distributed systems, cloud computing, and enterprise messaging architectures. Its robustness, interoperability, and adherence to standards have made it a popular choice for building scalable, resilient messaging infrastructures.

WebSockets is a communication protocol that enables real-time, full-duplex communication between a client, typically a web browser, and a server over a single, long-lived connection. Unlike traditional HTTP, which follows a request-response model, WebSockets facilitate bidirectional data exchange, allowing both the client and the server to initiate communication at any time. This persistent connection reduces overheads by eliminating the need for frequent HTTP requests and responses, making it ideal for applications requiring low-latency, high-frequency data updates, such as online gaming, chat applications, and financial trading platforms.

OPC UA (open platform communications unified architecture) is a standardized communication protocol primarily used in industrial automation and control systems. It provides a platform-independent, service-oriented architecture for secure and reliable data exchange between various industrial devices and software applications. OPC UA offers features such as encryption, authentication, and built-in redundancy, ensuring robust and interoperable communication within industrial networks.

Modbus, on the other hand, is a widely used communication protocol in industrial automation that facilitates communication between electronic devices. It operates over serial communication lines (Modbus RTU) or Ethernet networks (Modbus TCP/IP), allowing for the exchange of data between devices like programmable logic controllers (PLCs), sensors, and other industrial equipment.

HTTPS, or hypertext transfer protocol secure, is a communication protocol used for secure data transmission over the Internet. It ensures that any information exchanged between a web browser and a website is encrypted, making it highly resistant to interception or manipulation by malicious third parties. HTTPS operates by employing SSL/TLS protocols, which establish an encrypted connection between the client and the server. This encryption safeguards sensitive data such as login credentials, personal information, and financial details, enhancing the overall security and privacy of online interactions. By encrypting data in transit, HTTPS helps to prevent eavesdropping, tampering, and other forms of cyber-attacks, thereby fostering trust and confidence among users engaging in online activities.

XMPP, or extensible messaging and presence protocol, is an open-source communication protocol primarily used for instant messaging (IM) and presence information. It enables the exchange of messages between devices over the Internet in near real time. XMPP is decentralized, meaning it does not rely on a single central server, but rather operates through a network of interconnected servers. This decentralization fosters privacy and security, as users can choose their own servers or even host their own. XMPP supports a wide range of features beyond basic messaging, including file transfer, multi-party chat, and various extensions for voice and video communication. Its extensibility allows for the integration of additional functionalities, making it a versatile and adaptable protocol used in various applications beyond traditional instant messaging, such as IoT communication and social networking platforms.

The constrained application protocol (CoAP) is a specialized web transfer protocol designed for use with constrained nodes and constrained networks in the IoT context. CoAP is lightweight and efficient, making it suitable for devices with limited processing power and memory, as well as networks with low bandwidth and high packet loss. It operates over UDP, providing reliable and asynchronous communication. CoAP supports RESTful principles, allowing devices to easily interact with resources using methods like GET, POST, PUT, and DELETE, making it a key protocol for IoT applications where resource-constrained devices need to communicate with each other and with web servers efficiently.

The lightweight machine-to-machine (LWM2M) protocol is a communication standard designed for efficient management and interaction between IoT devices and servers. Developed by the Open Mobile Alliance (OMA), LWM2M provides a lightweight and secure framework for remote device management, data reporting, and firmware updates over various network protocols such as CoAP, MQTT, and HTTP. It defines a set of object models and operations for device provisioning, monitoring, and control, enabling seamless interoperability and scalability in IoT deployments. LWM2M's emphasis on low power consumption, small code footprint, and simplicity makes it particularly suitable for resource-constrained IoT devices in diverse applications ranging from smart homes to industrial automation.

3.3. Cyber Security

Regarding cyber security, we grouped our findings into four categories, as cyber security is an ever-evolving notion. In this survey, we compared the IoT platforms in terms of their encryption capabilities, their access control, the presence of intrusion detection, and the patching/security update support by the vendors.

Encryption in cyber security is the process of encoding information in such a way that only authorized parties can access it. It involves converting plaintext data into ciphertext using cryptographic algorithms and keys. This ensures that even if unauthorized individuals intercept the data, they cannot understand or misuse it without the corresponding decryption key. Encryption plays a critical role in safeguarding sensitive information transmitted over networks, stored on devices, or exchanged between parties, helping to maintain confidentiality, integrity, and privacy in digital communications and transactions.

Access control in cyber security refers to the practice of regulating who can access specific resources or perform certain actions within a system or network. It involves implementing various mechanisms such as authentication, authorization, and accountability to ensure that only authorized individuals or entities can access information or perform actions. Access control aims to protect sensitive data, prevent unauthorized modifications, and maintain the integrity and confidentiality of systems and resources. It encompasses techniques like user authentication through passwords, biometrics, or multi-factor authentication, as well as defining and enforcing access policies based on roles, privileges, and least privilege principles. Additionally, access control involves monitoring and logging access attempts and activities to detect and respond to unauthorized or suspicious behavior effectively.

Intrusion detection in cyber security refers to the process of monitoring networks or systems for unauthorized access, malicious activities, or policy violations. It involves the use of various technologies and methodologies to detect suspicious behavior or patterns that may indicate a security breach. Intrusion detection systems (IDS) analyze network traffic, system logs, and other data sources to identify potential threats in real-time or retrospectively. These systems can be either host-based, monitoring activities on individual devices, or network-based, examining traffic across the entire network. Upon detecting an intrusion, alerts are generated to notify security personnel, enabling them to respond promptly and mitigate the threat, thereby safeguarding the integrity, confidentiality, and availability of the organization's data and resources.

Patching or security updates in cyber security refer to the process of fixing vulnerabilities and weaknesses in software, operating systems, or applications to enhance their security and protect against potential cyber threats. These updates are crucial for maintaining the integrity and confidentiality of digital systems by addressing known security flaws that could be exploited by malicious actors. Patching involves regularly installing updates provided by software vendors or developers to mitigate risks associated with software vulnerabilities, ensuring that systems remain resilient against evolving cyber threats and adhere to best security practices. Failure to promptly apply patches can leave systems susceptible to exploitation, potentially leading to data breaches, unauthorized access, or other security incidents.

4. Analysis of Results

Having investigated the capabilities and characteristics of each platform, we created four tables where we filled in our findings. The metrics of the tables were derived from the works of [20,90,91], which we then expanded. Specifically, in [1], the authors only use six metrics (device management, integration, security, protocols for data collection, type of analytics, and support for visualization). In [90], Babun et al. use seven metrics for their comparison analysis (topology, programming languages, third-party support, extended protocol support, event handling, security, and privacy). Finally, in [91], Ray used 10 metrics for his platform's comparison (application development, device management, system management, heterogeneity management, data management, analytics, deployment management, monitoring management, visualization, and research).

Table 1 is labeled "Capabilities and cost" and it features our findings on whether or not the platform comes with a cost; the symbol "$" means that the platform has a subscription plan, whereas "Free" means that the platform has no cost. Furthermore, the table includes whether or not the platform is open-source (or partially open-source), as explicitly stated with the symbol "■" or not with the symbol "**-**"; for example, some platforms are entirely closed-source, thus they have the symbol "**-**", whereas some platforms provide some of their source code in open-source form to facilitate the integration of the platform with custom libraries, packages, APIs, or with other platforms; thus, they are assigned the symbol "■". In the remaining columns and the following tables, whenever a platform offers a feature, the symbol "■" will be used, while when it is not offered, the symbol "**-**" will be used. All of the platforms are hosted in the cloud, and some of them offer the option to also install it on the premises of their customers; for this reason, we included the column "Hybrid hosting", which differentiates the latter from the former. Next, we also included the columns "Data Analytics" and "Alerting and Notifications" to identify which platform offers the capability to analyze incoming data in real-time—most of the times using AI models and algorithms—and notify users with alerts and alarms either via emails, SMS, or chat channels and applications. Finally, the column "Device Management" identifies which platforms offer the ability to perform over-the-air (OTA) updates to the devices connected to the platform or the ability to control actuators connected to these devices. In cases where there is no field information to be included in the table, the symbol "-" is inserted in the appropriate cell.

Table 1. Smart City Platforms comparison—capabilities and cost (The symbol "**$**" states that the platform has a subscription plan, while the symbols "■" and "**-**" declare an open or not platform respectively.).

Citation No.	Platform	Cost	Open-Source	Hybrid Hosting	Data Analytics	Alerting and Notifications	Device Management
[50]	PwC Smart City	$	-	■	■	■	-
[51]	UniSystems City4Life	$	■	■	■	■	-

Table 1. *Cont.*

Citation No.	Platform	Cost	Open-Source	Hybrid Hosting	Data Analytics	Alerting and Notifications	Device Management
[52]	Arcadis IBI Group Smart City Platform	$	■	-	-	■	-
[53]	thethings.iO IoT Smart City Platform	$	-	■	■	■	■
[54]	Vodafone Smart Cities Platform	$	-	-	■	■	■
[55]	Nokia IMPACT IoT Platform	$	-	■	■	■	■
[56]	Huawei Smart City Solution Service	$	-	■	■	■	-
[44]	OpenMTC	**Free**	■	■	-	-	■
[45]	FIWARE N-Smart	**Free**	■	■	■	-	■
[57]	Invipo	$	-	■	■	■	-
[58]	ASTRI Smart City Platform	$	-	-	■	■	-
[59]	TIBCO Platform	$	-	■	■	■	-
[60]	Orchestra Cities by Martel Innovate	$	■	-	■	-	-
[61]	LG INFioT	$	-	■	■	■	-
[62]	ONEX Dimos	$	-	-	-	■	-
[63]	LTIMindtree Advanced Smart City Operating Platform	$	-	-	■	-	-
[64]	Lucy Zodion Ki. City Platform	$	-	-	■	-	-
[65]	Siemens Mindsphere	$	-	-	■	-	■
[66]	Bosch IoT Suite	$	-	■	■	-	■
[67]	ABB Ability	$		■	■	■	■
[68]	Schneider Electric EcoStruxure	$	■	■	■	-	■
[69]	Cumulocity IoT 10.17 by Software AG	$	-	■	■	■	■
[49]	EdgeX Platform	**Free**	■	■	■	-	■
[70]	Kaa IoT Platform Enterprise Edition	$	■	■	■	-	■
[71]	Altair IoT Studio	$	-	■	■	-	-
[72]	PTC ThingWorx	$	-	■	■	■	■
[73]	Davra IIoT Platform	$	-	■	■	-	■
[74]	AWS IoT	$	-	■	■	■	■
[75]	Azure IoT Central	$	-	■	■	■	■
[76]	NoTraffic	$	-	-	■	-	
[77]	Pycom Pybytes	$	-	-	-	■	■
[78]	ThingsBoard	$	■	■	-	■	■
[79]	Ubidots	$	-	-	■	■	■
[80]	IBM Watson IoT Platform	$	-	-	■	■	■
[81]	Oracle IoT	$	-	■	■	■	■
[82]	GE Predix	$	-	-	■	■	-

Table 1. *Cont.*

Citation No.	Platform	Cost	Open-Source	Hybrid Hosting	Data Analytics	Alerting and Notifications	Device Management
[83]	SAP IoT	$	-	■	■	■	-
[84]	Hitachi Lumada	$	■	-	■	-	■
[85]	Litmus Edge	$	-	■	■	-	■
[86]	Akenza	$	-	-	■	-	■
[87]	AVSystem Coiote IoT Device Management	$	-	-	■	-	■
[88]	Ayla IoT Platform	$	-	-	-	-	■
[89]	Simetric IoT platform	$	-	■	-	-	■
[90]	Actility ThingPark	$	-	■	■	-	■

Table 2 presents the results of our investigation regarding the options that each platform offers with respect to its communicating with devices. For simplicity, we have excluded the column with the reference numbers, as it is the same as the Table 1.

Table 2. Smart City Platforms comparison—communication with devices (The symbol "**?**" declares an unknown platform state, while the symbols "■" and "**-**" declare an open or not platform respectively.).

Platform	ZigBee/Z-Wave	NB-IoT	LTE-M	Cellular	Bluetooth/BLE	Wi-Fi/Ethernet	LoRaWAN	Sigfox
PwC Smart City	■	■	-	■	■	■	■	-
UniSystems City4Life	-	■	-	■	■	■	■	-
Arcadis IBI Group Smart City Platform	■	■	-	■	■	■	■	-
thethings.io IoT Smart City Platform	-	■	■	■	-	■	■	■
Vodafone Smart Cities Platform	-	■	■	■	-	■	-	-
Nokia IMPACT IoT Platform	-	■	■	■	■	■	■	■
Huawei Smart City Solution Service	■	■	■	■	-	■	-	-
OpenMTC	■	■	■	■	■	■	■	-
FIWARE N-Smart	-	■	■	■	■	■	■	■
Invipo	-	-	-	■	-	■	-	-
ASTRI Smart City Platform	-	■	-	■	■	■	■	-
TIBCO Platform	-	-	-	■	■	■	-	-
Orchestra Cities by Martel Innovate	-	-	-	■	-	■	■	-
LG INFioT	■	■	■	■	■	■	-	-
ONEX Dimos	?	?	?	?	?	?	?	?
LTIMindtree Advanced Smart City Operating Platform	?	?	?	?	?	?	?	?

Table 2. *Cont.*

Platform	ZigBee/Z-Wave	NB-IoT	LTE-M	Cellular	Bluetooth/BLE	Wi-Fi/Ethernet	LoRaWAN	Sigfox
Lucy Zodion Ki. City Platform	-	-	-	-	■	-	■	-
Siemens Mindsphere	-	-	■	■	■	■	-	-
Bosch IoT Suite	■	■	■	■	■	■	■	■
ABB Ability	■	-	■	■	■	■	■	-
Schneider Electric EcoStruxure	-	-	■	■	■	■	■	-
Cumulocity IoT 10.17 by Software AG	■	-	■	■	■	■	■	■
EdgeX Platform	■	-	-	■	■	■	-	-
Kaa IoT Platform Enterprise Edition	■	-	-	■	■	■	■	-
Altair IoT Studio	-	-	-	■	-	■	■	-
PTC ThingWorx	-	■	■	■	■	■	■	-
Davra IIoT Platform	■	■	■	■	■	■	-	-
AWS IoT	-	-	-	■	-	■	■	■
Azure IoT Central	-	-	-	■	■	■	■	■
NoTraffic	?	?	?	?	?	?	?	?
Pycom Pybytes	-	-	■	-	■	■	■	■
ThingsBoard	-	-	-	■	■	■	-	-
Ubidots	-	■	■	■	-	■	■	■
IBM Watson IoT Platform	-	-	-	■	-	■	-	-
Oracle IoT	-	■	-	■	-	■	■	-
GE Predix	-	-	-	■	-	■	-	-
SAP IoT	■	-	-	■	-	■	-	-
Hitachi Lumada	-	-	-	■	-	■	-	-
Litmus Edge	-	-	-	■	-	■	-	-
Akenza	-	■	■	■	■	■	■	■
AVSystem Coiote IoT Device Management	-	■	■	■	-	■	■	-
Ayla IoT Platform	■	-	-	-	■	■	-	-
Simetric IoT platform	-	■	■	■	-	■	-	-
Actility ThingPark	-	■	■	■	-	■	■	-

Table 3 summarizes our findings regarding the most common protocols used by the platforms that were investigated. Again, we have excluded the column with the reference numbers, as it is the same as the Table 1.

Table 3. Smart City Platforms comparison—protocols support (The symbol "**?**" declares an unknown platform state, while the symbols "■" and "**-**" declare an open or not platform respectively.).

Platform	MQTT	REST API	AMQP	WebSockets	OPC UA	Modbus	HTTPS	XMPP	CoAP	LWM2M
PwC Smart City	■	■	■	■	■	-	-	-	-	-
UniSystems City4Life	■	■	■	■	-	-	-	-	-	-
Arcadis IBI Group Smart City Platform	■	■	■	■	-	-	-	-	-	-
thethings.io IoT Smart City Platform	■	■	-	-	-	-	■	-	■	-
Vodafone Smart Cities Platform	■	-	■	-	-	-	■	-	■	-
Nokia IMPACT IoT Platform	■	■	-	-	-	■	■	-	-	■
Huawei Smart City Solution Service	■	-	-	-	-	■	■	-	■	■
OpenMTC	■	-	-	-	-	-	■	■	■	-
FIWARE N-Smart	■	-	-	-	■	-	■	-	■	-
Invipo	■	■	-	-	-	-	■	-	-	-
ASTRI Smart City Platform	?	?	?	?	?	?	?	?	?	?
TIBCO Platform	■	■	■	■	-	-	■	-	-	-
Orchestra Cities by Martel Innovate	■	■	■	■	-	-	■	-	■	■
LG INFioT	■	■	-	■	-	■	■	-	■	-
ONEX Dimos	?	?	?	?	?	?	?	?	?	?
LTIMindtree Advanced Smart City Operating Platform	?	?	?	?	?	?	?	?	?	?
Lucy Zodion Ki. City Platform	?	?	?	?	?	?	?	?	?	?
Siemens Mindsphere	■	■	■	-	■	■	■	■	■	■
Bosch IoT Suite	■	■	■	■	■	■	■	-	■	■
ABB Ability	■	■	-	-	■	■	■	-	■	-
Schneider Electric EcoStruxure	■	-	-	-	■	■	-	-	-	-
Cumulocity IoT 10.17 by Software AG	■	■	-	-	■	■	■	-	■	■

Table 3. *Cont.*

Platform	MQTT	REST API	AMQP	WebSockets	OPC UA	Modbus	HTTPS	XMPP	CoAP	LWM2M
EdgeX Platform	■	■	-	-	■	■	■	-	■	-
Kaa IoT Platform Enterprise Edition	■	-	■	-	-	-	■	-	■	-
Altair IoT Studio	■	■	■	-	■	■	■	-	-	-
PTC ThingWorx	■	■	-	-	■	-	■	-	■	-
Davra IIoT Platform	■	■	■	-	■	■	■	■	■	-
AWS IoT	■	■	■	■	■	-	■	-	■	-
Azure IoT Central	■	■	■	-	■	■	■	-	■	-
NoTraffic	?	?	?	?	?	?	?	?	?	?
Pycom Pybytes	■	-	-	-	-	■	■	-	-	-
ThingsBoard	■	■	-	-	■	■	■	■	-	-
Ubidots	■	■	-	-	-	-	■	-	-	-
IBM Watson IoT Platform	■	■	-	-	-	-	■	-	-	-
Oracle IoT	■	■	-	-	■	■	■	-	■	-
GE Predix	■	■	-	-	■	■	■	-	-	-
SAP IoT	■	■	-	-	-	■	■	-	■	-
Hitachi Lumada	■	■	-	-	■	■	■	-	-	-
Litmus Edge	■	-	■	-	■	■	■	-	-	-
Akenza	■	■	-	■	-	-	■	-	■	-
AVSystem Coiote IoT Device Management	-	■	-	-	-	-	-	-	■	■
Ayla IoT Platform	-	■	-	-	-	-	■	-	-	-
Simetric IoT platform	-	■	-	-	-	-	■	-	-	-
Actility ThingPark	■	■	-	-	-	-	■	-	-	-

Finally, Table 4 summarizes our findings about the cyber security measures that are offered by each platform. The column with the reference numbers is excluded, as it is the same as the Table 1.

Table 4. Smart City Platforms comparison—cybersecurity (The symbol "**?**" declares an unknown platform state, while the symbols "■" and "**-**" declare an open or not platform respectively.).

Platform	Encryption	Access Control	Intrusion Detection	Patching/Security Updates
PwC Smart City	■	■	■	■
UniSystems City4Life	■	■	■	-
Arcadis IBI Group Smart City Platform	■	■	■	■
thethings.io IoT Smart City Platform	■	■	■	■

Table 4. *Cont.*

Platform	Encryption	Access Control	Intrusion Detection	Patching/Security Updates
Vodafone Smart Cities Platform	■	■	■	■
Nokia IMPACT IoT Platform	■	■	■	■
Huawei Smart City Solution Service	■	■	■	■
OpenMTC	■	■	-	-
FIWARE N-Smart	■	■	-	-
Invipo	■	■	-	■
ASTRI Smart City Platform	?	?	?	?
TIBCO Platform	■	■	-	-
Orchestra Cities by Martel Innovate	■	■	-	-
LG INFioT	■	■	■	■
ONEX Dimos	?	?	?	?
LTIMindtree Advanced Smart City Operating Platform	?	?	?	?
Lucy Zodion Ki. City Platform	?	?	?	?
Siemens Mindsphere	■	■	-	■
Bosch IoT Suite	■	■	-	■
ABB Ability	■	■	-	■
Schneider Electric EcoStruxure	■	■	■	■
Cumulocity IoT 10.17 by Software AG	■	■	-	■
EdgeX Platform	-	■	-	-
Kaa IoT Platform Enterprise Edition	■	■	-	■
Altair IoT Studio	■	■	-	■
PTC ThingWorx	■	■	-	■
Davra IIoT Platform	■	■	-	■
AWS IoT	■	■	■	■
Azure IoT Central	■	■	■	■
NoTraffic	■	■	-	■
Pycom Pybytes	■	■	-	■
ThingsBoard	■	■	-	-
Ubidots	■	■	-	■
IBM Watson IoT Platform	■	■	■	■
Oracle IoT	■	■	-	■
GE Predix	■	■	■	-

Table 4. *Cont.*

Platform	Encryption	Access Control	Intrusion Detection	Patching/Security Updates
SAP IoT	■	■	-	■
Hitachi Lumada	■	■	-	■
Litmus Edge	■	■	■	-
Akenza	■	■	■	-
AVSystem Coiote IoT Device Management	■	■	■	-
Ayla IoT Platform	■	■	■	-
Simetric IoT platform	■	■	■	-
Actility ThingPark	■	■	-	-

In Figure 3, the results from Table 1 are presented, outlined as “Capabilities and cost”. As we can see from the results of Table 1, 81.8% of the platforms that were presented in this survey offer data analytics capabilities to their users. As many as 61.4% of the platforms offer a hybrid hosting model, and 63.6% of the platforms offer their users the ability to manage their devices. Nearly half of them (54.5%) offer some kind of alert and notifications to their users, and less than a quarter of them (22.7%) have open-source features. It is worth mentioning, although it is not depicted in this figure, that only three platforms were free, with a percentage as low as 6.9%.

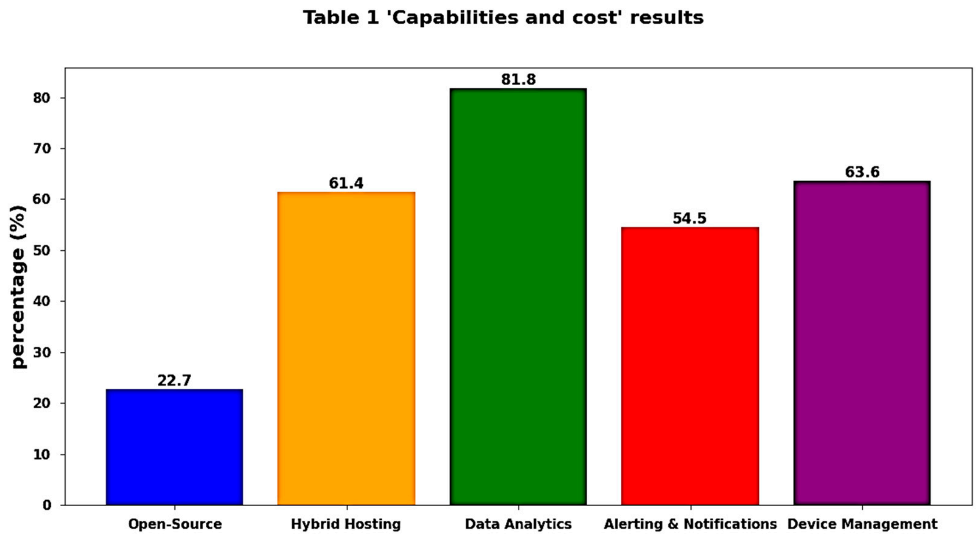

Figure 3. The results of Table 1, referring to capabilities and costs.

In Figure 4, we present the results of Table 2, referred to as “Communication with devices”. As can be seen in Table 2, Smart City Platforms comparison—Communication with devices, the Wi-Fi and Ethernet options undoubtedly stand out, with a strong percentage of support from the vendors (97.6%). At 92.7%, cellular networks are the runner-up, behind Wi-Fi/Ethernet, Bluetooth/Bluetooth Low Energy follows with 61%, and LoRaWAN comes next with 58.5%, being close to Bluetooth. LTE-M and NB-IoT are behind it, both with 48.8%, followed by ZigBee/Z-Wave at 31.7%. Less than one-fourth (24.4%) of the platforms offer communication with Sigfox devices.

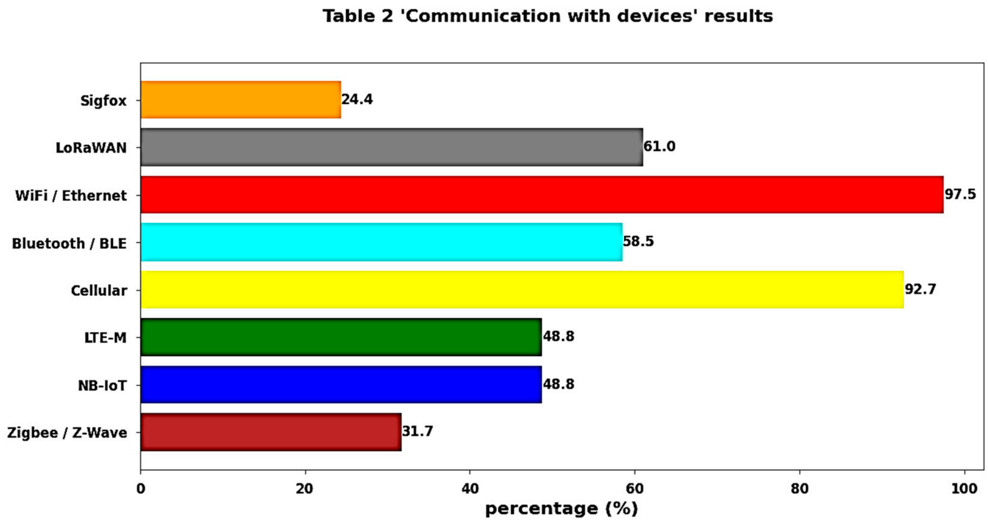

Figure 4. The results of Table 2, referring to adopted communication technologies.

In Figure 5, the results of Table 3 are presented, addressing "Protocols support". Here, the clear winner is MQTT, with a dominant percentage of 92.3% support from the vendors. Next, we see that HTTPS is supported by 87.2% of the platforms in this survey. Close to it, REST API, with 79.5%, comes third. To continue, CoAP, Modbus, OPC-UA, and AMQP are supported by 53.8%, 48.7%, 46.2%, and 35.9%, respectively. The list is concluded with the least-supported protocols: WebSockets, LWM2M, and XMPP, with 23.1%, 17.9%, and 10.3%, respectively.

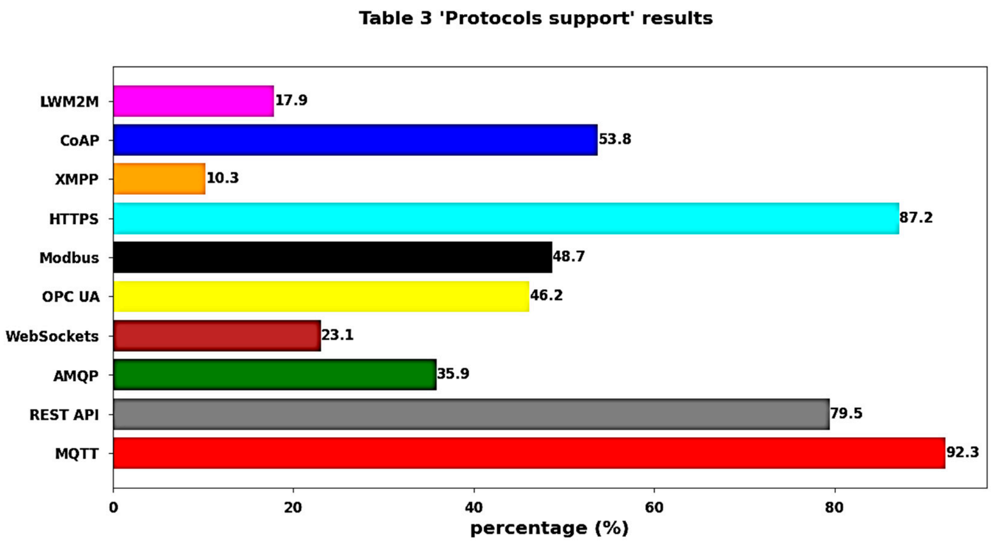

Figure 5. The results of Table 3, referring to supported protocols.

In Figure 6, we present the results of Table 4, "Cyber security". Here, we see that the majority of vendors offer both access control and data encryption options for security measures, with 100% and 97.5%, respectively. As many as 65% of the vendors offer regular patches and security updates to their customers, and only 45% of them offer network scanning for detecting intrusions.

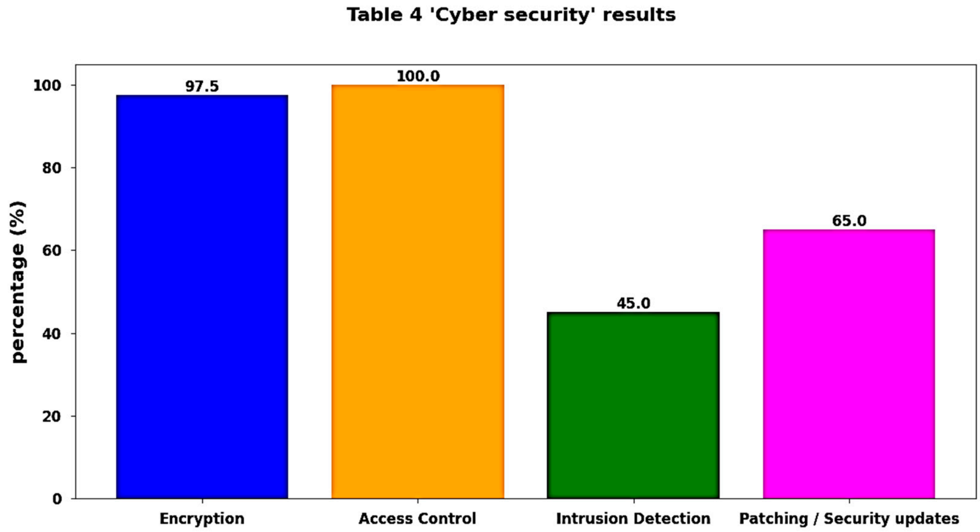

Figure 6. The results of Table 4, referring to cyber security measures.

As this survey proves, there are not many options available for municipalities when it comes to selecting a platform strictly for SCs. To tackle this, we decided to include IoT platforms from other areas of interest, like industry, agriculture, etc.

Furthermore, we noticed that—excluding the purely open-source platforms—there are no free options for IoT platforms available; although some of the platforms offer a free tier of their services, the scale of an SC is such that, in practice, it leads municipalities to choose the paid tier. This makes sense given the technologies, knowledge, and development required for a company to create an IoT platform.

To continue, another conclusion that can be derived from the results is that no paid IoT platform offers open-source elements, hybrid hosting, data analytics, alerting/notifications, and device management altogether. Only 12 out of the 44 investigated IoT platforms offer combinations of four of these characteristics.

Next, we notice that Wi0Fi/Ethernet communication and cellular networks are the de facto technologies that are used to enable communication between the devices and the cloud. LTE-M, NB-IoT, and LoRaWAN also have a great share. ZigBee/Z-Wave and Bluetooth/BLE seem to be found only in smart home platforms and applications. In an SC environment where the flow of data is constant, the use of Wi-Fi/Ethernet and cellular networks is the obvious choice since the need for low-power consumption is absent; vehicles have batteries, and the power grid is available for devices that are attached to buildings, to infrastructure, to street lights, etc.

Another useful conclusion is that the MQTT protocol is preferred. This makes sense as MQTT can be used over Wi-Fi/Ethernet and cellular networks, and it also enables device control, apart from publish/subscribe communication; so, it can be used both for controlling actuators and for reporting data generated from sensors. REST APIs over HTTPS are also preferred, which facilitates the integration of the platform with external tools, systems, and other platforms. After all, the use of REST APIs is widely employed in the era of microservices-based systems architecture for interacting with both containers and various databases, and for a system or platform to be scalable and expandable, it has to follow this architectural style.

Finally, it seems that all IoT platforms are investing more and more in cyber security aspects, with all of them requiring some kind of user authentication for their services. Data encryption further enhances the overall security of the system. More than half of the platforms offer regular security patches to their users, providing strong immunity against potential cyber-attacks.

5. Discussion

Although the interest in SC has increased greatly in the last 10 years, there are a few SC IoT platforms that can cover more than one use-case. As presented in Section 2, typical SC use-cases include traffic management, traffic monitoring, air quality monitoring, noise level monitoring, water quality monitoring, smart parking, street lighting control, public transport vehicles tracking, energy management, smart waste collection, and more.

Furthermore, none of these SC IoT platforms entirely cover the following characteristics: open-source features, hybrid hosting, data analytics, alerting and notifications, and device management; as a matter of fact, from Table 1, it can be derived that only 12 out of the 44 investigated platforms offer combinations of four out of five characteristics (open-source, hybrid hosting, data analytics, alerting and notifications, device management): Unisystem City4Life, thethings.iO IoT Smart City Platform, Nokia Impact IoT Platform, ABB Ability, Schneider Electric EcoStruxure, Cumulocity IoT by Software AG, Kaa IoT Platform Enterprise Edition, PTC ThingWorx, AWS IoT, Azure IoT Central, ThingsBoard, and Oracle IoT. Not a single one offers all five characteristics.

Of these 12 platforms, only 2 are purely concerned with SC use-cases: Unisystem City4Life and thethings.iO IoT Smart City Platform. City4Life supports the following SC use-cases: smart parking, remote control of intelligent street lighting, remote control of the public Wi-Fi network, collection and management of environmental data from sensors, use of video applications analytics, locating and monitoring the location of objects (e.g., bins) and vehicles (garbage trucks and waste management), smart traffic monitoring, public safety and protection, intelligent energy monitoring, intelligent management of citizen information systems, and monitoring of electric car chargers [51]; whereas thethings.iO IoT Smart City Platform supports the following SC use-cases: smart waste prevention, smart public services, smart lighting, and smart metering [53].

From the above, we can safely conclude that few IoT platforms designed purely for SC use-cases exist and that these few SC platforms neither support all the use-case scenarios of an SC nor offer all the desired characteristics presented in Table 1. City4Life does not offer an option for OTA updates for the devices that it is interacting with, whereas thethings.iO does not offer any open-source capabilities that would enable it to support more use-cases. Furthermore, from Table 2, we see that City4Life supports NB-IoT, cellular networks, Bluetooth/BLE, Wi-Fi/Ethernet, and LoRaWAN; whereas thethings.iO supports NB-IoT, LTE-M, cellular networks, Wi-Fi/Ethernet, LoRaWAN, and Sigfox. Regarding the communication protocols, from Table 3, we see that City4Life supports MQTT, REST APIs, AMQP, and WebSockets; whereas thethings.iO supports MQTT, REST APIs, HTTPS, and CoAP. Finally, from Table 4, we see that thethings.iO offers all the cyber security features, with City4Life only missing the patching/security updates. Therefore, it is obvious that although both platforms have similarities, they also have distinct characteristics, and ultimately, it is up to the end user to decide which one is appropriate to use.

Given the complex nature of every use-case in a SC, an SC IoT platform must be able to support as many wired and wireless communication technologies and protocols. MQTT over Wi-Fi, Ethernet, and cellular networks, as well as REST APIs, are used to facilitate the data exchange and convert every device to be interoperable. OPC UA and Modbus are preferred for controlling actuators. Although LTE-M is a technology that was designed to support more-frequent data transmissions up to 1 Mbps, and the WebSockets protocol is used in real-time applications where low latency and high throughput is required, both of them are not as supported by many SC IoT vendors as was expected.

Cyber security is an area that all vendors take seriously, and all of them provide some kind of user authentication and authorization for their services. Data encryption further enhances the overall security of the platforms. Frequent software patches ensure the longevity of the platform as they provide it with immunity against new threats.

This paper provides an overview of the state-of-the-art SC IoT platforms, highlighting their features and capabilities. This investigation encompasses diverse areas including device management, hosting, security, data collection protocols, analytics capabilities, and alerting support, enriching our understanding of SC IoT architecture and its constituent components and protocols. In order to achieve that, we investigated both open-source and proprietary IoT platforms and aggregated all the technologies and features that they offer. Then, we identified the most- and least-supported communication technologies and protocols, as well as the most common cyber security features of the platforms.

As a trending topic in both academia and industry, there are many IoT platforms available, and every year, new IoT platforms emerge from various organizations. Furthermore, there are occasions when an IoT platform cannot stand the test of time, and the organization decides to shut down its services, with the most notorious example being Google IoT Core, which was retired in 2023. Thus, this stands as a limitation of the study, namely, to be on par with every ongoing, retired, or freshly arrived IoT platform.

6. Conclusions

In this review paper, we investigated and compared 44 IoT platforms that could be used for developing SC solutions. Out of the 44 investigated platforms, only 12 offer combinations of four out of five important characteristics (open-source features, hybrid hosting, data analytics, alerting and notifications, and device management), and from these 12, only 2 are purely for SC use. Furthermore, there is a shortage of comprehensive SC IoT platforms that could support the majority of the functionalities and communication protocols. Ideally, such platforms would support various wired and wireless connections (e.g., Wi-Fi/Ethernet, cellular, LPWANs) and protocols (e.g., MQTT, HTTPS, AMQP, LWM2M) for data exchange and device interoperability. Additionally, control protocols like OPC UA and Modbus would be beneficial. While LTE-M and WebSockets offer advantages for frequent data and real-time applications, it seems that they have not been widely adopted by SC IoT vendors yet.

In envisioning the future of SCs, stakeholders must heed several key recommendations to ensure their success. First and foremost, prioritizing interoperability and standardization is paramount to facilitating the seamless integration of various technologies within urban infrastructure. As we proved, current SC IoT platforms lack total support for all communication technologies and protocols, and the vast majority of them do not offer open-source features that would enable them to support protocols and technologies not offered by their default portfolio. Collaboration between the public and private sectors is equally essential as it fosters collective efforts to tackle complex urban challenges effectively; this is easily understood by a large number of SC projects, as presented in the introduction, where we witness private companies working together with academia and municipalities to provide solutions to SC use-cases. Moreover, investing robust cyber security measures is imperative to safeguard sensitive data and critical infrastructure from potential threats. Embracing sustainable practices not only helps mitigate environmental impact but also enhances urban resilience in the face of future challenges. Furthermore, engaging citizens in decision-making processes is vital to ensure inclusivity and transparency in smart city initiatives. Lastly, stakeholders must commit to continuously evaluating and adapting strategies to align with evolving technology trends and the ever-changing needs of urban populations.

As previously stated, the realm of IoT platforms, emerging as a prominent subject of interest in both academic circles and the industrial domain, boasts a plethora of options. As time progresses, an increasing number of organizations are unveiling innovative IoT platforms, thereby enriching the technological landscape and providing a plethora of solutions to address ever-changing demands. This trend has become a focal point in both academic discourse and industry discussions, as the array of available IoT platforms continues to expand, with new offerings emerging annually from a diverse range of organizations. Such a dynamic environment poses a profound limitation to our study, underscoring the challenge of ensuring that we keep pace with the dynamic landscape of IoT platforms, which includes both established and emerging ones, as well as those that may have been phased out, as witnessed in the case of Google IoT Core, which was retired in 2023.

Expanding this, another limitation is the potentially significant updating of each platform, as some vendors push for major updates in their services; thus, the results from this survey could greatly differ in the future. Moreover, the results were derived from information that was found either on white papers from the websites of each platform or from posts in the social media accounts of the vendors; hence, they are not scientifically approved, an aspect potentially representing another limitation of the study. Finally, although in many cases, each vendor offers some real-life examples of solutions implemented using their platform, we were not able to validate the status of each solution, whether or not it is still functioning, the results of the implementation, and how it helped its users, topics that could be researched in the future.

Considering the potential for future research and study opportunities, the outlook seems to be quite promising, as there is an ever-increasing spread of SC solutions-based IoT platforms. As witnessed in Figure 1, the interest in Smart Cities is a substantial one, and given the works of [20,90,91], we see that there are now more IoT platforms than there were 7 years ago. As more IoT platforms continue to emerge in the following years, it will be necessary to conduct comparisons to assess the offerings provided by each of these platforms.

This work could be used as a basis for future researchers, to identify what platforms used to offer in 2023–2024, or to delve deeper into detailed comparisons regarding authentication and authorization mechanisms, cyber security measures during device provision and software updates, databases support, AI analytics support, etc. Furthermore, future researchers could propose their own multi-use-case open-source platform implementation covering all the characteristics of Table 1 and supporting the vast majority of the communication technologies from Table 2, the vast majority of the communication protocols from Table 3, and all the cyber security characteristics from Table 4.

We aim for our research to serve as a catalyst, encouraging fellow researchers to delve deeper into the utilization of IoT platforms regarding SC solutions on the whole.

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