Concept of an Adaptive IoT Platform for Smart Cities*

Ivan Tsiupa [1,*,†], Oleksandr Osolinskyi [1,†] Oleh Makara[1,†] Dmytro Diuh[1,†] and Andriy Semeshkin [1,†]

[1] *Department for Information Computer Systems and Control, West Ukrainian National University, Mykulynetska Street, 46A, Ternopil, 46000, Ukraine*

Abstract

The Internet of Things (IoT) and Smart Cities are evolving rapidly, attracting increasing interest from researchers, industry, businesses, and society as a whole. Fundamentally, IoT enables seamless connectivity between people and devices at any time and in any location, utilizing a variety of networks and services. The number of Internet-connected devices continues to grow at a rapid pace. IoT encompasses a diverse range of devices that offer versatile solutions for implementing Smart City projects. During the development and deployment of such projects, extensive networks of interconnected devices are employed. These devices are embedded in physical objects and linked to the Internet to support a wide range of communication tools and data exchange protocols. This level of integration forms a fundamental pillar of urban advancement, contributing to the improvement of living standards and fostering economic growth. Moreover, in a Smart City, millions of sensors are deployed in various domains such as smart transportation, smart parking, and others. These smart devices generate a continuously large volume of data to deliver services to citizens. Therefore, the efficient collection and processing of this data is a critical task for enabling effective decision-making and urban management. In other words, the data stream generated by these endpoints must be processed and delivered to the end user within an optimal time frame. In addition to handling the vast volume of data, these datasets exist in various formats and follow different semantic structures. Solving these issues with managing the heterogeneity of diverse IoT components is essential, as they can significantly hinder the efficient administration and functioning of smart city systems.

Keywords

Smart Cities, IoT, Data processing, exchange protocols, MQTT, RESTful

1. Introduction

Today, billions of smart devices equipped with sensors operate and transmit data over the Internet, collectively forming what is known as the Internet of Things (IoT). The IoT is a platform concept—a network of interconnected devices designed to enable seamless interaction between different objects.

RFID tags, mobile devices, smart electricity meters, robotic vacuum cleaners, intelligent refrigerators, and various environmental sensors are all part of the IoT ecosystem [1]. These devices are capable of interacting with one another and exchanging data at any time and from any location. The IoT represents a vast network of interconnected computing units, mechanical and digital machines, physical objects, and even individuals—each uniquely identifiable through a specific unique identifier (UID). These entities are capable of autonomously transmitting and receiving data over a network without the need for direct human-to-human or human-to-computer interaction [2].

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* Corresponding author.
† These authors contributed equally.
ivan.tsupa111@gmail.com (I. Tsiupa); oso@wunu.edu.ua (O. Osolinskyi); makarolehv@gmail.com (O. Makara); diuh.design@gmail.com (D. Diuh); a.semeshkin@wunu.edu.ua (A. Semeshkin);
0009-0008-5064-0256 (I. Tsiupa); 0000-0002-0136-395X (O. Osolinskyi); 0009-0000-3668-406X (O. Makara); 0009-0000-4249-6057 (D. Diuh); 0009-0003-0475-8599 (A. Semeshkin)

A wide range of physical objects can be embedded with sensors to collect data from the environment. This data can then be processed and analyzed through specialized data services. The resulting information serves as a foundation for the development of various smart infrastructures, including—but not limited to—smart grids, intelligent urban ecosystems, automated parking systems, and environmentally aware monitoring technologies [3].

Due to the rapid evolution and variability of IoT technologies, there is currently no universally accepted definition of IoT architecture. To simplify this complexity, a generalized three-layer architecture is commonly adopted. It consists of three primary layers: the perception layer, the network layer, and the application layer. Figure 1 illustrates the hierarchical structure of these distinct components [4].

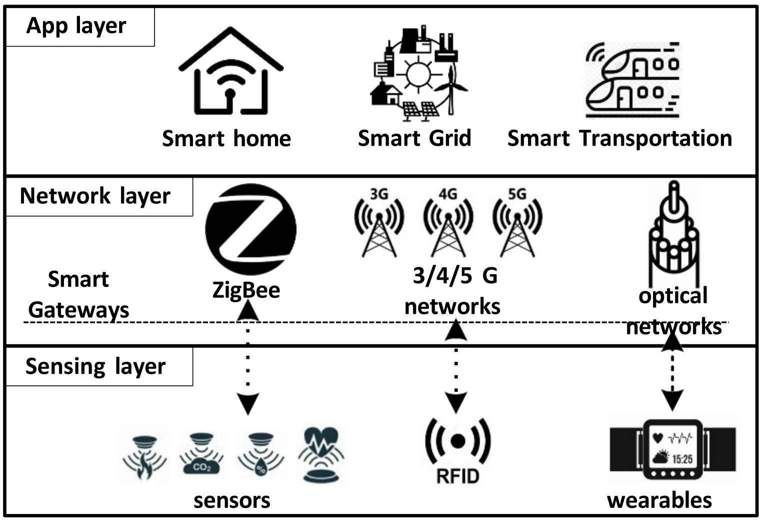

Figure 1: Three-level IoT architecture.

A brief description of each layer is provided below:

1. Sensing Layer responsible for detecting, identifying, collecting, and transmitting data through a network of interconnected devices connected to the Internet. It includes various components such as sensors, cameras, and other smart devices that capture and process environmental data. Moreover, this layer plays a crucial role in converting raw data into a structured digital format, enabling seamless data transmission across the network.

2. The main function of the Network Layer is to transfer data from the sensing layer to the application layer. It incorporates multiple communication technologies, such as Bluetooth and Zigbee, within the IoT ecosystem to efficiently route information from sensing devices to nearby gateways. Additionally, the network layer supports long-distance data transmission by utilizing advanced Internet technologies such as 4G and other high-speed communication protocols.

3. The Application Layer defines the interface of the overall IoT architecture and provides developers with tools to interact with the system. It is responsible for managing and presenting processed data to end-users and higher-level services.

In general, the first stage involves collecting data from the physical environment using sensors, which convert real-world signals into electrical data. In the second stage, the raw data is transmitted through intermediate nodes to cloud-based platforms or dedicated servers. In the final stage, the transmitted data is further processed using various technologies, including machine learning algorithms and artificial neural networks (ANNs), tailored to the specific needs of applications and end-users [6].

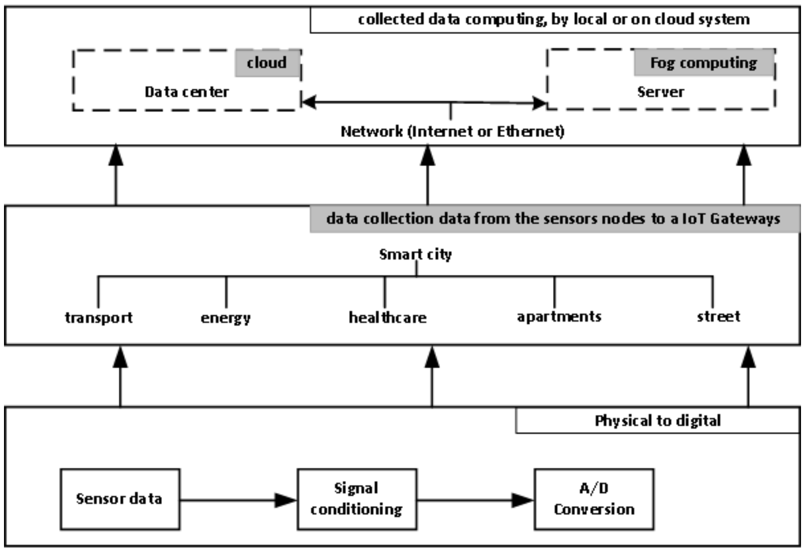

Figure 2: Stages of processing data from sensors.

1.1. Smart City

Effective communication and well-structured data management, supported by robust physical infrastructure, are fundamental pillars in the development of smart cities. Advanced computing technologies, a wide array of interconnected devices, and integrated servers collectively form the core operational components of a smart city [7]. The adoption of sensor technologies and the Internet of Things (IoT) has enabled the creation of intelligent environments, facilitating the efficient management of key urban sectors such as natural resources, transportation systems, healthcare services, governance frameworks, and energy distribution. Figure 3 offers a comprehensive overview of various applications within the smart city ecosystem [8].

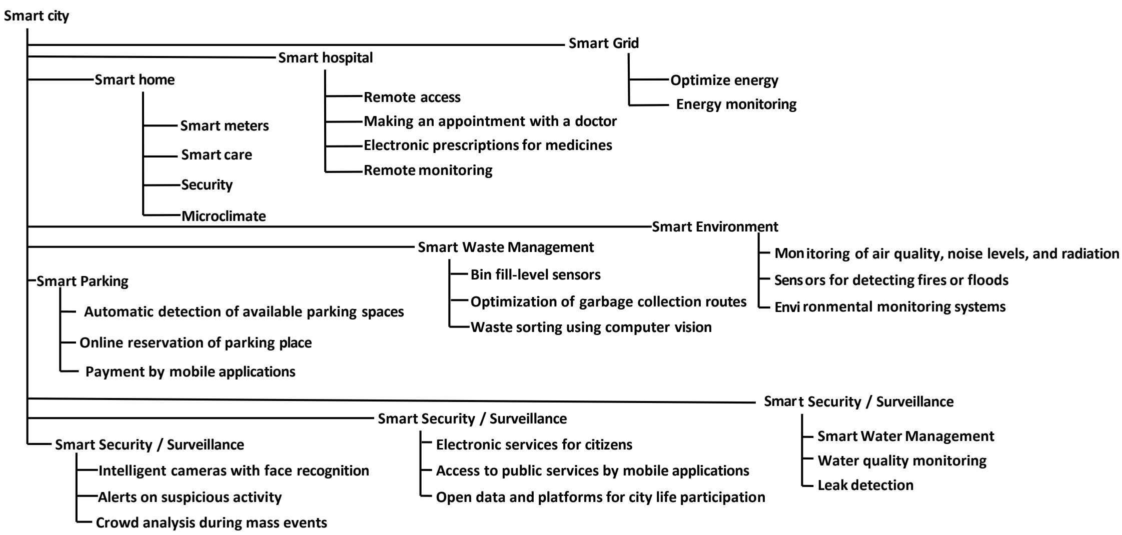

Figure 3: Smart city ecosystem.

Information about the city is continuously transmitted and collected from various sources, including smart buildings, intelligent transportation systems [9], agricultural infrastructures, smart power grids, smart businesses [10], security, and surveillance systems, among others. Most of this data is subsequently used to support urban decision-making processes through deep neural networks, systematic data analysis, and other advanced methods. In an advanced smart home environment, households are extensively digitized through the continuous monitoring of temperature levels, detection of smoke to identify potential fire hazards, tracking of daily energy consumption patterns, and analysis of water usage metrics. This data is actively utilized by the Smart City system to generate alerts and implement preventive actions in the event of emergency situations within the residence. Similarly, in intelligent transportation systems, optimized and highly efficient transport management plays a fundamental role within the broader infrastructure of a smart city.

The Internet of Things (IoT) acts as a vital communication bridge, enabling seamless interaction between various Smart City applications while also facilitating the generation of massive streams of data. These datasets are produced at exceptionally high velocities and exist in a wide variety of structural formats. Due to the inherently unstructured nature of the collected big data, it must be stored across multiple data centers using distributed database architectures. This approach ensures efficient processing, retrieval, and analysis of the information.

1.2. Data management issues

The primary issue concerning the collected data is the absence of a standardized or uniform data format, as well as the lack of a consistent standard for data exchange. For example, geolocation data—such as an address, building identification, region, or city—may be processed in different ways depending on the system. Similarly, two separate sensors monitoring the same parameter may use different units of measurement [11], leading to inconsistencies. Additionally, the collected data may be outdated and/or presented in aggregated statistical form, which can significantly hinder real-time functionalities and impair the development of decision support applications.

The second problem arises from the heterogeneity of network and sensor technologies. The growing number of interconnected objects in the physical world, collectively referred to as the Internet of Things (IoT) [12], has resulted in a highly diverse and complex ecosystem of devices. These devices, produced by different manufacturers and employing various communication protocols, require effective integration within a cohesive framework to ensure seamless interoperability.

The third fundamental issue is the lack of a standardized definition for indicators of measured physical quantities. For instance, gas concentration levels [13] may be assessed according to differing regulatory standards, while pollution levels may be interpreted using a variety of measurement frameworks, resulting in inconsistencies across different systems.

The absence of a unified Smart City platform capable of addressing these challenges has a significant impact on the design and implementation of modern smart city systems, ultimately limiting their efficiency, scalability, and interoperability.

1.3. Novelty and Contribution

Despite the widespread adoption of three-layer IoT architectures and commonly used protocols such as MQTT and REST, most existing smart city platforms lack adaptive capabilities, particularly in low-resource environments. This work presents an adaptive and lightweight IoT concept of the platform architecture that extends the classical model by incorporating fog computing and a unified identification mechanism for sensor integration.

The proposed concept introduces an enhanced three-layer architecture that integrates both fog and cloud computing layers with dynamic routing logic. Data flows are processed either locally on fog servers or remotely in the cloud, depending on current latency, data priority, and network conditions. This hybrid mechanism enables rapid local decision-making when necessary (e.g., in emergency detection), while also supporting large-scale data analysis in the cloud for long-term trend identification and planning.

Unlike rigid data pipelines used in other platforms, the proposed solution employs modular protocol adapters that can dynamically switch between REST and MQTT modes, ensuring flexibility and efficiency across varying deployment contexts.

2. Related works

The authors of [14] presented a "Smart Cities" application architecture for managing data collected via IoT devices, while the authors of [15] focused on analyzing various IoT device connection scenarios.

Works [16] and [17] introduce the development of IoT-related frameworks. In contrast, the research presented in [18] proposes management systems that utilize Big Data analytics technologies within the context of Smart Cities. In addition, the results in [19] describe a platform designed for the delivery of public services in Smart City environments. In [20], the authors presented service-oriented cyber-physical systems intended for mobile Smart City applications. The work in [21] introduces a system based on open IoT data sources.

Following the implementation of several Smart City projects, the researchers in [22] considered the fundamental issue of defining what constitutes a "Smart City." On one side, a Smart City represents a platform capable of efficiently executing key computational algorithms and supporting IT service infrastructures. On the other side, it provides for the systematic integration of a vast array of heterogeneous devices embedded throughout urban infrastructure and the city ecosystem as a whole.

Authors in work [23] researched novel types of sensor network systems. Depending on the sensor type, data can be collected on a variety of parameters, such as location, temperature, motion, orientation, vibration, humidity, acceleration, and changes in air composition. The collected data is then transmitted to the network layer for subsequent delivery to the information processing system [24].

For instance, the work [25] presents approaches for efficient data processing in IoT networks deployed in urban environments, and in [26] propose a dependable IoT architecture specifically designed for vehicle networks within smart transportation systems. In the work [27] conduct a detailed analysis of IoT device vulnerabilities using, emphasizing the growing need for secure smart city deployments. Additionally, in [28] explore sensing and data-driven control mechanisms applicable to smart buildings and smart city infrastructure.

These studies highlight various technological challenges and opportunities related to IoT deployments in urban settings. However, none of them offer a lightweight, fog-integrated, and modular IoT platform architecture with on-device adaptability and unified sensor identification as proposed in this work.

In addition to academic research, several IoT platforms have been developed and adopted for Smart City applications, including FIWARE, AWS IoT Core, and Azure IoT Hub.

FIWARE [29] is an open-source platform that offers standardized APIs and data models via its Context Broker and NGSI interfaces. It enables interoperability among different services but does not natively support fog computing or on-device analytics.

AWS IoT [30] and Azure IoT [31] are cloud-centric solutions with powerful analytics and monitoring tools. However, both platforms require a reliable cloud connection, which limits their applicability in mobile or low-connectivity scenarios. Additionally, implementing custom models or edge-based logic within these platforms is often complex and proprietary in nature.

Other important areas of advancement include mobile applications for Smart Cities, environmental monitoring sensors, and smart home automation systems.

2.1. Data acquisition in the IoT ecosystem

A fundamental problem within an Internet of Things (IoT) system lies in the huge volume of data generated by numerous sensors deployed across various environments. Transmitting and storing such large quantities of data presents significant difficulties, primarily due to the heavy demands placed on network bandwidth and storage capacity.

Over the past decade, numerous data acquisition methodologies have been developed with the aim of optimizing energy efficiency and improving the effectiveness of data collection in the context of IoT and smart city applications [32]. Figure 4 presents several distinct strategies employed for data gathering in IoT-based infrastructures.

Table 1
Comparison of the Proposed Concept with Existing IoT Smart City Platforms

Feature / Platform	FIWARE	Azure IoT	Proposed Platform
Protocol Support	REST, MQTT	AMQP, MQTT	REST, MQTT
Fog Computing	Limited	Yes	Full Support
Adaptive Offloading	No	Partial	Dynamic
Lightweight ANN Processing	No	No	Yes (in Fog Node)
Identifier Harmonization	No	No	Yes
Use in Low-Power Networks	Partial	No	Optimized
Open Source	Yes	No	Yes
Validated in Real Deployment	Limited	Yes (cloud)	Yes (edge + fog)

2.1.1. Tree-like mechanism

Within a tree-structured mechanism, all nodes are systematically organized in a hierarchical configuration, where data aggregation occurs at intermediate nodes. The aggregated data is transmitted into the root node to the next processing.

Another obstacle added with this approach is the establishment of an efficient and reliable system for data collection. Proposed solutions typically involve constructing a primary hierarchical tree across the IoT infrastructure and retrieving the required information through this structured framework [33].

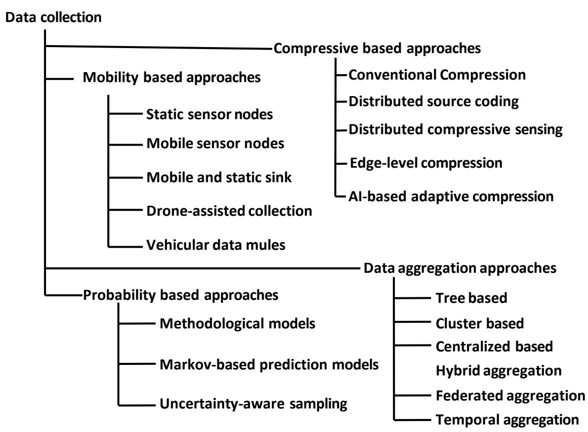

Figure 4: Approaches to data aggregation.

2.1.2. Cluster mechanism

In this approach, the network is divided into multiple clusters or groups, with each cluster consisting of a set of sensor nodes. Within each cluster, one node is designated as the cluster head, which plays a key role in managing communication and coordination among the nodes. The main responsibility of the cluster head is to aggregate and process the information collected from the individual sensor nodes in its cluster [34, 35].

According to the work [36], data reliability is ensured through the implementation of fault-tolerant protocols. Most of the existing research in this domain highlights the importance of employing a stable cluster head architecture, as it is crucial for maintaining the robustness and efficiency of data transmission throughout the network

2.1.3. Centralized mechanism

In this approach, each node transmits its data to the master node by following the shortest available path. All sensor nodes send their collected information to the most computationally powerful node in the network. The primary function of this central node is to aggregate the received data and consolidate it into a single unified packet for subsequent transmission.

2.1.4. Traditional compression

Conventional compression techniques require direct data transmission between sensors to reduce correlation during the information collection process [37]. This approach ensures that each sensor is capable of performing complex computations, while the overall efficiency of data compression is largely influenced by the specific routing strategies employed.

2.1.5. Mobile monitoring nodes with a fixed collection unit

One of the distinguishing features of this architecture is the inclusion of mobile sensor nodes. In recent years, this approach has attracted significant attention and has been actively investigated in many research works [38]. Owing to the mobility of these nodes, the architectural framework enables a substantial reduction in the total number of sensor nodes required for deployment, thereby optimizing resource utilization and enhancing overall system efficiency.

2.1.6. Data exchange format

The structure of data transmitted between devices via communication protocols needs to be standardized. Due to the limited computational and energy resources of IoT devices, the use of complex or expanded data formats is constrained for certain applications. Data is typically represented using formats such as JavaScript Object Notation (JSON) or eXtensible Markup Language (XML). However, differences in units of measurement, sampling rates, or numerical systems—especially when multiple platforms are involved—can lead to misinterpretation of the transmitted data.

3. The general architecture of the concept for Smart Cities using IoT

An interoperable platform must define clear architectural and platform-specific characteristics. As previously discussed, the most effective approach involves employing a three- layer architecture consisting of the things layer, an intermediate processing layer, and an integrated application layer.

The things layer includes a wide range of IoT devices that communicate using various network protocols and technologies. The intermediate layer acts as middleware or a gateway, facilitating interaction with IoT devices and enabling local data processing. This layer is typically implemented using multi-agent systems, service-oriented architectures, RESTful APIs, or publish-subscribe communication models.

The application layer is responsible for storing large volumes of data and ensuring its accessibility for advanced analysis and decision-making processes.

Previous studies [40, 41, 42] have proposed architectures that follow this structured three- tier model. At the foundational level, these works explore IoT devices equipped with sensors or network components responsible for managing sensor infrastructures. These devices connect to the platform through various access networks, such as Wi-Fi, Bluetooth, or LTE. They continuously collect, process, and transmit data, making it readily available for a wide range of applications, including large-scale data analytics and processing.

Figure 5 shows a three-level architecture that includes both fog-based and gateway-based approaches.

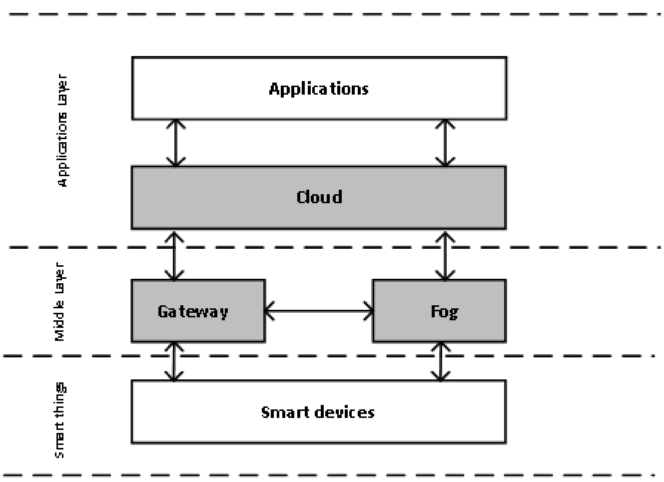

Figure 5: General architecture of the concept

According to [43], the system is also divided into fog and cloud computing layers, both of which are responsible for system offloading and data flow distribution.

In the architecture can use IEEE 802.11, IEEE 802.15.1, IEEE 802.15.6, and 3G/4G standards to ensure reliable communication between layers.

Similar to the approach described in [44], each component of the system—including the IoT Gateway, Fog Server, and Cloud Server (Figure 6)—is equipped with a set of adapters designed to support both MQTT and REST protocols over HTTP.

Each adapter instance is capable of functioning as an intermediary, enabling seamless communication with its corresponding component in another layer or entity.

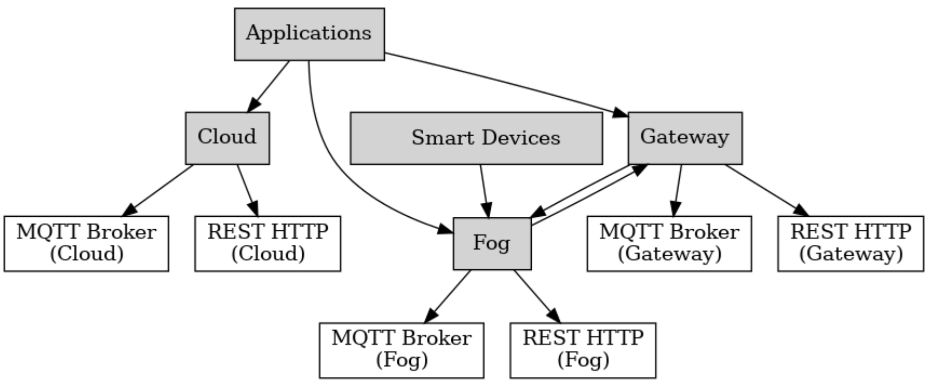

Figure 6: Organization of data transmission protocols.

Each IoT sensor is assigned a unique identifier, which serves as a key element for data aggregation by linking the identifier to both the specific type of sensor and the category of data being monitored. Data messages are transmitted through adapters, which serve as the payload within the designated application protocol. Once this transmission process is complete, applications can receive and process the data accordingly.

3.1. Description concept of the platform

On figure 7 shows the main components of the platform, which include applications, a cloud server, an IoT gateway or fog server, and IoT devices. At the top level, the applications are responsible for processing environmental data, performing intelligent analysis, applying various big data techniques, implementing machine learning models, and monitoring information to support decision-making for the efficient operation of a smart city.

The cloud server acts as a central element of the platform, providing core functionalities for data storage and processing. It ensures that applications have timely access to the required data. The information stored in the cloud is supplied by the IoT gateway and the fog server, which play a crucial role in preprocessing the data and serve as intermediaries for transmitting information between IoT devices and the cloud infrastructure.

Smart devices continuously monitor environmental parameters and transmit the collected data to either the gateway or the fog server for further analysis and processing.

All components of the system are designed to collect and analyze data related to safety, energy consumption, equipment malfunctions, and other relevant parameters.

3.1.1. Applications

Applications primarily function as software or hardware clients that interact with the platform and are capable of performing data mining operations or real-time monitoring. They achieve this by retrieving data from both cloud and fog servers through specific requests, enabling efficient data processing and analysis. Machine learning algorithms can be applied to generate estimates or forecasts of the metrics of interest.

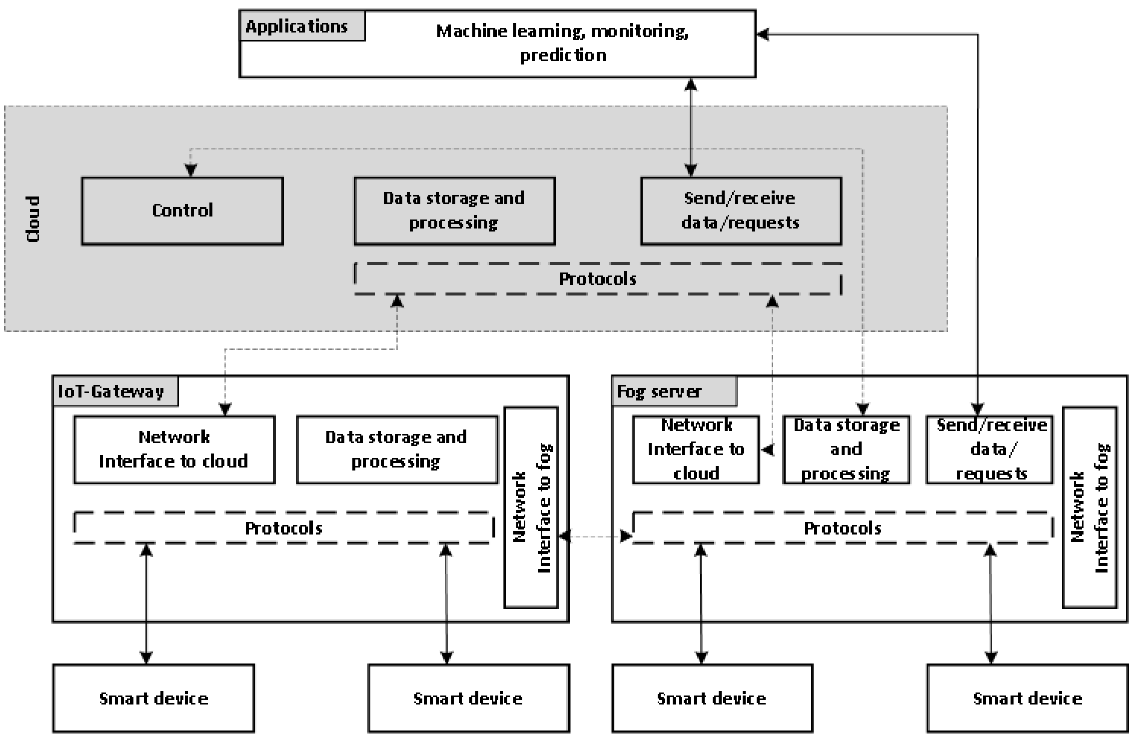

Figure 7: The main platform components.

In the initial scenario, the application subscribes to one or more branches of the MQTT broker that are of specific interest. This broker may be located on either a fog server or a cloud server, depending on the scale of the overall system. Each time new data related to specific indicators is published, the artificial neural network (ANN) is retrained to update its model. Subsequently, the user or another system can utilize the updated model to generate inferences and predictions. In an alternative use case, users can apply data mining techniques to extract relevant information from cloud or fog servers using RESTful services. The retrieved data can then be used to trigger actions on actuators or other control mechanisms. For example, if a high temperature is detected, the system can automatically activate fire protection mechanisms to mitigate potential hazards.

3.1.2. Cloud server

The cloud server integrates various system components. Its main functions include data analysis, as well as the storage and forwarding of data between gateways, fog servers, and applications.

3.1.3. Gateway for the Internet of Things

The gateway offers a visual interface for managing its parameters and facilitates data forwarding between IoT devices. Given that the gateway has limited computing power, most of its storage mechanisms are implemented using a local cache. This approach not only supports efficient data processing but also enables data integrity verification, thereby ensuring reliability and efficiency in the system's operation.

3.1.4. Fog server

In a fog server, data storage, processing, services, and protocols perform the same functions as those of a cloud server. However, the key difference is that the data processed by a fog server typically pertains to a specific local entity, such as a single building or household, rather than the entire city.

4. Experiments and evaluation

To evaluate the performance of the platform, an experiment was conducted to monitor environmental conditions. For this purpose, between five and twenty smart devices based on ESP32 microcontrollers were used, each equipped with sensors for measuring dust, gas, temperature, humidity, and noise. These devices were connected to a Wi-Fi network via a standard router, which was in turn connected via Ethernet cable to a fog server. A 4G mobile Internet connection was used for communication with the cloud.

The fog server was implemented using a Raspberry Pi 4 running an MQTT broker and a REST API web server. The cloud component of the system was emulated in a virtual environment like a real remote server. The sensors transmitted data at regular intervals of a few seconds, and both transmission protocols — MQTT and REST — were tested in parallel.

During the experiment, various parameters were monitored, including data transmission speed, system stability, data loss rate, CPU and memory usage on the fog server, and the convenience of data processing at different levels of the system architecture. The impact of increasing the number of devices on system efficiency was also analyzed. For instance, with five devices, the system operated stably and without noticeable delays. However, as five more devices were added, and later ten additional ones, a slight increase in latency and a noticeable rise in CPU load on the fog server were observed. Nevertheless, even with twenty devices, the system remained fully operational, and data loss remained minimal. When comparing the two communication protocols, it became evident that MQTT performed faster and consumed less Internet bandwidth, making it more suitable for applications that require frequent transmission of small messages. REST, on the other hand, imposed a greater load on the system but proved to be better suited for more complex operations or request-response interactions.

Overall, the experimental results demonstrated that the proposed approach is suitable for real-time data processing, offers a fast response time, and does not rely on a continuous cloud connection. The fog server handles on-site processing, which effectively reduces latency. The platform is flexible and can be applied to a variety of smart city scenarios. In the future, planned to test its performance in other domains, particularly in traffic management and energy consumption monitoring.

Figure 8 shows the network topology structure, where smart devices connect through a Wi- Fi access point integrated into a router. This router is directly connected to the fog server via an Ethernet cable, providing a stable wired connection. The communication between the IoT gateway and the fog server takes place over a local Wi-Fi network, enabling efficient data exchange. Additionally, a 4G network was used to ensure remote communication between the IoT gateway and the cloud infrastructure.

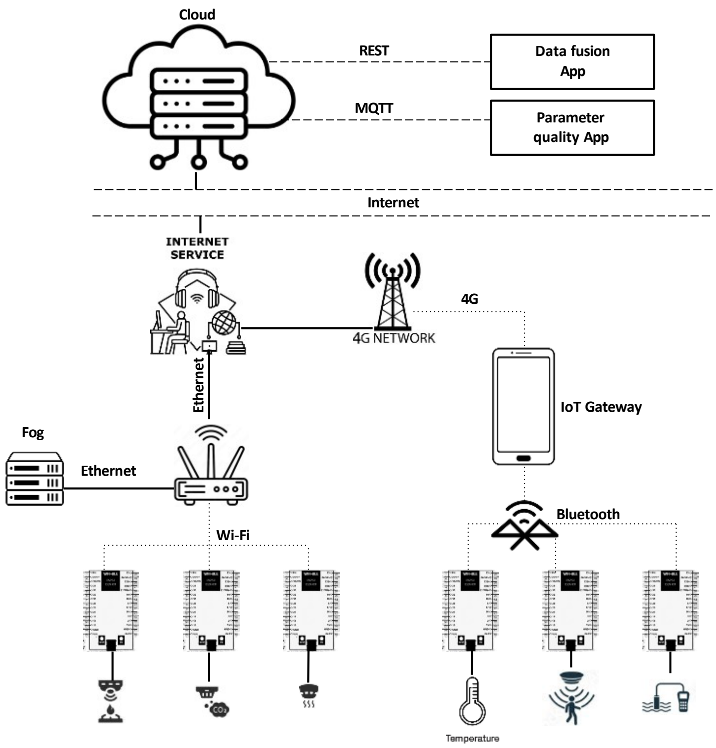

Figure 8: Experimental network topology.

Table 1 presents the maximum and average latency values recorded for each individual adapter. The REST and MQTT protocol showed a useful speed of about 500ms.

Table 2
The highest and mean latencies recorded for each adapter and communication protocol

Smart device	MQTT	REST
Max	700 ms	800 ms
Average	510 ms	525 ms

Conclusions

This work presents the concept of the platform based on the Internet of Things for Smart Cities, which implements a three-tier IoT architecture. The platform enables the collection, storage, and processing of data generated within urban environments or specific areas and objects, such as streets or buildings.

The system uses fog computing for localized data processing to ensure efficient real-time operation, while also using cloud-based services and dynamically allocated resources at the city-wide level to support large-scale data management and analysis.

In this concept proposes several key features:

1. Integration of heterogeneous sensors through smart devices;
2. Dual using of both fog and cloud interfaces, enhancing the platform's flexibility and allowing it to be adapted to various tasks involving data collection, analysis, and object management;
3. Support for deploying and running big data analytics and machine learning applications in the cloud, enabling comprehensive analysis of environmental conditions;
4. Standardized communication protocols for client applications, using REST and MQTT for endpoint interaction.

Declaration on Generative AI

The authors used GPT-4 and DeepL to prepare this paper: Grammar, Spelling, and Match Checker. After using AI instruments, the authors reviewed and deeply edited the content and are solely responsible for that content.

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