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THE ROLE OF INTERNET OF THINGS AND FOG COMPUTING IN SMART CITIES

Houda ERREGUI [1], Achraf EL AOUAQI [2], Hicham ABERBACH [2] and Abdelouahed SABRI [2]

[1] Department of Learning, Cognition, and Educational Technology, University of Education Sciences, Rabat, Morocco
[2] LISAC, Faculty of Science Dhar-Mahraz, University of Sidi Mohamed Ben Abdellah, Fez, Morocco

ABSTRACT

Smart cities represent the next evolution of urban centers, integrating advanced technologies to create better living environments. These cities will feature billions of connected devices, such as sensors and actuators, generating vast amounts of data. This data typically flows to cloud servers for processing. However, traditional Big Data analytics and cloud computing have proven inefficient in some scenarios, as not all data is pertinent enough for cloud-level processing. Transmitting all data from IoT and edge devices to the cloud consumes excessive storage and network resources. Fog computing emerges as a solution by decentralizing some data processing, analytics, and storage to the network's edge, closer to the data source. This approach alleviates the load on central servers and reduces latency, ensuring timely responses. Fog computing leverages edge computing to handle immediate data processing needs, making the overall system more efficient. This paper will cover the fundamental concepts of smart cities, IoT, and fog computing. It will present the important technologies and architectural frameworks that underpin these systems. Furthermore, several case studies will illustrate the practical applications and benefits of integrating fog computing with cloud computing and IoT in smart cities. These examples will demonstrate how such integrations lead to more efficient, responsive, and sustainable urban environments.

KEYWORDS

internet of things, fog computing, smart cities, edge computing, future technologies.

1. INTRODUCTION

In the last 20 years, we have witnessed the rise of new technologies and, more importantly, their implementations in our daily lives. It is easy to see how they shape our ways of living, from the way we order a taxi, buy products, and consume information to even affecting how we interact with other people. These forces of change are everywhere, not only in the devices that we hold dearly in our hands. They are in our vehicles, urban infrastructure, the healthcare that we receive, the monitoring systems that surround us, and many more areas. These and more are the reasons why smart cities are the natural result of the integration of IoT, municipal needs, innovative technologies, and powerful networking.

Innovative technologies are required now more than ever. The internet is expanding rapidly. Some predictions state that more than 16 billion devices will be connected by 2023 [1], while others estimate as many as 43 billion devices by the same date [2]. It is worth noting that these estimates do not account for the rapid development of new technologies that may occur. The sheer number of devices and the impact their deployment will have on our environment must be

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considered. ITSG, an international dynamic forward-thinking company, positions IoT as a disruptive technology across all industries and areas of society in the coming years [2].

This exponential growth in connective nodes is fueled by the proliferation of mobile devices, smart sensors serving a multitude of industries, and wireless sensor and actuator networks. New ideas and technologies are required to manage this growing ecosystem of Internet of Things (IoT) devices [3]. Until now, the cloud-based solution was the most feasible alternative adopted, but it has become well known that there are many performances, security, privacy, bandwidth, and consistency concerns that make solely cloud-based solutions inefficient for many use cases [4].

Referring to the technologies that urban nodes utilize, there is an ongoing trend of shifting from distributed computing resources for processing, network management, and storage to cloud-based centralized control for management purposes. Big data analytics and cloud services are driving this shift. However, despite efforts to efficiently integrate these technologies, cloud-based computing still faces major issues related to the scalability required for urban nodes with millions of inhabitants and billions of devices. If we define a node as a point of intersection with the network that can capture, receive, transmit, or act upon information, we begin to appreciate the problems that an overload of informational flux can create.

Below, in the first section, IoT definitions and technologies are presented, including an overview of the architecture and key components of the technology. The following section introduces smart cities, discussing common structures, practical applications of the paradigm, and case studies. The third section introduces fog computing, covering fundamental ideas and key differences from cloud-based solutions. This section concludes with an overview of how a smart city based on cloud computing and the Internet of Things, supported by fog computing techniques, could operate more efficiently than solely cloud-based solutions.

2. INTERNET OF THINGS

It is imperative for the purposes of this text to understand the fundamentals of IoT. IoT is a non-homogeneous, dynamic technology with borders that fade into other integrations. This brings a multitude of benefits while simultaneously posing a significant challenge due to its extensive reach and the need to address various real-world issues. This technology advocates for the integration of numerous devices, nodes, objects, and "things," utilizing the internet as the principal channel for communication between people and these devices. Despite the passage of many years since the conception of IoT technologies, multiple definitions can be found in reference materials. The European Commission provides a broad yet simple definition: "The Internet of Things allows people and things to be connected Anytime, Anyplace, with Anything and Anyone, ideally using Any path/network and Any service" [5]. Upon closer examination, we can observe the openness and flexibility inherent in this statement, as well as how the first part of the definition emphasizes connectivity availability and reliability, while the second part addresses the "how" aspect of connectivity. A more forward-looking definition is offered by Atzori et al. through their review of the CASAGRAS consortium report. They propose a "vision of IoT as a global infrastructure which connects both virtual and physical generic objects and highlights the importance of incorporating existing and evolving Internet and network developments into this vision [6]."

Referring to IoT without acknowledging its core technology is a mistake. The cloud is not merely the backbone of the IoT infrastructure; it is its essential enabling asset. According to the National Institute of Standards and Technology (NIST), cloud computing is defined as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" [7].

To provide further explanation, the basic simplified workflow of IoT can be outlined as follows:

- The object, or thing, senses, identifies, and communicates specific information.
- If necessary, an action is triggered after the data analysis is completed.
- The smart device provides status updates through services and feedback.
- The smart device offers comprehensive services and incorporates a mechanism to provide feedback to the administrative system, enabling it to understand the current status and outcomes of actions.

Based on the previous definitions, it is possible to extrapolate the notion that IoT is not merely a network architecture or technology; it is an ecosystem built around cloud-based computing, aiming to integrate as many devices as possible into its network to enhance their utility.

In the following section, a description of components by functional blocks will be provided, along with hardware technologies, communication protocols, and architecture that enable the deployment of IoT and cloud.

2.1. Fuctional Blocks of IoT

Given below [8] is the classification of IoT into blocks categorized by functionality.

2.1.1. Device

Is the foundation of the IoT paradigm. They provide actuation, sensing, control, and monitoring activities while being interconnected with other devices and sending data to the cloud-based servers or another back-end application.

2.1.2. Communication

Handles the communication between multiple nodes and the network server. It typically operates in the data, network, transport, and application layers.

2.1.3. Services

Provides functionalities for controlling services, modeling and discovering devices, as well as analytics and data publishing.

2.1.4. Management

This is the control and configuration interface of the IoT system.

2.1.5. Security

Provides a set of services that enable a secure system with features such as data authentication, authorization credentials, privacy policies, message integrity, content integrity, and data protection.

2.1.6. Application

This block is the front-end interface for the user, providing services and modules with monitoring capabilities, diagnosis, analytics, among others.

2.2. Hardware of IoT

These are the end devices that interact with and capture data from the physical world to be later sent to the cloud for storage or further processing. Below, three main classifications of the devices will be presented based on processing capabilities and deployment functionalities.

2.2.1. System On Chip (SOC)

Devices that have one or more Microcontroller Units (MCUs) are known as SoCs (System-on-Chip). The MCU can be 8, 16, or 32 bits. Generally, they also have General Purpose Inputs/Outputs (GPIO) and are programmed using a toolchain that writes directly into the MCU's SDRAM.

2.2.2. Single Board Computer (SBC)

An SBC is a computer in a small form factor. It typically consists of a circuit board with one or more microprocessors, I/O ports, memory, connectivity ports, and other components associated with a computer. Generally, these computers do not require any external devices or peripherals, besides a power source, to fulfill their functions.

2.2.3. Industrial Microcontroller (PLC and RTU)

Designed for industrial environments, Programmable Logic Controllers (PLCs) and Remote Terminal Units (RTUs) are the most utilized microcontroller-embedded devices, primarily due to their sturdiness and reliability for critical operations. The PLC resembles a microcontroller with enhanced capabilities, while the RTU is used for interfacing physical objects with distributed control systems. The main difference lies not in the functionalities but in the usage: RTUs are deployed for geographic telemetry, whereas PLCs are used in industrial floors or control areas.

2.3. Communication Technologies

To achieve the long-dreamed term of ubiquitous computing, where computational and communication capabilities are integrated into everyday objects [9], it is necessary for communication to be standardized, regulated, and innovated in order to deploy reliable networks on a massive scale with heterogeneous, interoperable, and context-aware capabilities. Below are presented some of the main communication technologies that are helping us achieve this goal:

2.3.1. RFID

Radio-Frequency IDentification (RFID) was one of the main forces behind the initial spread of IoT. The primary reason for this was the possibilities that this technology offered. By enabling us to write data onto small and lightweight tags, which could then be applied to a wide variety of objects or living beings, RFID opened up an immense array of applications. This capability is facilitated by storing and wirelessly sending and receiving packets of data to a uniquely identified tag that can be read by a specialized device. In its most basic configuration, these tags can be active or passive [10], and they find use across a broad spectrum of domains, from the logistics field to the healthcare industry.

2.3.2. NFC

Based on the ISO/IEC 18092 and ISO/IEC 14443 standards, Near Field Communication (NFC) is a wireless technology for short-range communication and, as a subset within the family of RFID, one of its main applications is found in face-to-face payment transactions.

2.3.3. Bluetooth

Based on the IEEE 802.15.1 standard, Bluetooth is a low-power and cost-effective wireless communication technology suitable for data transmission between devices over a range of 8-10 meters. Defined as a personal area network (PAN) communication and operating in the 2.4 GHz band, the data rates of the various versions range from 1 Mbps to 24 Mbps.

2.3.4. Wi-Fi

Under the IEEE 802.11 standard, it is possible to find the Wireless Local Area Network (WLAN) communication standards. These are specified as follows: 802.11a operates in the 5 GHz band, 802.11b and 802.11g operate in the 2.4 GHz band, 802.11n operates in both 2.4 GHz and 5 GHz bands, 802.11ac operates in the 5 GHz band, and 802.11ad operates in the 60 GHz band. Wi-Fi provides data rates ranging from 1 Mbps to 6.75 Gbps and a range from 20 meters to 100 meters, making it a highly capable standard for small networks.

2.3.5. WiMAX

Within the IEEE 802.16 standard, the collection of standards governing WiMAX (Worldwide Interoperability for Microwave Access) is specified. Providing data rates from 1.5 Mbps to 1 Gbps, the primary concern of this technology is establishing long-range, reliable connections.

2.3.6. ZigBee

Under the IEEE 802.15.4 standard, ZigBee is a short-range technology known for its low complexity, low power consumption, low cost, and duplex wireless communication [11]. It is primarily intended for low-data-rate communication between nodes in a network over short distances. With a data rate of 250 kbps, lower than Bluetooth, ZigBee is suitable for applications with low data traffic that require a large number of nodes.

2.3.7. LoRaWAN

Recently developed for long-range communications and designed by the LoRa Alliance, LoRa supports data speeds ranging from 0.3 kbps to 50 kbps. It operates in the 868 MHz and 900 MHz ISM bands and can establish communication with connected nodes within a range of 20 miles in unobstructed environments. The battery life of an attached node can last up to 10 years.

2.3.8. 4G LTE and 5G

IoT devices based on these standards can communicate over cellular networks. With data rates up to 100 Mbps, 4G is the evolution from the 3G and 2G standards. This protocol provides services such as Multimedia Messaging Service (MMS), Digital Video Broadcasting (DVB), and High-Definition TV content, as well as mobile TV [12].

In respect with 5G, the protocol has been operational since 2020, capable of providing speeds of 1 Gbps with several improvements over 4G, including higher capacity, reduced end-to-end latency, massive device connectivity, reduced costs, and consistent Quality of Experience [13]. Figure 1 in reference [13] illustrates some of the discussed technologies.

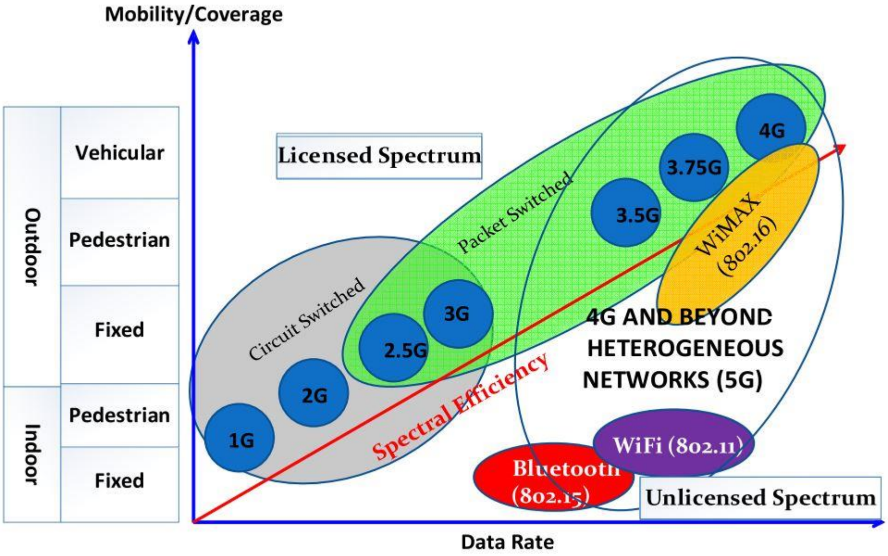

Figure 1. Graph presenting the reach of several communication protocols

2.4. Architecture

The overall architecture found in reference material is the three-level model for IoT composed of:

- Perception layer
- Network layer
- Application layer

For the purposes of this paper, the Cisco IoT architecture will be used as the reference model. The main reason behind this selection, among the several established by other industries and researchers [14], is the inclusion of a fog-edge layer upon which the rest of the paper will rely. Below, in [1, fig. 2], is the IoT reference model and its levels. It is worth mentioning that in a control pattern, information flows from the top of the model (level 7) to the bottom (level 1). The reverse is true for a monitoring pattern.

These days, many IoT solutions are extremely slow [15], and analyzing the big data sets will only become more difficult. Basing architecture solely on a cloud-based scheme for analysis will bring significant challenges in the years to come due to excessive data processing. This could be avoided with the efficient implementation of the previous model.

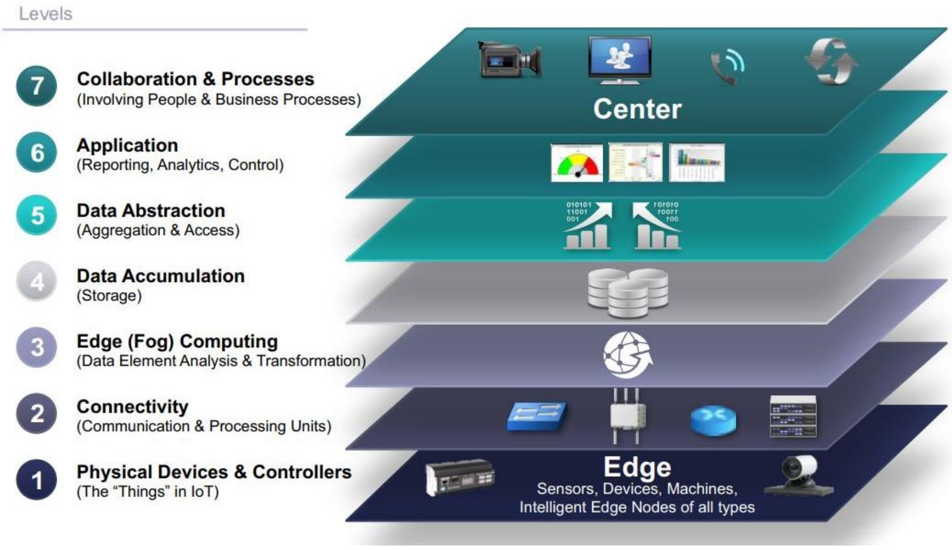

Figure 2. IoT architecture proposed by Cisco.

3. SMART CITIES

The Internet not only brought a revolution to the way people interconnect but also to the scale and pace at which they do it. Now that revolution is coming to the cities. A universal definition for smart cities is yet to be found, and recognizing the trends and technologies that shape this paradigm is challenging [16]. However, according to [17], the IoT creates a platform for devices that have sensing and actuating capabilities, which communicate seamlessly within the smart city ecosystem and allow for information sharing across platforms through several services accessed from the cloud.

The main focus of the smart city is the application of information technologies in almost every aspect of life, from embedded sensors in healthcare equipment in hospitals, water processing facilities, securing railway installations, monitoring systems on bridges, non-destructive tests in tunnels, roads, and bridges, building sanitation, power grid management, dam monitoring, to oil and gas pipeline status monitoring, while interconnecting all of them with other objects on a global scale [18].

Recent telecommunication technologies and data gathering, such as 5G, fog computing, and big data analytics, have brought new opportunities to cities in areas previously ignored because of their high reliability but low adaptability to change. In this field, IoT implementations have proven successful in the development of intelligent systems such as "smart grids, smart retail, smart homes, smart water, smart transportation, smart healthcare, and smart energy [17]." Another definition of when a city is considered to become or be "smart" comes from [19], noted as follows: When investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with wise management of natural resources, through participatory government.

For the practical purposes of this paper, a smart city will be referred to as an urbanized area where, through big data analysis aided by cloud and fog computing, contextual and real-time collected data (IoT), growth in quality of life is achieved for its inhabitants through sustainable means.

Several reasons can be mentioned to push forward our progression into fully-fledged smart cities. With the growth of the population showing no signs of stopping anytime soon, we need to secure and manage resources in a more efficient way. This could be achieved through tracking produce, exports, and imports with RFID technologies. Additionally, the public transport system is poised for a major transformation at its core with the widespread adoption of autonomous cars. Sensing and managing these vehicles will require extensive infrastructure in every city, not only to control the system but also to enhance it through reliable data collection, aided by sensor nodes that provide and act on real-time information.

The data needed to understand and improve citizens' lives is already out there; the only thing we are missing is the means to harness it in the most efficient and secure way, with privacy-oriented standards.

3.1. Structure

According to [20], in smart city applications creating continuous large data from non-homogeneous sources, state-of-the-art relational databases are not appropriate to handle such massive amounts of data, mainly due to finite processing speed and the associated costs of storage expansion. Big data analytics technologies are stepping forward to address this problem with solutions based on distributed data management and parallel processing, including capabilities for interactive data visualization.

The structure of big data in the smart city proposed in [9] is divided into several layers that enable the development of smart city technologies with efficient big data analytics and management. Each layer presents the potential functionality of big data components in smart cities.

3.1.1. First Layer

The smart environment or infrastructure is where the smart devices are located and interconnected in various configurations such as local or wide area networks. It is worth noting that this layer generates a massive amount of raw data per second.

3.1.2. Second Layer

The raw data is stored in a distributed database, and within the same layer, the data can be processed depending on queries from the upper layer. This analysis can provide the synthesis of patterns and statistics from large amounts of raw data using scalable machine learning algorithms or data mining algorithms.

3.1.3. Third Layer

The application services provide resources so that people and machines can access and share them with each other to make smart decisions. Some real-time applications available to users or machines include sentiment analysis, intelligent traffic management, fraud detection, and web display analysis.

With the results from the last layer, governmental entities, together with civic participation, can make informed decisions based on locally generated data and processes. Figure 1 presents a proposed architecture.

3.2. Applications of Smart Cities

From [9], [21-23], [25], and [41], we have the following applications of IoT technologies in smart cities.

3.2.1. Structural Health of Buildings

Monitoring and maintaining the conditions of historical buildings is critical in areas prone to degradation by external agents. With the help of IoT, the municipality can build a database of structural integrity captured by a network of sensors in the edifices. The data can include vibration, deformation, temperature, humidity, pollution, acoustics, and atmospheric metrics to provide a comprehensive assessment of the building's status.

3.2.2. Waste Management

This is an old and persistent issue in every city around the world, mainly due to expenses related to providing services and managing garbage in urban landfills. The use of intelligent waste containers with sensing capabilities to detect garbage levels can optimize the collection routes for shift workers. To implement this solution, every waste container should be connected to the network, and the information should be fed to the collectors in real-time.

3.2.3. Noise Monitoring

Often ignored, noise pollution is an issue that every major city suffers from; it is still unavoidable, but it can be efficiently monitored and controlled with the aid of IoT devices that log the peaks of sound produced in urban areas. Caution must be exercised regarding privacy issues. A solution could involve using sensors capable of detecting high levels of noise rather than microphones with high sound resolution.

3.2.4. Traffic Congestion

Having an accurate grasp of real-time traffic is a highly asset that can shorten travel times for all levels of urban transport. Solutions like camera-based monitoring are already available, but the implementation of low-cost and low-power consumption IoT devices can significantly enhance the technology without high investment costs, with a denser network of data collectors. Vehicle tracking via GPS, pressure sensors in the roads, and other sensors such as acoustic and air quality sensors can greatly improve the pool of data available to governmental entities.

3.2.5. City Energy Consumption

A smart city enhanced with energy flow tracking technology, enabled by monitoring nodes throughout the entire energy grid, can provide immense insights into energy consumption levels across spatial and temporal domains. It would even be possible to monitor different services provided by the municipality and prioritize them to optimize their efficiency. Additionally, integrating green energies and deploying them at the right moment would become easier tasks based on the analytics provided by the collected information.

3.2.6. Smart Lightning

Public lighting efficiency could be improved by adjusting light intensity using real-time data extracted from weather conditions, presence of people, and time of day. Fault detection can be another feature provided by the interconnection of the lighting devices. A side benefit could be the integration of Wi-Fi hotspots to provide internet access to citizens.

3.2.7. Automation and Hygiene of Public Buildings

Public buildings are a direct responsibility of government entities. IoT can provide a solution for monitoring and maintenance. Schools and administration offices can automate predictable tasks such as lighting, temperature, and humidity, while implementing an environmentally dynamic approach. By doing so, better quality standards will be provided to the users of these facilities while decreasing the costs of conditioning systems.

3.2.8. Water Management

Cities revolve around basic necessities such as water distribution. It is clear why water management is, and will continue to be, a critical focus for the development of smart cities. IoT technologies could help monitor the distribution of water, from consumption to transportation, and in predicting and detecting faulty pipes. This could help reduce water loss while providing actionable data for management purposes.

3.2.9. Greenhouse Gases Control

The gases emitted by urban nodes require an efficient monitoring method to deploy solutions. This can be achieved using a network of sensors with low-power consumption hardware and protocols provided by the IoT ecosystem. The analytics resulting from this monitoring could be presented not only to management entities but also to citizens. An example of this could be receiving notifications after driving a certain distance on a busy traffic day. This way, users can be aware of the amount of greenhouse gases they produce and consider alternatives such as using public transportation. This collaboration aligns with other smart services within the smart city ecosystem.

3.2.10. Transportation and Logistics

A highly automated and monitored transport system is of critical importance for future urban tasks. Providing efficient transportation at all levels is essential for the healthy development of cities. By deploying a grid of sensors and applying analytics derived from them, transportation optimization can be greatly enhanced. This approach can lead to interesting features and results, such as real-time creation of emergency lanes for critical health or law enforcement situations.

3.2.11. Smart Environments

Regarding households, IoT technologies are beginning to play a significant role, making tasks more easily manageable and automated, such as shopping, deliveries, and environmental conditioning through home automation systems implemented with edge devices like smart appliances and thermostats. These devices can remember user configurations and patterns for further customization.

3.2.12. Governance

Sentiment analysis, defined as "the examination of people’s opinions, sentiments, evaluations, appraisals, attitudes, emotions, and personal preferences towards entities such as products, services, organizations, individuals, issues, events, topics, and their attributes [22]," is a powerful tool to gather organic feedback from the population. As referenced by [21], it "can contribute to a better understanding of, and timely reactions to, public needs and concerns by city governments."

3.2.13. Social Wealth

With the advent of IoT implementations, it is necessary to remember that not everything is about increasing efficiency or creating better analytic reports. Focusing on livability is fundamental for the development of fully-fledged inhabited smart cities. Regarding this, [23] states: "While the role of the arts and arts organizations is often not explicitly emphasized, smart cities cannot achieve their holistic vision without embracing the creative arts." An applied example of art implementation can be seen in Sydney, Australia. When planning the transition to a smart city, the council decided to create new public art installations [24]. This demonstrates that art does not have to exist in isolation within smart cities; in fact, it could represent a new paradigm for artists to explore while implementing materialist, hardware-based expressions of their ideas.

3.2.14. Healthcare

The development of wearables involves not only applying IoT technologies to healthcare but also enhancing public spaces with smart feedback for users. This can be achieved by introducing sensors in public areas that send information back to users about ongoing activities and provide real-time recommendations, such as suggesting a restaurant for food while jogging.

3.3. Cases of Study

3.3.1. Padova, Italy

In an effort to promote the early adoption of IoT technologies and ICT solutions in public administration, a team of engineers implemented what they called the urban IoT “Padova Smart City.” An experimental wireless sensor network test-bed, comprising more than 300 nodes, was deployed in the city center of Padova and monitored from the University of Padova. This initiative included the development of smart grid and healthcare services, focusing on monitoring benzene levels, humidity, and temperature. A notable aspect of this project was the development of innovative IoT solutions, involving the customization and enhancement of IoT nodes and control software [25].

3.3.2. Stockholm, Sweden

In an effort to address traffic and environmental issues, Stockholm has recently implemented smart management and applications [26] with the goal of becoming the world's smartest city by 2040, aiming to provide the highest quality of life for its citizens and the best climate for business entrepreneurs [27]. In line with these efforts, waste-collecting vehicles have been deployed throughout the city to manage waste. The city council also places a strong emphasis on Green IT and e-services, which they consider key factors in urban development. It is worth noting that according to Stockab, the main fiber optic contractor in the country, the national network spans the equivalent of 30 times around the Earth, with 1.25 million kilometers of fiber optics, 5,500 kilometers of cabling, 600 cross-connect switches, and more than 15,000 connectors. With this infrastructure, and planned improvements to it, it is no surprise that they are striving for smart city capabilities.

3.3.3. Helsinki, Finland

Inspired by open public data, Helsinki is emerging as a leader in innovation within the smart cities field through the development of the 'Helsinki Region Infoshare Project'. In doing so, the country has become one of the pioneering open urban data platforms [19, 40]. According to [28], the national government of Finland publicly disclosed that "in 2013, more than 1,030 databases were made available covering a wide range of urban phenomena, including transportation, economics, environmental conditions, employment, and well-being". One proof of concept of their commitment to the development of smart cities is the Smart Kalasatamadistrict. It used to be commercial harbor area by the sea until the Finish entities established the goal to transform this district into fully develop smart community by 2030 and house 20,000 people while providing 8,000 jobs. One of the main visions for this district is to create “one hour per day [29]” for its inhabitants by becoming more resource wise. Part of the implementation will let users monitor in real time the electricity and water use of their homes to optimize consumption and, referring to the public grid, this will be designed having in mind automotive charging technology by equipping every third parking space with electric car charging stations.

4. FOG COMPUTING

The data being generated today by IoT or edge computing devices is massive [30]. Managing this influx of data that will be produced by sensors, actuators, and various devices is one of the biggest challenges faced in the deployment of an IoT system. Traditional cloud-based IoT systems, sometimes obsolete, are challenged by the large scale, heterogeneity, and high latency observed in certain cloud ecosystems [4].

The proposed solution is to decentralize applications, management, and data analytics into the network itself using a distributed and federated compute model [3]. This represents the goal of a fully enabled fog computing system.

In the past, there has been little consensus regarding the definition of fog computing. It was not until respected organizations stepped in that the definition began to gain more solid ground. The following section will present several definitions to provide a clearer understanding of this novel technology.

According to [3], Fog computing is a layered model designed to enable ubiquitous access to a shared continuum of scalable computing resources. This model facilitates the deployment of distributed, latency-aware applications and services, and comprises fog nodes (physical or virtual) situated between smart end-devices and centralized (cloud) services. Fog nodes are context-aware and support a unified data management and communication system. They can be organized into clusters-either vertically (to ensure isolation), horizontally (to support federation), or based on the latency-distance to smart end-devices.

In [4], it is characterized in a more simplistic form as 'a horizontal, system-level architecture that distributes computing, storage, control, and networking functions closer to the users along a cloud-to-thing continuum. According to [31], fog computing is a highly virtualized platform that provides compute, storage, and networking services between end devices and traditional Cloud Computing Data Centers, typically located at the edge of the network, but not exclusively. These definitions share common traits such as being an architectural approach, emphasizing low-latency communications, decentralization, and the ability to function independently but also integrate with the cloud.

A basic principle of the IoT Reference Model, proposed by Cisco, is that information processing should be done as early and as close to the edge of the network as possible [15]. This is to reduce the strain on the network and/or central server. Fog computing supports this in the cloud-to-thing scheme by dynamically and intelligently leveraging resources such as computing power, storage of unprocessed information, communication channels, and decision-making capabilities. This approach brings the true smartness closer to the network edge where data is generated, rather than relying solely on the cloud, which can be impractical due to transit times, especially in scenarios with high data density.

4.1. Differentiating Cloud Computing

Fog computing extends the cloud computing paradigm by enabling geo-distributed applications across the network [31]. Unlike traditional cloud computing, which primarily operates from centralized data centers, fog computing provides processing capabilities at the network's edge and intermediate points, reducing latency and enhancing processing efficiency. Context awareness is a critical feature of fog networks, especially with billions of IoT devices connected to the internet. This capability allows fog networks to prioritize and process data locally, determining which data should be forwarded to the cloud for centralized processing [8]. In essence, fog computing decentralizes system intelligence compared to the centralized approach of cloud computing.

4.2. Benefits of Fog Networks

Fog computing offers many benefits, including:

- Increased bandwidth requirements
- Significant reduction in latency
- More routing possibilities to reduce bottleneck issues
- Increased redundancy
- Minimization of request-response times
- Provision of network connectivity to centralized services.

As mentioned before, the fog computing model moves computation from the cloud closer to the edge. This is accomplished by implementing network nodes according to the following definition: the computational, networking, storage, and acceleration elements of this new model are known as fog nodes [4]. It is worth noting that these nodes do not reside merely on the edge but are distributed in one or more layers depending on the requirements of the system. This is illustrated in [4, fig. 3].

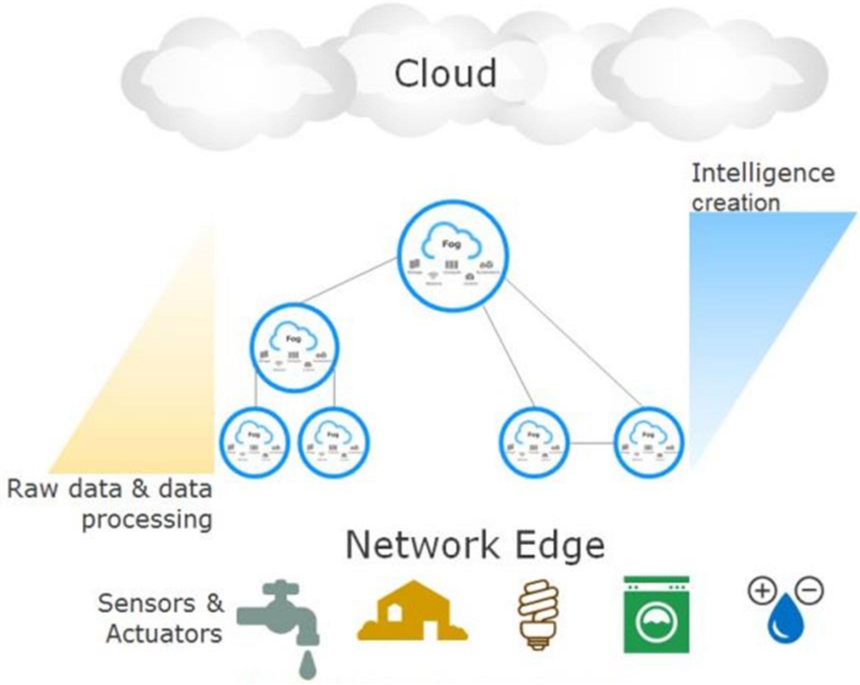

Figure 3. Gathering of intelligence by fog-cloud integration

4.3. Fog Node Definition

Being the core component of fog networks, fog nodes can be physical or virtual components such as gateways, switches, routers, servers, virtual machines, cloudlets, or virtualized switches, to mention some examples. These components need to be tightly integrated with edge devices, such as IoT devices, through an access network in order to control and communicate with other nodes in the network. An important trait of fog nodes is that they are geographically and logically aware within the mesh while functioning as an interchangeable bridge, managing and communicating between IoT devices, fog processing, and cloud centralized power according to real-time requirements. It is also possible to deploy the nodes in a centralized or decentralized manner. They can be configured as "stand-alone fog nodes that communicate among themselves to deliver the service or can be grouped to form clusters that provide horizontal scalability over dispersed locations, through mirroring or extension mechanisms [4]".

4.4. Fog Computing Essential Characteristics

These characteristics are fundamental in the fog computing paradigm and distinguish it from other approaches. It is important to note that an IoT device or edge device is not required to use all these features when working with a fog node:

- Contextual location awareness and low latency.
- Geographical distribution.
- Heterogeneity.
- Real-time interactions.
- Scalability and agility of associated fog-node clusters.

4.5. Fog Node Attributes

To facilitate the deployment of fog computing capabilities, fog nodes need to support one or more of the following attributes:

- Autonomy.
- Heterogeneity.
- Hierarchical clustering.
- Manageability.
- Programmability.

4.6. Edge Computing

This term is relevant for the purpose of this paper as it is often mentioned together with IoT devices. In simplified terms, the edge computing paradigm places processing power and applications at the network's periphery. For the purposes of this document, edge computing is interpreted as “the network layer encompassing the end devices and their users, providing local computing capabilities, for example, on sensors, meters, or other network-accessible devices [4]”.

It is key to notice the difference between fog computing and edge computing. While fog computing relies on a multi-layer architecture with hardware and software dynamically adapted for flexible configurations, edge computing is fixed in a predefined logical position close to the network's edge. Additionally, fog computing is hierarchical in nature, whereas edge computing is generally limited to peripheral devices. Furthermore, fog computing addresses networking, storage, control, and acceleration processes while maintaining communication with the cloud.

4.7. Service Models

Not so different from the traditional cloud computing model, fog computing service models are based on a service-oriented architecture, which can be understood as the functionality of the product provided from the vendor to the end user. The following, as stipulated by NIST [4]:

4.7.1. Software as a Service (SaaS)

In this model, the service delivered to the user is limited to running the fog provider’s application on the fog, while providing limited user-specific application configuration settings.

4.7.2. Platform as a Service (PaaS)

More powerful than the previous model, this allows the deployment of applications into fog computing clusters supported by the fog service provider. The user will have control over these applications and configuration settings for the application-hosting environment.

4.7.3. Infrastructure as a Service (IaaS)

In this final model, the provider delivers the processing, storage, networking, and computing resources required for a fully-fledged fog network. The user can run proprietary software but cannot modify the physical infrastructure, and should have control over operating systems, storage, and deployed applications.

4.8. Architecture

Below the architecture, proposed by the OpenFog consortium [3, fig. 4], groups the layers in 3 views that give a practical sense of the functionalities included.

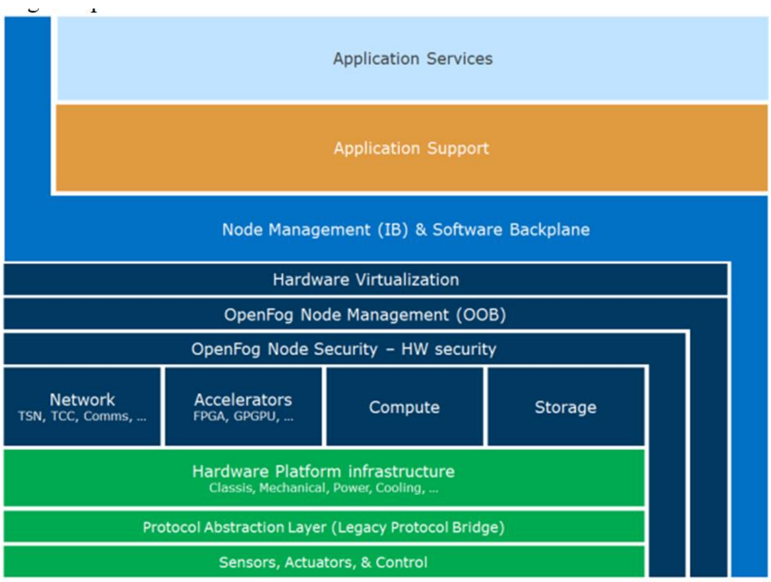

Figure 4. Proposed architecture by OpenFog Consortium

4.9. Integration of the Fog in Cities aided by IoT Technologies

Fog computing does not aim to create new smart cities but rather to enhance existing ones by implementing better technology and logistics to facilitate seamless data sharing. As mentioned before, the amount of data we generate continues to increase daily. According to information reported by IDC and EMC, the entire digital universe doubles in size every two years and generated 40,000 exabytes of data in 2020 [32]. Another estimate by [33] places this figure at around 35 zettabytes for the same year. In any scenario, the amount of data is tremendous and needs to be securely managed.

Today, it is possible to see the private sector quickly adapting to the smart city model, developing and testing new technologies for it. The former seeks to expand their competitive advantage, being the primary generators of data, while the massive explosion of IoT devices is considered the second source [34]. For the full development of smart cities with fog and cloud computing capabilities, both government and private sector entities are compelled to initiate new and innovative programs focused on finding technologically based sustainable solutions to address growing issues [35], such as the increasing complexity of network infrastructure.

Regarding the integration of the fog network into cities, [35] mentions: “We believe that better deployment of the fog framework will occur through a third-party service provider (e.g., ad-hoc cellular mobile networks) that can deploy and manage fog nodes for enterprise work”.

In contrast with previous years, big data in smart cities exhibits a new trait: geo-distribution [21], which can be addressed through networks of sensors that possess characteristics such as non-invasive, highly reliable, and low cost; thus, they can be widely distributed at various public infrastructures to monitor changes in their conditions over time [9]. As mentioned before, this data will be physically distributed across the urban area and will need to be processed and interpreted as a coherent whole.

Fog computing improvements in smart cities range from automated traffic control and waste management to smart energy distribution in buildings and homes, aiming to overcome challenges associated with rapid urban growth. Throughout this paper, it has been noted that fog computing moves processing power closer to where it is needed. Yi et al. [36] mention that this approach offers a unique solution for developing smart city projects without forsaking the benefits of a cloud infrastructure. This is achieved through the design and implementation of efficient binding architectures that enable high processing power and extensive connectivity, thereby providing smart applications with flexible resources for government entities and end-users. Kitchin [37] describes a smart city model with comprehensive control over ubiquitous processing power, supporting an economy driven by innovative policies and modernization.

The IoT structures and application frameworks required to fulfill the visions of smart cities necessitate high computational, networking, and storage capacities, while maintaining a certain level of modularity and compatibility to allow flexibility. In contrast to cloud-based computing, Byers and Wetterwald [38] have identified issues associated with centralized cloud management solutions applied in domains such as parking systems, road traffic control, and environmental monitoring within smart city scenarios. In [9], comprehensive research highlights a strong relationship between fog computing and big IoT data analytics within a hierarchical fog networking structure, enabling support for many node components and services for smart cities.

5. FURTHER RESEARCH

Lack of standardization is a problem that plagues these new technologies. With every major company trying to introduce its own architectures and solutions, the standardization landscape still appears very fragmented. In the case of fog computing, a relatively new technology, more efforts are being made to establish a solid foundation for further development in the hope of consolidating standards.

Relative According to [35], relative to fog computing platforms, they should “provide built-in support for various types of communication and application-level protocols”. It then describes how not all communication protocols need to be supported continuously. A solution to this could involve downloadable plug-ins that enable support for different languages. The flexibility provided by this solution is substantial, thanks to the capability of storing, deploying, and removing plug-ins inside fog nodes, such as analytical plug-ins written in R, Python, Matlab, Java, C/C++.

In the cloud-based server paradigm, code was primarily developed for centralized servers, including analytics and processing algorithms. In a fog network, there is a need for flexibility and cluster intelligence. This translates to researching distributed intelligence to be appropriately deployed across the nodes of a smart city network. The main reason is that quick responses and informed decisions need to be made promptly to create smarter, safer cities with a higher quality of life.

To achieve this, collaboration is necessary between “business logic, engineering processes, government policies, cost-efficient and computation-efficient computing models, and context-semantics-aware computing for real-time decision making, etc. [42]”.

Moreover, security and privacy are critical issues in developing future smart cities [43]. With nodes distributed across a city's area, physical intrusion is a possibility. This could be mitigated by implementing anti-tampering measures, such as sensors in the node containers [3]. It is evident that wireless attacks are as feasible in fog networks as with any other platform, but the critical issue here is the context-aware sensitive data that could be exposed. Strong security measures are necessary before deploying a network of sensors that capture and transmit sensitive data across the network(s).

6. CONCLUSION

Technology is evolving at a breathtaking pace. With the advent of the internet, our means of communication and interaction have been profoundly affected. It is clear that the next step in the implementation of technological advances that we are going to face is smart cities. The technologies associated with smart cities are projected to become enormous economic instruments in the coming decades, with predictions indicating they will be worth a cumulative $3.3 trillion by 2025 [39].

Cloud computing was initially seen as the solution for managing the big data generated in urban centers. However, over time, it has become increasingly clear that our telecommunications infrastructures are not prepared to handle the vast amount of data generated by IoT and edge devices. Fog computing addresses this challenge by distributing processing, storage, and communication loads. This paper provides a general overview of IoT technologies, smart city concepts, and case studies, culminating in a comprehensive exploration of fog computing and its integration with smart cities.

Finally, it can be stated that neither cloud computing nor fog computing alone are the complete solution for smart cities infrastructure. Individually, they lack the capability to fully address the challenges posed by this endeavor. However, seamless integration of both technologies might help achieve an efficient balance of resources while providing low latency, flexible, and scalable solutions for the development of fully-fledged smart cities

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