Smart City Development and Implementation through Fog/Edge Computing

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***Abstract*—With the proliferation of device-to-device networks and IoT-driven smart governance, smart economy and smart environments, the policies for sustainability and community health are blossoming among citizens. Fault tolerance started to increase interest in real-time applications and developed into a new area of interest for industries and academic research. By implementing the Cloud/Edge distributed patterns, the often-underutilized devices involved in traditional automation processes are optimized in order to eliminate the lack of expertise in their efficient exploitation.**

***Index Terms*—IoT-Internet of Things, WSN- Wireless-Sensor Networks, SDN- Software-Defined-Network.**

I. INTRODUCTION

In the latest years, the confinement of the constraints that marked our society for thousands of years has been gradually, but consistently, reduced by the evolution and dispersion of Wireless-Sensor Networks (WSNs [1]) among cities. IoT-based applications help to optimize and automate everyday city processes, thus creating a more sustainable and modern environment. Moreover, with the use of the countless available tools and Software-Defined-Network (SDNs) approaches (e.g. such as containers [2] and microservices [3]), elevated cloud algorithms and patterns may improve the key components of a system: response-time, latency, resource heterogeneity, availability and reliability.

From the Internet-of-Things (IoT) perspective, the innovations brought to the traditional automatization methods include **distributed task-scheduling** (e.g. by using a task graph as a finite state machine and partition them using a heuristic, the computational quota can be reduced and the deadlines excluded), **dynamic load balancing** (aiming to even the processor loads across the nodes by implementing asynchronous tasks to be performed [5]), **open systems interconnection model** (communicating by means of WSNs and SDNs, independent user behavior and resources heterogeneity can be achieved) and a **controlled area network protocol** (e.g. Low Energy Adaptive Clustering Hierarchy – LEACH – organizes the cluster such that the energy is equally divided in all the sensor nodes in the network, assuring robustness, scalability and energy efficiency).

The advantages of the continuous development in the field of information and communication technology (ICT) can be ultimately divided considering the computational type, as follows:

EDGE computing

- Permanently controlled and connected devices outperform traditional local-only applications and systems; **automation and control** occur as a result for a faster and timely output;
- Using advanced and complex cloud patterns and schemas, we can analyze the system outputs and converge towards a highly optimized result; by means of **monitoring and control technologies** (e.g. such as smart grid and smart metering), new operational patterns are revealed, new spot areas of potential improvement are discovered and future outcome predictions are available, leading to lower costs and higher productivity;

FOG computing

- Considering the **communication** between devices, also known as Machine-to-Machine (M2M [4]), security taxonomies ensure a permanent availability of the system and a greater quality, while the transparency is granted by the **high network throughput** and **lower latency** due to the use of local network means;
- Real-time operation systems (RTOS) and applications are encouraged to be used in order to exploit the task-scheduling management core and to parallelize the operations required to gather information, gaining this way **a better response-time** and a **lower latency**; with the recent standardization of the RTOS functions (e.g. POSIX 1003.b [5]), compounded devices are able to communicate with each other and ensure a lower powered mesh network.

Selecting the best Cloud algorithm patterns for data processing and implementing the optimal task-scheduling graph system is an important, yet challenging goal for both industry and academic institutions. As a wide variety of real-time operating system applications emerged during the past decade, the selection and research problems have become even more complex. In this proposal, we seek to systematically identify the performance bottlenecks of these systems and to improve the current research area of smart applications by comparing the theoretical heuristics with real-time use cases and scenarios.

The major objective of this paper is the research and

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Digital Object Identifier 10.32754/JMT.2023.1.06

implementation of crucial capabilities that can improve the overall population's well-being, by means of both Fog and Edge Cloud computing. We aim to deliver those results regarding the proposed subject from multiple perspectives, including resource efficiency, user experience, network area throughput, response time and the predictability of the resulting outcome.

In conclusion, the proposed research will have a massive impact on the way, based on the given results, we can automate an entire production process in order to gain lower execution time, higher standards for the final result and an environmentally friendly system.

II. DECENTRALIZED COMPUTING INFRASTRUCTURES

Decentralized computing infrastructure refers to a computing model where processing power, storage, and decision-making capabilities are distributed across multiple nodes or devices rather than relying on a centralized entity or server. It aims to distribute computational tasks and data across a network of interconnected nodes, enabling more efficient, scalable, and resilient computing systems.

Here are some key aspects and benefits of decentralized computing infrastructure:

1. Distributed Architecture: In a decentralized infrastructure, there is no single point of control or authority. Instead, the computational tasks and data are distributed across multiple nodes, which can be individual devices, servers, or even participants in a peer-to-peer network.
2. Redundancy and Resilience: Decentralization enhances system resilience by eliminating single points of failure. If one node or device fails, the system can continue to operate by utilizing other available nodes. This redundancy helps ensure high availability and fault tolerance.
3. Scalability: Decentralized infrastructure can scale more efficiently by adding new nodes to the network. As the system grows, additional computational power and storage can be easily incorporated by connecting new devices or nodes.
4. Improved Performance: By distributing computational tasks across multiple nodes, decentralized infrastructure can improve overall system performance. Tasks can be executed in parallel, reducing processing time and enabling faster response times for applications.
5. Data Privacy and Security: Decentralization can enhance data privacy and security by reducing the reliance on a central authority or server. With data distributed across multiple nodes, it becomes more challenging for unauthorized parties to access or manipulate sensitive information.
6. Lower Costs: Decentralized computing infrastructure can help reduce infrastructure and operational costs. It eliminates the need for expensive centralized data centers and enables the utilization of existing computing resources distributed across the network.
7. Autonomous Decision-Making: Decentralized systems can enable autonomous decision-making at the edge of the network. Instead of relying on a central authority for every decision, individual nodes can make local decisions based on predefined rules or algorithms.
8. Blockchain Technology: Blockchain is a notable example of a decentralized computing infrastructure. It enables distributed consensus, immutability, and transparency by maintaining a decentralized ledger across a network of nodes. Blockchain technology has applications beyond cryptocurrencies, such as supply chain management, smart contracts, and decentralized applications (DApps).

Decentralized computing infrastructure has gained prominence in various domains, including blockchain networks, peer-to-peer file sharing, content distribution networks, Internet of Things (IoT), and decentralized applications. It offers advantages in terms of scalability, resilience, security, and data privacy, providing an alternative to traditional centralized computing models.

EDGE computing, also known as edge technology, refers to a decentralized computing infrastructure that brings computation and data storage closer to the location where it is needed. In edge computing, data processing and analysis occur at or near the edge devices or sensors, rather than relying solely on centralized cloud computing infrastructure.

Traditionally, in cloud computing, data from edge devices is sent to a centralized data center or cloud server for processing and analysis. This approach can result in latency issues, increased network bandwidth requirements, and potential privacy concerns. Edge computing aims to address these challenges by moving computation closer to the data source, reducing latency, improving real-time processing capabilities, and enhancing data privacy.

With edge computing, small-scale data centers, called edge nodes or edge servers, are deployed at the edge of the network, such as in proximity to the devices or sensors generating the data. These edge nodes can be deployed in various locations, including factories, retail stores, vehicles, smart cities, or even on individual devices.

Here are some key characteristics and benefits of edge computing:

1. Edge Devices: Edge computing revolves around edge devices, which are typically sensors, devices, or machines located at the edge of the network. These devices generate and collect vast amounts of data, such as IoT sensors, surveillance cameras, wearables, or industrial machinery.
2. Proximity to Data Source: Edge computing aims to process and analyze data as close to the source as possible. By doing so, it minimizes the latency and bandwidth requirements associated with sending data to a centralized cloud or data center for processing.
3. Edge Nodes: Edge nodes, also known as edge servers or gateways, are deployed at the edge of the network to facilitate data processing and analysis. These nodes can be physical servers, virtual machines, or dedicated hardware devices. They act as intermediary points between edge devices and the centralized cloud.
4. Local Processing and Storage: Edge nodes have the computational power and storage capabilities to perform data processing tasks locally. They can run analytics algorithms, filter and aggregate data, apply machine learning models, and extract valuable insights from the incoming data.

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5. Real-Time and Near-Real-Time Applications: Edge computing is essential for applications that require real-time or near-real-time processing, where instantaneous response and low latency are crucial. Examples include autonomous vehicles, robotics, remote monitoring, augmented reality, and video analytics.
6. Data Filtering and Prioritization: Edge nodes often perform data filtering and prioritization before sending relevant data to the cloud. This helps reduce the volume of data transmitted, optimizing network bandwidth and cloud resources usage. Only high-value or aggregated data is sent to the cloud for further analysis or long-term storage.
7. Edge-to-Cloud Collaboration: While edge computing emphasizes local processing, it also collaborates with centralized cloud infrastructure. Some data may still be sent to the cloud for deeper analysis, historical trend analysis, large-scale machine learning, or archival purposes. Edge nodes act as intermediaries, enabling efficient data flow between the edge and the cloud.
8. Security and Privacy: Edge computing enhances security and privacy by keeping sensitive data within a local network, reducing exposure risks during data transmission. It allows for localized data processing and implements security measures closer to the edge, such as encryption, access controls, and anomaly detection.
9. Edge Application Ecosystem: Edge computing fosters the development of an ecosystem of edge applications tailored to specific use cases. These applications leverage the capabilities of edge nodes to deliver specialized services and real-time insights. The ecosystem includes software frameworks, tools, and APIs that facilitate application development and deployment at the edge.
10. Industry Applications: Edge computing has numerous applications across industries. In manufacturing, it enables real-time monitoring and predictive maintenance. In healthcare, it supports remote patient monitoring and personalized healthcare services. In retail, it facilitates personalized marketing and inventory management. These are just a few examples of how edge computing is transforming various sectors.

It's important to note that edge computing is a dynamic and evolving field with ongoing advancements in hardware, software, and networking technologies. As more devices become connected and data generation increases, edge computing will continue to play a vital role in enabling efficient and intelligent processing at the edge of the network.

FOG computing, also known as fog networking or fog architecture, is a decentralized computing infrastructure that extends the principles of edge computing. It aims to bring computing, storage, and networking capabilities closer to edge devices and sensors, enabling efficient data processing and analysis at the edge of the network.

Similar to edge computing, fog computing addresses the limitations of traditional cloud-centric architectures by distributing computing resources to the edge of the network. However, fog computing introduces additional layers of intermediate computing nodes between the edge devices and the centralized cloud infrastructure.

Here are the key characteristics and components of fog computing:

1. Fog Nodes: Fog computing involves the deployment of fog nodes, which are intermediate computing devices positioned between edge devices and the centralized cloud. These nodes can be routers, switches, gateways, or dedicated fog servers that provide computing, storage, and networking capabilities.
2. Hierarchical Architecture: Fog computing establishes a hierarchical architecture with multiple tiers or levels of fog nodes. The lower-tier fog nodes are located closer to the edge devices, while the higher-tier nodes are further up in the network hierarchy. This hierarchy allows for efficient data processing and analysis at different levels of the network.
3. Data Processing and Analytics: Fog nodes in fog computing perform data processing and analytics tasks closer to the edge devices. They can run real-time analytics algorithms, apply machine learning models, perform data aggregation, and make immediate decisions based on the local context. This reduces latency and enables faster response times for time-critical applications.
4. Data Storage and Caching: Fog nodes also provide local storage and caching capabilities. They can store frequently accessed data, pre-process data, and serve cached content to edge devices. This reduces the need to transmit large volumes of data to the cloud and enhances data access speed.
5. Collaboration with Cloud: Fog computing collaborates with the centralized cloud infrastructure. While fog nodes handle immediate processing tasks, they can communicate with the cloud for long-term storage, complex analytics, or resource-intensive tasks. Fog nodes act as gateways, optimizing the flow of data and computation between the edge and the cloud.
6. Resource Proximity and Bandwidth Optimization: Fog computing places computing resources in close proximity to edge devices, minimizing latency and conserving network bandwidth. This proximity allows for faster data processing, real-time analytics, and reduced reliance on the cloud for every computation task.
7. Interoperability and Standardization: Fog computing aims to support heterogeneous devices, networks, and protocols. It focuses on interoperability and standardization to ensure seamless communication and integration across different fog nodes and edge devices. Standards such as the OpenFog Consortium and the Industrial Internet Consortium help drive interoperability efforts.
8. Security and Privacy: Fog computing addresses security and privacy concerns by implementing security measures at the edge and fog nodes. Encryption, access controls, authentication, and secure communication protocols are applied to protect data and ensure secure interactions between devices and nodes. Localized processing also helps enhance privacy by keeping sensitive data within a trusted network.
9. Dynamic Resource Allocation: Fog computing enables dynamic resource allocation, allowing fog nodes to adapt their computing and storage capabilities based on the workload and demands of edge devices. This flexibility optimizes resource utilization, improves scalability, and supports varying application requirements.

10. Industry Applications: Fog computing has applications in various domains. In smart cities, it facilitates intelligent traffic management, environmental monitoring, and smart energy grids. In industrial automation, it enables real-time monitoring, predictive maintenance, and quality control. In healthcare, it supports remote patient monitoring and real-time diagnostics. These are just a few examples of how fog computing is transforming industries.

Fog computing extends the benefits of edge computing by introducing hierarchical structures and intermediate computing nodes. It provides a balance between edge processing and centralized cloud resources, enabling efficient data processing, real-time analytics, and enhanced scalability in distributed computing environments.

III. EXAMINATION OF EDGE AND FOG COMPUTING

Decentralized infrastructure refers to a computing and networking model where control, decision-making, and data processing are distributed across multiple nodes or devices rather than being centralized in a single authority or entity. It aims to create a system that is resilient, scalable, and less reliant on a central point of control. Decentralized infrastructure is often associated with blockchain technology, but it can be implemented in various other contexts as well.

TABLE I. EDGE COMPONENTS

Layer	Component
Cloud	Big data processing
Edge	Data caching & buffering
Device	Sensors & Controllers

Edge computing architecture is a distributed computing model that brings computational power and data processing closer to edge devices. It typically consists of three layers: the cloud layer, the edge layer, and the device layer. The cloud layer provides storage, complex analytics, and global connectivity. The edge layer performs local data processing, low-latency decision-making, and caching. The device layer includes edge devices that sense and collect data, perform basic processing, and enable real-time interactions. This architecture enables faster data processing, reduced latency, improved scalability, and efficient utilization of resources in decentralized environments.

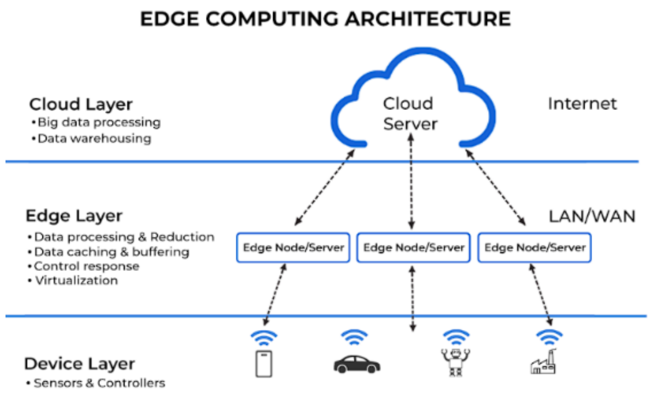

Figure 1. Edge Computing Architecture

1. **Cloud Layer**: The cloud layer represents the centralized cloud infrastructure that provides computational power, storage, and services to support edge computing. It typically consists of large-scale data centers and servers in remote locations. The cloud layer offers the following functionalities:
    - Data Storage and Management: The cloud layer provides vast capabilities to store and manage large amounts of data generated by edge devices. It offers scalable and reliable storage solutions, such as databases, data lakes, or object storage, allowing data to be retained for historical analysis, long-term storage, and backup purposes.
    - Complex Analytics and Processing: The cloud layer enables complex data analytics, machine learning, and resource-intensive computations. It leverages the computational power and advanced algorithms available in the cloud to perform deep analysis, train machine learning models, and derive insights from aggregated data collected from multiple edge nodes.
    - Global Connectivity and Services: The cloud layer provides global connectivity and access to services, enabling seamless communication and coordination between edge devices and the centralized cloud infrastructure. It offers APIs, service endpoints, and service-oriented architectures to facilitate interaction and integration with edge applications and devices.
2. **Edge Layer**: The edge layer represents the intermediate layer between the cloud and the edge devices. It comprises edge nodes or servers that are located closer to the edge devices and act as intermediaries for data processing and communication. The edge layer offers the following functionalities:
    - Local Data Processing: Edge nodes in the edge layer have computational capabilities to process and analyze data locally. They can perform real-time or near-real-time data processing tasks, such as data filtering, aggregation, transformation, and running analytics algorithms. Local processing helps reduce latency and enables faster response times for time-critical applications.
    - Low-Latency Decision-Making: The edge layer supports local decision-making based on predefined rules, policies, or algorithms. By making decisions closer to the edge, it reduces the need to send all data to the cloud for decision-making, enabling faster responses and reducing dependence on cloud connectivity.
    - Data Filtering and Prioritization: Edge nodes in the edge layer often perform data filtering and prioritization to reduce the volume of data transmitted to the cloud. They analyze and filter data at the edge, sending only relevant, high-value, or aggregated data to the cloud for further processing or storage. This optimization minimizes bandwidth requirements and optimizes network resources.
    - Caching and Content Delivery: The edge layer can provide caching capabilities to store frequently accessed data, applications, or content. Caching at the edge improves data access speed, reduces the need to retrieve data from the cloud repeatedly, and enhances the performance of applications and services delivered to edge devices.
3. **Device Layer**: The device layer represents the edge

Digital Object Identifier 10.32754/JMT.2023.1.06

devices themselves, such as sensors, IoT devices, industrial machinery, wearables, or embedded systems. These devices generate and collect data at the edge of the network. The device layer offers the following functionalities:

- Data Sensing and Collection: Devices in the device layer capture, sense, and collect data from the physical world. They monitor environmental conditions, gather sensor readings, capture images or videos, and collect various types of data. These devices act as the primary data sources in the edge computing ecosystem.
- Local Data Processing: Some edge devices have limited computational capabilities and can perform basic data preprocessing and filtering tasks locally. This local processing helps reduce the amount of data transmitted and ensures that only relevant or actionable data is sent to the edge layer or to the cloud for further analysis.
- Real-Time Interactions: Devices in the device layer enable real-time interactions with the physical world. They can control actuators, trigger actions, and respond to events in real-time, providing immediate feedback

TABLE II. FOG COMPONENTS

Layer	**Component**
Cloud	Massive data processing
Fog	Real-time data storage
End Devices	Data processing

Fog computing architecture extends edge computing by introducing hierarchical structures and intermediate fog nodes. It includes the cloud layer, the fog layer, and the device layer. The cloud layer offers centralized storage and advanced analytics, while the fog layer performs localized data processing, storage, and caching. Fog nodes act as intermediaries, enabling faster data processing, real-time analytics, and reduced reliance on the cloud. The device layer consists of edge devices that generate data. This architecture optimizes resource proximity, enhances scalability, and supports diverse applications in distributed computing environments.

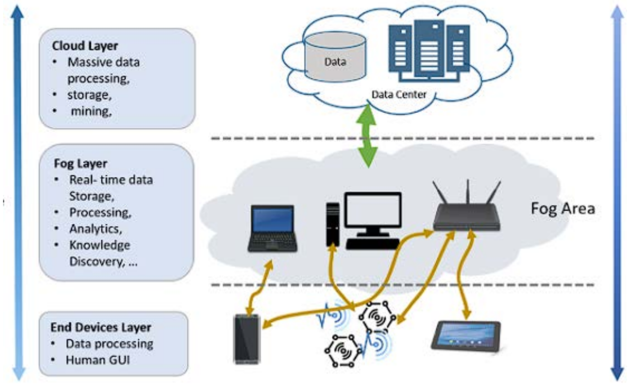

Figure 2. Fog Computing Architecture

1. Cloud Layer: The cloud layer in fog computing represents the centralized cloud infrastructure, similar to traditional cloud computing. It consists of data centers that provide extensive storage, computing power, and services. The cloud layer offers the following functionalities:
    - Data Storage and Management: The cloud layer provides scalable and reliable storage solutions for long-term data storage, backup, and archiving. It offers databases, data lakes, and object storage to handle large volumes of data generated by fog nodes and end devices.
    - Complex Analytics and Machine Learning: The cloud layer leverages its computational capabilities to perform complex data analytics, machine learning, and AI algorithms. It can handle resource-intensive tasks such as deep learning, predictive modeling, and data mining on large datasets.
    - Global Connectivity and Services: The cloud layer provides global connectivity and access to services, allowing fog nodes and end devices to communicate with the cloud infrastructure. It offers APIs, service endpoints, and service-oriented architectures to facilitate integration and interaction between fog computing components.
2. Fog Layer: The fog layer is the intermediate layer between the cloud and the end devices. It comprises fog nodes or servers located closer to the network edge. The fog layer provides the following functionalities:
    - Localized Data Processing: Fog nodes in the fog layer perform localized data processing, analytics, and decision-making. They have the computational power to run real-time or near-real-time algorithms, filters, and data aggregation tasks. Localized processing reduces latency and enables faster response times for time-critical applications.
    - Data Storage and Caching: Fog nodes offer local storage capabilities to store and cache frequently accessed data. This reduces the need to transmit large volumes of data to the cloud, enhances data access speed, and reduces bandwidth consumption.
    - Resource Proximity and Optimization: The fog layer places computational resources in close proximity to the end devices, minimizing latency and conserving network bandwidth. This proximity enables efficient data processing, real-time analytics, and optimized resource utilization.
    - Collaboration with the Cloud: Fog nodes collaborate with the cloud layer for tasks that require additional computational power, advanced analytics, or long-term storage. They act as gateways, optimizing the flow of data and computation between the edge and the cloud.
3. End Device Layer: The end device layer consists of edge devices, such as sensors, IoT devices, and industrial machinery, located at the network edge. These devices generate and collect data. The end device layer offers the following functionalities:
    - Data Sensing and Collection: End devices sense and collect data from the physical environment. They capture sensor readings, monitor environmental conditions, capture images or videos, and collect various types of data.

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- Local Data Processing: Some end devices have limited computational capabilities and can perform basic data preprocessing and filtering tasks locally. This local processing reduces the amount of data transmitted and ensures that only relevant or actionable data is sent to the fog layer or the cloud for further analysis.
- Real-Time Interactions: End devices enable real-time interactions with the physical world. They can control actuators, trigger actions, and respond to events in real-time, providing immediate feedback or initiating actions based on the data they collect.

The fog computing architecture combines the strengths of cloud computing and edge computing, allowing for localized data processing, reduced latency, efficient resource utilization, and collaborative data processing between fog nodes and the cloud.

IV. CONCLUSION

In conclusion, both edge computing and fog computing are distributed computing paradigms that aim to bring computational capabilities and data processing closer to edge devices, enabling real-time or near-real-time analytics, reduced latency, and efficient resource utilization.

Edge computing focuses on processing data at the network edge, typically within the edge nodes or devices themselves. It emphasizes local data processing, low-latency decision-making, and reduced dependence on the centralized cloud infrastructure. Edge computing is ideal for latency-sensitive applications, where real-time insights or immediate responses are critical.

On the other hand, fog computing extends edge computing by introducing intermediate fog nodes or servers between the edge and the cloud. The fog layer provides localized data processing, storage, caching, and collaboration with the cloud. It optimizes resource proximity, enhances scalability, and supports diverse applications in distributed computing environments.

Both edge computing and fog computing offer several benefits, including:

1. **Reduced Latency**: By processing data closer to the source, both paradigms significantly reduce latency, enabling faster response times and real-time decision-making.
2. **Bandwidth Optimization**: Local processing and filtering at the edge or fog layer reduce the volume of data that needs to be transmitted to the cloud, optimizing bandwidth utilization and minimizing network congestion.
3. **Improved Reliability and Resilience**: Distributed computing architectures enhance system reliability and resilience by eliminating single points of failure. With redundant edge or fog nodes, the system can continue operating even if individual components fail.
4. **Enhanced Data Privacy and Security**: By keeping sensitive data closer to the edge, edge and fog computing reduce the need for data transmission and storage in centralized locations, enhancing data privacy and security.
5. **Scalability and Flexibility**: Edge and fog computing architectures can easily scale by adding new edge or fog nodes to the network. This flexibility allows for efficient resource allocation and the ability to accommodate increasing demands.

While edge computing focuses more on the edge devices themselves, fog computing introduces an intermediate layer that enables collaboration between the edge and the cloud. The choice between edge computing and fog computing depends on the specific requirements of the use case, such as the need for real-time processing, data volume, resource availability, and the level of collaboration with the centralized cloud infrastructure.

Ultimately, both edge computing and fog computing play vital roles in enabling efficient and intelligent processing of data at the network edge, facilitating the growth of IoT applications, real-time analytics, and the development of new use cases in various industries.

ACKNOWLEDGEMENT

This work was supported by a grant of the Ministry of Research, Innovation and Digitization, CNCS/CCCDI - UEFISCDI, project number PN-III-P2-2.1-SOL-2021-0063, within PNCDI III.

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