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Enhancing Urban Surveillance with Fog Computing, Mobile Cloud, and Big Data Analytics in 5G Networks

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Abstract

The new emerging applications in 5G network, in the context of the Internet of Everything (IoE), will introduce high mobility, high scalability, real-time, and low latency requirements that raise new challenges on the services being provided to the users. Fortunately, Fog Computing and Cloud Computing, with their service orchestration mechanisms offer virtually unlimited dynamic resources for computation, storage and service provision, that will effectively cope with the requirements of the forthcoming services. 5G will use the benefits of centralized high performance computing cloud centers, cloud and fog RANs and distributed peer-to-peer mobile cloud that will create opportunities for companies to deploy many new real-time services that cannot be delivered over current mobile and wireless networks. This paper evaluates a model for fog and cloud hybrid environment service orchestration mechanisms for 5G network in terms of energy efficiency per user for different payloads.

Keywords: 5G Networks, Energy Efficiency, Radio Access Networks (RAN), Fog Computing, Cloud Computing

Introduction

The advent of 5G technology marks a significant evolution in wireless communication, enabling a new era characterized by enhanced connectivity and performance. With the rise of the Internet of Everything (IoE), urban environments are increasingly adopting smart technologies that require real-time data processing and low-latency communication (Zhang et al., 2019). Urban surveillance systems, which leverage IoT devices and sensors, are poised to benefit tremendously from these advancements, addressing security and operational challenges in densely populated areas (Akkus et al., 2020). 5G networks introduce key features such as high throughput, ultra-reliable low latency communication (URLLC), and massive machine-type communication (mMTC) (Hossain et al., 2019). These characteristics are essential for applications that demand immediate responses, such as video surveillance, emergency response systems, and public safety monitoring (Shahid et al., 2021). However, the implementation of these applications also presents new challenges, particularly in terms of data processing, storage, and resource management (Li et al., 2020).

Fog computing emerges as a promising solution to these challenges by extending cloud capabilities closer to the network edge. This proximity reduces latency and bandwidth use, enabling quicker data processing and response times (Bonomi et al., 2012). Fog nodes can analyze data locally before sending it to the cloud, which is particularly beneficial for time-sensitive applications such as surveillance, where real-time insights are crucial (Chen et al., 2019). Furthermore, fog computing enhances data privacy and security by minimizing the amount of sensitive data transmitted over the network (Maqsood et al., 2020).

In tandem with fog computing, mobile cloud computing provides a flexible and scalable resource pool that can support the computational demands of urban surveillance systems (Zhao et al., 2020). By integrating mobile cloud solutions with fog computing, organizations can dynamically allocate resources based on real-time needs, enhancing both efficiency and effectiveness (Xia et al., 2018). Big Data analytics further complements these technologies by enabling the processing and analysis of vast amounts of data generated by surveillance systems, transforming raw data into actionable insights (Zhao et al., 2021). This paper builds upon prior studies presented in conference papers, proposing a novel architecture for a hybrid cloud and fog computing environment within 5G networks. The proposed environment is examined specifically regarding its energy efficiency. The structure of the paper is as follows: Section 2 provides an overview of the requirements of

5G networks from various perspectives, highlighting key challenges and opportunities. Section 3 details the architecture of the hybrid fog and cloud computing environment in the context of 5G, including its components and interactions. Section 4 evaluates the energy efficiency of this environment, focusing on performance metrics for different payload scenarios and analyzing user energy consumption. Finally, Section 5 concludes the paper, summarizing the findings and suggesting directions for future research and development in this domain.

Service Requirements in 5G

The transition to 5G networks introduces a range of service requirements that are essential for supporting advanced applications and use cases, particularly in urban environments. These requirements can be categorized into three main classes: enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine-type communication (mMTC) (ITU, 2015).

Enhanced mobile broadband (eMBB) focuses on providing high data rates and improved user experiences for applications such as virtual reality (VR), augmented reality (AR), and high-definition video streaming. This service aims to deliver peak data rates of up to 20 Gbps, with average user experiences of 100 Mbps in dense urban areas (3GPP, 2017). The high bandwidth and low buffering times are crucial for applications that demand seamless connectivity, thus setting the stage for an immersive user experience.

In tandem with eMBB, ultra-reliable low-latency communication (URLLC) is designed to support mission-critical applications that require extremely low latency and high reliability. Applications like autonomous vehicles, remote surgery, and industrial automation are particularly sensitive to delays, necessitating a target latency of less than 1 millisecond and reliability levels exceeding 99.9999% (Foukas et al., 2017). This highlights the need for robust network architectures that can ensure timely and accurate data delivery alongside the high data rates offered by eMBB.

Moreover, massive machine-type communication (mMTC) complements these service requirements by enabling connectivity for a vast number of devices, such as sensors and IoT devices. This requirement focuses on connecting up to one million devices per square kilometer efficiently and cost-effectively (Zhang et al., 2019). By facilitating the seamless integration of smart devices into urban infrastructure, mMTC supports applications like smart grids and environmental monitoring, which are critical for enhancing urban living.

the diverse service requirements of 5G networks—ranging from high data rates and low latency to massive device connectivity—reflect the need for a versatile and robust communication infrastructure capable of supporting a wide array of applications. As urban environments increasingly adopt smart technologies, addressing these requirements will be essential for the successful deployment of 5G networks.

Fog and Cloud Computing Environment in 5G Networks

The integration of fog and cloud computing within 5G networks represents a transformative shift in data processing, storage, and management, particularly for applications that require low latency and real-time responsiveness. Cloud computing provides centralized resources and services accessible over the internet, offering high scalability and extensive storage capabilities (Armbrust et al., 2010). However, as urban environments generate massive amounts of data from IoT devices, the need for processing that data closer to its source becomes critical. This necessity is met by fog computing, which serves as an intermediary layer that brings computation and storage closer to end-users, thereby reducing latency and bandwidth usage (Bonomi et al., 2012).

In the context of 5G networks, the synergy between fog and cloud computing enhances service delivery for various applications, including urban surveillance and autonomous vehicles (Zhang et al., 2019). While the centralized cloud can manage extensive data processing and long-term storage, fog nodes handle immediate processing and analytics at the network edge, ensuring rapid responses. For example, in smart surveillance systems, fog nodes can process video data locally to detect anomalies in real time, sending only relevant information to the cloud for further analysis or storage (Chen et al., 2019). This architecture not only optimizes bandwidth but also enhances data privacy by limiting the transmission of sensitive information.

The benefits of this hybrid fog-cloud environment in 5G networks include improved energy efficiency, reduced latency, and enhanced resource allocation. By distributing processing tasks across fog nodes and centralized cloud resources, the system can dynamically adapt to varying demands, leading to optimized energy consumption (Maqsood et al., 2020). However, this architecture also introduces challenges, such as the complexity of service orchestration and security concerns related to data management across multiple nodes (Zhao et al., 2020). Addressing these challenges is crucial for maximizing the potential of fog and cloud computing in 5G environments.

The integration of fog and cloud computing within 5G networks offers a compelling solution to the challenges posed by modern applications that require real-time processing and low latency. By leveraging the strengths of both computing paradigms, this hybrid environment not only enhances service delivery but also meets the growing demands of urban infrastructures. Ongoing research and development are essential for overcoming the associated challenges, ensuring that the full potential of 5G can be realized.

An overview of such 5G network architecture in a hybrid fog and cloud computing environment is given in Figure 1. The architecture consists of centralized cloud computing nodes in 5G core, and the fog computing nodes in the 5G RAN.

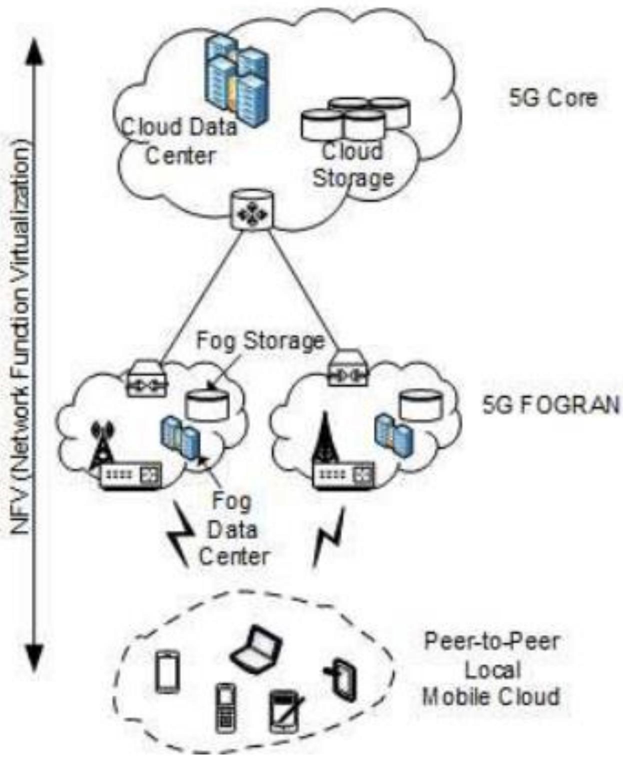

Figure 1: 5G Network Architecture in a Hybrid Fog and Cloud Computing Environment

The centralized cloud computing nodes are powerful, centralized and high-performance computing platforms located in 5G core. They provide to the smart devices 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. Like that the limited data processing and storage capabilities of the mobile devices are solved by moving both the data storage and data processing away from the mobile device to the cloud computing nodes. Fog computing nodes (FCN) are typically located away from the main cloud data centers, at the edge of the network. They extend the cloud computing at the edge of the network. Cloud computing on fog nodes enables low and predictable latency. The main features of fog computing nodes are their proximity to end users, and their dense geographical distribution.

They provide applications with awareness of device geographical location and device context. The fog nodes support the mobility of devices i.e. if a device moves far away from the current servicing FCN, the fog node can redirect the application on the mobile device to associate with a new application instance on a fog node that is now closer to the device.

Architecture Evaluation of Fog and Cloud Computing in 5G Networks

The architecture of fog and cloud computing in 5G networks is designed to optimize resource utilization, reduce latency, and enhance service delivery for various applications. This evaluation focuses on key aspects such as scalability, energy efficiency, latency, and security, which are critical for supporting the diverse requirements of modern applications.

Scalability

One of the primary advantages of the hybrid fog-cloud architecture is its scalability. Cloud computing provides virtually unlimited resources, allowing for the dynamic allocation of computational and storage capacities as demand increases (Armbrust et al., 2010). Fog computing complements this by enabling localized processing, which allows networks to scale efficiently by distributing resources across multiple nodes. This combination ensures that both individual user demands and large-scale deployments can be effectively managed, making it suitable for urban environments with a high density of IoT devices.

Energy Efficiency

Energy efficiency is a significant consideration in the evaluation of this architecture. Fog computing reduces the need for extensive data transmission to centralized cloud servers, which not only saves bandwidth but also minimizes energy consumption (Maqsood et al., 2020). By processing data closer to the source, fog nodes can lower the overall energy footprint of the system. Furthermore, dynamic resource allocation allows for energy-efficient operations, as resources can be adjusted based on real-time demands, further optimizing energy usage.

Latency

Low latency is a critical requirement for many 5G applications, especially those involving real-time data processing, such as autonomous driving and smart surveillance. The fog-cloud architecture addresses this need by leveraging fog nodes to handle time-sensitive computations locally. This reduces the round-trip time for data transmission and processing, allowing for faster responses compared to traditional cloud-only solutions (Chen et al., 2019). The architecture aims for latency levels of less than 1 millisecond, meeting the stringent requirements of applications relying on ultra-reliable low-latency communication (URLLC).

Security

Security remains a crucial aspect of any computing architecture, particularly in a hybrid model where data traverses multiple nodes and networks. While fog computing can enhance security by processing sensitive data locally and minimizing exposure during transmission, it also introduces new vulnerabilities. The distributed nature of fog nodes requires robust security protocols to protect against unauthorized access and data breaches (Zhao et al., 2020). This necessitates a comprehensive security strategy that encompasses both fog and cloud environments, ensuring end-to-end security across the architecture. The evaluation of the fog and cloud computing architecture in 5G networks highlights its potential to meet the diverse requirements of modern applications. With its scalability, energy efficiency, low latency, and enhanced security, this hybrid approach represents a significant advancement in resource management and service delivery. As urban environments increasingly adopt smart technologies, ongoing research and development will be essential to address the challenges associated with this architecture and to fully realize the benefits it offers.

Table 1 : Energy per bit for different RAN types and different data file size

	RAN Type		
Parameter	3G	4G	5G
Energy per bit [μJ/bit] (Data File: 10 KB)	100	170	17
Energy per bit [μJ/bit] (Data File: 10 MB)	4	0.3	0.03

Energy Efficiency per User in Fog and Cloud Computing Services

Energy efficiency per user (EE) in fog and cloud computing services is a critical metric, particularly in the context of 5G networks. It reflects how effectively energy resources are utilized to deliver data to users, taking into account both the energy consumed in the radio access network (RAN) and the characteristics of the data being transferred.

The energy efficiency per user can be expressed mathematically as:

$EE = Eb \times D / N$

where:

- EE is the energy efficiency per user,
- Eb is the energy consumed per bit transmitted, which varies depending on the type of RAN employed (e.g., centralized vs. distributed),
- D is the size of the data file being transferred,
- N is the number of users sharing the same network resources.

Energy per Bit (Eb)

The energy per bit (Eb) is influenced by several factors, including the architecture of the RAN, the modulation scheme used, and the distance between the transmitter and receiver. In fog and cloud computing environments, optimizing Eb can significantly enhance overall energy efficiency. For instance, distributed RANs may leverage local fog nodes to reduce the transmission distance and associated energy costs, thus leading to lower Eb values.

Size of Data File (D)

The size of the data file being transferred (D) directly affects energy consumption. Larger files require more energy to transmit, but utilizing fog computing can mitigate this by allowing data processing closer to the user. By processing and filtering data locally at fog nodes, only essential information may need to be transmitted to the user, thereby reducing the effective size of the data being sent over the network.

Impact of User Density (N)

The number of users (N) sharing the same network resources also plays a vital role in energy efficiency. In a densely populated area, the ability to share resources among users can lead to significant energy savings. Fog computing enables efficient resource allocation by dynamically managing data flows and optimizing the distribution of tasks across multiple users, ultimately enhancing the energy efficiency per user.

The energy efficiency per user in fog and cloud computing services is a product of the energy per bit transmitted, the size of the data file, and the number of users. By optimizing each of these components, particularly through the deployment of fog computing resources, 5G networks can achieve significant improvements in energy efficiency, making them more sustainable and effective for modern applications. Continued research into the interplay between these factors will be essential for maximizing energy efficiency in future network architectures.

Results Analysis

Our simulation scenario included 10 cloud computing centers and evaluated three types of Radio Access Networks (RANs): 3G, 4G, and 5G. We varied the number of users from 100 to 1,000 to assess energy efficiency across different conditions. For simplicity, we neglected the impact of the distance between smart user devices and the RAN on energy efficiency. The results, illustrated in Figure 2, reveal several key observations regarding the performance of each RAN type.

The 3G RAN exhibits significant energy wastage when transferring large data files. This inefficiency is due to outdated technology and lower bandwidth capabilities, which struggle to meet the demands of modern applications that require high data throughput. Consequently, the energy consumed per bit is considerably higher, resulting in poor overall energy efficiency. As user demands increase, these limitations become even more pronounced, underscoring the inadequacy of legacy systems for contemporary data requirements.

In contrast, the 4G RAN demonstrates improved energy efficiency for transferring large data files compared to 3G. This enhancement arises from better bandwidth and more advanced technologies that facilitate more efficient data transmission. However, the 4G RAN also has a drawback; it shows energy wastage for small data file transfers. In these cases, the overhead associated with network protocols can lead to inefficiencies, causing the 4G RAN to perform worse than 3G. This paradox indicates that while 4G excels for larger data transfers, it is less effective for smaller ones, highlighting the importance of context in evaluating network performance.

The most significant finding is that the 5G RAN consistently achieves the best energy efficiency, regardless of the size of the data files being transferred. This performance advantage can be attributed to the advanced features of 5G technology, which include higher bandwidth, lower latency, and improved resource management capabilities. Whether users request large or small data files from fog or cloud computing centers, the 5G RAN optimizes energy usage effectively. This consistency underscores the suitability of 5G for modern applications that demand both real-time processing and high data rates. The results of our simulation highlight the varying energy efficiencies of different RAN types under diverse conditions. The 3G RAN demonstrates significant inefficiencies for large data transfers, while the 4G RAN exhibits mixed performance depending on data size, being more effective with larger files but less so with smaller ones. Conversely, the 5G RAN emerges as the most efficient option overall, adeptly handling a range of data transfer needs while minimizing energy consumption. These findings emphasize the critical role of adopting advanced network technologies, such as 5G, to enhance energy efficiency in fog and cloud computing environments, making them more viable for future urban applications.

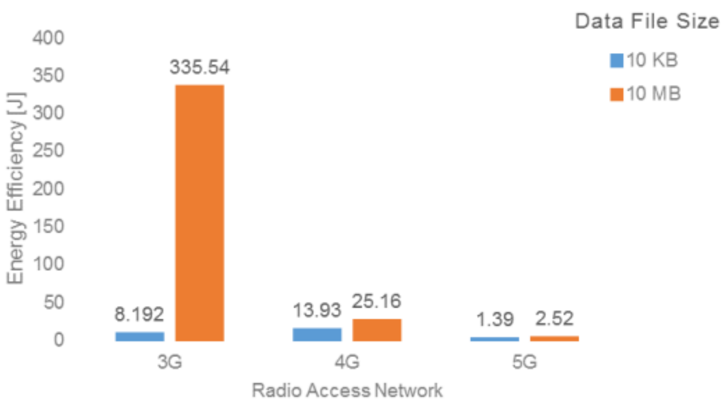

Figure 2: Energy Efficiency in 5G Network in the Hybrid Fog and Cloud Computing Environment

In 5G network where the user device will be served by different RANs, it has to make choice which RAN will be the most suitable for transferring data files. The choice should be make primarily of the size of data files being transferred, throughput, latency, energy efficiency, etc. The algorithm for such RAN selection will be our future work direction.

Conclusion

This paper evaluates energy efficiency per user across different payloads and networks. The results demonstrate that the 5G RAN consistently achieves the best energy efficiency for data transfer, regardless of file size, when compared to 3G and 4G RANs. This finding underscores the potential of 5G networks to serve as the backbone of the digital society, economy, and everyday life.

In this evolving landscape, the cloud within 5G networks will increasingly be distributed among client devices, including those with mobility, effectively transforming traditional cloud architecture into a fog computing model. As a result, more virtual network functionalities will operate in this fog environment, providing ubiquitous services to users. This shift will facilitate the emergence of new Application as a Service (AaaS) paradigms, wherein devices, terminals, machines, smart objects, and robots will become innovative tools capable of producing and utilizing applications, services, and data.

Finally, the selection of the most suitable RAN should be guided primarily by the size of data files being transferred, throughput, and latency requirements. Developing an algorithm for effective RAN selection based on these factors will be a key direction for future research. This work aims to further optimize energy efficiency and service delivery in fog and cloud computing environments within the context of 5G networks.

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