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Reducing Transmission Latency and Optimizing Power Consumption in Fog Computing to Improve Performance in Fog-Cloud Computing

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Abstract
The important problems of latency and power inefficiency in fog-cloud computing systems are discussed in this work. Driven by growing demand for real-time processing in Internet of Things (IoT) applications, these difficulties compromise the performance of distributed systems. This work aims to minimize transmission latency and power consumption so that seamless integration between fog and cloud computing layers may be attained, hence improving system performance. Emphasizing important issues such as resource allocation algorithms, energy-efficient task scheduling, and latency reduction approaches in fog computing, a thorough evaluation of the body of current research was undertaken. Though many fall short in achieving the dual goals of lowering latency and concurrently optimizing energy use, existing studies emphasize the possibilities of fog computing in bridging the gap between IoT devices and centralized cloud servers. The study also shows that while many techniques and frameworks have been suggested for individual optimization, there is a dearth of coherent approaches addressing both elements in concert. The results of this work emphasize the need to use hybrid optimization techniques based on dynamic workload allocation and energy-aware scheduling. While preserving power economy, advanced techniques using machine learning-based predictive models were shown to dramatically lower latency. The results imply that further studies should concentrate on creating scalable, adaptive systems able to balance sustainable energy practices with real-time performance requirements. By offering practical insights on optimizing fog- cloud architectures, therefore allowing better QoS (Quality of Service) and promoting the spread of IoT-based applications, this work adds to the increasing corpus of knowledge.

Keywords: *IoT; cloud computing; fog computing; fog-cloud architectures; QoS*

1. Introduction

Being an innovative method to strengthen the connection between IoT devices and major cloud frameworks, fog computing appeared. Fog computing reduces demand for hubs at the cloud data center since it provides distributed resources close to the source of data, hence it speeds up the application and data processing (Kopras et al., 2022). However, as IoT applications require high temporal responsiveness, problems such as delays in transmitting data from fog to the cloud layer, and excessive power consumption become the key challenges to achieving maximum performance in fog-cloud systems (Huang et al., 2022). These problems impact how well the systems that work on latency-sensitive applications like: smart cities, self-driving cars, etc., and healthcare monitoring work (Shafik et al., 2021; Jalouricor et al., 2021). A type of latency that results from interruptions along the connectivity path between IoT devices, fog nodes, and cloud servers, this type of latency significantly hampers the ability of fog-cloud systems to meet real-time demands (Bhai et al., 2021; Kishor et al., 2021). However, due to the distribution of fog computing, there is the continuous consumption of energy as many edge nodes compute, store and transmit numerous data concurrently. This, indeed, poses a complex and complex challenge: Such aspects have to be addressed in a way that they do not offset the capabilities of systems (Kumar et al., 2022; Keshavarznejad et al., 2021). The focus of this work is to analyze and state reasonable approaches to minimize transmission delay and at the same time optimize the power utilization in fog-cloud systems. Thus, addressing these problems comprehensively allows the study to contribute to the general improvement of such systems to guarantee their ability to support the tremendously high demands of IoT-based applications. Reducing latency and operational energy use in this analysis, observing the balance between the two, and developing strategies that achieve a balance in optimization require this as well. Method of Reducing Power Consumption and Latency Different approaches are stated in this work concerning power usage and latency issues. Transmission delay is solved by edge cache, workload balancing, and job scheduling ensuring quicker data processing in the fog nodes (Alatoun et al., 2022; Oprea et al., 2021), Figure 1 [1-6].

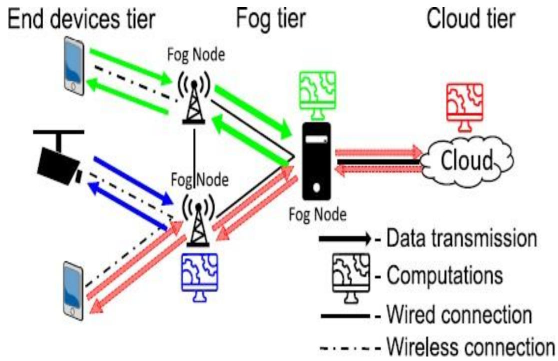

Figure 1 Schematic Fog Networking Architecture (Kopras et al., 2022)

It then becomes possible to prioritize such activities given that the prediction algorithms and the machine learning models that enable better resource allocation and time-sensitive task prioritizing are available. The work focuses on energy-optimal scheduling algorithms, dynamic resource control, and hardware modifications in fog nodes in terms of power. Another research area investigated to enhance the sustainability of fog computing operations is demand-based service scaling and integration of renewable energy sources. The research also stresses the concept of coupling fog with clouds and presents the benefits of the hybrid architecture of fog-or-cloud computing based on load management and latency and energy constraints [7-12].

2. Literature Survey

The main architecture of an IoT-fog-cloud application is established in this paper (Wang et al., 2023), then an algorithm for Energy efficiency via an integrated approach computation model is presented. Using a fog offloading strategy for the fog-enabled IoTs, Fog-Enabled Smart Cities (FESC) are suggested to minimize service delay and reaction time. The authors have created an analytical model assessing the efficiency of the suggested paradigm in lowering IoT service latency. The Alternating Direction Method of Multipliers (ADMM-VS) method performs far worse than the suggested model. Therefore, fog-enabled smart grids find whether computation will be carried out autonomously or semi-autonomously on fog nodes or in the Cloud by optimizing response and processing times.Authors (Xiao and Krunz et al., 2021) document a five-month measurement investigation of the wireless access latency between connected cars and a fog/cloud computing system driven by commercially accessible LTE networks. Using a fog/cloud architecture, they present Adaptive Fog, a framework for autonomous and dynamic switching between many LTE networks. Maximizing the service confidence level—defined as the chance that the latency of a certain service type is below some threshold is the fundamental goal of AdaptiveFog. They provide a new statistical distance metric, weighted Kantorowicz-Rubinstein (K-R), to measure the performance difference across many LTE networks. Two scenarios considering finite- and infinite-horizon optimisation of short-term and long-term confidence are studied. Authors (Li et al., 2021) pre-cache the user's request and estimate the content of the user's next- time slice demand using the neural network model after analyzing the request data. Then, determine the most suitable edge node cache deployment strategy and raise user experience quality. At last, a video caching system for mobile edge computing with synchronized latency and energy usage is suggested with coordinated optimization of both. The optimization issue is solved using the Branch and Bound method. The authors lastly evaluated our method against the LFU, PBC, COC, and R-LCCA algorithms. High cache hit rates of the algorithm, according to experimental data, help to lower the cost of video providers and enhance the user experience quality. This paper (De Mendonca et

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al., 2022) formalizes a Time Constrained One-Shot Open First Price Auction for resource allocation in vehicular fog computing and investigates the trade-offs on the functioning of fog nodes under various vehicle concentrations and network circumstances. We evaluate significant elements of the performance of fog nodes in Vehicular Fog Computing using large-scale simulation research. Authors demonstrate that despite the availability of processing capability of fog nodes, present wireless network standards may define the boundaries of processing. Their findings show that trade-offs on the functioning of fog nodes concerning message overhead and processing redundancy are necessary to get high task completion ratio. At last, they assess the social welfare distribution of the job allocation attained using an auction in which higher message rates result in more expenses. In this study (Farooqi et al., 2022), the authors created a priority-based fog computing model for smart urban vehicle transportation that lowers the fog computing delay and latency. 5G localized Multi-Access Edge Computing (MEC) servers have also been used to enhance the fog computing infrastructure to satisfy the latency and Quality of Service (QoS) standards, thereby greatly lowering the delay and latency. Compared to the trial conducted under just cloud computing architecture, we reduced the data latency by 20%. They also cut the processing latency by 35% as opposed to using cloud computing architecture. First, the suggested EaDO approach in (Hazra et al., 2022) describes the emergency information of the arriving tasks along with the attribute values. To increase the schedulability, the EaDO technique then arranges the emergency activities utilizing a layered feedback queue system. Furthermore, used for optimum matching between planned activities and active computing equipment—including dispersed fog devices and centralized cloud servers—is a graph-theoretic technique known as Hall's theorem. Extensive simulation findings show that the EaDO approach greatly lowers the energy consumption rate of the industry-produced tasks by up to 23%-30% over the current techniques [13-19].

3. Reducing Transmission Latency

Fog computing targets certain major issues that relate to latency and power consumption of the system, through decentralization of operations and close association with the end-user. The following classifications present ways of minimizing transmission latency and maximizing power consumption in the fog-cloud system, Figure 2 [20].

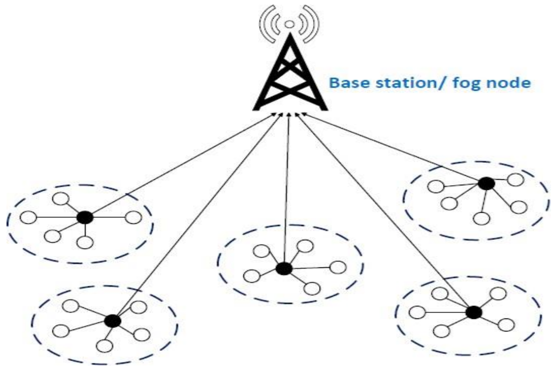

Figure 2 Clustering Framework of Fog Architecture (Malik et al., 2021)

3.1. Edge Computing

The concept of edge computing makes decisions by keeping latency low as most of the computing has to be done away from the core and less data has to be transmitted to the cloud (Varmaghani et al., 2021). These processes are however performed locally and in a real-time manner hence reducing energy consumption (Malik et al., 2021). Finally, future works should be mainly on developing new and lighter edge algorithms that are capable of learning from the diverse edge devices that are available on the market, as well as the dynamic management of suitable resources. Further, establishing general designs to stretch draws between confused prototypes and consistent fog layers straightforward for toughening gossamer is also inevitable, Figure 3 & 4.

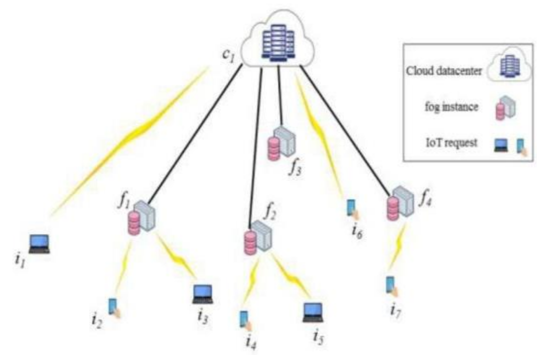

Figure 3 IoT and Fog Cloud Framework Generalized (Dahiya et al., 2021)

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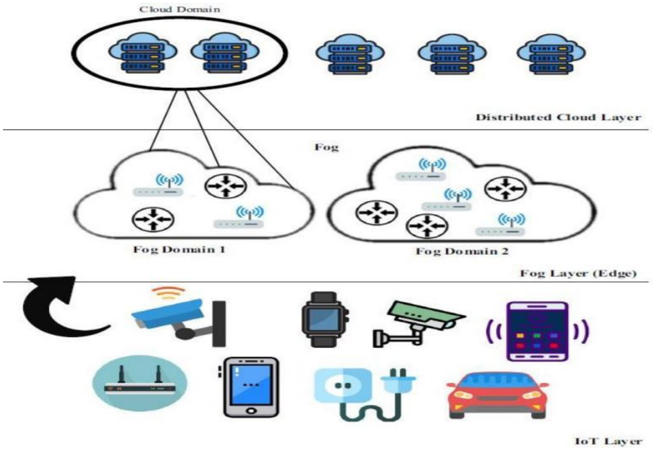

Figure 4 Instance of environment model; i indicates service request, f indicates fog instance (Jafari & Rezvani, 2023)

3.2. Caching

Caching techniques keep data at fog nodes or edge devices that are commonly used for data access, thus minimizing the duration and workloads that would otherwise aggregate data in the cloud (Ijaz et al., 2021). As such, while using proximity-based caching, the latency is reduced, while that of power efficiency is increased. High availability caching techniques, in consideration of user requirements and load variations, represent two distinctive innovation domains. Cache management and replacement strategies that draw from machine learning algorithms to anticipate future trends in data traffic and to design appropriate replacement mechanisms promise to be highly effective in improving fog-cloud systems (Dahiya et al., 2021) [21-26].

3.3. Optimized Routing

Optimized data forwarding guarantees that data flows through the fog network through the shortest and least power-consuming channels (Jabour and Al-Libaway, 2021). Redundancy elimination also helps to lower power consumption and eliminate congestion to help minimize transmission times (Reyana et al., 2023). Future work should go further in detail concerning the context-aware and machine-learning routing protocols. They can achieve dynamic optimization in response to changes in the network at the fog-cloud setting, thereby guaranteeing efficient data transmission. The analysis of these areas of improvement will therefore help to improve and sustain these systems [27-30].

4. Optimizing Power Consumption in Fog Computing

Another important concern realized in fog computing is to minimize power utilization to meet the energy utility without compromising performance. The following classifications highlight specific strategies to achieve this:

4.1. Energy-Efficient Hardware

Hardware power management mechanism is a fundamental factor in minimizing the power consumption of fog computing structures (Guerrero et al., 2022). Low-power processors, energy-optimized sensors, and high-efficiency network interfaces are some examples. Other advances embrace dynamic voltage and frequency scaling (DVFS) and low-energy dormant modes. The following research topics must be addressed when designing future computing hardware that should have been efficient in both compliance and power consumption along with smart energy management abscess.

4.2. Dynamic Resource Allocation

Automatic resource allocation and management allow for the most effective distribution of computation and storage services according to load necessities (Wang et al., 2021). The interactive nature of fog systems allows them to utilize real-time and predictive models to manage resources to reduce power usage (Wang et al., 2024). Using a machine learning algorithm, workload patterns can be foreseen hence allowing adjustments to be made way before the resources are fully utilized (Jafari and Rezvani, 2023). Further, the use of the energy-efficient approach to prioritizing tasks can help avoid the consumption of power during demand peaks (Ahmad et al., 2023).

4.3. Power-Aware Scheduling

Power-aware scheduling includes minimizing energy consumption while directing tasks in the networks (Sarkar et al., 2021). Through appropriate scheduling of low and high-energy jobs concerning the demand curve, power requirements can be controlled efficiently. Additional optimizations may be achieved by heuristic-based scheduling algorithms and energy-cost- aware scheduling frameworks to compromise the system’s performance for energy efficiency.

4.4. Renewable Energy Sources & Environmental Effect

Power-aware Solar and wind solutions are widely used today as sources of renewable energy and their incorporation into fog computing systems will greatly minimize the impact of these systems on the environment. A combination of renewable power systems and conventional power systems for instance integrating wind and hydro power with thermal power sources can guarantee supply reliability while at the same time reducing emissions of carbon. More exploration of energy harvesting technologies and green deployment methodologies will even more advance green fog computing systems. Improvements in power usage in these areas shall create the much-needed foundation for green and sustainable fog computations.

5. Challenges and Research Gap

Especially for those applications that demand low latency and efficient energy consumption, fog computing has emerged as a promising paradigm to deal with problems in traditional cloud computing. However, there are still several gaps in the current literature that hinder it from reaching its achievement. This part reveals the key research opportunities within the domain of scalability, security, and standardization to specify a rigorous plan for future endeavors.

5.1. Scalability

Scalability is a basic quality inherent in each of the distributed computing systems (Maitiet et al., 2022; Kaur and Kaur, 2021). It talks about the degree of potential to handle the increasing amount of workload or to extend the system to acquire more resources without expanding performance. According to the concept of fog computing, the ability to perform such management depends on scalability in concern with the dynamic and heterogeneous nature of edge devices and applications. Though important, numerous issues still exist:

Dynamic Resource Allocation: Due to the extremely dynamic nature of fog networks, they are not well suited to some of the current resource allocation systems. An area of challenge is the ability to design necessary algorithms to achieve resource availability and distribution based on demand in real-time without high latency and power consumption (Abbasi et al., 2021; Bebortta et al., 2023). For this, the researchers should look into the reinforcement learning and the prediction models. When the workload distribution is not balanced in the fog nodes, computation appears to be lagging particularly in some nodes (Vijarania et al., 2023; Jia et al., 2021). Practices such as adaptive load redistribution and distribution of work scheduling need more research.

Fog computing, therefore, entails a broad range of devices, with varying computing capabilities and communication interfaces, across several heterogeneous devices (Singh et al., 2021, Aldossary, 2023). One persistent challenge is ensuring that such gadgets work cooperatively without requiring much overhead all the time. Thus, the researchers are forced to look at some cross-platform systems and lightweight solutions of the middleware type. Higher latency and energy usage are derivable from the fact that the communication overhead rises as the number of devices in a fog network increases. What we do require are good methods of communication that will be able to run efficiently along with explosive growth of the network.

5.2. Security

Due to its decentralized nature and location near the end consumer, security is a major concern of the fog computing model. As mentioned often in the context of many edge devices when the processing capability is limited, vulnerabilities augment and using strong security methods becomes cumbersome. Important difficulties consist:

- Some challenges that can be noticed include the various data that is being handled and sent among the fog nodes require privacy and security to be maintained (Mishra et al.,2023; Vemireddy and Rout, 2021). In many places, data breaches could happen due to unauthorized access or manipulation of the network. Solve these problems with the help of creative cryptographic approaches including homomorphic encryption and lightweight encryption.
- The characteristic of the devices in the fog networks as being varied and dynamic has implications on access control and authentication (Zhang et al., 2021; Das and

Inuwa, 2023). Due to the computing need of the methods, these become insufficient at times, with conventional techniques. As a result, the authors can determine distributed identity management methods, including the application of blockchain-based authentication, as the next steps to enhance security while maintaining efficiency.

- This is a list of risks that fog networks are exposed to and ways in tackling cyber threats such as; Distributed Denial of Service (DDoS) attacks and malware. However, machine learning and anomaly detection algorithms as real-time threat detection have great potential yet they need further improvements in terms of false positives and computational complexity.
- One of the main challenges is the secure transfer of data to/from multiple fog nodes (Abidoye and Kabaso, 2021; Potu et al., 2022). More often than not, measures in use today are characteristic of either low security or high latency. Security of multiple parties computing and differential privacy should be focus of future work in order to facilitate safe exchange of data with minimal performance degradation.

While fog nodes are normally deployed in open and unsecured environments, they are susceptible to external physical intervention. This danger is substantially lessened by the creation of safe boot systems together with hardware that cannot easily be tampered with.

5.3. Standardization

To achieve broad acceptance and interoperability of fog computing solutions, the latter has to be standardized. As vital as it is, fog computing does not have universally well-defined indicators this hampers organization and creates fragmentation. Several elements call for attention:

- Several implementations of fog computing lack a clear architectural foundation which affects the compatibility of the systems (Osman et al., 2023; Munneb et al., 2021). Going back to the establishment of the fog systems, perhaps, it would be essential to build global reference architectures, which will be compatible and scalable.
- Communication requirements of fog computing among which data sharing between NDs, edge devices and cloud are among. Integration of the components effectively and without failure of interaction relies on standard communication methodologies addressed for fog conditions (Natesa and Gudetti, 2021; Kaliyaperumal, 2024).
- Service Quality (QoS) Metrics: To compare and assess the system performance, a framework for characterization and standardization of QoS in fog computing systems is needed. Basic descriptors for marking characteristics such as latency, power consumption, and dependability should be integrated into the instruments of benchmarking.
- These challenges make simplifying and implementing fog applications difficult due to the lack of standardized development tools and APIs (Abdullah and Jabir, 2022; Sampaio et al., 2021). Through the application of standard APIs and development platforms, the development process may be made less complicated, and integration may be promoted.
- Fog computing executes over multiple geographical regions with varying requirements in terms of government control (Mahaptra et al., 2024; Wu et al., 2023), [50]. Building confidence and acceptance, therefore, requires the creation of global best practices related to data sovereignty, data privacy, and data compliance.
- In general, good standardizing calls for interdisciplinary cooperation of academics, businesses and regulatory agencies. An important function of consortia and working groups, related to fog computing, contributes to speeding up the development of the best practices and standards.

In fog computing, there are two significant issues for which a pragmatic approach is necessary, these include, reduced transmission latency and energy consumption. Improved and safer fog computing systems are realized through the ways that gaps in scalability, security, and standardization are addressed. Security demands powerful protected mechanisms to protect information and devices, whereas scalability aspires to innovative efforts in managing and integrating resources. On the other hand, standardizing fosters collaboration and ensures that different implementation has a similar level of quality with other implementations of that same concept or ideas. In this way, the application of fog computing will enhance its performance and reliability for utilization across many subject areas.

Conclusion and Future Work

This research underlines the following research limitation in fog computing: abridging the transmission latency of the fog-cloud system to cut the time it takes for a message to travel the full length of the system, and minimizing energy consumption of the fog-cloud system while at the same time maximizing its performance. This looks at areas like scalability, security and standardization, discussing matters like dynamic resource allocation, data security and the requirement for standard methods of communication. The matters discussed above are seen as developmental sections that can find application in particular further studies; more effective resource management, successful protective provisions, and coherent patterns for the broad populace engagement. Therefore, this analysis offers a richness of added-value propositions to the literature to warrant real and theoretical improvements to the field.

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