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Energy-Efficient Fog Computing: A Review and Future Directions

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ABSTRACT- Fog computing has emerged as a promising paradigm to meet the increasing demands of latency-sensitive and bandwidth-intensive applications in the era of the Internet of Things (IoT) and edge computing. However, the proliferation of fog nodes introduces significant energy consumption challenges, particularly in resource-constrained environments. This paper presents a comprehensive review of energy-efficient techniques in fog computing, focusing on optimization strategies to minimize energy consumption while meeting application requirements. We categorize existing research efforts based on their approaches, including task scheduling, resource allocation, communication protocols, and energy harvesting techniques. Additionally, we identify key open challenges and propose future research directions to further enhance energy efficiency in fog computing environments.

KEYWORDS- Fog Computing, Energy Efficiency, Internet Of Things, Edge Computing, Resource Allocation, Task Scheduling, Communication Protocols, Energy Harvesting.

I. INTRODUCTION

Fog computing, a paradigm that extends cloud computing to the edge of the network, has gained traction due to several motivating factors such as Reduced redundancy, Bandwidth optimization, Improved Privacy and Security, Scalability etc [1]. Fog computing enables processing and data storage closer to the end-users or IoT devices, reducing latency compared to traditional cloud computing. This is critical for applications requiring real-time responses, such as autonomous vehicles or industrial automation. By processing data locally at the edge rather than transmitting it to distant cloud servers, fog computing helps in optimizing network bandwidth [2]. This is particularly beneficial in scenarios with limited or expensive bandwidth, such as remote areas or mobile networks. With sensitive data being processed and stored closer to the source, fog computing offers enhanced privacy and security compared to transmitting data over long distances to centralized cloud servers. This is especially important for applications dealing with personal or confidential information. Fog computing architecture supports scalability by distributing computation and storage across a network of edge devices. This allows for efficient scaling to accommodate varying workloads and demands, ensuring consistent performance even during peak usage periods.

However, despite its numerous advantages, fog computing faces challenges related to energy consumption, including resource constraints, dynamic workload, heterogeneity. Many edge devices in fog computing environments, such as sensors or IoT devices, are resource-constrained in terms of processing power, memory, and energy capacity [3]. Efficient utilization of these limited resources is essential to ensure optimal performance while minimizing energy consumption. Workloads in fog computing environments can be highly dynamic and unpredictable, leading to fluctuations in resource utilization and energy consumption. Efficient resource management and workload scheduling strategies are necessary to adapt to changing demands while minimizing energy overhead. Fog computing environments typically consist of a diverse range of edge devices with varying capabilities and energy profiles. Managing this heterogeneity and ensuring compatibility and interoperability among different devices while optimizing energy usage poses a significant challenge.

Energy efficiency is crucial in fog computing for several reasons. Energy-efficient fog computing architectures can help reduce operational costs associated with powering and maintaining edge devices. By optimizing energy consumption, organizations can lower their electricity bills and improve the overall cost-effectiveness of their fog computing infrastructure. Energy-efficient fog computing reduces the carbon footprint associated with IT operations by minimizing energy consumption and greenhouse gas emissions. This aligns with sustainability goals and contributes to environmental conservation efforts. Many edge devices in fog computing environments are powered by batteries or renewable energy sources with limited capacity [4]. Maximizing energy efficiency helps prolong battery life and extend the operational lifespan of these devices, reducing the frequency of battery replacements and associated maintenance costs. Energy-efficient fog computing architectures can enhance the reliability and availability of edge services by ensuring continuous operation even in resource-constrained environments. By minimizing energy consumption, organizations can mitigate the risk of power failures and ensure uninterrupted service delivery to end-users.

Rest of the article is arranged as follows: section 2 provide an overview of task scheduling in Fog Computing, in section 3, structure of scheduling task is discussed. In the next section resource provisioning of fog computing is discussed in details. In section 5 communication protocols are discussed. Further, various challenges that is faced during achieving in energy efficiency is debated, followed by the conclusion

II. OVERVIEW OF TASK SCHEDULING IN FOG COMPUTING

Task scheduling in fog computing involves allocating computational tasks to edge devices in a manner that optimizes various performance metrics such as makespan, cost latency, energy consumption, and resource utilization [5]. The goal is to effectively utilize the available computing resources while meeting application requirements and constraints. Here's an overview of task scheduling in fog computing along with energy-aware algorithms and dynamic workload allocation strategies:

- **Task Offloading:** This involves deciding which tasks should be offloaded from the central cloud to the edge devices for execution. Offloading decisions are based on factors such as task characteristics, network conditions, and device capabilities.
- **Resource Allocation:** Once tasks are offloaded to edge devices, resource allocation strategies determine how these tasks are mapped to available computational resources. This includes CPU, memory, and bandwidth allocation to ensure efficient execution.
- **Load Balancing:** Load balancing techniques distribute tasks among edge devices to evenly utilize resources and avoid overloading specific devices. Dynamic load balancing algorithms continuously monitor resource usage and adjust task assignments accordingly.

A. *Energy-Aware Task Scheduling Algorithms*

- **Energy-Efficient Task Offloading:** Algorithms aim to minimize energy consumption by intelligently offloading tasks to edge devices with lower energy costs. This involves considering factors such as device energy profiles, communication overhead, and task characteristics [6].
- **Dynamic Voltage and Frequency Scaling (DVFS):** DVFS adjusts the operating voltage and frequency of processors to match workload demands, reducing energy consumption during periods of low activity while maintaining performance [7].
- **Energy-Aware Load Balancing:** Load balancing algorithms consider energy consumption as a metric alongside other performance criteria. They aim to evenly distribute tasks while minimizing overall energy usage across edge devices.
- **Predictive Models:** Predictive models analyze historical workload data and predict future resource demands to optimize task scheduling and energy usage proactively.

B. *Dynamic Workload Allocation Strategies*

- **Proactive Resource Management:** These strategies anticipate changes in workload and resource availability to preemptively adjust task assignments. Predictive analytics and machine learning techniques are often used to forecast workload patterns and resource demands [8].
- **Adaptive Task Scheduling:** Dynamic task scheduling algorithms continuously monitor system conditions and adapt task assignments in real-time to accommodate changing workload characteristics and resource availability.
- **Fault Tolerance and Resilience:** Dynamic workload allocation considers fault tolerance mechanisms to ensure system resilience in the face of device failures or network disruptions. Redundancy and replication techniques may be employed to maintain service continuity [9].
- **Edge-to-Edge Collaboration:** Collaboration among edge devices enables dynamic workload redistribution to optimize resource utilization and energy efficiency across the fog computing infrastructure. Peer-to-peer communication protocols facilitate efficient task migration and load balancing [10].

  By employing energy-aware task scheduling algorithms and dynamic workload allocation strategies, fog computing environments can achieve better resource utilization, reduced energy consumption, and improved overall performance while meeting application requirements and constraints.

III. STRUCTURE OF SCHEDULING TASKS IN FOG COMPUTING

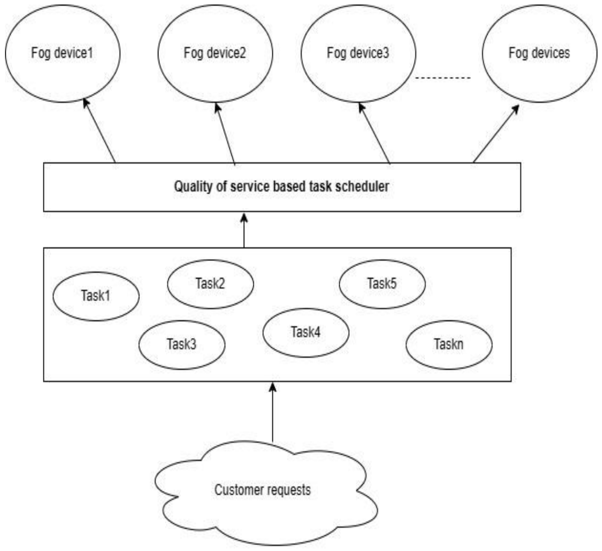

Figure 1: Task scheduling in Fog Computing

The primary mission of the scheduling algorithms is to improve performance, efficiency, and throughput while reducing costs and power consumption. Cost, energy efficiency, makespan, response time are some crucial QoS factors taken into account for the most effective task scheduling shown in Figure 1. QoS parameters for scheduling may depends upon application requirement such as in health sector emergency cases, delay in critical tasks is not tolerable. For manufacturing industries, reliability and cost are vital parameters

IV. RESOURCE PROVISIONING IN FOG COMPUTING

Resource provisioning and management in fog environments involve allocating and managing computational resources across heterogeneous edge devices to efficiently support various applications and services. Here's an overview of resource provisioning and management, along with energy-aware resource allocation algorithms and optimization techniques for heterogeneous fog nodes [11]

A. Resource Discovery:

Fog environments typically consist of a diverse set of edge devices with varying capabilities and resource availability. Resource discovery mechanisms identify and catalog available resources across the network, including CPU, memory, storage, and network bandwidth.

B. Resource Monitoring:

Continuous monitoring of resource utilization and availability provides insights into the current state of the fog environment. Monitoring metrics such as CPU usage, memory utilization, and network traffic help in making informed decisions regarding resource allocation and optimization.

C. Resource Allocation:

Resource allocation strategies determine how computational tasks and services are mapped to available resources in the fog environment. This involves dynamically provisioning resources based on application requirements, user demand, and system constraints.

D. Resource Orchestration:

Resource orchestration involves coordinating the allocation and management of resources across multiple edge devices to support complex workflows and service compositions. Orchestration frameworks automate resource provisioning and scaling to streamline deployment and management tasks.

E. Reinforcement Learning:

Reinforcement learning algorithms adaptively optimize resource allocation based on feedback from the environment. By learning from experience, these algorithms dynamically adjust resource provisioning and management strategies to maximize energy efficiency while meeting application performance goals.

F. Task Scheduling and Load Balancing:

Heterogeneous fog nodes require efficient task scheduling and load balancing techniques to evenly distribute computational workload across devices with different capabilities. Dynamic load balancing algorithms consider factors such as processing power, memory capacity, and energy efficiency to optimize resource utilization.

G. Resource Virtualization:

Resource virtualization techniques abstract physical resources into virtualized containers or slices, allowing flexible allocation and management of resources across heterogeneous fog nodes. Virtualization enables efficient resource sharing and isolation, improving overall system scalability and performance [12].

H. Edge Intelligence:

Edge intelligence algorithms leverage machine learning and AI techniques to optimize resource allocation and management in heterogeneous fog environments. These algorithms adaptively adjust resource provisioning strategies based on real-time data and environmental conditions to maximize system efficiency and responsiveness [13].

I. Resource-aware Service Placement:

Resource-aware service placement algorithms consider the resource requirements and constraints of deployed services when selecting suitable fog nodes for deployment. By matching services to nodes with compatible resource profiles, these algorithms minimize resource contention and optimize system performance [14].

By leveraging energy-aware resource allocation algorithms and optimization techniques tailored for heterogeneous fog nodes, organizations can effectively provision and manage resources to meet the diverse needs of edge computing applications while minimizing energy consumption and maximizing system performance.

V. COMMUNICATION PROTOCOLS FOR ENERGY EFFICIENCY

For fog networks, which consist of resource-constrained edge devices, employing low-power communication protocols, data aggregation and compression techniques, and energy-efficient routing protocols is crucial to optimize energy consumption, reduce communication overhead, and prolong the lifespan of edge devices. Here's an overview of each:

A. Low-Power Communication Protocols for Fog Networks

- **IEEE 802.15.4:** This standard is widely used for low-power wireless personal area networks (WPANs) and is the foundation for many IoT communication protocols such as Zigbee and Thread. It offers low data rates and low-power consumption suitable for battery-operated devices in fog networks.
- **Bluetooth Low Energy (BLE):** BLE is designed for short-range communication with low-power consumption, making it suitable for IoT applications in fog computing environments. It enables energy-efficient data transmission between nearby devices, often used for sensor networks and wearable devices [15].
- **LoRaWAN:** LoRaWAN is a long-range, low-power wireless communication protocol designed for IoT applications. It enables devices to communicate over long distances with minimal power consumption, making it suitable for fog networks spanning large geographical areas [16].
- **NB-IoT and LTE-M:** Narrowband IoT (NB-IoT) and LTE-M are cellular IoT technologies designed for low-power, wide-area communication. They provide efficient connectivity for IoT devices in fog networks, offering extended coverage and improved energy

efficiency compared to traditional cellular networks [17].

B. *Data Aggregation and Compression Techniques*

- **Spatial Data Aggregation:** In fog networks, spatially correlated data from multiple sensors can be aggregated to reduce redundancy and minimize the amount of data transmitted over the network. Aggregating data at the edge nodes before forwarding it to the cloud helps conserve energy and bandwidth.
- **Temporal Data Aggregation:** Temporal data aggregation techniques exploit the temporal correlation of sensor data to reduce transmission frequency and conserve energy. Edge devices can aggregate data over time intervals and transmit summarized information instead of sending raw data continuously.
- **Lossless Compression Algorithms:** Lossless compression techniques such as gzip or deflate can reduce the size of data payloads transmitted over the network without losing any information. Compressing data before transmission reduces bandwidth usage and energy consumption in fog networks.
- **Lossy Compression Techniques:** In scenarios where some loss of data fidelity is acceptable, lossy compression algorithms like JPEG or MP3 can be used to further reduce data size. These techniques are particularly useful for multimedia data such as images, audio, and video in fog networks [18].

C. *Energy-Efficient Routing Protocols*

- **Low-Energy Adaptive Clustering Hierarchy (LEACH):** LEACH is a popular clustering-based routing protocol for wireless sensor networks (WSNs) that aims to prolong network lifetime by rotating cluster heads and reducing energy consumption through data aggregation and localized processing [19].
- **Energy-Efficient Multi-Hop Routing:** Multi-hop routing protocols such as AODV (Ad hoc On-Demand Distance Vector) and DSR (Dynamic Source Routing) can be adapted for fog networks to route data through energy-efficient paths, avoiding nodes with low battery levels and minimizing transmission distances [20].
- **QoS-Aware Routing Protocols:** Quality of Service (QoS)-aware routing protocols prioritize energy-efficient routes while considering application-specific requirements such as latency, reliability, and bandwidth. These protocols dynamically adapt routing decisions based on network conditions and resource availability in fog networks.
- **Geographic Routing:** Geographic routing protocols use location information to forward data packets towards their destination, minimizing the number of hops and energy consumption. By leveraging geographical proximity, these protocols optimize routing paths and conserve energy in fog networks [21].

By leveraging low-power communication protocols, data aggregation and compression techniques, and energy-efficient routing protocols, fog networks can effectively manage energy consumption, reduce communication overhead, and prolong the operational lifespan of edge devices, ultimately enhancing the reliability and sustainability of edge computing infrastructures.

While significant progress has been made in improving energy efficiency in fog computing environments, several challenges remain. Future research directions and potential solutions, as well as integration with emerging technologies like AI and blockchain, can address these challenges and further enhance energy efficiency. Here's an overview:

VI. CHALLENGES IN ACHIEVING ENERGY EFFICIENCY

Managing resource heterogeneity across fog nodes remains a challenge. Integrating devices with varying capabilities and energy profiles while ensuring efficient resource allocation and utilization is essential. Fog environments experience dynamic workloads and unpredictable resource demands. Developing adaptive resource provisioning and workload management techniques to handle fluctuating workloads while maintaining energy efficiency is crucial. As fog computing deployments grow in scale, managing resource scalability becomes increasingly complex. Scalable resource provisioning and management mechanisms are needed to support large-scale fog networks while minimizing energy consumption. Energy-efficient security mechanisms are necessary to protect sensitive data and ensure privacy in fog computing environments. Addressing security and privacy concerns without compromising energy efficiency remains a challenge. Lack of interoperability and standardized protocols across fog devices hinders seamless integration and efficient resource utilization. Developing interoperable standards and protocols can facilitate efficient communication and resource management in fog environments.

VII. CONCLUSION

Energy-efficient fog computing has the potential to revolutionize the IoT and edge computing landscape by addressing the energy consumption challenges inherent in these distributed architectures. By integrating energy-aware optimization techniques, fog computing can enable the proliferation of latency-sensitive and bandwidth-intensive applications while maintaining sustainability and cost-effectiveness. Furthermore, energy-efficient fog computing fosters innovation in various domains, including smart cities, healthcare, industrial rautomation, and transportation, unlocking new opportunities for efficiency, resilience, and connectivity in the digital age.

CONFLICT OF INTERREST

The authors declare that they have no conflict of interest.

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