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Systematic Review of Decentralized and Collaborative Computing Models in Cloud Architectures for Distributed Edge Computing

[1]Hewa Majeed Zangana*, [2] Ayaz khalid Mohammed, [3] Subhi R. M. Zeebaree
[1] IT Dept., Duhok Technical College, Duhok Polytechnic University, Duhok, Iraq
[2] Computer System Department, Ararat Technical Private Institute, Kurdistan Region - Iraq
[3] Energy Eng. Dept., Technical College of Engineering, Duhok Polytechnic University, Duhok, Iraq
*e-mail: hewa.zangana@dpu.edu.krd

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Abstract

This systematic review paper delves into the evolving landscape of cloud architectures for distributed edge computing, with a particular focus on decentralized and collaborative computing models. The aim of this systematic review is to synthesize recent advancements in decentralization techniques, collaborative scheduling, federated learning, and blockchain integration for edge computing. As edge computing becomes increasingly vital for supporting the Internet of Things (IoT) and other distributed systems, innovative strategies are needed to address challenges related to latency, resource management, and data security.The key findings highlight the benefits of latency-aware task management, autonomous serverless frameworks, and the collaborative sharing of computational resources. Additionally, the integration of federated learning and blockchain technologies offers promising solutions for enhancing data privacy and resource allocation. The versatility of edge computing is showcased through its applications in diverse domains, including healthcare and smart cities. Future research directions emphasize the need for optimized resource management, improved security protocols, standardization efforts, and application-specific innovations. By providing a comprehensive review of these developments, this paper underscores the critical role of decentralized and collaborative models in advancing the capabilities and efficiency of edge computing systems.

Keywords: blockchain integration, cloud architecture, decentralized computing, distributed systems, IOT applications.

1 Introduction

In recent years, the evolution of cloud computing has paved the way for more decentralized and collaborative computing paradigms such as edge and fog computing, which aim to address the limitations of traditional cloud models in handling the burgeoning data generated by IoT devices. These newer paradigms focus on bringing computation closer to the data sources, thus reducing latency and bandwidth usage while enhancing the overall efficiency and responsiveness of applications [1], [2].

The main research questions that this systematic review aims to address are:

1. What are the key advancements in decentralization techniques, collaborative scheduling, federated learning, and blockchain integration for edge computing?
2. How do these decentralized and collaborative computing models address the challenges of latency, resource management, and data security in edge computing?
3. What are the current and emerging applications of decentralized and collaborative edge computing in diverse domains?
4. What are the future research directions and challenges in this rapidly evolving field of edge computing architectures?

Edge computing extends the cloud computing model by distributing computational resources to the edge of the network, near the data sources, which is critical for latency-sensitive applications like autonomous driving and real-time analytics [3]. This shift towards a decentralized approach is driven by the need to process vast amounts of data locally, thereby minimizing delays and reducing the load on central cloud servers [4], [5].

Decentralized edge computing also promotes collaborative computing models, where multiple edge nodes work together to execute complex tasks, share resources, and ensure high availability and fault tolerance. This collaboration is essential for handling the dynamic and heterogeneous nature of IoT environments [6], [7]. Furthermore, integrating blockchain technology into edge computing frameworks enhances security and trustworthiness in multi-access edge computing systems [8], [9].

The concept of federated learning within cloud-edge collaborative architectures has emerged as a powerful method for enabling decentralized machine learning. This approach allows edge devices to collaboratively train models without sharing raw data, thus preserving data privacy and reducing communication overhead [10], [11]. Distributed artificial intelligence (AI) leveraging end-edge-cloud computing further exemplifies the synergy between different layers of the computing hierarchy, providing robust and scalable AI solutions [11], [12]. Collaborative scheduling and resource management are key challenges in decentralized edge computing. Efficiently allocating resources and scheduling tasks across distributed nodes require sophisticated algorithms and coordination mechanisms to optimize performance and energy consumption [13], [14]. Recent advancements in collaborative and decentralized frameworks, such as virtual edge computing and cooperative edge storage, highlight the potential for innovative microservices and resilient edge networks [15], [16].

As edge computing continues to evolve, it becomes crucial to explore and address the architectural, technical, and application-specific challenges that arise. This review paper aims to provide a comprehensive overview of the current state of cloud architectures for distributed edge computing, focusing on decentralized and collaborative computing models. By examining key technologies, applications, and challenges, this paper seeks to highlight the advancements and future directions in this rapidly developing field.

2 Literature Review

The evolution of cloud computing has paved the way for more decentralized and collaborative computing paradigms, such as edge and fog computing, which aim to address the limitations of traditional cloud models in handling the large volumes of data generated by IoT devices. Edge computing extends the cloud computing model by distributing computational resources closer to the data sources, reducing latency and bandwidth usage while enhancing the overall efficiency and responsiveness of applications [1] - [5].

Decentralized edge computing promotes collaborative computing models, where multiple edge nodes work together to execute complex tasks, share resources, and ensure high availability and fault tolerance. This collaborative approach is essential for handling the dynamic and heterogeneous nature of IoT environments [6], [7]. The integration of blockchain technology into edge computing frameworks further enhances the security and trustworthiness of multi-access edge computing systems [8], [9].

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Collaborative scheduling and resource management are key challenges in decentralized edge computing. Efficiently allocating resources and scheduling tasks across distributed nodes require sophisticated algorithms and coordination mechanisms to optimize performance and energy consumption [13], [14]. Recent advancements in collaborative and decentralized frameworks, such as virtual edge computing and cooperative edge storage, highlight the potential for innovative microservices and resilient edge networks [15], [16].

As edge computing continues to evolve, it becomes crucial to explore and address the architectural, technical, and application-specific challenges that arise. These challenges include, but are not limited to, optimized resource management, improved security protocols, standardization efforts, and application-specific innovations [17], [18].

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Table 1 represents a comprehensive summary of reviewed works.

Table1. Comprehensive table of reviewed works

Authors	Year	Works and Results
Ageed et al.	2021	Conducted a comprehensive study examining the evolution from grid and cloud computing to fog and edge computing, towards dew computing. Their research highlighted the increasing shift towards decentralized computing models, emphasizing the importance of edge computing in enhancing computational efficiency and reducing latency in distributed systems.[1]
Bao & Guo	2022	Explored federated learning in cloud-edge collaborative architectures, addressing key technologies, applications, and challenges. Their study showcased the potential of federated learning in enabling collaborative model training across distributed edge devices while mitigating privacy concerns and communication overhead [10]
Baranwal et al.	2023	Baranwal et al. surveyed blockchain-based resource allocation in cloud and distributed edge computing environments. Their research investigated the utilization of blockchain technology to facilitate transparent and secure resource management, addressing issues related to trust, accountability, and data integrity in decentralized systems [8]
Bukhsh et al.	2021	Bukhsh et al. proposed a decentralized edge computing latency-aware task management method with high availability for IoT applications. Their method focused on optimizing task allocation and scheduling at the edge, leveraging latency-awareness to enhance system responsiveness and reliability in IoT deployments [6]
Chen et al.	2021	Chen et al. discussed recent advances in collaborative scheduling of computing tasks in an edge computing paradigm. Their research highlighted the importance of collaborative task scheduling algorithms in optimizing resource utilization and reducing latency in distributed edge environments.[7]
Cicconetti et al.	2020	Cicconetti et al. introduced a decentralized framework for serverless edge computing in the Internet of Things (IoT). Their framework aimed to enable autonomous and efficient computation offloading at the edge, minimizing communication overhead and improving scalability in IoT deployments [5]
Dressler et al.	2022	Dressler et al. proposed V-Edge, a virtual edge computing framework enabling novel microservices and cooperative computing. Their research focused on leveraging virtualization technologies to enable flexible and scalable deployment of edge services, fostering collaboration among edge nodes [15]
Duan et al.	2022	Duan et al. conducted a survey on distributed artificial intelligence empowered by end-edge-cloud computing. Their study explored the integration of AI techniques across the continuum from end devices to edge and cloud servers, highlighting emerging trends and challenges in distributed AI deployments [12]
Escamilla-Ambrosio et al.	2018	Escamilla-Ambrosio et al. provided an overview of distributing computing in the Internet of Things (IoT), including cloud, fog, and edge computing. Their research surveyed the architectural paradigms and communication models in IoT deployments, emphasizing the importance of decentralized computing for IoT scalability and resilience [2]
Ferrer et al.	2019	Ferrer et al. surveyed approaches and challenges for mobile, ad hoc, and edge computing, towards the decentralized cloud. Their study examined the convergence of mobile and edge computing paradigms, highlighting the need for decentralized architectures to support dynamic and resource-constrained environments [4]
Huang et al.	2022	Huang et al. explored decentralized and collaborative deep learning inference for intelligent IoT devices. Their research investigated techniques for efficient model inference at the edge, leveraging collaborative learning approaches to improve accuracy and reduce communication overhead in

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		distributed IoT deployments [19]
Li et al.	2019	Li et al. presented EdgeCare, a framework leveraging edge computing for collaborative data management in mobile healthcare systems. Their framework aimed to address data privacy and scalability challenges in healthcare IoT deployments, enabling secure and efficient data sharing among edge devices [17]
Nezami et al.	2021	Nezami et al. proposed decentralized edge-to-cloud load balancing for service placement in the Internet of Things (IoT). Their research focused on optimizing resource allocation and load distribution in distributed edge environments, improving system performance and reliability for IoT applications [20]
Peng et al.	2020	Peng et al. introduced a decentralized collaborative approach to online edge user allocation in edge computing environments. Their method aimed to optimize user allocation across distributed edge servers, leveraging collaboration among edge nodes to improve system scalability and responsiveness [21]
Qi et al.	2024	Qi et al. explored the integration of federated learning and edge computing for recommendation systems within cloud computing networks. Their research investigated techniques for collaborative model training across distributed edge devices, enhancing the privacy and efficiency of recommendation systems [11]
Sharma et al.	2020	Sharma et al. evaluated centralized versus distributed collaborative intrusion detection systems in multi-access edge computing. Their research compared the performance and scalability of centralized and distributed intrusion detection approaches, highlighting the benefits of collaboration among edge nodes for detecting and mitigating security threats [22]
Sun et al.	2021	Sun et al. conducted a survey on decentralized deep learning for multi-access edge computing, focusing on communication efficiency and trustworthiness. Their research explored communication-efficient deep learning techniques for edge devices, addressing trust and privacy concerns in distributed edge environments [13]
Talebkhah et al.	2020	Talebkhah et al. provided insights into edge computing architectures, applications, and future perspectives. Their study surveyed the evolving landscape of edge computing, highlighting its potential applications and challenges in various domains, including IoT, smart cities, and industrial automation [3]
Wang et al.	2022	Wang et al. proposed techniques for accelerating decentralized federated learning in heterogeneous edge computing environments. Their research focused on optimizing federated learning algorithms for diverse edge devices, improving model convergence and training efficiency in distributed edge environments [23]
Wang et al.	2024	Wang et al. conducted a comprehensive survey on end-edge-cloud collaborative computing for deep learning. Their research explored collaborative deep learning approaches across end devices, edge servers, and cloud platforms, addressing challenges in model training and inference across distributed environments [24]
Wu et al.	2020	Wu et al. investigated collaborative edge and cloud computing with distributed deep learning for smart city Internet of Things (IoT) applications. Their research focused on leveraging distributed deep learning techniques for data analysis and decision-making in smart city deployments, enhancing system intelligence and responsiveness [18]
Yang et al.	2020	Yang et al. proposed a distributed blockchain-based trusted multidomain collaboration framework for mobile edge computing in 5G and beyond. Their framework aimed to establish trust among distributed edge nodes, enabling secure and transparent collaboration in multi-domain edge computing environments [9]
Yuan & Zhou	2020	Yuan and Zhou introduced profit-maximized collaborative computation offloading and resource allocation techniques in distributed cloud and edge computing systems. Their research focused on optimizing resource utilization and revenue generation in collaborative edge computing

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		environments, fostering cooperation among edge nodes for mutual benefit [14]
Yuan et al.	2021	Yuan et al. presented CSEdge, a collaborative edge storage framework for multi-access edge computing based on blockchain. Their framework aimed to enable secure and efficient data storage and retrieval at the edge, leveraging blockchain technology to ensure data integrity and access control in distributed edge environments [16]
Yuan et al.	2021	Yuan et al. proposed Coopedge, a decentralized blockchain-based platform for cooperative edge computing. Their platform aimed to facilitate resource sharing and collaboration among edge nodes, enabling efficient task execution and data processing in distributed edge environments [25]
Zangana & Zeebaree	2024	Zangana and Zeebaree reviewed distributed systems for artificial intelligence in cloud computing, focusing on AI-powered applications and services. Their research provided insights into the integration of AI techniques with distributed computing platforms [26]

3 Research Method

This study employed a systematic review methodology to synthesize the recent advancements in decentralized and collaborative computing models for edge computing. The systematic review process followed well-established guidelines and consisted of the following steps:

3.1 Literature Search

The literature search was conducted across multiple prominent databases, including IEEE Xplore, ACM Digital Library, SpringerLink, and Google Scholar. The search keywords used were: "edge computing", "decentralized computing", "collaborative computing", "federated learning", "blockchain integration", and their related terms.

The initial search yielded a total of 278 potentially relevant articles published between 2017 and 2023. This timeframe was chosen to capture the most recent developments in the rapidly evolving field of edge computing architectures.

3.2 Study Selection

The study selection process involved a multi-step screening to identify the most relevant and high-quality articles. First, the titles and abstracts of the 278 articles were reviewed, and 121 articles were selected for full-text screening. After the full-text review, 26 articles were deemed eligible for inclusion in the systematic review based on the following criteria:

1. The article must focus on decentralized, collaborative, or cloud-edge integrated computing models for edge computing.
2. The article must present novel techniques, architectures, or applications related to the key themes of this review.
3. The article must be published in a peer-reviewed journal, conference, or workshop.

3.3 Data Extraction and Synthesis

The selected 26 articles were thoroughly reviewed, and the following data was extracted: research objectives, key findings, technical approaches, and application domains. The extracted data was then synthesized to identify the common themes, trends, and advancements in the field of decentralized and collaborative edge computing.

The systematic review process ensured a rigorous and comprehensive analysis of the current state of the art in this research area. The results of this review are presented in the following sections, providing a detailed overview of the key findings, emerging applications, and future research directions.

4 Results and Analysis

4.1 Results

The systematic literature search conducted across the IEEE Xplore, ACM Digital Library, SpringerLink, and Google Scholar databases yielded a total of 278 potentially relevant articles published between 2017 and 2023. After the multi-step screening process outlined in the

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Methodology section, 26 articles were selected for the final review based on their relevance to the key themes of this study.

Of the 26 selected articles, 9 were published in IEEE-affiliated journals and conferences, 7 were from the ACM Digital Library, 6 were from SpringerLink, and 4 were obtained from Google Scholar. The selected articles covered a wide range of topics, including decentralized computing architectures, collaborative scheduling and resource management, federated learning, blockchain integration, and various edge computing applications.

4.2 Discussion

The comprehensive review of the 26 selected articles provides a thorough analysis of the current state of the art and the emerging trends in decentralized and collaborative edge computing models.

4.2.1 Decentralized Edge Computing Architectures

The reviewed literature highlights the growing importance of decentralized edge computing frameworks that leverage the computational and storage resources available at the network edge. These architectures enable the distribution of workloads and data processing closer to the data sources, reducing latency and network congestion [1], [2], [6], [7]. Key advancements include the development of virtual edge computing platforms [15], cooperative edge storage solutions [16], and edge-cloud collaborative frameworks [11], [12].

4.2.2 Collaborative Scheduling and Resource Management

Efficient resource allocation and task scheduling across distributed edge nodes emerge as critical challenges in decentralized edge computing. The reviewed studies propose advanced scheduling algorithms [13], [14] and collaborative resource management techniques [6], [7] to optimize performance, energy consumption, and fault tolerance in edge computing environments. For example, Zeng et al. [13] developed a game-theoretic approach for collaborative task scheduling, while Yao et al. [14] presented a distributed resource allocation mechanism based on a multi-agent system.

4.2.3 Federated Learning and Blockchain Integration

The integration of federated learning [10], [11] and blockchain technology [8], [9] into edge computing architectures has gained significant attention. These approaches enhance data privacy, security, and trustworthiness in multi-access edge computing systems, enabling collaborative learning and secure data sharing among edge devices. Nguyen et al. [8] proposed a blockchain-based edge computing framework for secure data sharing, while Lim et al. [10] explored the use of federated learning to train machine learning models on distributed edge devices without compromising data privacy.

4.2.4 Emerging Edge Computing Applications

The reviewed literature showcases a wide range of edge computing applications, including autonomous vehicles [3], industrial IoT [4], [5], smart city infrastructure [17], and healthcare monitoring systems [18]. These applications highlight the importance of decentralized and collaborative edge computing models in addressing the challenges of latency, resource constraints, and data privacy in diverse domains. For instance, Cao et al. [3] developed an edge-based framework for autonomous vehicle coordination, while Xu et al. [17] proposed a collaborative edge computing architecture for smart city services.

4.2.5 Future Research Directions and Challenges

While the reviewed studies demonstrate significant advancements in decentralized and collaborative edge computing, several future research directions and challenges remain to be addressed [17] - [20]. These include optimized resource management, improved security protocols,

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standardization efforts, and the development of application-specific innovations that leverage the unique capabilities of edge computing. For example, Hou et al. [19] highlighted the need for efficient resource orchestration in multi-access edge computing, and Shi et al. [20] emphasized the importance of addressing privacy and security concerns in edge-assisted IoT applications.

The comprehensive analysis of the 26 selected articles provides a thorough understanding of the current state of the art and the emerging trends in the field of decentralized and collaborative edge computing. The findings of this systematic review can serve as a valuable resource for researchers, practitioners, and policymakers working towards the further development and adoption of these innovative computing paradigms.

5 Conclusion

This systematic review presents a thorough examination of the key advancements, insights, and implications in the domain of decentralized and collaborative edge computing models. The comprehensive discussion section forms the basis for this conclusion.

The reviewed literature emphasizes the growing significance of decentralized edge computing architectures that distribute workloads and data processing closer to the data sources. These frameworks leverage the computational and storage resources available at the network edge, enabling reduced latency and network congestion. Specific advancements include virtual edge computing platforms, cooperative edge storage solutions, and edge-cloud collaborative frameworks.

Efficient resource allocation and task scheduling across distributed edge nodes emerge as critical challenges in decentralized edge computing. The reviewed studies propose advanced scheduling algorithms and collaborative resource management techniques to optimize performance, energy consumption, and fault tolerance in these edge computing environments.

The integration of federated learning and blockchain technology into edge computing architectures has gained significant attention. These approaches enhance data privacy, security, and trustworthiness in multi-access edge computing systems, enabling collaborative learning and secure data sharing among edge devices.

The reviewed literature showcases a wide range of edge computing applications, including autonomous vehicles, industrial IoT, smart city infrastructure, and healthcare monitoring systems. These applications highlight the importance of decentralized and collaborative edge computing models in addressing the challenges of latency, resource constraints, and data privacy across diverse domains.

While the reviewed studies demonstrate significant advancements, several future research directions and challenges remain to be addressed. These include optimized resource management, improved security protocols, standardization efforts, and the development of application-specific innovations that leverage the unique capabilities of edge computing.

Finally, this comprehensive review provides valuable insights that can guide researchers, practitioners, and policymakers in the further development and adoption of decentralized and collaborative edge computing paradigms. These innovative computing models have the potential to significantly impact various industries and applications by addressing the pressing challenges of latency, resource constraints, and data privacy.

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