A Survey of Edge Management and Orchestration in Edge Computing

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Abstract

Edge computing, a transformative technology paradigm, extends cloud computing capabilities closer to data sources and end-users, offering low latency, high bandwidth, and real-time data processing. This paper comprehensively explores edge management and orchestration, delving into key aspects such as infrastructure management, resilience, data processing, task management, policy enforcement, cost optimization, and real-world case studies. It also highlights emerging trends, underscoring the importance of effective edge management in securing data, ensuring efficiency, and meeting the dynamic demands of modern applications. Edge computing's promising future hinges on automation and advanced technologies, and effective edge management positions organizations at the forefront of technological innovation.

Keywords: Edge computing, Edge management, Edge orchestration, Edge security, Edge data processing, Edge resource allocation, IoT, Edge computing trends, Edge computing applications, Automated edge management, Edge computing optimization

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1. Introduction

Edge computing has emerged as a transformative technology paradigm that promises to revolutionize the way we process and manage data. Unlike traditional cloud computing, which centralized data processing and storage in remote data centers, edge computing extends these capabilities to the edge of the network, closer to data sources and end-users. This proximity offers low latency, high bandwidth, and real-time data processing, making it a game-changer for a wide range of applications.

This paper serves as a gateway to understanding the fundamentals of edge computing, its key characteristics, and the pivotal role of edge management and orchestration in optimizing its potential. From infrastructure management to resilience and security, data processing, and cost optimization, edge management plays a critical role in ensuring the success of edge computing initiatives.

As the digital landscape continues to evolve, the importance of effective edge management and orchestration becomes increasingly apparent. This guide delves into the intricacies of edge management and explores its diverse aspects, from real-world case studies to emerging trends, to provide a comprehensive understanding of this dynamic and transformative field.

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2. Edge Computing Fundamentals

Edge computing is a fundamental paradigm that takes cloud computing to the next level by bringing the processing power closer to the data sources and end-users, reducing latency and improving performance. This approach leverages the low latency, high bandwidth, and real-time data processing capabilities inherent at the edge of the network, where devices and sensors generate vast amounts of data. By processing data closer to its origin, edge computing optimizes response times and enhances the efficiency of various applications, making it especially vital in use cases requiring immediate and time-sensitive decision-making, such as autonomous vehicles, industrial automation, and smart cities. Edge computing thus plays a pivotal role in harnessing the full potential of the Internet of Things (IoT) and delivering a seamless, responsive, and efficient user experience[AOEiliA+23]. Figure 1 is the visual representation of the results from related work in the field of edge service orchestration. In Figure 1a, you can see how works are categorized based on the experiments conducted. Meanwhile, Figure 1b breaks down works using container orchestration, sorting them by the tool used or whether a custom implementation was employed. Figure 1c highlights the count of works that incorporate a specific Quality of Service (QoS) parameter for service scheduling, and Figure 1d outlines the hardware utilized for running edge nodes, along with the frequency of occurrences in the relevant works.

(a) Type of applied experiment methodology.

(b) Utilized container orchestration tool.

(c) Targeted QoS parameter.

(d) Type of hardware running the edge nodes.
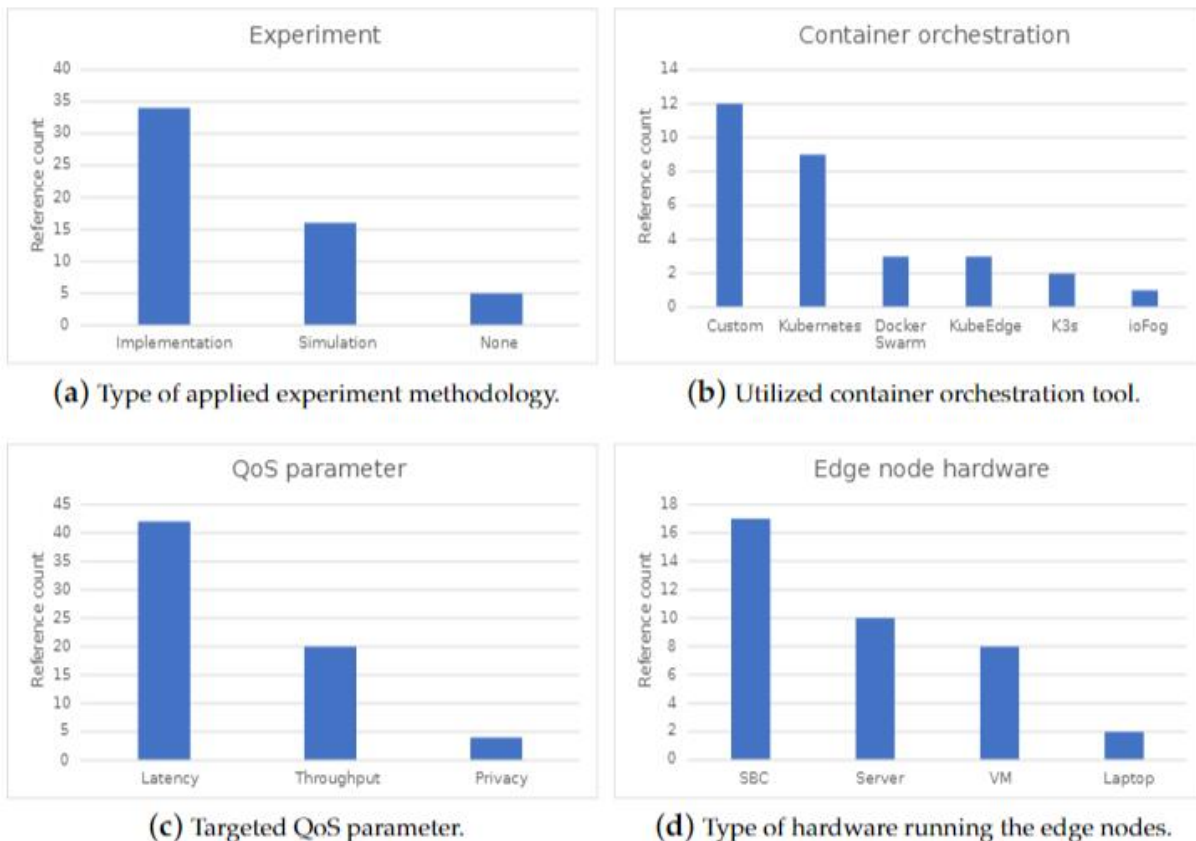
Figure 1. General summary of a related work survey (distribution by category)
[AOEiliA+23]

2.1 Edge vs. Cloud Computing

Edge computing and cloud computing represent two distinct computing paradigms that serve different purposes. While cloud computing revolves around centralized data storage and processing in remote data centers, edge computing takes a decentralized approach by bringing computational resources closer to the data sources and end-users. In cloud computing, data is sent to these remote data centers for analysis and processing, which can introduce latency and delays, particularly in applications requiring real-time responses [Vaquero19]. In contrast, edge computing is characterized by its low latency and high bandwidth capabilities, allowing data to be processed locally, at or near the source, significantly reducing the delay in data analysis and decision-making. This makes edge computing ideal for applications like autonomous vehicles, IoT devices, and industrial automation, where instantaneous responses are critical. Both cloud and edge computing have their strengths and are often used in conjunction to create a hybrid approach, combining the scalability and cost-effectiveness of the cloud with the low latency and real-time capabilities of edge computing to meet the diverse needs of modern applications and services.

2.2 Key Characteristics of Edge Environments

Key characteristics of edge environments extend beyond their suitability for low-latency and reduced backhaul traffic applications like video streaming, delivery, and surveillance systems [Chiang23]. One distinctive feature is the volatile nature of the edge environment, where resource availability can change dynamically. This volatility poses challenges for orchestrating and managing resources effectively, requiring sophisticated mechanisms for load balancing and resource allocation. Moreover, edge computing leverages its proximity to end-users to provide low-latency and real-time applications, enhancing user experiences in scenarios where immediate responses are critical. On the other hand, cloud computing excels in providing scalability and reliability for large-scale data processing and storage, making it an ideal choice for applications with substantial computational needs and data storage requirements. The synergy between edge and cloud computing creates a powerful combination, allowing organizations to harness the benefits of both paradigms to meet the diverse and evolving demands of modern applications while addressing the unique characteristics and challenges presented by edge environments.

2.3 Infrastructure Management in Edge Computing

Infrastructure management in edge computing is a multifaceted discipline that encompasses several crucial aspects, each vital for the efficient and reliable operation of edge environments. These facets include resource allocation and optimization, service deployment and scaling, network management, and addressing the inherent challenges in this dynamic ecosystem.

2.4 Resource Allocation and Optimization

Resource allocation and optimization are pivotal in the context of edge computing, particularly given the diversity of computing equipment found in edge scenarios. The heterogeneity of devices and hardware demands meticulous orchestration of computing resources to ensure optimal performance and minimize latency. Lightweight versions of orchestration platforms like Kubernetes shown as Figure 2, such as K3s and MicroK8s, have been developed to tackle this

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challenge, allowing for efficient and streamlined resource allocation [AOEiliA+23]. These solutions help adapt computing resources to the specific needs of edge applications, enhancing their responsiveness and reliability.
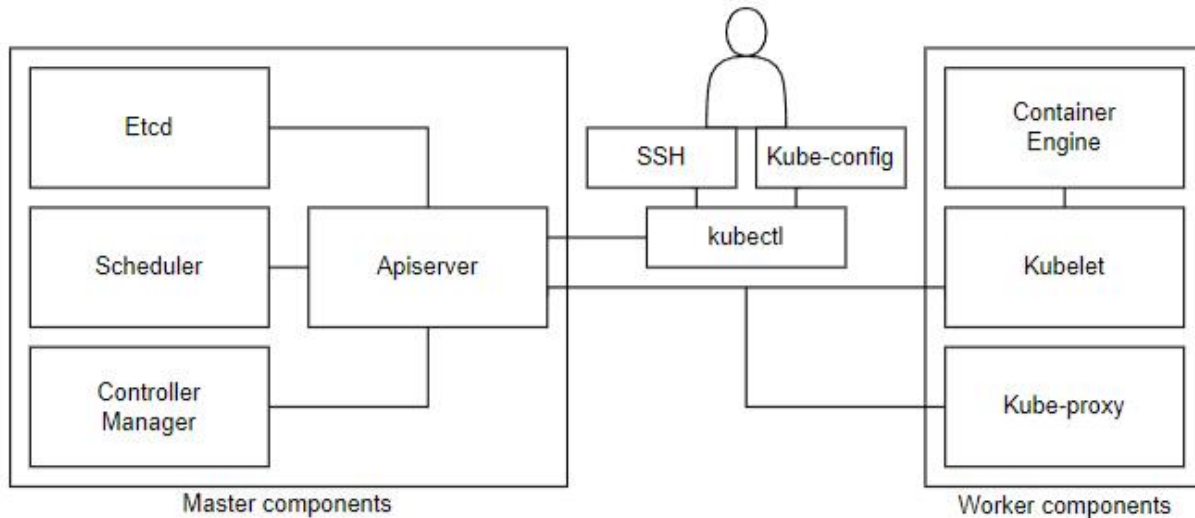

Figure 2. Kubernetes architecture [AOEiliA+23]

2.5 Service Deployment and Scaling

Service deployment and scaling represent another critical facet of infrastructure management in edge computing. Efficiently deploying and scaling services within edge environments is essential to cater to fluctuating demand and ensure high service availability. Orchestration tools like KubeEdge and ioFog play a pivotal role in this process, facilitating the deployment, operation, and networking of microservices [Jiang18][Pahl15]. They empower edge environments to dynamically adjust their service portfolios to meet varying workloads, enhancing the adaptability and scalability of edge computing solutions.

2.6 Network Management in Edge Environments

Network management within edge environments is fundamental for achieving efficient communication and connectivity. Given the distributed nature of edge computing, effective network management is essential to ensure seamless data transfer and interactions among devices and services. Platforms like the Eclipse ioFog offer capabilities for communication among microservices, augmented with additional components such as AMQP Router and Proxy. These components enable efficient communication and translation of HTTP requests, ensuring that edge devices and services can interoperate seamlessly and efficiently [Vaquero19].

2.7 Challenges and Strategies

Challenges in infrastructure management for edge computing are multifaceted, including the management of heterogeneous resources, addressing the dynamism of edge environments, and ensuring efficient orchestration and optimization of resources [Vano23]. As edge computing

continues to evolve and grow, strategies are emerging to overcome these challenges. Lightweight orchestration solutions like K3s and MicroK8s and orchestration tools like KubeEdge and ioFog are part of the strategy to address the diverse needs of edge computing environments, ensuring that they can meet the unique demands of a wide array of applications while maintaining high performance and reliability. Additionally, edge computing solutions are becoming increasingly adaptive, allowing them to dynamically scale and allocate resources as required, ultimately enhancing the capabilities and efficiency of edge environments.

3. Resilience and Security in Edge Environments

The assurance of resilience and security within edge environments is of paramount importance to ensure the stability and integrity of edge computing systems. This section delves into the key considerations regarding fault tolerance and resilience strategies, security and privacy concerns, as well as risk assessment and mitigation.

3.1 Fault Tolerance and Resilience Strategies

In the dynamic landscape of edge computing, fault tolerance and resilience strategies are essential to uphold system stability even in the face of failures and disruptions. Achieving this necessitates the deployment of techniques like redundancy, load balancing, and failover mechanisms [AOEiliA+23]. Redundancy, for instance, entails having backup resources or components readily available to assume the workload in case of a failure. Load balancing ensures that tasks are distributed evenly among resources, optimizing performance and mitigating the risk of overload. Failover mechanisms automatically switch to backup resources when primary components fail, ensuring uninterrupted service. Grover and Garimella (2018) proposed an agent-based model to tolerate faults and improve reliability of Edge servers in a hierarchical cloud-fog-mist-dew architecture [Shahraki22]. These strategies collectively form a robust framework that enables edge environments to withstand and recover from unexpected events, ultimately enhancing reliability and uptime.

3.2 Security and Privacy Concerns

Security and privacy concerns loom large in the context of edge computing, primarily due to the distributed nature of edge environments. Safeguarding against potential threats and vulnerabilities is a top priority. This includes fending off malicious attacks, protecting sensitive data, and implementing secure communication protocols. Robust security measures must be in place to thwart intrusions and data breaches. Moreover, ensuring data privacy is paramount, especially when handling sensitive information. Implementing secure communication protocols helps in safeguarding data in transit, like use of blockchain to ensure data privacy and service reliability in IoT scenarios [Guo20]. These collective efforts fortify the edge environment against security breaches and maintain the confidentiality and integrity of data, ultimately fostering trust among users and stakeholders.

3.3 Risk Assessment and Mitigation

A proactive approach to risk assessment and mitigation is indispensable in managing potential threats and vulnerabilities in edge environments. This involves evaluating the impact of identified risks, implementing tailored security measures, and continually monitoring and updating security protocols. By identifying potential risks and understanding their implications, organizations can develop mitigation strategies that align with their specific operational context. Continual monitoring ensures that security measures remain effective in the face of evolving threats [Vaquero19]. This iterative process empowers edge environments to stay resilient and secure, adapting to emerging risks and providing a robust and protected infrastructure for a wide range of edge computing applications.

3.4 Policy Enforcement Mechanisms

Effective policy enforcement, interoperability, and standardization are pivotal to the success and scalability of edge computing systems. This section delves into the key components of policy enforcement mechanisms, the challenges and solutions in achieving interoperability, and the critical role of edge computing standards and best practices.

Policy enforcement mechanisms in the realm of edge computing are essential to ensure system security and regulatory compliance. These mechanisms are designed to seamlessly integrate with existing network management systems while accommodating user mobility, all the while maintaining edge-to-edge service continuity [Carnevale18]. The enforcement of policies is indispensable to guarantee data privacy, security, and compliance with regulations, which is especially crucial in applications like healthcare, finance, and critical infrastructure. Policy enforcement mechanisms are needed to establish trust and access control with edge devices under different organizational boundaries [Tam22]. These mechanisms adapt and evolve as edge computing environments continue to grow and face evolving threats and regulatory landscapes.

3.5 Interoperability Challenges and Solutions

Interoperability challenges surface in the complex environment of edge computing, where different technologies such as cloud, edge, and IoT converge [Shahraki22]. The integration of these technologies requires a harmonious orchestration to ensure seamless data exchange, communication, and operation. The Osmotic Computing paradigm emerges as a solution to abstract services and infrastructure, facilitating the fluid flow of services between cloud, edge, and IoT. It enables the creation of a unified ecosystem where these technologies coexist and interoperate seamlessly. Solving interoperability challenges is integral to harnessing the full potential of edge computing, allowing organizations to build comprehensive and interconnected systems that cater to diverse use cases and industry needs.

3.6 Edge Computing Standards and Best Practices

Standardization and adherence to best practices are foundational for ensuring the smooth integration and interoperability between various edge computing platforms and components. Industry bodies like the OpenFog consortium and ETSI MEC drive the development of edge

computing architectures, testbed implementations, and best practices to enable end-to-end IoT services [Slamnik-KrijeAitorac23]. These initiatives focus on defining common frameworks, protocols, and interfaces to ensure efficient resource utilization and enhance the user experience in edge computing environments. By establishing standardized protocols and best practices, the industry can ensure consistency, reliability, and security, and promote the adoption and expansion of edge computing in various sectors, ultimately fostering innovation and collaboration in this dynamic and evolving field.

4. Data Management and Processing at the Edge

Efficient data management and processing are pivotal aspects of edge computing, where data is generated and consumed at the network's periphery. This section delves into the core elements of data management strategies, edge intelligence, and data processing technologies, and their significance in harnessing the potential of edge environments.

4.1 Data Management Strategies

Data management strategies at the edge are multifaceted and encompass critical components like location-awareness, computation placement, replication, and recovery [AOEiliA+23]. These strategies are essential to grapple with the extensive data distribution characteristic of edge clouds. In this distributed landscape, edge resources are tasked with both computation and data storage [Jiang18]. Location-awareness ensures that data is processed in proximity to its source, minimizing latency and enhancing efficiency. Computation placement involves intelligently allocating computing resources to specific tasks, optimizing performance. Replication strategies enhance data availability, safeguarding against data loss or unavailability in case of node failures. Finally, recovery mechanisms ensure that data can be restored in the event of disruptions, contributing to system reliability and resilience.

4.2 Edge Intelligence and Data Processing

Edge intelligence and data processing technologies play a pivotal role in the efficient processing of data at the edge. These technologies empower the inclusion of remote and constrained devices in the processing plane, surmounting challenges such as limited resources, unstable network environments, and device heterogeneity [Pahl15]. Edge intelligence allows for localized decision-making and data processing, reducing the burden on central data centers. This is particularly crucial in scenarios where immediate responses are vital, such as autonomous vehicles and industrial automation. By bringing intelligence to the edge, organizations can unlock the full potential of their data and ensure that data-driven insights can be generated in real-time, enhancing operational efficiency and user experiences.

4.3 Data Storage and Processing Technologies

Various data storage and processing technologies are integral to the successful implementation of edge computing. For instance, container engines like Docker and Podman are employed to build and run container images, offering lightweight and efficient solutions for edge computing

[Vano23]. Containers are highly portable, allowing applications to run consistently across various edge devices and environments. This flexibility is vital in edge computing, where device heterogeneity is common. Furthermore, the management of virtualized resources, including nodes and edges, is crucial within edge clouds. These resources, coupled with compute, storage, and network resources, enable seamless interactions between end devices and traditional cloud computing data centers [Vaquero19]. Collectively, these technologies empower organizations to manage their data and processing needs at the edge efficiently, ensuring that edge computing environments can effectively support a wide array of applications while maintaining data integrity and accessibility.

4.4 Task Management in Edge Computing

Effective task management lies at the heart of edge computing systems, where tasks are diverse and dynamic, demanding meticulous orchestration. This section delves into the critical facets of task scheduling and workload allocation, real-time task management, and task monitoring and optimization.

4.5 Task Scheduling and Workload Allocation

Task scheduling and workload allocation are fundamental to optimizing the operation of edge computing systems. These processes involve the efficient assignment of tasks to edge servers based on the available resources, while minimizing task completion times and adhering to stringent latency constraints [Pahl15]. Task scheduling algorithms and strategies play a pivotal role in ensuring that tasks are allocated to the most appropriate edge resources. Workload allocation, in turn, aims to balance the distribution of tasks across the available resources, ensuring that no resource is overburdened and that tasks are executed in proximity to their data sources. These strategies are essential for enhancing system efficiency and responsiveness, making them crucial for various edge computing applications.

4.6 Real-time Task Management

Real-time task management is a critical component of edge computing, particularly when considering users' services and the dynamic nature of wireless connections [Vaquero19]. This aspect involves orchestrating users' services in a way that minimizes interruptions in task offloading. It must account for factors such as users' mobility and the inherent uncertainty of wireless connections, ensuring that tasks continue to execute seamlessly as users move through edge environments. Real-time task management is essential in use cases like mobile edge computing, where consistent and uninterrupted service delivery is paramount. It necessitates the use of sophisticated mechanisms to maintain the flow of data and tasks, even when connectivity conditions are unpredictable.

4.7 Task Monitoring and Optimization

Task monitoring and optimization are essential for continuously improving the performance and efficiency of edge computing systems. These processes involve the evaluation of various metrics, including energy consumption, latency, and security. Managing energy consumption spans both

network equipment and user devices, with an emphasis on optimizing power usage to extend device lifespans and reduce the environmental footprint. Reducing latency is achieved through efficient workload assignment and task prioritization, ensuring that tasks are processed as quickly as possible. Furthermore, ensuring information security, cyber-security, forensic security, and network security are integral components of task monitoring and optimization [Vano23]. These measures are vital to protect sensitive data, detect and mitigate security threats, and maintain the overall integrity and reliability of edge computing systems. Collectively, these aspects are instrumental in ensuring that edge computing systems operate effectively and securely in a dynamic and data-intensive landscape.

5. Efficiency and Cost Optimization

Efficiency and cost optimization are critical considerations in the design and operation of edge computing systems. This section explores the core elements of energy efficiency strategies, cost optimization in edge environments, and sustainable practices that contribute to a greener and more cost-effective edge computing ecosystem.

5.1 Energy Efficiency Strategies

Energy efficiency strategies in edge computing are instrumental in optimizing resource consumption and reducing the environmental footprint. One approach involves the use of dynamic computation offloading algorithms based on Lyapunov Optimization. These algorithms aim to enhance the Quality of Experience (QoE) while simultaneously minimizing energy consumption [Carnevale18]. By intelligently offloading computation tasks to the most energy-efficient resources, organizations can ensure that edge computing systems operate with minimal energy consumption, which is particularly crucial in mobile and battery-powered edge devices.

Another strategy involves the adoption of caching models for edge networks. A notable example is the Deep Q-Network (DQN) model proposed by Cui, which optimizes video caching in edge networks [Shahraki22]. By strategically caching content at the edge, data can be retrieved locally, reducing the need for resource-intensive network requests and thus lowering energy consumption. These energy-efficient strategies are instrumental in promoting sustainability and reducing operational costs.

Additionally, Merluzzi et al. introduce a dynamic resource allocation strategy for Edge Machine Learning (EML) applications. This strategy focuses on the efficient utilization of radio and CPU resources, which enhances end-to-end delay and accuracy [Tam22]. By optimizing the allocation of resources, edge computing systems can operate with a reduced energy footprint, ensuring that resources are used efficiently without compromising performance.

5.2 Cost Optimization in Edge Environments

Cost optimization in edge environments is crucial to ensure that the deployment and operation of edge computing systems remain financially sustainable. One avenue for cost optimization is through efficient Service Function Chain (SFC) orchestration. Guo introduced a dynamic hierarchical SFC orchestration algorithm based on Deep Reinforcement Learning (DRL) [Guo20].

This algorithm minimizes orchestration costs while simultaneously enhancing the quality of service [Vano23]. By dynamically orchestrating SFCs based on real-time conditions, organizations can allocate resources judiciously, reducing operational costs and ensuring that services are delivered efficiently.

5.3 Sustainable Practices in Edge Computing

Sustainability in edge computing is facilitated through innovative practices and technologies. The use of consortium blockchain, in conjunction with DRL-based algorithms, contributes to sustainability efforts. Guo integrates consortium blockchain into the distributed SFC orchestration model, enabling trusted resource sharing among edge computing participants [Guo20]. This not only enhances security but also fosters sustainable practices by promoting resource collaboration and minimizing redundant infrastructure.

DRL-based algorithms further optimize service provision and resource allocation, leading to cost and energy savings [Guo20]. These algorithms make real-time decisions on task offloading, resource allocation, and network management based on the evolving operational environment, ensuring that resources are used efficiently, thereby contributing to cost reduction and energy conservation. By incorporating sustainable practices and advanced technologies, edge computing systems can align with eco-friendly objectives and economic viability, helping organizations meet the growing demands for efficiency and sustainability.

6. Case Studies and Practical Applications

This section sheds light on real-world examples of successful edge management, lessons learned from deployments, and emerging trends that are shaping the landscape of edge management.

6.1 Real-world Examples of Edge Management Success

Real-world examples of edge management success serve as testaments to the tangible benefits that can be reaped from the implementation of edge computing. Plastiras offers a compelling case study by reviewing the utilization of machine learning (ML) techniques at the edge of a network. They demonstrate significant improvements in performance and efficiency through a computer vision case study, emphasizing the transformative power of ML at the edge [Shahraki22].

Rodrigues delves into the practical application of ML in mobile edge computing (MEC) and its impact on network management within MEC. Their examination extends to diverse devices and the challenges they present, highlighting the concrete advantages of ML in addressing the intricacies of MEC environments [Slamnik-KrijeAitorac23].

Liu presented a case study focusing on the deployment of ML techniques in multi-access edge computing (MAEC) for IoT and 5G networks. Their work investigates mobility management and pricing strategies as integral components of these technology integrations, providing insights into how ML can streamline operations and enhance network performance [Vano23].

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Xu explores the concept of edge intelligence, encompassing various aspects like edge offloading, inference, training, and caching. They emphasize the relevance of device-to-device solutions and the diverse computing paradigms that shape the edge landscape. Through their study, they reveal the potential of edge intelligence in revolutionizing various industries and use cases [Guo20].

Aslanpour introduced the innovative concept of server-less edge computing, a paradigm shift that reimagines resource provisioning, accounting, and pricing in edge environments. Their work highlights how this concept can streamline resource management, reduce operational overhead, and promote cost-effective edge solutions. These case studies collectively underscore the transformative power of edge computing and its capacity to drive innovation in a multitude of domains [Taleb17].

6.2 Lessons Learned from Deployments

Lessons learned from deployments in the field of edge management are invaluable in shaping best practices and refining strategies. Practical experiences offer insights into the nuances and challenges faced in edge computing environments. Deployments have revealed the significance of efficient task management, data processing, security, and optimization in edge ecosystems. Edge management success often hinges on the adaptability and scalability of solutions, enabling organizations to meet the evolving demands of edge applications while maintaining operational efficiency.

6.3 Emerging Trends in Edge Management

Emerging trends in edge management signify the evolving landscape of edge computing. As Vano mentioned that new workload virtualization approaches, such as WebAssembly modules, and the joint orchestration of heterogeneous workloads are emerging trends in edge management [Vano23]. These trends encompass a wide array of innovations, such as the integration of machine learning and artificial intelligence at the edge, enhanced security measures to protect sensitive data, and more advanced orchestration and resource allocation techniques. Edge management is also evolving to address the increasing demand for sustainability and energy efficiency in edge computing. As edge environments continue to grow and diversify, so too will the trends that shape the future of edge management, ensuring that it remains a dynamic and rapidly evolving field at the forefront of technological advancement.

7. Summary

Edge computing is a transformative paradigm that extends cloud computing to the edge of the network, closer to data sources and end-users. This comprehensive guide has explored key aspects of edge management and orchestration, shedding light on critical elements such as infrastructure management, resilience and security, data handling, task management, policy enforcement, cost optimization, and real-world case studies.

Key takeaways include the importance of efficient resource allocation, the need for resilience and security measures, the significance of effective data management and processing, and the role of policy enforcement and interoperability. Furthermore, the guide underscores the potential for edge

computing to revolutionize various industries and showcases real-world case studies as evidence of its transformative power.

The future prospects of edge management and orchestration are promising, with automation and advanced technologies playing pivotal roles in enhancing edge computing capabilities. Effective edge management and orchestration are vital for securing data, ensuring efficiency, and meeting the dynamic demands of modern applications. By embracing best practices in edge management, organizations can position themselves at the forefront of technological innovation, providing cutting-edge solutions for a rapidly evolving digital landscape.

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8. List of Acronyms

IoT	Internet of Things
5G	5th Generation Wireless
MEC	Mobile Edge Computing
ML	Machine Learning
DRL	Deep Reinforcement Learning
QoE	Quality of Experience
QoS	Quality of Service
MAEC	Multi-Access Edge Computing
SFC	Service Function Chain
DL	Deep Learning
DQN	Deep Q-Network
EML	Edge Machine Learning
AMQP	Advanced Message Queuing Protocol
HTTP	Hypertext Transfer Protocol
ETSI	European Telecommunications Standards Instute
GUI	Graphical User Interface
SDN	Software-Defined Networking

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