Enhancing Quality of Service in Software-Defined Internet of Things (SD-IoT) Environment: a review

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Abstract. The Internet of Things (IoT) connects billions of devices via the Internet, providing real-time intelligent services. Software-Defined Networking (SDN) represents an advanced solution for managing traffic and resources in these IoT environments, enabling centralized and flexible management through the separation of control and data. This article provides an in-depth analysis of current approaches to addressing Quality of Service (QoS) challenges in SD-IoT networks. It examines specific techniques such as QoS routing, dynamic load balancing, real-time traffic classification, and adaptive rule placement, highlighting key results such as improved efficiency of QoS routing algorithms and the benefits of load balancing strategies based on heuristic optimization. The article also identifies persistent challenges, such as issues related to scalability. Finally, it proposes future research directions, including the integration of artificial intelligence to enhance the adaptability of management models and address the growing complexities of SD-IoT networks.

Keywords. IoT, SDN, Software-Defined IoT, QoS

1 Introduction

The Internet of Things (IoT) represents a critical global infrastructure for modern society, enabling the interconnection of physical and virtual objects through Information and Communication Technologies (ICT). This interconnectivity allows objects to collect data, perform autonomous actions, and provide intelligent services that enhance quality of life [1]. From smart home automation to advanced industrial systems, IoT encompasses a diverse range of applications that redefine interactions between people, machines, and physical environments [2]. However, the rapid growth of IoT has introduced several major challenges. Firstly, the exponential proliferation of devices connected to the Internet has generated a massive volume of data. This rapid growth contributes to a complex heterogeneity, where various types of devices (sensors, actuators, embedded devices) require precise management and coordination. This increased complexity of IoT networks directly impacts Quality of Service (QoS), compromising critical aspects such as latency and bandwidth [3].

Traditional network architectures are particularly vulnerable to these growing challenges. Designed for predictable and homogeneous traffic, they struggle to meet the unpredictable and varied demands of modern IoT applications. Fragmentation of management policies and distribution of controls across multiple devices make it difficult to ensure consistent and reliable QoS. This is where Software-Defined Networking (SDN) emerges as an innovative and promising solution. SDN centralizes network control, enabling dynamic and centralized resource management. By providing a holistic view of the network, SDN facilitates rapid and effective response to the changing needs of IoT applications [4]. For instance, in smart cities, SDN optimizes traffic management and urban infrastructure, enhancing both security and operational efficiency. Similarly, in the Industrial Internet of Things (IIoT) [2], SDN enables optimal management of production chains, minimizing downtime and maximizing efficiency.

Integrating SDN principles with the specific requirements of connected objects, the concept of Software-Defined Internet of Things (SD-IoT) represents a significant advancement [4]. SD-IoT combines SDN's flexibility with IoT network complexity, offering an adaptive solution that promises substantial improvements in QoS across diverse application domains. To overcome the challenges of Quality of Service (QoS) in SD-IoT networks, several advanced techniques are explored in the literature, each aimed at optimizing resource management and ensuring optimal network performance. Firstly, traffic classification plays a crucial role. Technologies such as Machine Learning (ML) [5], are used to dynamically analyze and classify IoT traffic, enabling efficient resource allocation based on specific application needs. Furthermore, flow rule placement schemes are essential for managing the limited flow table of switches [6]. These schemes optimize the use of available memory space by strategically placing flow rules to minimize

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conflicts and maximize packet processing efficiency. QoS-aware routing is another critical aspect [7]. Optimization algorithms, fuzzy logic [8], and heuristics [9] are applied to determine the most appropriate paths in the network, considering criteria such as latency, bandwidth, and reliability. Load balancing in SD-IoT networks plays a crucial role for both links, devices, and controllers [10]. Advanced load balancing strategies ensure equitable distribution of traffic among various available paths, minimizing bottlenecks and enhancing overall network stability. Additionally, load balancing of controllers is facilitated through techniques such as switch migration [11], enabling dynamic redistribution of workloads among SDN controllers.

This paper examines the role of Software-Defined Networking (SDN) in enhancing Quality of Service (QoS) within the context of the Internet of Things (IoT). By centralizing control and dynamically managing resources, SDN addresses the complexities presented by the diverse and voluminous data traffic in IoT environments. The study reviews various techniques such as QoS routing, traffic classification, load balancing, and rule placement to optimize network performance. The focus lies in integrating SDN with IoT (SD-IoT) to develop efficient management models tailored to meet the intricate demands of IoT deployments. Our motivation stems from the observation of a scarcity of comprehensive works covering these critical aspects, underscoring the importance of exploring and consolidating these advancements for the future evolution of IoT networks. The article is structured as follows: Section 2 provides an overview of SDN-IoT networks. Section 3 reviews the current approaches and mechanisms for managing QoS in the SDN-IoT context. Section 4 discusses future research directions. Finally, Section 5 presents the conclusion.

2 Background

2.1 Software-Defined Networking (SDN)

The underlying technologies have evolved, but network management has remained stagnant for decades. Typically, networks that are designed and maintained manually are no longer effective in meeting current demands for speed and ease of management. In contrast, automating network resources and service management provides operational teams with multiple advantages, including increased agility and flexibility. In this context, Software-Defined Networking (SDN) is presented as the solution designed to make network infrastructures more flexible and easier to manage. SDN offers numerous benefits and can be applied to various fields. It can be integrated with new technologies such as 5G, the Internet of Things (IoT), and smart cities, providing programmability and a centralized global view of the network.

The Open Networking Foundation initially defined SDN as a solution that separates the control plane from the data plane, allowing the control plane to become directly programmable [12]. Today, SDN is globally recognized as an architecture that opens the network to applications. It encompasses two key aspects: enabling applications to program the network to accelerate deployment and providing better network visibility. The SDN architecture consists of three distinct layers, each playing a crucial role in intelligently and flexibly managing the network (Fig. 1) [13]. At the top is the application layer, encompassing network services and applications that define network management rules and policies such as Quality of Service (QoS), dynamic routing, access control, proxy services, and load balancing. This layer interacts with the SDN controller through the Northbound API, abstracting underlying complexities and fostering innovation. The control layer, or control plane, acts as the SDN network's brain. The SDN controller, central to this layer, manages the network in real-time by translating requests from the application layer into operational directives for the data plane. It establishes flow tables, defines data processing policies, and gathers network state information, communicating with network devices via the Southbound API and protocols like OpenFlow. Lastly, the data layer, or data plane, forms the physical and virtual foundation of the SDN network, comprising devices such as switches, routers, and access points. This layer executes the controller's decisions by forwarding data packets according to established rules, ensuring the transmission and reception of data in alignment with policies set by the control layer.

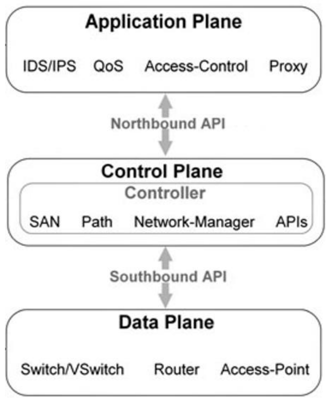

Fig. 1. SDN architecture [13]

2.2 Internet of Things (IoT)

According to the ITU, IoT is defined as a global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) objects based on interoperable, existing, and evolving information and communication technologies [1]. The primary goal of the Internet of Things is to enable objects to be connected to other objects and individuals, at any time and in any place, using any network, path, or service.

Various researchers have proposed different IoT architectures. The fundamental architecture consists of three layers, as shown in Figure 2 [2].

- **Application layer:** This layer provides specialized services to users by defining a variety of applications where the Internet of Things can be leveraged. These applications include industrial automation, smart environmental management, and connected transportation solutions.

- **Network layer:** This layer in enables smart objects, network devices, and servers to connect, facilitating the transmission, processing, and exchange of data among them.
- **Perception layer:** This is the physical layer, which includes sensors that detect and collect information about the environment.

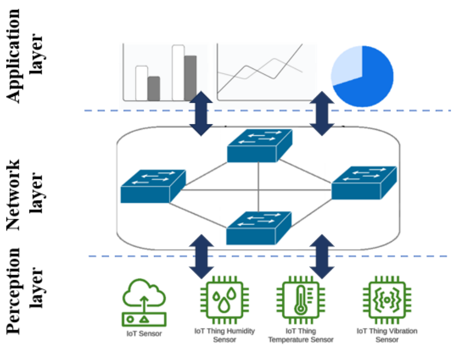

Fig. 2. IoT architecture [2]

Quality of Service (QoS) management in networks, particularly within the Internet of Things (IoT) ecosystem, introduces distinct challenges that require a fundamental reevaluation of conventional approaches. Traditional models such as IntServ, which relies on per-flow resource reservation, and DiffServ, which manages sessions independently while aggregating traffic based on shared QoS requirements, have proven effective in classical wired and wireless networks. However, they are inadequate for the scale and complexity of IoT-driven applications. To address these limitations, novel QoS frameworks need to be designed, specifically adapted to the multi-layered structure of IoT architectures. In this context, [14] categorizes QoS metrics according to each layer of the IoT architecture, as outlined in Table 1, offering insights into how quality management can be optimized for this evolving technological landscape.

Table 1. Quality of Service Metrics for IoT Systems

layer	QoS metrics
Application layer	Scalability, Reliability, Pricing, Response Time, Capacity, Security and Privacy, Dynamic Availability.
Network layer	Jitter, Bandwidth, Throughput and Efficiency, Availability, Monetary Cost, Security and Privacy, Interoperability, Reliability, Network Connection Time.
Perception layer	Weight, Interoperability, Flexibility, Availability, Reliability, Response Time, Range, Mobility Support, Drift, Power Consumption, Security, Precision, Sensitivity, Long-Term Stability.

2.3 Software-Defined IoT (SD-IoT):

Software-Defined Networking, as a new intelligent network technology, addresses issues related to IoT. SDN, with its agility and elasticity, appears to be a promising network technique for achieving a robust IoT, often referred to as SD-IoT. Various research efforts are being conducted to propose IoT architecture models based on SDN [15]. The most used SD-IoT architecture in the literature is the one illustrated in Figure 3. It consists of four layers, combining the layers from both SDN and IoT architectures.

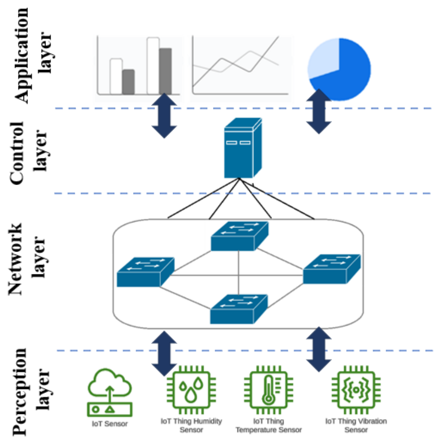

Fig. 3. SD-IoT architecture [15]

3 Current Approaches and Quality of Service Management Mechanisms in the SDN-IoT Environment

Software-Defined Internet of Things represents a pivotal technological advancement in network management, supporting various real-time applications. SDN separates control logic from routing devices, enabling centralized management via a single controller, crucial for industrial IoT applications and sensor networks. To ensure optimal quality of service, mechanisms such as routing, traffic classification, load balancing, and rule placement are employed. However, managing many heterogeneous IoT devices with a centralized controller poses challenges, necessitating the adoption of multiple controllers in a distributed environment. Integrating machine learning techniques, optimization algorithms, heuristic algorithms, and fuzzy logic helps address these challenges more effectively. For instance, Deep Reinforcement Learning (DRL) optimizes real-time routing and traffic management policies. Recent research on enhancing QoS, based on SDN principles and applied to environments like IoT, generally identifies four main areas of concern: Traffic classification (TC), Quality of Service Routing (QoSR), Load balancing (LB) on links, controllers, and devices for centralized and distributed architectures, and Rule placement (RP). An analysis of the existing literature on these deployment issues is provided below, highlighting the advantages of the approach while acknowledging its limitations.

3.1 Traffic classification and Quality of Service Routing

In SD-IoT environments, efficient traffic classification is crucial for managing diverse data streams from various applications and devices. A significant method using the Naïve Bayes algorithm to reduce latency in video streaming is described in in [16], though it may be limited in precision. Martin et al. [17] proposed a deep learning architecture for predicting IoT traffic, facing challenges related to temporal complexity. Another method combines a semi-supervised algorithm with DPI for classifying flows into different QoS classes [18]. Additionally, a random forest classification model with SFS feature selection improves efficiency but encounters issues with generalization and training time [5].

In IoT deployments, where numerous connected devices generate data with varying performance requirements, QoS routing becomes vital for optimal user experience. This approach optimizes transmission paths by considering factors such as latency, bandwidth, and reliability. In [19], a QoS-based routing scheme in SDN is explored, addressing bandwidth optimization but facing complexity challenges. [20] presents a QoS routing method for SDN-based IoT networks using a greedy approach for K shortest paths, though it is limited to delay and loss metrics. Park et al. [21] introduce a framework combining QoS with dynamic network evolution, but it has high computational overhead. Other methods, such as AQRA [7] and QSroute [22], focus on adaptive routing and QoS-awareness, enhancing performance but struggling with scalability and load balancing. Path optimization and load balancing in QoSR are discussed in [23], stressing the need for better management tools. Segment Routing [24] conserves memory through logical paths, while [25] addresses TCAM limitations with approximate algorithms for improved load balancing. An ant colony optimization algorithm in [26] prioritizes sensitive flows in SD-IoT, but scalability and real-world validation remain concerns. Additionally, energy consumption is a crucial aspect in SD-IoT. An approach using the LSOA algorithm to optimize routing and reduce energy consumption in SD-IoT networks is proposed in [27], although scalability issues persist. The GM-WOA method [28] enhances energy performance by balancing network load in SDN-compatible WSNs. The Fuzzy-IAVOA [8] and an integration of SDN with the RPL protocol [29] focus on optimizing resource management and reducing energy consumption. In [30], a novel software-defined network methodology is proposed to improve routing efficiency and reduce energy consumption in Industrial IoT (IIoT) networks, tailored to diverse QoS requirements. However, further empirical validation and research into integrating machine learning techniques are needed to enhance QoS management in real IIoT environments. ROSA [31] offers a centralized solution for flow optimization in industrial IoT environments, using parallel algorithms to reduce energy consumption while maintaining QoS. Lastly, the MQ-LoRa model [32] integrates optimization algorithms and deep learning to improve QoS and energy management in LoRa-based IoT networks. However, the study highlights the need for further research into LoRa's resilience to security attacks and the management of IoT device mobility.

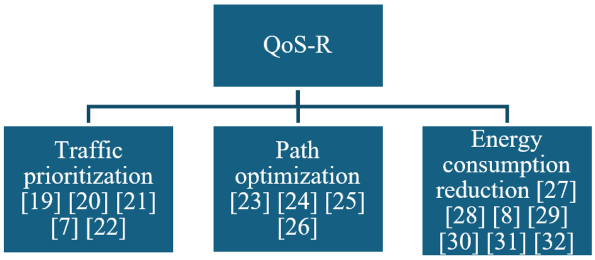

Fig. 4. Classification of QoS-R approaches

3.2 Load balancing (LB) on links, devices and controllers

The Software-Defined Internet of Things (SD-IoT) offers a flexible platform for the efficient management of IoT networks through programmable controllers. Ensuring Quality of Service is a crucial priority in this context, requiring precise traffic and resource management. To achieve this objective, load balancing of links and resources, whether in a centralized or distributed control plane (Figure 5), is essential to prevent congestion and ensure efficient, uninterrupted data transmission.

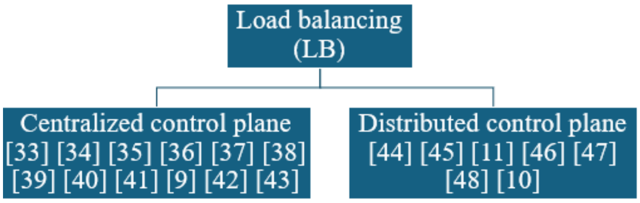

Fig. 5. LB approaches

Wang et al. [33], proposed L2RM, a route management framework aimed at avoiding flow table overload by monitoring switch queue utilization through a dynamic polling system (DIP). However, this approach shows limitations during failures, leading to increased controller response times. TALB [34], on the other hand, suggests a machine-to-machine (M2M) traffic distribution based on QoS thresholds. Yet, the lack of consideration for specific M2M application needs may limit the effectiveness of this solution. In [35], an innovative SDN architecture is introduced to extend the lifespan of wireless sensor networks (WSN) in IoT environments by monitoring link load via the OpenFlow protocol. Nonetheless, this approach relies on a centralized architecture, making it vulnerable to central controller failures and presenting latency management challenges. Furthermore, [36] proposes three techniques to improve load balancing in SDN networks: network size reduction through principal component analysis (PCA), queue utilization prediction using deep neural networks (DNN), and load balancing. However, this approach faces difficulties in large-scale networks due to overload on the central router. Studies [37] and [38] focus on routing and memory management in data centers, particularly through multiple regression algorithms and minimized rule placement mechanisms for switches. These solutions, however, remain constrained by slow error notifications and the lack of large-scale evaluations. Additionally, [39] proposes an SDN framework for load balancing in IoT environments, integrating heuristic methods to anticipate resource needs and balance the load on IoT servers. The DASLM algorithm [40], introduces a dynamic load management mechanism in SDN environments, offering improvements in latency and bandwidth usage by intelligently redirecting HTTP requests. However, this approach remains susceptible to central controller failures, posing a single point of failure. Moreover, the genetic optimization (GO) and ant colony optimization (ACO) approaches [41], aim to optimize load balancing by considering energy consumption and path length but suffer from issues such as premature convergence and local optimization. Neghabi et al. [9], explored load balancing using metaheuristic algorithms, highlighting their advantages in improving network performance. However, they reported limitations like premature convergence and sensitivity to local optima under high loads. In [42], an energy-efficient and secure architecture maximizes resource utilization in a Fog environment, but real-world validation is still needed. Finally, S-FoS [43] combines fuzzy logic-based anomaly detection and multi-objective optimization (NSGA-III) to balance load and minimize delays in IoT-Fog networks. While simulations have shown promising results, this approach may be limited by computational overload in large-scale networks.

In distributed control planes, controllers can operate independently, while hierarchical control planes feature a central controller overseeing subordinate controllers. However, decentralized control architectures may suffer from uneven workload distribution among controllers, leading to inefficient resource use. Load balancing is critical to optimize flow management and enhance network resilience. Switch migration is a key technique in distributed control planes, enabling balanced task distribution among controllers and improving network efficiency and robustness. A dynamic strategy for mapping switches to controllers, which minimizes controller changes, is proposed in [44], including a fractional migration approach and a heuristic algorithm for optimization. The Efficiency Aware Switch Migration (EASM) method [45], aims to reduce unnecessary control traffic during switch migration, although its scalability in large IoT environments remains unproven. The Dynamic Switch Migration Load Balancing (DSMLB) approach [11], manages control plane overload by real-time monitoring of load ratios, optimizing migration efficiency while minimizing resource usage. Similarly, ESCALB [46] enhances multi-domain IoT load management by allocating slave controllers through a multi-criteria decision-making process. While promising, ESCALB faces scalability and QoS challenges in large-scale environments. Further innovations include the Grey Wolf Optimization Affinity Propagation (GWOAP) algorithm [47], which uses intelligent clustering to optimize controller placement and balance loads in SDN-IoT networks. LB-SMOA [48], based on the Spider Monkey Optimization Algorithm, also targets efficient load distribution but raises concerns about scalability and robustness in real-world scenarios. Additionally, AI-enhanced methods for SD-IoT networks [10] improve routing and offloading, significantly reducing latency and packet loss, though energy consumption metrics remain unaddressed, potentially affecting system performance in operational environments.

3.3 Rule placement (RP)

Optimizing the placement of routing rules in data plane devices has become a crucial research topic in recent years. This challenge is particularly complex due to the memory constraints of switches. In [49], the authors proposed an adaptive flow rule aggregation scheme that is QoS-aware for SDN-enabled IoT networks to address the issue of flow table overflow in SDN switches. This scheme utilizes a key-based mechanism capable of rapid aggregation while sufficiently reducing the number of flow rules, with minimal impact on IoT traffic QoS. FlowStat [50] is a flow rule placement approach based on statistics in SDN networks, aiming to reduce the memory load on forwarding devices while maintaining flow visibility. Using Max-Flow-Min-Cost optimization for path selection, the approach includes route selection, rule installation, and rule distribution, helping to avoid network congestion. However, the limited selection of routing paths based on QoS metrics represents a critical issue that needs to be addressed to ensure better quality of service and optimal scalability. In [51], a novel approach for rule placement in switches is presented, considering both serial and parallel connections between adjacent switches. This method introduces the use of an innovative data structure called OPTree (Ordered Predicate Tree) to represent rules and facilitate their management. Two OPTree algorithms are developed for rule establishment and lookup. However, despite considering the arrangement of adjacent devices, the approach generates a significant number of rules, which can burden the SDN controller, especially when using tree or star topologies that exacerbate this challenge.

In [52], the authors proposed a novel adaptive flow rule placement system, DeepPlace, based on deep reinforcement learning for SD-IoT networks. DeepPlace enables fine-grained traffic analysis while ensuring traffic flow QoS and proactively preventing flow table overflows in the data plane. The authors of [6] introduced a deep reinforcement learning-based method to address rule placement in SDN switch flow tables, optimizing resource usage by removing underutilized rules to make space for more frequently used ones. In [53], the authors proposed a scheme combining rule placement and switch migration to balance controller load while mitigating flow table overflow. The CAR (Cost-Aware Routing) algorithm optimizes rule placement based on flow table occupancy, and the BCSM (Benefit-Cost Switch Migration) algorithm selects switch migrations to maximize overall network benefits. Finally, MAPQ [54] (Mobility Aware flow rule Placement with Q-learning) is a very recent scheme that offers a proactive solution by monitoring the future positions of end devices to update the flow rules of switches based on their past movements, thereby optimizing the success rate in wireless environments.

4 Challenges and Future Directions

In the field of Software-Defined Internet of Things, which represents a crucial technological advancement in network management for various real-time applications, several major challenges currently hinder the assurance of optimal Quality of Service. SDN enables centralized network management by separating control logic from routing devices, using a single controller, which is crucial for IoT applications [4]. However, managing numerous heterogeneous IoT devices with a centralized controller poses difficulties, necessitating the adoption of multiple controllers in a distributed environment to better handle increasing complexity [55]. Integrating techniques such as machine learning [38] [5] [36] [18], optimization algorithms, heuristic algorithms, and fuzzy logic helps address these challenges more effectively. For example, DRL optimizes real-time routing policies and traffic management. Despite these advancements, a thorough analysis of available literature highlights several limitations of current approaches. Current research often focuses on specific aspects such as traffic classification, QoS-based routing, load balancing, and rule placement, but fails to comprehensively integrate all essential criteria for efficient and integrated management of SDN-IoT networks. Therefore, there is a critical need to develop more holistic methodologies that account for the diversity of IoT devices, heterogeneous networks, variable traffic conditions, and specific QoS requirements.

Moving forward, research should concentrate on several promising avenues to enhance QoS in SD-IoT networks. Firstly, through an analysis of existing approaches, it is evident that critical QoS parameters such as availability, security, fault tolerance, reliability, network resilience, and traffic models have been largely overlooked. This gap underscores the crucial importance of integrating these parameters into a comprehensive model that encompasses traffic classification, QoS-based routing, load balancing of nodes, links, and controllers in a distributed control environment, as well as rule placement. Such a holistic approach could not only guide future research but also significantly enhance the effectiveness of currently used methodologies. Secondly, while smart cities have been extensively studied in research and practical applications, other sectors such as healthcare and industry have received less attention. Exploring data and analysis in these domains offers promising research opportunities for the future. It is crucial to note that the choice of techniques may vary depending on the application type, highlighting the need to consider this diversity when developing specific approaches. Lastly, the diversity of resources poses a critical challenge in optimizing Quality of Service. Most studies have often assumed homogeneity of available resources to simplify modeling, thereby neglecting significant disparities in terms of capacity, costs, and energy consumption among different network components. This heterogeneity requires a more nuanced approach to ensure efficient resource allocation and genuine improvement in Quality of Service.

5 Conclusion

Recent advances in SDN-IoT networks have demonstrated their potential to address the complex challenges of Quality of Service (QoS) management in IoT environments. However, limitations remain, particularly regarding scalability, robustness in complex environments, and the management of heterogeneous resources and dynamic workloads. To further enhance the efficiency and adaptability of these systems, integrating artificial intelligence (AI) offers a promising path forward. AI would enable the development of QoS management models capable of making autonomous decisions based on real-time data and sophisticated analytical forecasts. This approach aims to optimize network resource utilization while continuously improving user satisfaction and the performance of critical IoT applications. Therefore, future research should focus on applying advanced machine learning and AI techniques to improve QoS management in SDN-IoT networks. This would foster the development of smarter, more resilient networks capable of tackling emerging challenges with greater efficiency.

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