A Novel Blockchain-based System for Service Quality Improvement in Multi-Tenant O-RANs

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***Abstract*—Open Radio Access Networks (O-RANs) are transforming the landscape of telecommunications to better performance and higher cost-efficiency by enabling network operators to integrate diverse vendor components. Nevertheless, the involvement of multiple Network Service Providers (NSPs) and Mobile Network Operators (MNOs) also brings new challenges in the management of computation and network resources. To resolve this challenge, we propose a blockchain-based framework to guarantee secure, transparent, and decentralized resource allocation in O-RAN systems. Our resource allocation mainly considers the tradeoff of cost and service quality. Our design facilitates real-time adjustments to resource distribution based on dynamic network conditions and incorporates user feedback to optimize service quality continuously. By integrating a Proof-of-Reputation (PoR) consensus mechanism, the framework enhances the reliability and integrity of transactions among competing vendors without central oversight. We evaluate the performance of our design through extensive simulations, which demonstrate significant improvements over the baselines in resource utilization and service delivery across various network scenarios.**

I. Introduction

Open Radio Access Network (O-RAN) represents a transformative paradigm in the field of telecommunications, redefining the traditional architecture of radio access networks [1], [2]. This open and standards-based architecture enables network operators to mix and match components from various vendors, fostering innovation, competition, and cost-efficiency. By decoupling hardware and software functionalities, O-RAN not only promotes vendor diversity but also facilitates easier network management and optimization. Additionally, O-RAN caters to diverse user needs, providing a customizable and scalable framework that accommodates the evolving requirements of both mobile network operators and end-users.

In the O-RAN architecture, a variety of Network Service Providers (NSPs) and Mobile Network Operators (MNOs) coexist within the same network ecosystem. This multiplicity, while beneficial, introduces complex challenges associated with the efficient, equitable, and secure interaction and integration of these entities. These issues have garnered significant interest from both academic researchers and industry professionals, leading to a focused examination of the underlying dynamics and potential solutions [3], [4]. For instance, mobile users, for the first time, get the flexibility to shift among multiple network service providers offering similar services in the O-RAN environment. Nevertheless, if such service reallocation is carried out without proper and efficient management and coordination, much chaos, performance degradation, and unhealthy competition may be introduced [5].

The only pioneering work addressing such challenges, i.e., [6], proposes a resource allocation system that allows each radio unit (RU) to choose from different available NSPs and MNOs for the balance of service costs among all RUs. Despite such research efforts, there is no efficient strategy designed under the multi-vendor O-RAN system that dynamically allocates the resources needed by RUs over NSPs and MNOs with different qualities and prices for the best service quality and cost efficiency. Moreover, it is essential to provide feedback experience of mobile users to the resource allocation system to eliminate the impacts of volatile mobile environments such as user mobility and network fluctuation, on service quality. Such impacts may even differ from vendor to vendor within the same area. In addition, no existing mechanism exists in O-RAN systems to guarantee the consensus of resource allocation among multiple competing vendors without involving a centralized trusted party.

To address the aforementioned problems, we propose a blockchain-based service quality management system for multi-tenant O-RANs. To specify the improvement of service quality, we analyze the tradeoff between service quality and cost. The blockchain is for users to propose the evaluation of services. The main contributions of this paper are in the following.

- We analyze the tradeoff between service quality and cost in multi-tenant O-RANs.
- We propose a blockchain structure to support service quality management in multi-tenant O-RANs.
- We implement the proposed system and conduct simulations. The results show that our proposed system can improve stability while maintaining the trade-off between service quality and cost.

The rest of this paper is organized as follows. In Section II, we describe the scenario and formulate the problem. In Section III, we introduce the service quality computation and maintenance. In Section IV, we proposed the blockchain that supports the system. Simulation results are presented in Section V. Section VI briefly reviews the related work, and the last section concludes this paper.

II. Problem Statement and Model

In this section, we first introduce the background of O-RAN, and then we formulate the resource allocation problem in the O-RAN environment.

A. Multi-Tenant O-RAN Scenario

Users request services from O-RAN through various user equipment (UEs), such as smartphones and edge devices. When a UE requires services or computing resources, it interacts with the nearest base station, which includes an RU. From the perspective of UEs, RUs are black boxes with hidden implementation details, and UEs simply pay fees to RUs for the services needed to complete their tasks. In contrast to traditional cellular networks, where each UE is bound to a specific MNO and NSP, O-RAN offers the advantage of MNOs and NSPs can provide services to all UEs connected to the network. Depending on the specific location and status of each RU, the RU selects suitable MNOs and NSPs for UEs that connect to the RU to require services. Consequently, UEs connect to RUs within range and request services, while RUs select the appropriate MNOs and NSPs to provide services.

In this paper, we focus on the service quality improvement problem in multi-tenant O-RAN. We propose a system designed for a simplified multi-tenant O-RAN model. Our proposed system is deployed onto clouds, which further distribute lower-level implementation across central units, distributed units, and radio units at the broadly distributed cell sites through RAN intelligent controllers. Basic O-RAN standards, including interfaces, frameworks, and hardware architectures, are beyond the scope of this paper and have been studied [2].

B. Problem Formulation

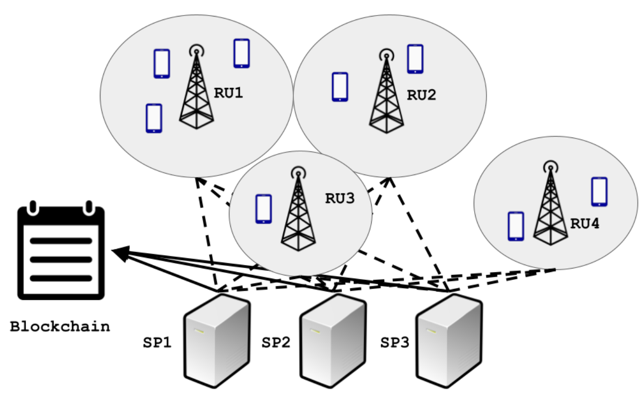

Fig. 1. A simple graph to show the participants in the model.

We illustrate the participants in our simplified model in Fig. 1. To provide service to UEs, RUs rely on cloud services from MNOs and network services from NSPs. Since both cloud and network services are quantifiable, we simplify the problem by considering MNOs and NSPs as service providers (SPs). We denote the set of SPs as $\mathcal{N} = \{1, 2, \ldots, N\}$, and the set of RUs as $\mathcal{R} = \{1, 2, \ldots, R\}$ that require services from SPs. The cost of one unit of resources for different RUs varies depending on the location and ownership of the SPs, denoted by $C_{r,n}$. The required number of resource units is represented by $W_{r,n}$.

Inspired by [7], [8], the function that expresses satisfaction of UEs should exhibit strict monotonicity and concavity. We define the range of this function as a quality service ratio between 0 and 1, where 0 denotes poor quality and 1 represents excellent quality, with quality increasing monotonically. The amount of required resources is proposed by the UE. The quantity of resources is directly related to service quality, with quality approaching the upper limit once resource allocation reaches a certain level, leading to diminishing returns in service quality improvement.

Hence, we select the concave function $f(Q, W) = \frac{Q}{Q+W}$, where Q represents the service quality parameter and W denotes the number of resources. While $Q, W \in (0, \infty]$, $f(Q, W)$ yields the final quality within $[0, 1]$. The service quality parameter Q is tied to the corresponding SP, as it hinges on the capacity and condition of the SP. Q remains concealed from all participants except the SP itself. With a fixed W, $f(Q, W)$ rises as Q increases, as a higher quality parameter implies superior service quality while offering a fixed resource quantity. Conversely, with a fixed Q, $f(Q, W)$ declines as W increases. Augmenting the required resources prolongs processing times and complicates resource management, thereby diminishing service stability.

The service quality offered by SPs may fluctuate due to various factors. For instance, a cloud server might undergo maintenance, reducing available resources and impacting service quality. Consequently, the parameter Q used to express service quality is non-explicit and subject to change. From the perspective of UEs, they are aware of the resource requirement W and the final result of quality $f(Q, W)$. To estimate the real-time Q of SPs for RUs, we utilize the historical evaluation from UEs. UEs requesting services from RU R give the evaluations, and by aggregation, the service quality parameter dependent on services provided by SP n is denoted as $Q_{r,n}$. $Q_{r,n}$ is dynamically adjusted based on evaluations of UEs. The payment from RU r to SP n is $C_{r,n}W_{r,n}$, where $C_{r,n}$ is the cost of one unit resource and $W_{r,n}$ is the total amount of resources.

Our paper addresses the challenge of assigning the proper SP for each task proposed by an UE through an RU. Upon task completion, the UE proposes an evaluation of the service quality. These evaluations are stored in a blockchain maintained by all SPs.

III. Service Quality Management

In this section, we first analyze the strategy that how UE selects SP to provide services, and then we discuss the details of computing service quality parameters.

A. SP Selection Strategy

Assume that UE u proposes task t with W_t, denoting the required resources. As u cannot directly interface with SPs, it connects to the O-RAN network by RU r based on physical location. r can leverage resources from an SP to finish the task.

If r selects n to serve the task, the payment is $C_{r,n}W_t$, where $C_{r,n}$ represents the unit cost. Depending on the historical data, an aggregated evaluation $Q_{r,n}$ is computed, yielding the expected quality of service as $\frac{Q_{r,n}}{Q_{r,n}+W_t}$.

As UEs have different requirements, we propose the following possible strategies.

- Lowest cost: This strategy selects n to minimize $C_{r,n}W_t$.
- Highest quality: This strategy selects n to maximize $\frac{Q_{r,n}}{Q_{r,n}+W_t}$.

The lowest cost and highest quality strategies are straightforward. However, while maximizing $\frac{Q_{r,n}}{Q_{r,n}+W_t}$, there might be diminishing marginal utility. In other words, as $\frac{Q_{r,n}}{Q_{r,n}+W_t}$ approaches 1, the cost to improve $\frac{Q_{r,n}}{Q_{r,n}+W_t}$ to $\frac{Q_{r,n}}{Q_{r,n}+W_t}+\epsilon$ is higher than the cost to improve $\frac{Q_{r,n}}{Q_{r,n}+W_t}-\epsilon$ to $\frac{Q_{r,n}}{Q_{r,n}+W_t}$. Therefore, we introduce the following strategy.

- Tradeoff bounded highest quality: UE gives a tradeoff α, and the strategy selects n maximizes $\frac{Q_{r,n}}{Q_{r,n}+W_t}$, while $C_{r,n}W_{r,n} \le \frac{\alpha Q_{r,n}}{Q_{r,n}+W_t}$.

Considering the relationship between cost and service quality, we define α as a parameter representing the tradeoff between cost and service quality for RU r. When $C_{r,n}W_{r,n} > \frac{\alpha Q_{r,n}}{Q_{r,n}+W_{r,n}}$, from the perspective of r, the cost outweighs the service quality provided. When $C_{r,n}W_{r,n} \le \frac{\alpha Q_{r,n}}{Q_{r,n}+W_{r,n}}$, the service quality surpasses expectations. The previous strategies without a tradeoff bound are special cases where $\alpha = \infty$. By providing the maximum affordable α, UE can identify SPs offering acceptable service quality at a corresponding price. This ensures that when seeking the highest quality service, the price from the SP will not exceed the acceptable tradeoff limit.

B. Updating Service Quality Parameter

Following the defined quality function, $f(Q_{r,n}, W_{r,n}) = \frac{Q_{r,n}}{Q_{r,n}+W_{r,n}}$, UE can evaluate the quality of the current service as the output $f(Q_{r,n}, W_{r,n})$. By combining $f(Q_{r,n}, W_{r,n})$ and $W_{r,n}$, UE infers an updated service quality parameter $Q_{r,n}$. The updated $Q(r,n)$ value contributes to the aggregation of the final updated quality assessment.

When computing the $Q_{r,n}$, the value could be very large when $W_{r,n}$ is large and $f(Q_{r,n}, W_{r,n})$ approaches 1. Therefore, it is necessary to constrain the range. Let $1-\epsilon$ be the upper bound of the service quality, while ϵ represents the allowable error of service quality. By adjusting the ϵ, the range of $Q_{r,n}$ can be controlled.

An aggregated service quality parameter is computed from the records by different UEs evaluating services provided by SP n through RU r. Theoretically, the aggregated service quality parameter undergoes constant change as UEs continue to require services and propose evaluations. However, synchronizing the information across the network is limited by the network bandwidth and transmission speed. Leveraging the inherent properties of blockchain technology, we facilitate network members in reaching a consensus on aggregated service quality parameters. Whenever a new block is generated, the aggregated service quality parameters are also updated and synchronized across all participants. The update frequency aligns with the block generation frequency. In other words, the block generation frequency is contingent upon the required frequency of updates for the aggregated service quality parameter. Further details on the blockchain will be elaborated in Section IV.

The aggregated service quality parameter is calculated by the weighted average of service quality parameters obtained from finished tasks. Different weighting methods can be employed, with options ranging from static to dynamic, depending on the specific conditions of the environment and application.

IV. Blockchain Structure

In this section, we discuss the blockchain structure that supports service quality management in multi-tenant O-RANs.

A. Purposes of Enabling Blockchain

The primary purpose of the blockchain is to maintain a distributed ledger that supports the evaluations from UEs, thus enhancing service quality. This support encompasses three aspects. Firstly, the distributed ledger ensures that evaluations recorded in the blockchain are immutable and transparent, allowing all UEs and RUs to access historical records securely, free from concerns about data manipulation. Secondly, blockchain technology empowers the scalability of the evaluation system, as newly joined participants can obtain historical data upon successful blockchain integration. Third, the rewarding mechanism of blockchain incentivizes participants to maintain accurate evaluations and compute precise aggregated results.

A side advantage of integrating the blockchain into the system is its ability to record payment transactions created by the participants. For example, RUs owned by different MNOs need to pay for leasing computational resources from DU-CU functions [6], while UEs pay rental fees for acquired resources [9]. As a generalized public ledger, blockchain facilitates payment processes in a decentralized, untrusted environment.

B. Blockchain Delays

In a wireless network, the performance of the blockchain may suffer due to network delays. Previous research [10] has examined potential impacts, including transaction queueing delay and block propagation delay. These delays depend on hardware capabilities. In the O-RAN context, wireless connectivity occurs between UEs and RUs. Given the high latency of wireless connections and potential resource constraints of UEs, deploying the proposed blockchain system on edge cloud servers with low communication latency and ample network bandwidth, rather than on wireless devices with inherent delays, can alleviate queuing and propagation delays caused by limited resources and wireless network conditions.

C. Blockchain Participants

Multiple roles in the blockchain work together to implement the purposes of the blockchain. As previously discussed, considering the capability of devices, SPs serve as miners in the blockchain. While UEs cannot fulfill the role of the miners, they can access the content stored in the blockchain. In addition, UEs can propose transactions to make payments or evaluations. These transactions are processed by miners and recorded in the blockchain if they are valid. Although UEs are expected to pay fees for these services, determining the accurate strategy is beyond the scope of this paper.

D. Blockchain Design

Based on the objectives of blockchain, we design a specified blockchain structure for resource allocation in multi-tenant O-RANs.

The block information section comprises essential details necessary for constructing a blockchain, such as block index, timestamp, and hash values. In blockchain terminology, the block index and timestamp denote the position of the current block within the blockchain, while hash values are employed by other blockchain participants to validate the authenticity of the block.

The primary function of the blockchain is to record evaluations from UEs via transactions. Each transaction includes the UE identifier of the transaction initiator and the evaluation of service quality. Simultaneously, adhering to the formula $f(x)$, the quantity of requested resources is also included in the transaction details.

Payment transactions are incorporated into the block, containing information such as payer, payee, amount of currency exchanged, and signatures for verification. While payment methods are not the primary focus of our paper, we mention them here to underscore that our system supports various payment mechanisms.

The consensus part stores data pertinent to the consensus mechanism of the blockchain, including proof of the current block generator. Additionally, as a crucial part requiring validation, the updated service quality parameters are stored within this section. Further details will be discussed in the subsequent subsection.

E. PoR Mechanism

Following the consensus mechanism, all participants of the blockchain can reach a consensus on the blockchain content. While the classic Proof-of-Work (PoW) mechanism demands significant computational resources, it is not suitable for scenarios where edge clouds provide resources to UEs. Instead, we adopt the Proof-of-Reputation (PoR) mechanism, which has two advantages in this case. Firstly, it saves computational resources. PoR blockchain does not require participants to consume computational resources to solve hash problems in PoW. Second, it incentivizes miners to improve their reputation, which is the service quality in our case. The PoR mechanism selects miners with high reputations as block generators, thereby motivating miners to show high reputation and service quality.

In line with the PoR mechanism in [11], we use the highest increment of service quality parameter of edge clouds to select the generator of each block. This choice prevents miners from consistently representing only a small fraction of edge clouds. However, instead of selecting the highest value of the service quality parameter, we opt for the highest increment. This decision mitigates the risk of participants manipulating their service quality to maximize profits. Furthermore, to counteract this potential manipulation, we impose an additional constraint on the block generator: they must possess a service quality parameter within the top 50%. Research in [11] has demonstrated that this constraint effectively prevents malicious participants from exploiting the system for additional gains.

F. Blockchain Updates

Blockchain relies on the miners to be maintained. During a given block duration, a distinct block generator can be unequivocally identified from a set of valid transactions, which includes evaluations from UEs. However, discrepancies may arise if different miners receive varied transaction sets due to network delays. Moreover, a miner could potentially manipulate its block's transaction set to position itself as the generator with the highest increment of service quality parameters. To address this, we introduce a tiebreaker mechanism. If multiple miners simultaneously publish blocks at the same height, the miner with the block containing the most valid transactions is chosen as the block generator. This method resolves most conflicts. In the event of a continued tie, factors such as the size of each service quality parameter within the miner's block, the aggregate sum of all edge cloud service quality parameters, and the block hash value are compared to break the tie. Finally, consensus among all participants ensures the identification of a unique latest block and its corresponding generator.

The block generator is responsible for updating the service quality parameters of edge clouds. Based on the updated service quality parameters, the block generator also computes the result of the aggregated quality parameter for transactions included in the next block. These parameter results are pivotal for achieving consensus. If the block generator gives results that cannot match the previous blocks and current transactions, the block will not be validated by other participants.

V. Simulation

In this section, we show the performance of our proposed system by designing various simulations. We test multiple measurements in our simulator. The results prove that our proposed system successfully provides good quality services to RUs.

A. Simulation Settings

We generate a network with 1000 RUs and 100 SPs. The cost of providing unit resource $C_{r,n}$ for RU r and SP n is generated by normal distribution $\mathcal{N}(100, 20)$. The quality service provided by SP n, Q_n, is generated by uniform distribution in range $[50, 150]$, and for each task, the real provided service quality is generated by normal distribution $\mathcal{N}(Q_n, 10)$.

We generate an event list to simulate. The event list includes two types of events. The first event indicates a UE proposes a task t, including the information that the connected r, the required amount of resource W_t, the tradeoff parameter α_t, and the strategy. The second event indicates the service quality of SP n is changing to another normal distribution $\mathcal{N}(Q_n, \sigma_n^2)$, which is hidden from UEs and RUs. After finishing the task t, UE proposes the evaluation of the corresponding SP. While the number of proposed evaluations not on the blockchain reaches 100, the SP with the highest increment of service quality parameter will be the generator of a new block, and these proposed evaluations will be recorded to the blockchain. We use the average service quality parameters in the latest 10 blocks to be the aggregated service quality parameters of all SPs. UEs will make decisions following the newest aggregated evaluations. The simulation ends when the number of blocks reaches 1000.

B. Performance of Different Strategies

In this simulation, we divide the RUs into four types to run four different strategies. Three strategies maximize the supposed quality with different α parameters in $\{100, 1000, \infty\}$, while $\alpha = \infty$ means there is no tradeoff bound. Another strategy minimizes the cost of the task. Each type of RU follows one strategy and with the same total number of RUs. We simulate 100000 tasks, and RUs have the same probability of receiving a task by a UE. The blockchain will have 1000 blocks while each of the blocks has 1000 evaluations from the proposed tasks. We compute the average unit cost and the average service quality for each RU's tasks. The results are demonstrated in Fig. 2 and 3.

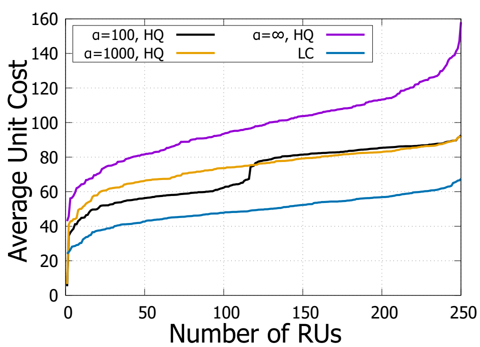

Fig. 2. The simulation result of the average unit cost. Each data point (x, y) on a line indicates that x RUs in the case have the average unit cost smaller or equal to y.

Fig. 2 shows the average unit cost of all strategy types. For each RU, we compute the average unit cost of all tasks. Each line in Fig. 2 indicates the sorted average cost of all RUs of the corresponding strategy type. The basic highest quality strategy ($\alpha = \infty$, HQ) and lowest cost strategy (LC) have the highest average unit cost and lowest average unit cost, respectively. The cost of the highest quality strategy is approximately two times the cost of the lowest cost strategy. By importing the tradeoff parameter, the cost can be reduced effectively. While tradeoff parameter$\alpha = 100$ and 1000, the cost is reduced to 71.86% and 75.05%, respectively.

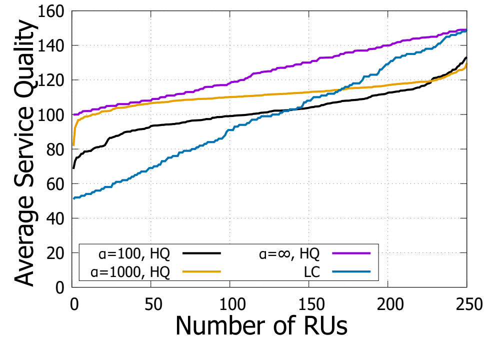

Fig. 3. The simulation result of the average service quality. Each data point (x, y) on a line indicates that x RUs in the case have the average service quality smaller or equal to y.

By a similar method, we count the average service quality of all tasks proposed by each RU, and Fig. 3 shows the sorted results. The order of four lines indicating four strategies is the same as the order in Fig. 2, implying the tradeoff between low cost and high service quality. The lowest cost strategy receives only 79.3% quality compared to the highest quality strategy. While tradeoff parameter$\alpha = 100$ and 1000, the quality is improved to 103.13% and 112.61%, respectively. Moreover, the stability of providing service is also effectively improved, inferred by the improvement of the variance. The variance of the lowest cost strategy is 804.91, while the variances of $\alpha = 100$, and $\alpha = 1000$ when maximizing service quality are 152.07 and 45.33, respectively.

VI. Related Work

Google Fi introduces an innovative hybrid approach to dynamically switch users between cellular and Wi-Fi for optimal connectivity [12]. The conventional reliance on centralized servers for MNO selections among users leads to decreased flexibility and robustness in the system.

Resource allocation in multi-tenant network environments has been well-studied. Caballero et al. [13] formulate the network slicing game in which each tenant and user maximizes their own utility. Their formulated game system converges to an equilibrium. Tran et al. [8] discuss the situation that aggregated UE demands may select multiple service providers for purchasing service. They build a multi-leader multi-follower Stackelberg game to resolve the situation. Different from the works, our system focuses on not only the price, but also the services quality. The demand relationship in a network is fluctuating while the service quality is changing.

In O-RAN background, the resource allocation problem is also attractable. In many aspects of O-RAN, there are a lot of rooms to be improved, and it is an emergency to complement many part of rooms. For instances, the resource allocation in O-RAN includes ultra-reliable low-latency communication [14], [15], DU-CU deployment [5], [16], [17], xApps/rApps management [18], [19]. Mondal et al. [6] study the fairness payment for RUs deployed by different MNOs. Since the RUs need to connect to DU-CUs and clouds, RUS need to pay the necessary operational expenditure (OPEX). They design a Vickrey-Clarke-Groves (VCG) auction-based mechanism to minimize the total OPEX for all resources while extracting truthful demands from RUs. Their mechanism assumes that the RUs know their upcoming demands from UEs and report them before resource allocation.

Utilizing blockchain to manage resource allocation in a network has been widely studied. For example, Huang et al. [20] deploy blockchain to manage resource allocation in a pervasive edge computing environment. Blockchain can also help network security to avoid misreporting or manipulation [11]. The blockchain technique has been deployed to RAN environments to implement various applications [21], [22]. Xu *et al.* propose a framework that supports identity management and privacy-preserving communication [23]. In this framework, users communicate through virtual identities and addresses registered on the blockchain, hence preserving the privacy of the real identities. The authors of [9] envisioned blockchain technology to provide trust and traceability to the automation of O-RAN management. Their study introduces two automated RAN sharing mechanisms, based on auctioning and an open marketplace. Their work emphasizes architectural design, leaving room for further improvements in algorithmic optimization.

VII. Conclusion

In this paper, we have proposed a novel PoR blockchain-based network to improve the service quality in multi-tenant O-RANs. We have formulated the model for UEs to require services from SPs through RUs. Focusing on the cost and service quality, we have analyzed the tradeoff between the cost and service quality. We have designed a PoR blockchain system for UEs to evaluate SPs. Our simulations show that our system meets the expectations to balance the cost and service quality, also improves the stability of quality service.

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