Information-Centric Massive IoT-Based Ubiquitous Connected VR/AR in 6G: A Proposed Caching Consensus Approach

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***Abstract*—The development of massive IoT has not only brought about a wealth of hardware resources but also brought about the problems of difficult data management, resource running and low efficiency. The emergence of sixth-generation (6G) network will not only provide faster data rates, more device connections but also bring ubiquitous virtual reality/augmented reality (VR/AR) services. In the 6G era, large-scale IoT devices will generate VR/AR service and resource requirements, and the network will also face unprecedented pressure to respond to the ubiquitous VR/AR requirements. To address the above issues, this article proposes the information-centric massive Internet of Things (IC-mIoT) suitable for 6G large-scale VR/AR content distribution to improve the efficiency of IC-mIoT and fully guarantee the Quality of Service (QoS) of users. First, this article introduces the blockchain for IC-mIoT nodes and proposes a new consensus mechanism Proof-of-Cache-Offloading (PoCO). Second, an architecture using blockchain-enabled IC-mIoT for VR/AR is proposed in this article. The massive IoT resources are fully integrated and scheduled to support large-scale VR/AR applications and IC-mIoT. Third, a Stackelberg game model and a cache index selection and calculation algorithm are formulated for blockchain-enabled cache offloading. The analysis and performance simulation results indicate the superiority and effectiveness of the proposed scheme.**

***Index Terms*—6G, blockchain, information-centric network (ICN), massive IoT.**

I. Introduction

THE SIXTH generation (6G) mobile network is expected to cast high-speed and high-efficiency transmission standards to adapt to the further development of new applications [1]. Virtual reality/augmented reality (AR/VR) is considered as one of the most important high-throughput application-level requirements of 6G. Once AR/VR can be used more simply, conveniently and without location restrictions, it will promote the rapid development of AR/VR services and applications, and then stimulate the rapid development and maturity of AR/VR devices themselves. In the 6G era, the interaction form of media will develop into high-fidelity AR/VR interaction, and even ubiquitous VR/AR-based holographic information interaction. The ubiquitous AR/VR will become an inevitable application supported by 6G, and will be deeply integrated with massive IoT [2]. The required data rate will far exceed other applications we currently know, which puts greater pressure on the network to potential risks. For the ubiquitous VR/AR requirements in 6G scenarios, it is very important to provide VR/AR with the required resources (e.g., computing power, storage space, graphics processing capabilities, communication resources) through massive IoT devices to achieve the enhancement of VR/AR capabilities feasible [3].

With the widespread adoption of massive IoT, the number of connected devices is growing at an exponential rate, which is contributing to ever increasing, massive data volumes [4]–[7]. The development of massive IoT has brought about an abundance of potential resources but also caused problems, such as difficult data management, resource congestion, and low system efficiency. Recent studies pointed out that IoT scales better than the traditional host-centric IP model in an information-centric network (ICN) architecture [8]. ICN is a novel decentralized architecture in IoT, which provides a potential approach to cope with large-scale VR/AR content distribution in 6G enabled massive IoT. Both VR and AR consume a large volume of bandwidth to provide a satisfactory experience for the consumers. Therefore, as an information-centric architecture, it offers in-network caching of VR/AR content, which makes it more ideal for a wide range of IoT devices. However, the difficulty of multiple ICN routers cooperation in a trusted and efficient way still poses challenges to the security and large-scale application of ICN in 6G enabled massive IoT. Therefore, the trust and cooperation problem of information-centric massive IoT (IC-mIoT) needs to be solved urgently.

Blockchain is a feasible way to address the above-mentioned trusted collaboration problem. A blockchain is a distributed architecture that is replicated and shared among the peers of a certain network [9]. Compared with the traditional public blockchain, the permissioned blockchain has advantages in terms of efficiency, cost, flexibility, and privacy protection. This provides a perfect platform for using IC-mIoT for VR/AR content distribution in the 6G network. In this

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article, an IC-mIoT architecture-based ubiquitous connected VR/AR content caching and distribution architecture in 6G is proposed. Meanwhile, we also proposed the corresponding blockchain application mode and a caching consensus mechanism. The goal of this article is to provide a detailed approach of how blockchains and ICN work to realize and guarantee the enhancement of ubiquitous connected VR/AR in 6G enabled massive IoT. Therefore, motivated by previous works, we exploit the advantages of blockchain, including permissioned blockchain and consensus mechanism, to achieve the enhancement of secure VR/AR content efficient caching and distribution.

1) This article proposes the IC-mIoT for ubiquitous VR/AR content distribution in 6G. To improve the efficiency of IC-mIoT and fully guarantee the Quality of Service (QoS) of users, a blockchain-enabled IC-mIoT for VR/AR sharing architecture is proposed in this article.
2) This article proposes a new consensus mechanism Proof-of-Cache-Offloading (PoCO) and introduces the permissioned blockchain for IC-mIoT. The permissioned blockchain is used to incentivize the VR/AR content caching of nodes and ensure the sharing of mIoT resources. A cache resource market for trading mIoT device resources is proposed.
3) A cache index (CI) selection and calculation algorithm and a Stackelberg game model are formulated for blockchain-enabled cache offloading. The massive IoT resources are fully integrated and scheduled to support the ubiquitous VR/AR applications and IC-mIoT.

The remainder of this article is organized as follows. The related work is given in Section II and the strengths of the proposed scheme are described. Our system model and architecture of the proposed scheme are presented in Section III. Both the basic implementation of the scheme and the proposed algorithm for blockchain based cache offloading are provided in Section IV. Simulation results are shown in Section V to estimate the performance of the scheme. Final conclusions are drawn in Section VI.

II. Related Work

Being expected to be put into use around 2030, the opportunities, challenges, use cases and related applications of 6G have been frequently studied and illustrated [10], [11]. Ten important trends in the cellular industry and the outlook of 6G is proposed in [12] to shed light on possible directions of 6G while searching for new directions and breakthroughs. A comprehensive discussion of 6G is given in [18] based on the review of 5G developments, covering visions and requirements, technology trends and challenges, aiming at tackling the challenge of coverage, capacity, the user data rate, and movement speed of mobile communication system. As a new multiple-access method, delta-orthogonal multiple access (D-OMA), is introduced for massive access in future 6G cellular networks [14]. As an important part of 6G-related technologies, some artificial intelligence (AI) methods have been introduced into 6G networks. Tang *et al.* [13] provided a survey on various machine learning (ML) techniques applied to communication, networking, and security parts in vehicular networks and envision the ways of enabling AI toward a future 6G vehicular network. Potential technologies for 6G to enable mobile AI applications, as well as AI-enabled methodologies for 6G network design and optimization are discussed in [17]. Blockchain is also being discussed in 6G as an emerging distributed architecture. The opportunities and challenges related to blockchain usage in 6G and the possible directions for overtaking these challenges are discussed in [15]. Hewa *et al.* [16] explored the role of blockchain to address formidable challenges in 6G, future application opportunities and potential research directions.

In 6G scenarios, extensive distributed device security and efficient content distribution are potentially important requirements. Therefore, both blockchain and ICN are considered potential mainstream technologies in 6G [19]–[22]. Chen *et al.* [23] proposed a reputation management mechanism that combines negative and positive transaction records in the ICN of vehicular network. Sharma *et al.* [24] focused on using drones as on-demand nodes for efficient caching for the mobile-edge computing-enabled drone network. As a content-centric approach, ICN have been recently regarded as an alternative to the traditional host-centric network paradigm [25]–[27]. Obvious benefits of ICN in terms of improved interest/content sharing scheme and better reliability has already raised ICN as a highly promising networking techeology for environments, such as IoT [8]. Information-centric technology is integrated with fog computing for the novel content-aware network architecture [28], [29]. For the VR/AR service, Hu *et al.* [30] proposed a new architecture for UAV clustering to enable efficient multimodal multitask offloading to enabled AI-based the computing, caching, and communication resources. Current state-of-the-art research on edge caching and computing with a focus on AR/VR applications and tactile Internet is proposed in [31] to discuss applications, opportunities, and challenges.

Although the related research on ICN and blockchain in massive IoT has been extensively studied, few works have focus on applying blockchain to the content sharing of 6G, especially for the approach to supporting ubiquitous VR/AR. Therefore, compared with the existing work, the advantages of this article lies in the following points. First, we propose a VR/AR content distribution architecture in 6G to meet the requirements of 6G networks and massive IoT. Second, to ensure the safe and stable operation of this distributed system, we introduced the blockchain and integrated the features of IC-mIoT with the cache offloading tasks. Third, we have fully considered the feasibility and specific operational details of our proposed mechanism and algorithm in 6G-enabled massive IoT.

III. Basic Architecture

A. Scenarios of IC-mIoT-Based Ubiquitous Connected VR/AR in 6G

With the large-scale commercial deployment of 5G networks, more and more research institutions and related

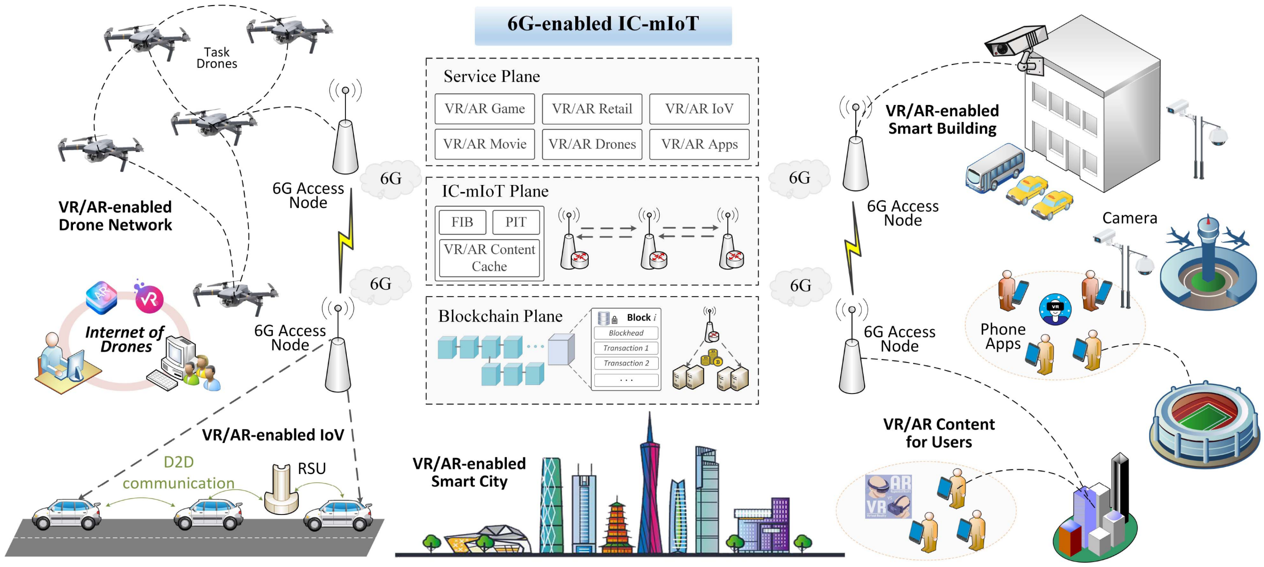

Fig. 1. Basic scene of 6G-enabled information-centric massive Internet of Things for ubiquitous VR/AR.

researchers have begun to study the 6G mobile communication systems [32]. Human production and living space are constantly expanding and the types and scenarios of information interaction requirements are becoming more and more complicated in the 6G era. The 6G network is expected to empower millions of connected devices and ubiquitous AR/VR applications that could operate seamlessly with high data rates and low latency. The ubiquitous connection of AR/VR means that the network can be expected to meet the high-speed requirements of users at any time and any place. These requirements are not only for the peak rate but also the extremely high requirements for the average network rate and coverage. As shown in Fig. 1, VR/AR content service in 6G will penetrate into various scenarios, including the integrated network of airspace, sky, earth, sea, and wireless tactile network.

In 6G networks, there will be far more applications and demands for VR/AR than today. To cope with more and more VR/AR services and demands, more intensive IoT resources will also be fully mobilized. Massive IoT devices can be presented as a network of surrounding things which are connecting to the Internet, such as various sensors, vehicles, devices that can be monitored, detected, controlled. The range of activities of massive IoT devices will greatly expand the geographic space for communication access. In 6G-enabled smart cities, the content services of VR/AR will penetrate into every corner of daily lives, including Internet of Vehicles (IoV), UAV networks, user services, and smart buildings. For example, VR/AR-based driving assistance systems, VR/AR game services, VR/AR-based drone monitoring systems, VR/AR movies, etc. This type of VR/AR-based service is cached in IC-mIoT nodes to respond to requests from edge users. Blockchain is mainly used to ensure the safety and traceability of various transactions in 6G scenarios. Meanwhile, the smart contracts that have been formed in the past are stored in the blockchain to ensure the safe and stable operation between the ICN routers.

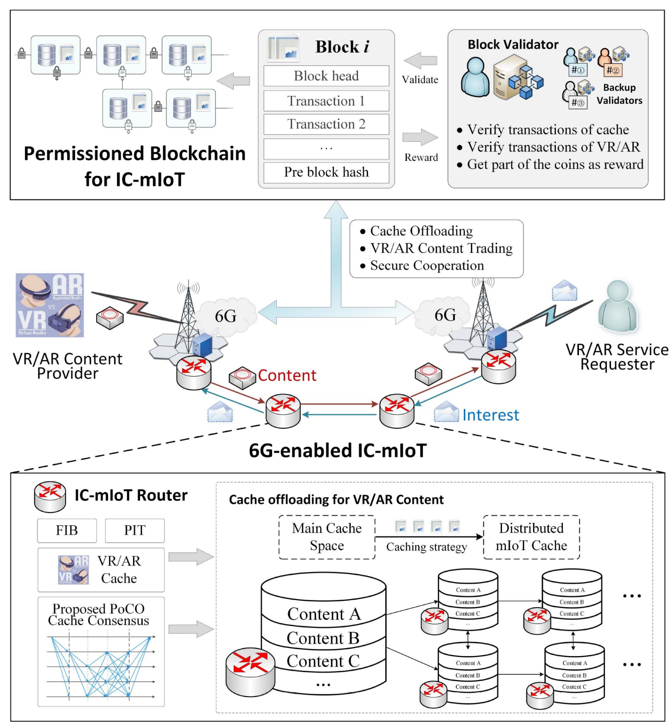

Fig. 2. Architecture of blockchain-enabled IC-mIoT for VR/AR.

B. *Architecture of Blockchain-Enabled IC-mIoT for Ubiquitous VR/AR*

As shown in Fig. 2, the architecture of blockchain-enabled IC-mIoT for VR/AR mainly includes blockchain, 6G-enabled IC-mIoT network and a large number of IoT devices.

1) Role of Permissioned Blockchain: In this architecture, the blockchain is mainly used to record transactions and collaboration contracts in IC-mIoT, including VR/AR paid content transactions, resource transactions (computing, storage, graphics, communication) between ICN nodes, and IoT. Therefore, the behavior of the node will be recorded by the blockchain to achieve traceability to monitor the behavior of the devices participating in the IC-mIoT. The permissioned blockchain operates the blockchain among a group of known, identified and frequently censored participants who operate under the governance model and generate a certain degree of trust. The permissioned blockchain of IC-mIoT provides a way to protect interactions between a group of entities that share a common goal but may not fully trust each other. Therefore, the permissioned context also provides a better environment for the operation of some lighter consensus mechanisms.

2) IC-mIoT Network: In the architecture of IC-mIoT, users do not care where the acquired content comes from, they only care what the content is. This principle makes content the first element in the network, thus replacing the IP-centric network. It decouples the content from the IP location and locates and routes the requested content through a unified content name. Compared with traditional content, VR/AR content has high latency requirements and large data volume. Therefore, IC-mIoT needs high-speed transmission and transmission of the 6G network to quickly spread interest packets and efficiently distribute data packets. As a potential resource provider, IC-mIoT nodes can request cache offloading from mIoT devices through resource pricing. Through the transaction of resources, ICN nodes can obtain a large amount of resources from mIoT devices for VR/AR content services to help them have a higher probability of being accounted, and then obtain the revenue of transactions verification. These transactions are stored in the permissioned blockchain composed of IC-mIoT routers.

3) VR/AR Content Distribution: For the VR/AR content requests from users, the IC-mIoT nodes will check whether there are corresponding VR/AR contents that can be matched in the current cache list to be returned. The cache list records all the contents stored by the IC-mIoT node and the nodes assisting in caching. According to the aforementioned cache offloading relationship between IC-mIoT node and mIoT devices, the corresponding cache content in the cache list can be stored locally on the node, or on the mIoT device that has a contractual relationship with it. If there is no matched VR/AR content for the interest, the pending interest table (PIT) is inquired. If there is a corresponding content item in the PIT, then this item in PIT is updated and the interest packet is discarded. If the interest PIT is not matched, the forwarding information base (FIB) is then inquired. If there exists a matched item in the FIB, the interest packet is then forwarded through the destination interface according to the predefined forwarding rules and the VR/AR content of the PIT is updated. Otherwise, this interest is discarded. On the other hand, if the IC-mIoT node receives a VR/AR data packet, it will also inquire the current cache list. The packet will be discarded if the packet is already in the cache list and the PIT is then inquired. If there exists a matched item in the PIT, the packet is then cached and forwarded to all matching interfaces and the entry is subsequently removed from the PIT. If no match is found in the PIT, which means that the VR/AR content is irrelevant to the potential service of the node, then the data packet will be discarded.

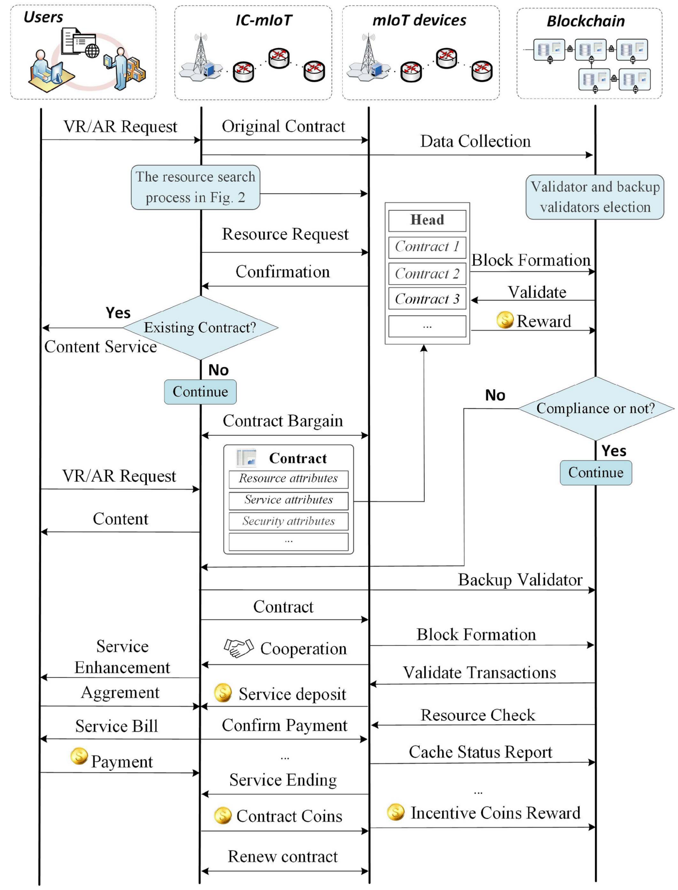

Fig. 3. Workflow of blockchain-enabled IC-mIoT for VR/AR.

C. Workflow of Blockchain-Enabled IC-mIoT

Fig. 3 shows the main workflow of the blockchain-enabled IC-mIoT for VR/AR sharing. For VR/AR service, the user first sends its content request for VR/AR to IC-mIoT, and waits for a response from the IC-mIoT. After the access node receives the request, it will search the for corresponding content and returns the content to the user. For the IC-mIoT node, it forms a resource transaction with mIoT devices. Because IC-mIoT nodes require a large amount of cache space, mIoT devices nodes lease some of their storage space to IC-mIoT nodes. Resource transactions between ICN nodes and mIoT are packaged into blocks and recorded in the blockchain, and the validator of the blockchain verifies the transactions. The validator of the transaction in the block can thus receive a portion of the transaction amount to receive a reward. At the same time, the verifier must collateralize a larger amount of coins to the blockchain. Usually, the amount is greater than the potential benefits it can obtain. If there is any false or malicious act, that is, when the validator of the block is a malicious node, the deposit will be seized. After the service contract between the ICN node and the mIoT node ends, it settles the service bill and negotiates whether to continue the contract. If a new contract is formed between them, the transaction of the new contract between them will continue to be recorded in the blockchain. During this process, the IC-mIoT routers can request cache space from mIoT to enhance its cache capacity

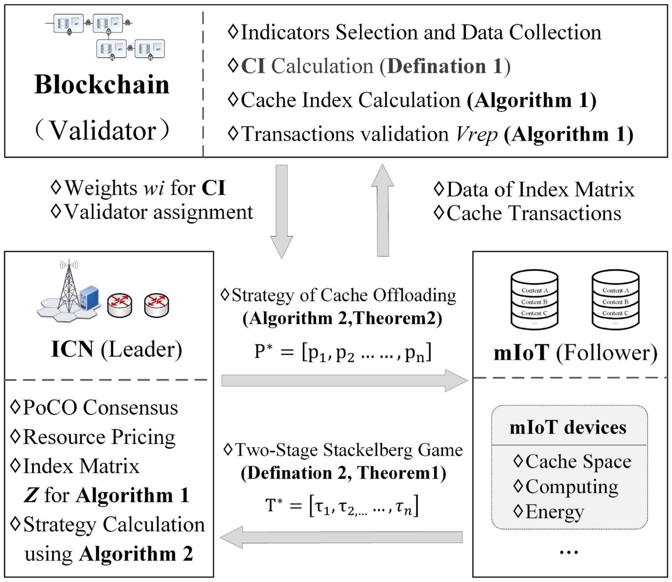

Fig. 4. System model of the proposed scheme.

and mIoT devices can earn income from this. Meanwhile, to ensure data security and trusted collaboration, the mIoT device will also pay a deposit to the ICN node, and the deposit will be returned at the end of the service to ensure the legality of its actions. All of the transactions will be guaranteed and protected by the blockchain.

IV. Proposed Scheme

A. Blockchain-Based Cache Offloading

In the IC-mIoT network proposed in this article, we consider the caching problem of VR/AR content, to optimize the cache space and strategy of IC-mIoT routers to provide high popularity content in time. To incentivize the nodes participating in IC-mIoT to try their best to provide better services for users, in this architecture, the router can request cache offloading to mIoT devices near it. In this way, a transaction is formed between the routing node and the resource node of IC-mIoT. Therefore, we use the cache utility of the nodes as the index to serve as the basis of the consensus mechanism to select the verifier of the transaction. All transactions, including cache resource transactions, VR/AR content transactions, etc., will be recorded in the blockchain waiting for verification by the verifier. At the same time, these transactions can also be paid through cache coins. Since block verifiers can get a part of the transaction amount as a reward, all IC-mIoT in the blockchain will try their best to improve their cache utility to obtain a higher probability of becoming a block verifier.

Fig. 4 shows the architecture of the process, definitions and algorithms of the scheme proposed in this article. The various functions and relationships of blockchain, ICN and mIoT are shown in detail in the figure. In general, blockchain and IC-mIoT select validators and verify transactions. ICN will purchase available cache-related resources from mIoT in order to become a validator and obtain revenue. In this process, the user's QoS will also increase as the overall cache space increases. The rest of this section will expand and introduce the algorithms and definitions in detail according to the flow and relationship of Fig. 4. Meanwhile, the main symbols used in the model and their corresponding meanings are shown in Table I.

TABLE I
Main Symbols and Meanings Used in This Article

Symbols	***Meanings***
CI	Cache Index
s_{ij}	Covariance of standard matrix elements
l_{ij}	The load of original index on the new index
w_i	O The weight of the selected indicators
P_i	Probability to be a validator of the block
$\varphi(T^*)$	The utility of the cache resources obtained by RoC
$\omega(T^*, P^*)$	Total revenue from cache resource pricing
$\omega_i(\tau_i, p_i)$	Single-node cache pricing revenue
$\varepsilon_i(\tau_i)$	Communication resource cost
$e_i(\tau_i)$	Energy resource cost
p_i	Pricing for cached resources
τ_i	Shared cache resources
$J(D_t, \Theta_t)$	The action value function
$\pi(D_t)$	The updated operation strategy

B. Cache Index Selection and Weight Calculation

The measuring of the IC-mIoT node effectiveness may include multiple aspects. Some obvious indicators, such as cache hits and cache hit ratios, can obviously be used to measure the effectiveness of IC-mIoT nodes. Other indicators, such as the number of FIB/PIT requests, the throughput of communications, and the total content size of nodes over time, may also be related to the actual utility of IC-mIoT. For many cache-related factors, our goal is to determine which factors can be used to measure the cache utility of an IC-mIoT node and its corresponding weight. Therefore, we hope to have a unified standard to quantitatively analyze and measure the cache capacity of an IC-mIoT node.

Definition 1: We assume that there are cache-related standardized indicators $\mathbb{X} = \{\chi_i, \chi_2, \ldots, \chi_n\}$ and corresponding $W = (w_1, w_2, \ldots, w_n)$. We define the following CI for ICN and give the following calculation formula:

$$\mathrm{CI} = \sum_{i=1}^{n} w_i \cdot \chi_i \quad i = 1, 2, \ldots, n. \tag{1}$$

Our goal is to collect the cache-related data of IC-mIoT nodes, and then determine some of the indicators most relevant to the actual utility of the cache, and quantify them. Therefore, the main purpose of CI is to quantify the actual utility of the cache based on the weights and corresponding data.

As the method of weight determination in this article, principal components analysis (PCA) aims to use the idea of dimensionality reduction to convert many and complicated indicators into a few comprehensive indicators, which is a technique to simplify data sets. PCA is often used to reduce the dimension of the data set, while maintaining the feature of the data set that contributes the most to the variance. This is done by retaining the low-order principal components and ignoring the high-order principal components. The algorithms and ideas of PCA are also used in data processing and analysis in many fields [37], [38].

In the mechanism proposed in this article, we use PCA to determine the most important indicators and corresponding weights that are most relevant to the cache. The calculated weight will then be used for the election of blockchain validators in the consensus mechanism proposed in this article.

We will first construct a standardized sample matrix for each index $\mathbb{X} = \{\chi_i, \chi_2, \ldots, \chi_n\}$ related to the ICN cache with its corresponding sample value. The corresponding sample value of each indicator χ_i is $\chi_i = (x_{i1}, x_{i2}, \ldots, x_{ip})^T$. So we can get the standardized matrix $Z_{n\times p} = [z_{ij}]$ as follows:

$$\begin{cases} z_{ij} = \frac{x_{ij}-\overline{x_j}}{s_j^2} & \\ & i = 1, 2, \ldots, n \\ \overline{x_j} = \frac{\sum_{i=1}^{n} x_{ij}}{n} & \\ & j = 1, 2, \ldots, p \\ s_j^2 = \frac{\sum_{i=1}^{n} x_{ij}-\overline{x_j}}{n-1}. & \end{cases} \tag{2}$$

Subsequently, we find the covariance matrix $S_{n\times n}$ for the standardized data matrix $Z_{n\times p} = [z_{ij}] = (Z_1, Z_2, \ldots, Z_n)^T$

$$S_{n\times n} = \begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nn} \end{pmatrix}$$
$$= \begin{pmatrix} \mathrm{Cov}(Z_1, Z_1) & \mathrm{Cov}(Z_1, Z_2) & \cdots & \mathrm{Cov}(Z_1, Z_n) \\ \mathrm{Cov}(Z_2, Z_1) & \mathrm{Cov}(Z_2, Z_2) & \cdots & \mathrm{Cov}(Z_2, Z_n) \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{Cov}(Z_n, Z_1) & \mathrm{Cov}(Z_n, Z_2) & \cdots & \mathrm{Cov}(Z_n, Z_n) \end{pmatrix}. \tag{3}$$

We use the following formula to calculate the covariance and construct the matrix $S_{n\times n} = [s_{ij}]$:

$$\begin{aligned} s_{ij} &= \mathrm{Cov}(Z_i, Z_j) = E\big[(Z_i - E[Z_i])(Z_j - E[Z_j])\big] \\ &= \frac{1}{n-1}\sum_{k=1}^{n}(z_{ki} - \overline{z_i})(z_{kj} - \overline{z_j}). \end{aligned} \tag{4}$$

We can obtain the eigenvalues of the matrix by solving the above characteristic equation $|\lambda I - S| = 0$ of the covariance matrix, and arrange these features in descending order. The eigenvalues of the matrix in descending order are denoted by $\lambda^* = (\lambda_1, \lambda_2, \ldots, \lambda_n)$.

According to the proportion of each feature value to the sum of the feature values, we can select the top k indicators with cumulative features greater than η. Usually $\eta = 80\%$–85%

$$\mathrm{ConSum}(k) = \frac{\sum_{i=1}^{k}\lambda_i}{\sum_{i=1}^{n}\lambda_i} \geq \eta. \tag{5}$$

Therefore, we can get k new comprehensive indexes, denote as $\mathbb{F} = \{F_1, F_2, \ldots, F_k\}, \quad i = 1, 2, \ldots, k$, and calculate the load of each original index on the new index F_i

$$\begin{aligned} l_{ij} &= L(F_i, \chi_j) = \sqrt{\lambda_i} \cdot a_{ij} \\ & i = 1, 2, \ldots, k, \quad j = 1, 2, \ldots, n. \end{aligned} \tag{6}$$

In the above formula, $\alpha_i = (a_{i1}, a_{i2,\ldots,a_{in}})^T$ is the unit eigenvector corresponding to λ_i. Therefore, we can use these load values to calculate the weight corresponding to each original index. We denote the weight as $W = (w_1, w_2, \ldots, w_n)$

$$w_i = \frac{\sum_{k=1}^{n}\left(l_{ik} \cdot \lambda_k / \sum \lambda_i\right)}{\sum_{k=1}^{n}\lambda_k / \sum \lambda_i}. \tag{7}$$

Through the weight calculated by the above process and the standardized index value, we can calculate the value of CI, and the comprehensive CI value is associated with the IC-mIoT cache utility. In the cache offloading scheme proposed in this article, the verifier of the block will also periodically collect data randomly according to the indicators to update the weight value.

C. Proof-of-Cache-Offloading Consensus Mechanism

In the proposed mechanism, the transaction process of IC mioT's VR/AR content cache mainly includes but is not limited to the following aspects: 1) resource transaction between ICN node and IoT device; 2) transaction verifier can obtain part of the transaction amount as commission; and 3) paid VR/AR content.

Since the election of block validator is based on the CI, all nodes participating in the blockchain want to improve their cache hit quantity and hit rate index to become block validator, and then obtain the income of verification transactions

$$\mathrm{CI}^{\mathrm{sum}} = \sum_{k=0}^{T_i/t}\mathrm{CI}_{(i),k} \cdot t, \quad (T_i = k \cdot t \in \mathbb{T}). \tag{8}$$

In the above equation, t denotes the basic time period of VR/AR content caching. In the PoCO consensus mechanism proposed in this article, we believe that IC-mIoT nodes with better caching performance should be given a higher probability to become a block verifier, and thus obtain benefits. If we take $\mathbb{N}$ as the set of nodes participating in the PoCO consensus, we can get the probability that each IC-mIoT node becomes the final block validator as follows:

$$P_i = \frac{\mathrm{CI}_i^{\mathrm{sum}}}{\sum_i \mathrm{CI}_i^{\mathrm{sum}} \cdot \delta_i} \quad \begin{cases} \delta_i = 1, & N_i \in \mathbb{N} \\ \delta_i = 0, & N_i \notin \mathbb{N}. \end{cases} \tag{9}$$

Based on the PoCO consensus mechanism above, we have designed the following consensus algorithm to select the validator of the blockchain. After collecting the data corresponding to the diversified indicators, the weights of these indicators are obtained through the proposed Algorithm 1 based on PCA.

D. Stackelberg Game-Based ICN Utility Optimization

1) Problem Formulation: In the cache offloading scheme proposed in this article, we divide the state of the IC-mIoT routers into three types: 1) requester of cache offloading (RoC, leader); 2) provider of cache offloading (PoC, follower); and 3) nodes that do not participate in cache offloading.

Algorithm 1 PoC Consensus Algorithm in IC-mIoT

Input: n cache indicators, the original data $\mathbb{X}$ corresponding to the indicator, the statistical time period T, and the data d_{it} within the statistical time, representative election ratio τ

Output: Validator $Vrep^*$ and the probability P_i that each ICN node n_i becomes $Vrep^*$.

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1: Normalize the raw data X of the indicator to matrix Z_{n×p}
2: Calculate the covariance matrix S_{n×n} from Z_{n×p} according to Eq.(4)
3: Find the eigenvalues of matrix S_{n×n}
4: Determine k principal components by Eq.(5)
5: Calculate the load of n indicators on k components
6: Recalculate the weights of n indicators by Eq.(7)
7:     for all t_i ∈ T do
8:         Calculate CI^{sum} according to Eq.(8)
9:     end for
10:    for all node n_i do
11:        Calculate P_i according to Eq.(9)
12:    end for
13: Choose representative Vrep* according to probability P_i
14: Vrep* Mortgage deposit and verify transactions
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We denote the certain cache offloading IC-mIoT requester as R_{RoC}, who requests assistance in caching through resource pricing to improve its cache utility. According to the connectivity of the mIoT devices, the potential resource nodes that can provide cache offloading services are denoted as $\mathbb{P} = \{R_{\mathrm{PoC},1}, R_{\mathrm{PoC},2} \cdots R_{\mathrm{PoC,n}}\}$.

To improve its cache performance and obtain a higher probability of becoming a block validator and providing better services to users, RoC will request cache offloading from PoC. Therefore, our goal is to satisfy the conditions of cache offloading, while enabling RoC and PoC participating in cache offloading to maximize their benefits.

To get the optimal cache offloading strategy between IC-mIoT routers and the available resource mIoT devices, we propose the game $\mathbb{G} = \{S_{\mathrm{RoC}}, S^{\mathrm{PoC}}_{C_{\mathrm{PoC}}\in\mathbb{P}}; \Pi_{\mathrm{RoC}}, \Pi^{\mathrm{PoC}}_{C_{\mathrm{PoC}}\in\mathbb{P}}\}$. In the game $\mathbb{G}$, $S_{\mathrm{RoC}} = \{\sum_{C_{\mathrm{PoC,i}}\in\mathbb{P}} \tau_i \geq D_{\min}, p_{\min} \leq p_i \leq p_{\max}\}$ is the pricing strategy of RoC that is designed to meet its cache offloading needs. $S^{\mathrm{PoC}}_{C_{\mathrm{PoC}}\in\mathbb{C}} = \{\tau_i, i \in N, \eta \cdot S_{i,\max} \leq \tau_i \leq \mu \cdot S_{i,\max}\}$, where τ_i represents the cache resources provided by PoC_i to RoC and $\lambda \in [0, 1]$ limit the range of communication resources provided by $C_{\mathrm{PoC,i}}$.

In $\mathbb{G}$, Π_{RoC} and $\Pi^{\mathrm{PoC}}_{C_{\mathrm{PoC}}\in\mathbb{C}}$ are the utility functions of RoC and PoC. We use these two utility functions to measure the benefits of PoC and RoC. Given resource vector $T^* = \{\tau_1, \tau_2, \ldots, \tau_n\}$ and price vector $P^* = \{p_1, p_2, \ldots, p_n\}$, the objective function of RoC can be formulated as follows:

$$\begin{aligned} \max\ & \Pi_{\mathrm{RoC}}\big(T^*, P^*\big) \\ & = \varphi\big(T^*\big) - \omega\big(T^*, P^*\big) - C \\ \text{s.t.}\ & \begin{cases} D_{\min} \leq \sum_{i\in\mathbb{P}} \tau_i, \quad i \in \mathcal{N} \\ p_{\min} \leq p_i \leq p_{\max}. \end{cases} \end{aligned} \tag{10}$$

In the above equation, $\varphi(T^*)$ represents the revenue that RoC obtained after obtaining PoC resources, including storage, communication and computing resources. $\omega(T^*, P^*)$ represents the price paid by RoC for cache resources, that is, the product of unit price and the amount of cache resources.

On the other hand, taking into account of the cache offloading limitations of PoC, the objective function of PoC can be formulated as follows:

$$\begin{aligned} \max\ & \Pi_{\mathrm{PoC}}(\tau_i) \\ & = \omega_i(\tau_i, p_i) - \varepsilon_i(\tau_i) - e_i(\tau_i) \\ \text{s.t.}\ & \begin{cases} \lambda \cdot S_{i,\max} \leq \tau_i \leq \eta \cdot S_{i,\max} \\ e_i(\tau_i) \leq E_{\max} \\ \varepsilon_i(\tau_i) \leq \mathrm{Comm}_{i,\max}. \end{cases} \end{aligned} \tag{11}$$

In the above PoC utility function, $\omega_i(\tau_i, p_i)$ represents the income obtained by resource node i through resource pricing. $\varepsilon_i(\tau_i)$ is the price that PoC needs to pay for managing the stored content and $e_i(\tau_i)$ is the energy cost that it needs to pay in the above process.

Therefore, in this game, RoC purchased the cache resources of PoC through resource pricing and used this to enhance its effectiveness as an IC-mIoT node. For the revenue of this part, PoC needs to sell part of its storage space and corresponding communication resources and energy consumption. The game proposed in this article and the utility functions of PoC and RoC is based on the characteristic and process of IC-mIoT and some related researches on Stackelberg game[33]–[36]. We will then introduce the specific form of the utility function in detail as follows.

2) Utility Function Formulation: For the RoC node, its overloaded cache space requirements will be offloaded by different PoC nodes. Correspondingly, the RoC will provide a certain reward for the cache resources of the PoC according to the cache space provided by the PoC. We set the service satisfaction obtained by RoC cache offloading as an exponential expression according to [39] and [40]. Since RoC is in a full load state, we consider its expenditure on energy consumption to be constant C_E. We set a price to a unit of storage resource, so the price that RoC needs to pay is the sum of the product of price and resource. Therefore, we have the following utility function for RoC:

$$\begin{cases} \varphi(T^*) = e_0 - k_i e^{-h_i \sum_{i\in\mathbb{P}} \tau_i + r} \\ \omega(T^*, P^*) = \sum_{i\in\mathbb{P}} p_i \cdot \tau_i. \end{cases} \tag{12}$$

In the above equation, $\varphi(T^*)$ is the effectiveness of RoC due to the acquired cache resources. $\omega(T^*, P^*)$ is the price that RoC pays PoC for the corresponding resources. C is a constant part of this process. Therefore, the specific expression of the RoC utility function is as follows:

$$\Pi_{\mathrm{RoC}}\big(T^*, P^*\big) = e_0 - k_i e^{-h_i \sum_{i\in\mathbb{P}} \tau_i + r} - \sum_{i\in\mathbb{P}} p_i \cdot \tau_i - C. \tag{13}$$

On the other hand, the PoC nodes need to utilize part of the communication and energy resources for RoC cache offloading. Therefore, although it has received a reward from RoC, it needs to face the decline in QoS of its own users. In addition, more communication load means a corresponding increase in energy consumption. According to working process of IC-mIoT, the utility function of PoC are formulated as

$$\begin{cases} \omega_i(\tau_i, p_i) = p_i \cdot \tau_i \\ \varepsilon_i(\tau_i) = m_i \ln(1 + n_i\tau_i) \\ e_i(\tau_i) = a_i \cdot \tau_i^2 + b_i \cdot \tau_i + c_i. \end{cases} \tag{14}$$

In the above equation, $\omega_i(\tau_i, p_i)$ is the income that PoC sells its cache resources. $\varepsilon_i(\tau_i)$ is the corresponding communication resource that it needs to pay. To provide cache-related services, part of PoC's communication resources will be occupied, and this part is considered to be the cost of PoC. We set the resource occupation of communication as a logarithmic function. $e_i(\tau_i)$ refers to the energy cost of the node. Therefore, the specific expression of the PoC utility function is as follows:

$$\Pi_{\mathrm{PoC}}(\tau_i) = p_i \cdot \tau_i - m_i \ln(1 + n_i\tau_i) - \left(a_i \cdot \tau_i^2 + b_i \cdot \tau_i + c_i\right). \tag{15}$$

In the above equation, θ_i is a parameter used to indicate user QoS. For a communication system, the utility of QoS is usually greater than energy, so α_i, β_i, and γ_i are a smaller number for θ_i they are all positive numbers.

3) Calculating Nash Equilibrium: Given that $T^* = \{\tau_1, \tau_2, \ldots, \tau_n\}$ is the cache offloading strategy of PoC and $P^* = \{p_1, p_2, \ldots, p_n\}$ is the reward strategy of RoC, we have the following definition.

Definition 2: In $\mathbb{G} = \{S^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}; \Pi^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}\}$, T^* is the Nash equilibrium (NE) of the game if $S_{\mathrm{PoC,i}}$ if the best response to the noncooperative subgame and $\Pi_{\mathrm{PoC}}(\tau^*, p^*) \geq \Pi_{\mathrm{PoC}}(\tau', p^*)$.

Theorem 1: A unique NE of $\mathbb{G} = \{S^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}; \Pi^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}\}$ exists when the condition $m_i \cdot n_i^2 \leq a_i$ is met.

Proof: In order to verify the existence of the unique NE, we first derive the utility function of the PoC. The first derivative $(\partial \Pi_{\mathrm{PoC}}/\partial \tau_i)$ and the second derivative $(\partial^2 \Pi_{\mathrm{PoC}}/\partial \tau_i^2)$ of Π_{PoC} to τ_i are as follows:

$$\begin{aligned} \frac{\partial \Pi_{\mathrm{PoC}}}{\partial \tau_i} &= -\frac{\partial \log(n_i \cdot \tau_i + 1) m_i}{\partial \tau_i} \\ &\quad - \frac{\partial a_i \tau_i^2 + b_i - \tau_i + c_i}{\partial \tau_i} + \frac{\partial p_i - \tau_i}{\partial \tau_i} \\ &= p_i - \frac{m_i \cdot n_i}{1 + n_i \cdot \tau_i} - 2a_i\tau_i - b_i. \end{aligned} \tag{16}$$

Then, we continue to find the second derivative function of the utility function of PoC

$$\begin{aligned} \frac{\partial^2 \Pi_{\mathrm{PoC}}}{\partial \tau_i^2} &= \frac{\partial - 2a_i\tau_i}{\partial \tau_i} - \frac{\partial b_i}{\partial \tau_i} - \frac{\partial \frac{m_i \cdot n_i}{(n_i \cdot \tau_i + 1)}}{\partial \tau_i} + \frac{\partial p_i}{\partial \tau_i} \\ &= \frac{m_i \cdot n_i^2}{(1 + n_i \cdot \tau_i)^2} - 2a_i. \end{aligned} \tag{17}$$

According to the above equation, $(\partial^2 \Pi_{\mathrm{PoC}}/\partial \tau_i^2)$ is a decreasing function of τ_i. So $(\partial^2 \Pi_{\mathrm{PoC}}/\partial \tau_i^2) \leq 0$ if $m_i \cdot n_i^2 \leq a_i$. This gives the condition that a PoC can become a provider of cache space. If we let $(\partial^2 \Pi_{\mathrm{PoC}}/\partial \tau_i^2) \leq 0$, we can get whether a PoC is suitable for RoC to provide all kinds of resources, which is $[(m_i n_i^2)/(2 \cdot (n_i \cdot \tau_i + 1)^2)] \leq a_i$. So when $m_i \cdot n_i^2 \leq a_i$, we have a second order function $(\partial^2 \Pi_{\mathrm{PoC}}/\partial \tau_i^2) \leq 0$.

If this condition is met, Π_{PoC} is convex function and a unique NE exist in $\mathbb{G} = \{S^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}; \Pi^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}\}$. In addition, we have the following price:

$$p_i = \frac{m_i \cdot n}{1 + n_i \cdot \tau} + 2a_i\tau + b_i. \tag{18}$$

■

Theorem 2: A unique Stackelberg equilibrium (SE) exists in game $\mathbb{G} = \{S_{\mathrm{RoC}}, S^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}; \Pi_{\mathrm{RoC}}, \Pi^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}\}$ when $m_i \cdot n_i^2 \leq a_i$. So that the pricing strategy $P^* = \{p_1, p_2, \ldots, p_n\}$ can maximize the benefits of RoC.

Proof: In order to verify the existence of the unique SE, we first derive the utility function of the RoC. The first derivative $(\partial \Pi_{\mathrm{RoC}}/\partial \tau_i)$ and the second derivative $(\partial^2 \Pi_{\mathrm{RoC}}/\partial \tau_i^2)$ of Π_{PoC} to τ_i are as follows by using (9):

$$\begin{aligned} \frac{\partial \Pi_{\mathrm{RoC}}}{\partial \tau_i} &= chk \cdot e^{(-h_i \cdot \tau_i + r)} \\ &\quad - \left(\frac{\partial 2a\tau_i^2 + b \cdot \tau_i}{\partial \tau_i} + \frac{\partial \frac{m_i \cdot n_i \tau_i}{(n_i \cdot \tau_i + 1)}}{\partial \tau_i} \right) \\ &= c \cdot h \cdot k \cdot e^{-h \cdot \tau_i + r} - 4a_i\tau_i - b_i \\ &\quad - \frac{m_i \cdot n_i}{1 + n_i \cdot \tau_i} + \frac{m_i \cdot n^2 \cdot \tau_i}{(1 + n_i \cdot \tau_i)^2}. \end{aligned} \tag{19}$$

Then, we continue to find the second derivative function of the utility function of RoC

$$\begin{aligned} \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_i^2} &= chk \cdot \frac{\partial e(-h \cdot \tau_i + r)}{\partial \tau_i} - \frac{\partial 4a_i\tau_i}{\partial \tau_i} \\ &\quad - \frac{\partial b_i}{\partial \tau_i} - \frac{\partial \frac{m_i \cdot n_i}{(n_i \cdot \tau_i + 1)}}{\partial \tau_i} + \frac{\partial \frac{m_i n_i \tau_i^2}{(n_i \cdot \tau_i + 1)^2}}{\partial \tau_i} \\ &= -c \cdot h^2 \cdot k \cdot e^{-h \cdot \tau_i + r} - 4a \\ &\quad + \frac{2m_i \cdot n_i^2}{(1 + n_i \cdot \tau_i)^2} - \frac{2m_i \cdot n^3 \cdot \tau_i}{(1 + n_i \cdot \tau_i)^3}. \end{aligned} \tag{20}$$

By using the condition of $[(m_i n_i^2)/(2 \cdot (n_i \cdot \tau_i + 1)^2)] \leq a_i$ in Theorem 1, we have the following inequality:

$$\frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_i^2} \leq -c \cdot h^2 \cdot k \cdot e^{-h \cdot \tau_i + r} - \frac{2m_i \cdot n_i^3 \cdot \tau_i}{(1 + n_i \cdot \tau_i)^3} \leq 0. \tag{21}$$

Therefore, the unique SE of the game $\mathbb{G} = \{S_{\mathrm{RoC}}, S^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}; \Pi_{\mathrm{RoC}}, \Pi^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}\}$ exists and the cache offloading strategy $\tau^* = \{\tau_1, \tau_2, \ldots, \tau_n\}$ can be found. ■

When $m_i \cdot n_i^2 \leq a_i$, we have $(\partial^2 \Pi_{\mathrm{RoC}}/\partial \tau_i^2) < 0$. According to (20), the following Hessian matrix is a diagonal matrix:

$$H_{ij} = \begin{pmatrix} \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_1 \partial \tau_1} & \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_1 \partial \tau_2} & \cdots & \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_1 \partial \tau_n} \\ \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_2 \partial \tau_1} & \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_2 \partial \tau_2} & \cdots & \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_2 \partial \tau_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_n \partial \tau_1} & \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_n \partial \tau_2} & \cdots & \frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_n \partial \tau_n} \end{pmatrix} \tag{22}$$

$$\frac{\partial^2 \Pi_{\mathrm{RoC}}}{\partial \tau_i \partial \tau_j} = \begin{cases} c \cdot h \cdot k \cdot e^{-h \cdot \tau_i + r} - 4a_i - b_i & \\ -\frac{m_i \cdot n_i}{1 + n_i \cdot \tau_i} + \frac{m_i \cdot n^2 \cdot \tau_i}{(1 + n_i \cdot \tau_i)^2} < 0, & i = j \\ 0, & i \neq j. \end{cases} \tag{23}$$

Algorithm 2 mIoT Device Collaboration Strategy Algorithm

Input: Utility function Π_{RoC}, resource requirements $D_{\min}$, iteration times M, exploration-utilization related parameters ϵ

Output: Optimal cache offloading strategy $\tau^* = (\tau_1, \tau_2, \cdots, \tau_n)$ and corresponding resource unit price p_i

```
Obtain utility related parameters from PoC
Initialization parameters: t = 0, ϵ ∈ (0, 1), m = 0,
Initialize J(D_t, Θ_t) = 0
    repeat
    for t = 0, 1, 2,    T − 1 do
        Calculate the current utility value
        Update action-value function J(D_t, Θ_t) according to Eq.(24)
        Update current strategy π(D_t) according to Eq.(25)
    end for
m ← m + 1
Decrease the value of ϵ
    until m ≥ M
```

Therefore, in a IC-mIoT system, if the aforementioned $m_i \cdot n_i^2 \leq a_i$ is met, we can find an optimal cache offloading strategy. Therefore, the unique SE of the game $\mathbb{G} = \{S_{\mathrm{RoC}}, S^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}; \Pi_{\mathrm{RoC}}, \Pi^{\mathrm{PoC}}_{C_{\mathrm{PoC}} \in \mathbb{P}}\}$ exists and the cache offloading strategy $T^* = \{\tau_1, \tau_2, \ldots, \tau_n\}$ can be found using the following algorithm.

E. Cache Strategy Algorithm Based on Reinforcement Learning

The above two theorems and their proofs show that we can find a pricing strategy and corresponding cache offloading method to maximize the effectiveness of PoC and RoC. However, the maximum value of the above utility function (13) is difficult to find a specific solution in an analytical way. Therefore, we will use reinforcement learning to find an optimal value with acceptable error.

We define u_t as the instantaneous utility value generated at time t. For the cache offloading strategy $\Gamma = \{\tau_1, \tau_2, \ldots, \tau_n\} \in \mathbb{T}$, the decision-making agent can calculate the real-time utility value by the following formula:

$$u_t(\tau_i) = \Pi_{\mathrm{RoC}}\left(T^*, P^*\right) = e_0 - k_i e^{-h_i \sum_{i \in \mathbb{P}} \tau_i + r} - \sum_{i \in \mathbb{P}} \left(\frac{m_i \cdot n}{1 + n_i \cdot \tau_i} + 2a_i\tau_i + b_i \right) \cdot \tau_i - C. \quad (24)$$

In each attempt, the action-value function $J(D_t, \Theta_t)$ can be updated by the following formula:

$$J(D_t, \Theta_t) \leftarrow u_i + \gamma \min_{\Theta'_{t+1}} J\left(D_t, \Theta'_{t+1}\right). \quad (25)$$

After the action-value function $J(D_t, \Theta_t)$ is determined, the operation strategy can be updated according to the following formula:

$$\pi(D_t) \leftarrow \mathrm{argmin}_{\Theta'_t} J\left(D_t, \Theta'_{t+1}\right). \quad (26)$$

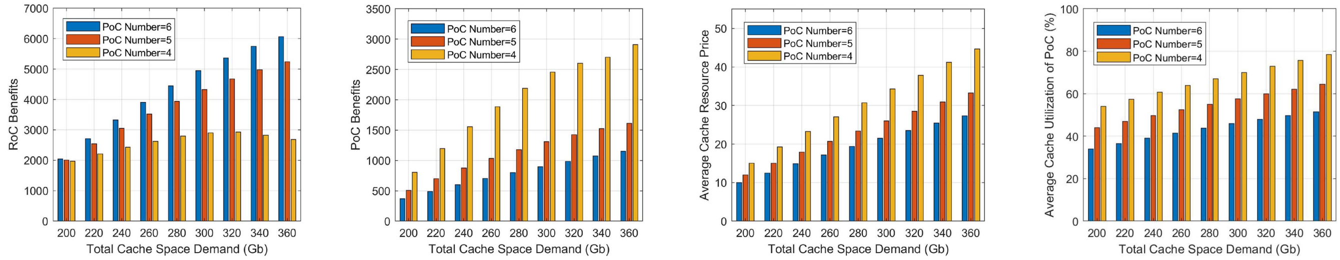
Based on the above system model and mathematical derivation, we have designed the following algorithm to find the best mIoT device collaboration model. The proposed Algorithm 2 is based on the above main formulas. After obtaining the information of the utility function, it can gradually explore the optimal solution under the restricted conditions.

V. Simulations and Experiments

In this section, we carried out detailed simulations and experiments on the algorithms and schemes proposed in this article. The efficiencies and explanations of the proposed scheme are given in this section by a series of comparisons and results, including the results and theoretical analysis of the Stackelberg game, the simulation of the consensus mechanism and the impact of this mechanism on the cache, etc. Our scheme is simulated based on MATLAB, which is running on a server with Intel i7 6700 CPU and 16-GB RAM. We establish the IC-mIoT network and nodes, simulate the behaviors and functions of IC-mIoT routers and resource nodes. We established an IC-mIoT network and assumed that some of the router nodes can obtain various resources of nearby mIoT devices to enhance their capabilities. The IC-mIoT router has its own storage space and computing power. By determining its own storage space requirements, it requests storage resources from nearby available resource nodes. Then mIoT nodes provide corresponding supporting storage, computing and communication services. The service utility of the IC-mIoT router has also improved. The main variables simulated in this article include cache space requirements, available cache resources, consensus mechanism, etc.

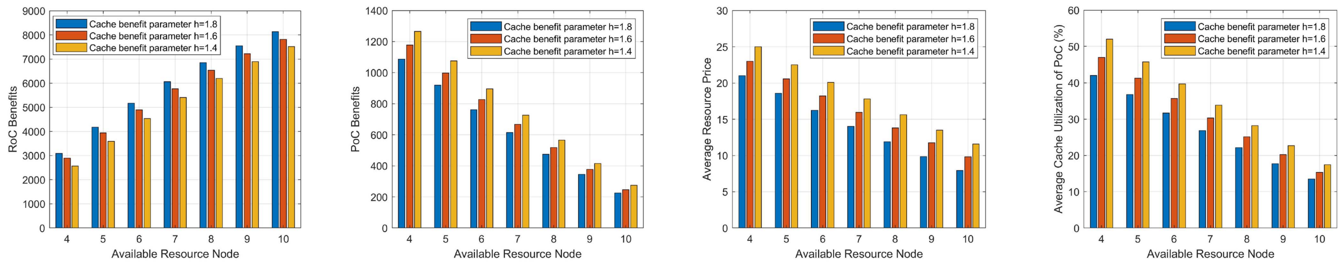
First, we simulated the game process between the IC-mIoT router and the mIoT resource nodes. Through the simulation of the reinforcement learning algorithm proposed by this article and the utility functions of both parties. Fig. 5 shows the changes of various indicators with the increase of resource demand. Specific indicators include PoC utility, RoC utility, average resource price, and PoC resource utilization. The benefits of PoC and RoC is the most intuitive expression used to measure the utility of IC-mIoT nodes and mIoT devices. The corresponding average cache resource price and utilization rate can provide a macroperspective. As shown in Fig. 5(a), we can see that when more resource nodes contribute resources to IC-mIoT, the effectiveness of RoC will increase. It is worth mentioning that when the demand for resources is too large, the utility of RoC may also decline. Fig. 5(b) shows the benefits of PoC. The higher the resource demand, the higher the utility PoC will be, and when there are fewer resource nodes, the PoC will get higher returns. Fig. 5(c) shows that the average cache resource price is affected by the total cache demand. The price of resources will increase as nodes and demand increase. Fig. 5(d) shows that the cache utilization ratio of resource nodes will increase with the increase of demand and the number of nodes under the proposed scheme.

In the experiment of Fig. 5, we studied the changes of the above indicators with the number of resource nodes and made comparative experiments under different benefit parameters h. The h in the utility function is mainly used to reflect the overall level that the cache resource can bring to the RoC. As shown in Fig. 6(a), the utility of RoC will increase with the



(a) (b) (c) (d)

Fig. 5. Impact of cache space requirements on various indicators. (a) Benefit of RoC. (b) Benefit of PoC. (c) Cache price. (d) Cache utilization.



(a) (b) (c) (d)

Fig. 6. Impact of the number of available resource nodes on various indicators. (a) Benefit of RoC. (b) Benefit of PoC. (c) Cache price. (d) Cache utilization.

increase of available resource nodes. And with the increase of the parameter h, RoC's income is rising, which is consistent with the meaning of h. Fig. 6(b) shows that with the increase of resource nodes, the benefit of PoC will decrease. If the same resources can bring more efficient use to RoC, that is, the value of h is larger, the benefit of PoC is lower. This phenomenon has a similar conclusion in the price of cache resources. In Fig. 6(c), the larger the number of resource nodes, the more potential RoC resources available, so the price of cache resources will also decrease accordingly. The result of Fig. 6(d) is also very obvious. More resource nodes will reduce the cache resource utilization. A higher h also means that RoC can make better use of cache resources and reduce cache utilization.

Further, we studied whether the way IC-mIoT routers request resource storage from resource nodes through resource pricing can improve the overall performance and effectiveness of the IC-mIoT network. Therefore, we compared the resource changes of the IC-mIoT router before and after using the cache offloading mechanism proposed in this article in Fig. 7. We can clearly see that the storage resources of IC-mIoT have been improved. As we all know, more storage space can significantly improve the service quality of the ICN network. Without cache offloading, the cache resources of IC-mIoT nodes are limited. However, permissioned blockchains have certain access conditions, which means that not all nodes can join the system. Therefore, through the cache offloading mechanism proposed in this article, IC-mIoT nodes and mIoT devices form certain restrictive relationships. Thanks to the addition of mIoT devices, the overall cache performance of the system has also been improved.

We also simulated the impact of different consensus mechanisms on the IC-mIoT network. We compared the PoCO consensus mechanism proposed in this article with the traditional Proof of Work (PoW). Fig. 8 compares the two consensus machines from three aspects: 1) cache hit rate; 2) cache hit number; and 3) node traffic. As shown in Fig. 8(a) and (b), the number of cache hits and the cache hit rate of the transaction validators selected by PoCO are significantly better. Because the consensus process of PoCO fully considers the cache resources, these two indicators are the most able to reflect the cache effectiveness. Fig. 8(c) compares the throughput of the nodes selected under the two consensus mechanisms. The higher throughput indicates that the content resources of the node are more abundant. This further proves that PoCO is more suitable for the environment of IC-mIoT. The calculation of PoW mainly depends on the computing resources of the node, and the PoCO proposed in this article mainly measures the cache capacity of the node, and the consensus process does not require a lot of resources.

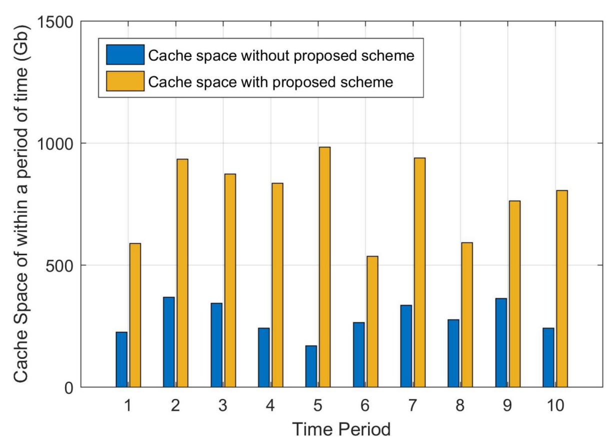


Fig. 7. Effect of the proposed scheme on the cache space.

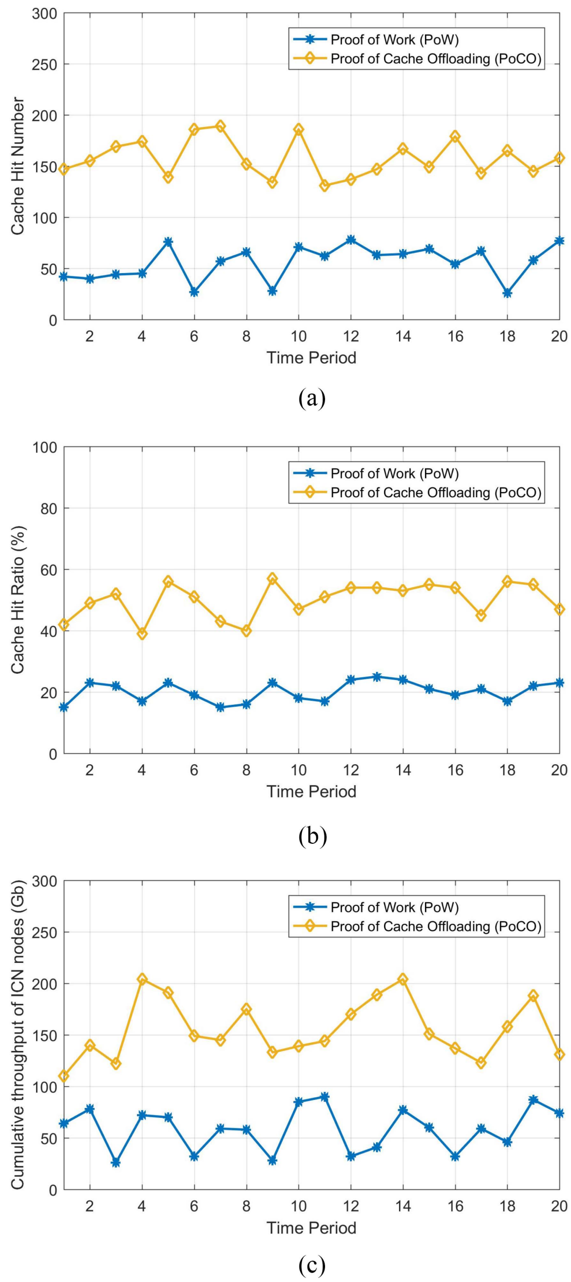


Fig. 8. Comparison of the same index under different consensus mechanisms. (a) Comparison of cache hits. (b) Cache hit rate comparison. (c) Throughput comparison.

VI. Conclusion

In this article, we focused on building an IC-mIoT network to achieve ubiquitous VR/AR services in women 6G. We introduced an ICN architecture for mIoT, and made full use of the characteristics of 6G to provide users with ubiquitous VR/AR services. Through the improvement of the basic idea and application architecture of the blockchain, we have designed a brand new consensus mechanism PoCO to protect various types of content and resource transactions in IC-mIoT. In addition, this article also designed the corresponding algorithm for consensus mechanism PoCO index selection and optimal cache offloading strategy between nodes. The simulation results fully illustrate the superiority and feasibility of the scheme proposed in this article.

With the gradual deployment of 5G networks, the application, architecture and challenges of future 6G networks are very worth looking forward to. For future work, we hope to further explore the problems brought by the characteristics of the 6G network in the application, as well as the possibility of fully mobilizing and utilizing the large-scale edge nodes in the 6G network.

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