Decentralized Resource Allocation for Video Transcoding and Delivery in Blockchain-Based System With Mobile Edge Computing

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***Abstract*—The blockchain-based video systems are designed to build a decentralized and flexible video ecosystem by enabling a direct interaction among users, video providers (VPs), and service providers. In blockchain-based video systems, the heterogeneous qualities and formats of the video streams usually require massive computational resources to transcode them into different versions and formats to meet distinct requirements of users. However, current blockchains cannot handle massive and heterogeneous video streaming due to limited computing capacity and long transaction times. To deal with this issue, in this paper, leveraging mobile edge computing (MEC) technology, we propose a blockchain-based MEC architecture, where small base stations (SBSs) allocate their computation as well as communication resources for providing video streaming in a distributed and secure manner. Moreover, to improve the operation efficiency, we use a series of smart contracts to enable a self-organized video transcoding and delivery service without a centralized controller. Then, users, SBSs, and VP could adjust their strategies according to the transactional information on blockchain. Moreover, we formulate the video transcoding and delivery problem as a three-stage Stackelberg game. We analyze the sub-game equilibrium in each stage and the interplays of the three-stage game. Last, we propose an iterative algorithm to solve the problem. Simulation results show that the proposed approach could obtain the good performance in terms of average time to finality (TTF), average access delay, and network cost.**

***Index Terms*—Mobile edge computing, blockchain, smart contracts, video transcoding, resource allocation.**

I. Introduction

THE ubiquitous penetration of video streaming services significantly fuels a dramatical growth of mobile data traffic in current wireless networks. According to the Cisco report, mobile video traffic will occupy 79% of the global mobile data traffic by 2022[1]. With the increasing of the demands for video services, video streaming platforms like Netflix and YouTube have become popular over the past decade. However, these video streaming platforms suffer from a lot of disadvantages, such as low profit for video providers, high monthly charge and low privacy for users, etc. In addition, due to the heterogeneous devices and dynamic network conditions, the video steams have to be converted into different bitrate versions to satisfy distinct requirements of users. These multiple copies of video files with different bitrates are stored on the central servers, which bring huge costs of video storages and bandwidth.

Recently, blockchain has been proposed as a promising decentralized solution and has been applied in various distributed scenarios [2]–[4]. The blockchain essentially is a distributed public ledger, which records transactions in a public or private peer-to-peer (P2P) network. Leveraging blockchain technology, several startups (e.g., flixxo, Livepeer, VideoCoin, etc.) are able to build decentralized P2P networks with flexible monetization mechanisms for providing video streaming services. In this new era of blockchain-based video streaming, video providers (VPs), users, and service providers can perform video trading without the intervention of any third party [5]. Moreover, the video sharing processes could be self-organized by utilizing smart contracts, which are autonomous programs and deployed to achieve self-executing and self-enforceable transactions [6]. However, due to the limited computing capabilities, current blockchain-based video systems cannot enable video transcoding, which transforms a video from one version to another version on the fly to release the huge burden of the storage and bandwidth.

On the other hand, mobile edge computing (MEC), which brings the computing capabilities to the edges of the network, is considered as a promising technology to support video streaming services to the users [7], [8]. In general, small base stations (SBSs) equipped with MEC servers provide low-latency services to users and release the bandwidth and the storage costs[9]. The authors in [10] propose an MEC-based architecture to enable the MEC server to convert the bitrate version of the video based on the network condition and user requirements. In [11], the authors propose a video bitrate adaptation algorithm considering the varying wireless channel conditions. The integration of blockchain and MEC may bring substantial benefits and be an

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inspiring thought for this interesting area. A lot of works have been done on the MEC and blockchain to give a full play of their advantages. Next subsection presents the related works on blockchain, MEC, and game theory-based solutions.

A. Related Works

As pioneer works, the authors in [12], [13] introduce edge computing for mobile blockchain and propose economic computing resource managements based on Stackelberg game model. To deal with the mining problems, the authors in [14] propose an auction-based edge computing resource allocation mechanism, where mobile users (miners) are able to offload the mining works to an edge computing service provider (ECSP). To maximize the revenue of the ECSP, the authors in [15] propose a deep learning (DL) resource allocation scheme in mobile blockchain networks. However, these works adopt proof of work (PoW) protocol for achieving consensus in blockchain network, where block mining and blocks synchronization among all participants result in high cost and long delay, and thus makes them unsuitable for delay-sensitive and energy-limited video streaming.

To address this issue, the authors in [16] investigate the consensus propagation problem in Proof of Stake (PoS)-based consortium blockchain networks. They utilize game theory to model the interaction among the blockchain user and miners. The authors in [17] propose an enhanced Decentralized Proof of Stake (DPoS) consensus scheme with two-stage soft security solution, i.e., miner selection and block verification, for secure vehicle data sharing in blockchain enabled Internet of Vehicles (IoV). Utilizing consortium blockchain and smart contract technologies, the authors in [18] propose a secure data sharing system for efficient data storage and sharing without authorization in vehicular computing and networks.

Game theory is an efficient and flexible tool that studies the interaction and cooperation process among various nodes and parties in networks. In edge caching networks, the authors in [19] investigate an interplay among wireless network operator, the sponsored content service providers, and mobile users under a hierarchical three-stage Stackelberg game framework. The applications of Stackelberg game are also effectively investigated for resource allocation in mobile cloud computing systems [20], virtual resource management in wireless relaying networks [21], computing resource allocation in fog networks [22], etc. In game theory literature of blockchain networks, the authors in [23] model the mining process as a cooperative game among miners. In the mining process, miners form a coalition to accumulate their computational power and have steady reward. In MEC-enabled mobile blockchain networks, the authors in [13], [16] model the mining process as Stackelberg game to maximize the revenue of the ECSP and the utility of the blockchain. Although, a lot of seminal works have modeled the resource allocation and blockchain-based mining process as Stackelberg games, these two areas have been addressed separately. In our paper, we take the resource allocation and blockchain-based consensus process into consideration and model them as a Stackelberg game which should be well investigated to optimize the utilities of resource and consensus process.

Currently, MEC offers a feasible way for video transcoding to support adaptive video streaming services to the users. We have investigated several issues regarding video transcoding and delivery by leveraging MEC and other technologies. Leveraging the wireless virtualization technique, a content caching and computing framework is proposed in [7] to improve the video service in information-centric heterogeneous networks. Considering the MEC, caching, and soft-defined networks (SDN), a joint adaptive video rate, computing resource, and traffic engineering problem is investigated in [9]. In [24], we propose a hybrid computing offloading approach in fog networks, where users have multiple and independent tasks that can be offloaded at fog nodes or at a remote cloud cooperatively. In [25], leveraging MEC technology, we investigate the video transcoding and delivery problem in ultra dense networks and propose a joint SBS selection, task scheduling, and resource allocation scheme for supporting video streaming services. The integration of blockchain and MEC for video transcoding and delivery may bring significant benefits and become an inspiring thought for this interesting area. A blockchain-based MEC framework is proposed in [26] to provide a flexible and effective video streaming service by adaptively adjusting block size and selecting different offloading models for video streaming. In [27], we also leverage MEC technology and investigate the resource allocation for video transcoding and delivery problem in blockchain-based networks. However, the consensus process, latency of block generation, and incentive mechanisms, which are important parts of blockchain-based systems, are not considered jointly.

B. Main Contributions

In this paper, we investigate the video transcoding and delivery problem in blockchain-based MEC networks. The major contributions of this paper are presented as follows:

- We propose a blockchain-based MEC network architecture to handle the large-scale video requests from distinct user devices in a decentralized and secure manner. In the proposed architecture, without any centralized controller, the blockchain maintains publicly auditable video transaction records among VP, SBSs, and users.
- To improve the operation efficiency and resource utilization, we propose a video transcoding and delivery approach, which envisions a set of smart contracts to build a self-organized video trading market. In the proposed approach, VP, SBSs, and users are enforced by smart contract terms and adjust their strategies based on the transactional information recorded on blockchain.
- To address the interactions among VP, SBSs, and users dynamically, we formulate the optimization problem, including resource allocation, video trading, and consensus process, as a three-stage Stackelberg game. Then, using a backward induction method, we discuss the sub-game

equilibrium for each stage and the interactions of the three stages. Finally, we propose an iterative algorithm to derive a feasible solution.

- The simulation results are discussed and analyzed to evaluate the effectiveness of the proposed video transcoding and delivery approach regarding average time to finality (TTF), average access delay, and network cost in wireless networks.

The remainder of our work is organized as follows. Section II discusses the motivation of the integration of blockchain and MEC for video streaming, and presents the proposed blockchain-based MEC network architecture as well as the video transcoding and delivery approach. Section III introduces the system model, and the problem formulation in details. In Section IV, the analysis of three-stage Stackelberg game is presented and an iterative algorithm is proposed. Section V discusses the simulation results. Finally, we summarize this paper in Section VI.

II. Blockchain-Based MEC Network Architecture

In this section, we first discuss the motivation of the integration of blockchain and MEC for video steaming services. Then we present the blockchain-based MEC network architecture and the video transcoding and delivery approach.

A. Motivation of the Integration of Blockchain and MEC for Video Streaming

To give a clear motivation of the integrated blockchain and MEC for video streaming, we discuss the advantages and challenges of the integration of blockchain and MEC for video transcoding, respectively.

1) The Advantages of Integration of Blockchain and MEC for Video Streaming: The same decentralization character of both the blockchain and MEC built on the computation, communications, as well as their different complementaries makes their combination become natural. On one hand, blockchains protect the accuracy, consistency, and validity of the data and video files in a transparent way. With the blockchain technique, each participant manages its own keys, and transactional data are encrypted and stored on blocks, which is feasible to achieve privacy and security without any third party controls. Smart contracts facilitate the video trading and the use of resources on demand for the requested service. The blockchains and smart contracts have practical effectiveness in video trading markets across the different infrastructures and operators under insecure network conditions. On the other hand, MEC servers provide the storage and computation capacity for the video transcoding and the consensus process in blockchain. The integration of blockchain and MEC for video streaming aims at supporting secure, decentralized, and incentive video services to fulfill the application requirement.

2) The Challenges of Integration of Blockchain and MEC for Video Streaming: Although the integrated blockchains and MEC can enjoy the advantages of both them, there are several challenges to be addressed to provide video streaming services.

- Architecture Design: Because of these heterogeneous and disparate environments, it is difficult to deal with the issues of security management, service management, and data sharing in a centralized control system. The blockchain enables the data sharing in a decentralized and secure way under a distributed merely architecture. Thus, it is essential to design an architectural network that integrates blockchain and MEC techniques effectively to perform network management.
- Resource Management: Since each video file is split into a set of segments, and users may request each segment at different bitrate versions, the resource allocation for video transcoding is a crucial issue. The blockchain technique enables the resources allocation on demand by utilizing the smart contracts. Then, the design of smart contracts needs to be addressed to perform resource allocation strategies for video trading in an incentivized, automatic, and distributed manner.
- Quality-of-Service Requirements: With the rapid development of wireless technologies, the massive demand for low-latency and high-definition (HD) video streaming services poses severe challenges on the current wireless networks, especially in large-scale and dynamic network environments. The video trading processes among the multiple participants should be well designed.
- Scalability and Adaptability: Scalability is an essential issue in designing a distributed blockchain-based MEC architecture to manage the growing number of devices and the massive amount of data. On the other hand, resource allocation strategies should be dynamically adjusted according to the current network conditions and the distinct requirements of the users.

B. Blockchain-Based MEC Network Architecture

We consider a virtual P2P blockchain network as the backbone of the decentralized video sharing network [5]. Every participant (e.g., a VP, an SBS or a user) in the network maps itself as a node in the overlay blockchain network. The core components of the network architecture are as follows.

1) User: The users include various types of end devices, such as smartphones, tablets, wearable devices, and so on. The users send video requests to SBSs via wireless access links. Then, after paying to VPs and SBSs through the blockchains, they can enjoy video streaming services smoothly.

2) Video Provider: The VPs, which include individuals and companies, upload a set of their videos into networks to earn money from users that request their videos. At the same time, they have to pay to SBSs for utilizing caching and computing resources. With edge caching and MEC technologies, VPs can put some videos proactively to SBSs in proximity to users by paying SBSs through the blockchain for occupying storage and computing resources.

3) Small-Cell Base Station: These SBSs equipped with MEC servers work as service providers and provide their computing capability and resources in service of transcoding and distribution of video. They constitute wireless gateways to establish user sessions and transmit all of the requested video streams. Additionally, they will be incentivized via fees paid by the VPs and users to transcode videos into all the necessary formats and deliver video to users. The SBSs can also analyze the video popularity based on the transaction data on the blockchain and proactively cache videos of the VPs.

C. Proposed Video Transcoding and Delivery Approach

This subsection present the proposed approach that involves several smart contracts for supporting the self-organizing and correct execution of the video transcoding and delivery.

1) System Initialization: The VP, SBSs, and users in the system map themselves as nodes in the blockchain network using a pair of asymmetric keys (public/privacy) and a certificate, denoting as PK_i, SK_i and $Cert_i$, respectively. Using the hash-code of the public key, each node can be identified in the blockchain-based video system with a unique address $H(PK_i)$, where $H(\sim)$ denotes a collision-resistant, irreversible hash function. In the initial stage, node i uploads its addresses, downloads the last data about its transactions, and checks the integrity of its transactions.

2) Bidding and Selling Video Files: As shown in Fig. 2, during a video trading process, users first requests several video files with specific preferences including the number of videos, the quality levels of videos, and expected serving time to SBSs. Then, a video brokering contract (VBC) that indicates required videos and some user preferences is created and published. The VPs are informed of the published VBC and create video licensing contracts (VLCs). Each VLC specifies the video price, the maximum price to SBSs for transcoding and delivery, and a reference to the VBC. Once the VLC arrives in the blockchain, SBSs would publish video delivery contracts (VDCs), which specify the resource prices for delivering video to the user and the reference to the VLC. Lastly, the original VBC selects the cheapest one among all the related VDCs to perform the video transcoding and delivery and terminates all other contracts. Here, we use a three-stage Stackelberg game to model video bidding, negotiation, and transactions among VPs, SBSs, and users. More details are discussed in Sections IV and V.

3) Paying and Earning for Video Files: In the process of video trading, users pay for the video transaction through an address of a VP and pay for the delivery transaction through an address of an SBS, respectively. VP needs also pay for the video transcoding transaction through addresses of SBSs. Then the payees (VPs or SBSs) generate transaction records, and the payers (VPs or users) verify and digitally sign the transaction and upload them to the blockchain.

4) Carrying out Consensus Process: Regarding the consensus process, each user publishes proof-of-view, and the SBS releases a proof-of-service to the blockchain. The VP also publishes a cryptographic proof that makes the SBS process and deliver the video. If a fraudulent node is detected, the penalty mechanisms would be triggered, the corresponding invalid transaction is cancelled, and the payers (e.g., VP and users) refund their payments. When the blocks which include their transactions are verified and uploaded into blockchain, the VPs and SBSs get their video fee and service fee, respectively. Considering the computation-intensive of PoW protocol, we introduce a PoS consensus mechanism in this paper. Without loss of generality, the block producer (SBS) of a new block is chosen depending on the amount of its 'stake' and the age of the 'stake'. If the blocks are successfully added into blockchain, the chosen SBS will get reward.[1] On the contrary, the SBS has to lose its stakes and rights to participate in the consensus process in the future if it validates a fraudulent transaction or block. In this way, considering the vast staked tokens, the SBSs are generally incentivized to generate blocks correctively.

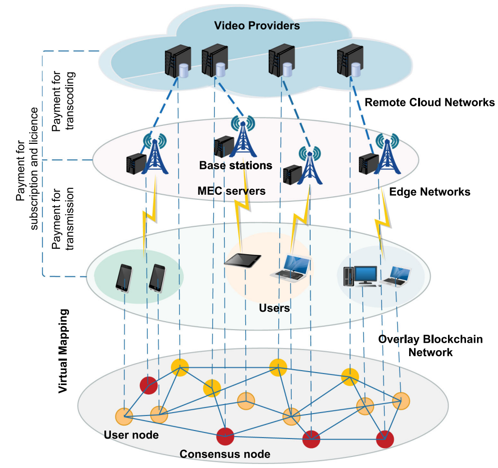

Fig. 1. Blockchain-based MEC network.

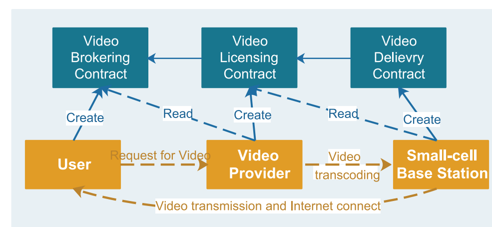

Fig. 2. Blockchain-based process for video delivery.

III. System Model and Problem Formulation

In this section, we present the system model and formulate the video transcoding and delivery problem as a three-stage Stackelberg game.

A. System Model

We consider a video transmission scenario in wireless downlink systems. As shown in Fig, 1, $\mathcal{M}$ SBSs that have limited caching and computing capacities are deployed to provide services to the users and VPs. We consider that one VP provides video files to $\mathcal{N}$ users served by SBSs. All video files $f \in \mathcal{F}$ are split into l fixed-length segments, which have multiple bitrate versions. Then, we use a rate β_n, where $0 < \beta_n \leqslant 1$, to scale down the original video and denote the different quality levels of video required by user n. For simplicity, each user can only choose one quality level of one video segment. We consider that

[1]SBSs can also act as validators which are responsible for new block validation before a new block is finalized. If the new block cannot be validated by most of validators (2/3), it cannot be finalized or append to the blockchain.

TABLE I
COMPARATIVE STUDY OF OUR WORK WITH EXISTING WORKS ON BLOCKCHAIN AND MEC

Subject	Ref.	Use case	Purposes	Contributions
Blockchain	[6]	Video delivery	Enabling a user-centric video delivery services chain	Proposing a model for collaborative blockchain-based video delivery with smart contracts
	[5]	Content delivery	Constructing an autonomous content caching market	Proposing a decentralized proactive caching framework which employs the smart contracts
	[16]	Consortium blockchain network	Optimizing the delay of propagation process and the transaction fee	Modeling the interaction among the blockchain user and miners as a Stackelberg game
	[17]	Internet of vehicles	Ensuring security and traceability of data sharing	Proposing a two-stage soft security enhancement solution, i.e., miner selection and block verification
	[23]	Bitcoin systems	Exploring the affects of mining pools in Bitcoin	Using a game theoretic model for team formation and reward sharing in mining pools
	[28]	Video content verification	Verifying video received by a mobile device equipped with a camera	Using the Swype code and additional information to improving the accuracy of the video verification
MEC	[7]	Information centric networks	Meeting the demand for data caching and computing services	Designing an information-centric heterogeneous networks framework for content caching and computing
	[8]	Information centric networks	Supporting adaptive video streaming services	Designing a cloud video transcoding system for elastically allocating computing resource
	[9]	Wireless networks	Enhancing the video service with MEC and edge caching	Considering video data rate, computing resource, and traffic engineering to maximize the video quality
	[10]	HTTP video delivery	Relaxing network congestion and improving user experience	Proposing an architecture for adaptive HTTP video streaming with MEC
	[11]	Mobile video systems	Increasing the video capacity and QoE of the wireless network.	Proposing a rate adaptation algorithm to change the video encoding and transmission rate.
	[24]	Fog networks	Supporting delay-sensitive applications and reliable access services	Proposing an integrated fog and cloud computing approach for computational tasks offloading
	[25]	Ultra-dense networks	Achieving a delay-optimal transcoding for users	Proposing a joint SBSs selection, tasks scheduling, and resource allocation approach
	[29]	Media cloud	Delivering on-demand adaptive video streaming services	Exploring a three-way tradeoff between the caching, transcoding, and bandwidth costs at edge server
	[30]	Dynamic adaptive video streaming	Optimizing the streaming quality and minimizing the cost	Performing video transcoding and delivery for adaptive streaming in an online manner
	[31]	Cloud computing	Ensuring efficient utilization of the transcoding servers	Proposing an approach for stream based admission control and job scheduling for video transcoding
	[32]	Web applications	Providing virtual machine provisioning for multi-tier web applications and video transcoding	Proposing a virtual machine provisioning with an admission control mechanism
Blockchain and MEC	[12]	Mobile blockchain	Facilitating blockchain applications in future mobile IoT systems	Developing a prototype of MEC enabled blockchain systems
	[13]	Mobile blockchain	Supporting the mining tasks to offload to ECSP	Proposing optimal pricing-based edge computing resource management for mobile blockchain
	[14]	Mobile blockchain	Guaranteeing the truthfulness, individual rationality, and computational efficiency	Proposing an auction-based edge computing resource allocation mechanism for mobile blockchain
	[15]	Mobile blockchain	Offloading the mining tasks from the mobile devices	Developing an auction based on DL for the edge resource allocation
	[26]	Video streaming	Maximizing the average video transcoding profit	Proposing a blockchain-based framework with an adaptive block size for video streaming with MEC
	[27]	Video streaming	Providing secure and decentralized video trading services	Proposing a video transcoding and delivery approach based on MEC and blockchain
	This Paper	Video streaming	Providing a secure video transcoding and delivery services	Proposing a video transcoding and delivery approach with MEC and blockchain-enabled smart contracts

the channel keep unchanged during the transmission of a packet, and perfect instantaneous Channel State Information (CSI) is available.

In the blockchain-based video systems, the SBSs with MEC servers are considered as the consensus nodes equipped with roughly synchronized clocks to perform the consensus process in the blockchain network. All transaction data of video is stored, broadcasted, and verified among consensus nodes in a chain of "blocks". The block records amounts of transactions and is linked to the previous block, forming an ordered list of blocks, called "blockchain". Every block is generated in a slotted manner with a fixed time interval. We consider that these M SBSs generate blocks with block size S_B (MB) and block interval T (seconds). The users and VP act as light nodes and only send/receive requests for videos due to the limited computing capabilities. Every SBS has the maximum computing resource, denoted as $F_{\max,m}$ (Mbps) and allocates some portion of the computing resource for video transcoding to VP denoted as f_m (MHz) and power resource to user n, denoted as p_{mn} (W). The price of resource, including computing resource and power resource, is charged by each SBS and denoted as z_m. Table II lists the main parameters in the system model.

B. Content Request Processing Model

Users are usually willing to obtain a high bitrate of video streaming for better watching experience when wireless channels are capable of transmission. While the users have to get a lower bitrate level of video to avoid playback stalling if the wireless channels experience severe interference or fading.

TABLE II
LIST OF KEY NOTATIONS

Notation	Definition
$\mathcal{M}$, $\mathcal{N}$, $\mathcal{V}$	Set of SBSs, users, and video files
δ^2	Noise variance
S_B	block size
w_{mn}	Frequency band occupied by SBS m for serving user n
p_{mn}	Transmission power of SBS m to user n
$\|h_{mn}\|^2$	Channel gain between SBS m and user n
$B(fl)$	Total bitrate of the l-th segment of video file f
$T_{n,thr}$	Maximum delay of task j required by user n
f_m	Computing capability of SBS m allocated to VP
$F_{max,m}$	Occupied computing resource for validating the block
$Task_m$	Maximum Computing capability of SBS m
β_n	Quality level of video required by user n
z_m and γ_m	Resource price and cost of SBS m
ϕ	Content cost of VP
λ_g, λ_v	Block generation reward and validation reward
ζ_f, ζ_p	Coefficients of computing and power price
α_f, α_v	Coefficients of resource cost and video revenue of VP
μ_v, μ_p	Coefficient of video and power cost of user
$a_m \in \{0,1\}$	SBS selection by VP to process its videos
$q_{nf} \in \{0,1\}$	Content selection by user n

Here, we mainly investigate the impact of the transcoding and distribution of video streaming service and leave the cache strategies for future work. Assume that the SBSs have proactively cached some popular videos and have adequate computing resources for transcoding [33]. We consider that every SBS caches all bitrate versions for a few top popular video segments and only the highest version for less popular video segments [29]. Suppose that the n-th user requires quality level β_n of video segment f_l, where B_{fl} (bits) denotes the total bitrate of the l-th segment of the video file f and the $T_{n,thr}$ denotes the maximum access delay required by user n.

C. Communication Model

Suppose that user n requests a set of video files and obtains these videos by accessing to SBS m via wireless access links. To avoid the interference among users, we consider the nearby interfering SBSs uses different spectrum resource which is orthogonally assigned to each user within the same SBSs [34]. Let $|h_{mn}|^2$ denote the wireless channel gain between user n and SBS m and w_{mn} denote the allocated bandwidth of SBS m to user n. The available transmission rate of user n that accesses to the m-th SBS is written as

$$\mathcal{R}_{mn} = w_{mn} \log_2 \left(1 + \frac{p_{mn}|h_{mn}|^2}{\delta^2}\right), \tag{1}$$

where δ^2 represents the power spectrum density of the additive white Gaussian noise (AWGN).

D. Consensus Model

Without loss of generality, the election of SBS for block generation is determined by the SBSs' stakes, which are measured by the transcoding and delivery reward in the latest epoch. Every epoch is composed of T time slots and has a fixed time interval. In the PoS-based consensus protocol, at each time slot, an uncompromisable random leader-election process is adopted to designate a unique SBS for block generation. Followed by [35], at time slot t, we assume that the stakes held by the SBSs are static and denoted by $S(t) = [s_1(t), ..., s_M(t)]$. The block producer election process is made up of a distribution $\mathcal{D}$ and a deterministic function $F(\cdot)$ with a random seed $\rho \leftarrow \mathcal{D}$, $F(S, \rho, t)$ outputs a unique SBS index $m (1 \leqslant m \leqslant M)$ for block generation with probability

$$\mathbb{P}_m(t) = \frac{S_m(t)}{\sum_{i=1}^{M} S_i(t)}. \tag{2}$$

The random variable $m \leftarrow F(S, \rho, t)$ is independent of t.

We adopt a standard Follow-the-Satoshi (FtS) algorithm, which resembles the process of biased coin-tossing and randomly designates a leader's address, to facilitate the PoS-based election process [35]. Through indexing a sub-set of tokens controlled by the consensus nodes and tracking the owner's address of a random token index, the election of SBS for block generation can be accomplished. The randomness of token selection is guaranteed by the seeding function $\rho \leftarrow \mathcal{D}$, which is implemented using the hashcode of the precedent block head.

E. Latency of Block Generation

To evaluate the latency of the blockchain generation, we consider TTF, which measures how long it takes to receive a reasonable guarantee that the transaction recorded in blockchain is irreversible and finalized [36]. In PoS-based consensus process, the transaction processing consists of two phases, i.e., generate a block and reach a consensus on the generated block among the validators. As such, the TTF for the transactions contains the block generation time (i.e., block interval) and the block validation time. For an SBS m, we derive the latency of block generation as follows:

$$\mathcal{L}_m(f_m) = T_I + \frac{Task_m}{F_{\max,m} f_m} + \xi S_B |\mathbb{M} - 1|, \tag{3}$$

where T_I is the block interval, $Task_m$ is the occupied computing resource for validating the block for SBS m. Similar to that in [37], the time for the block broadcasting and comparison among validators is a function of the block size S_B, network scale (i.e., the number of validators $|\mathbb{M} - 1|$) and average validation speed of each validators, which is denoted as $\xi S_B |\mathbb{M} - 1|$. Here, ξ is a pre-defined parameter of generated block broadcasting and validation, which can be obtained from statistics of previous block validation processes.

F. Problem Formulation

The video transcoding and delivery problem is formulated as a three-stage Stackelberg game, as illustrated in Fig. 3. In three-stage Stackelberg game, the upstage is the leader and the downstage acts as the follower. The leader selects the strategy first and the follower reacts subsequently. In Stage I, an SBS m acts as the leader and determines the resource price z_m. In Stage II, the VP, as the follower of Stage I, decides how many computing resources and which SBS to select as service providers based on the resource price. Then, the VP acts as the leader of Stage II and determines the video price to users. In Stage III, a user n, as the follower of Stage II, selects which

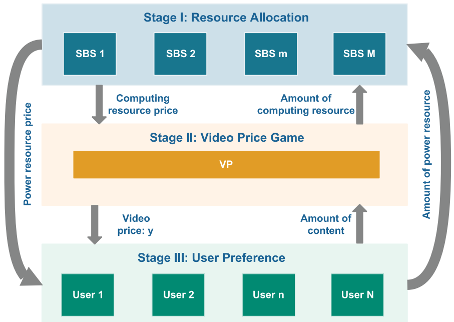

Fig. 3. Three-stage Stackelberg game model.

quality level of videos to purchase from VP and how much power resource to purchase from SBSs.

1) Resource Allocation Model for SBSs: The revenues of SBSs are made up with two parts, including the resource revenue and the block generation and validation reward. Every SBS performs the resource allocation non-cooperatively and gains as many revenues as possible.

To incentivize SBSs to stay active for providing services, we calculate the SBS's stake by its service reward (transcoding and delivery reward) received in the latest epoch. Thus, the probability for electing SBS m as the block producer in the next epoch is determined by the ratio between its service reward and the total service reward of the other SBSs in the current epoch, which is denoted as

$$\mathbb{P}_m = \frac{(z_m - \gamma_m)(\zeta_f a_m f_m + \zeta_p \sum_{n=1}^{N} p_{mn})}{\sum_{i=1, i\neq m}^{M} (z_i - \gamma_i)(\zeta_f a_i f_i + \zeta_p \sum_{n=1}^{N} p_{in})}, \tag{4}$$

where γ_m represents the resource cost of SBS m (e.g., the computing cost and the communication cost), $a_m \in \{0, 1\}$ represents whether VP chooses SBS m to deliver its video or not. If VP chooses SBS m, $a_m = 1$; otherwise, $a_m = 0$.

Let λ_g denote the block generation reward and λ_v denote the block validation reward in an epoch. The utility function of SBS m is formulated as

$$\begin{aligned} \mathcal{U}_{SBS}^{m}(z_m) &= (z_m - \gamma_m)\left(\zeta_f a_m f_m + \zeta_p \sum_{n=1}^{N} p_{mn}\right) \\ &\quad + (\lambda_g - C_g)\mathbb{P}_m + (\lambda_v - C_v) \\ &\quad \times (1 - \mathbb{P}_m) - \chi \mathcal{L}_m(f_m), \end{aligned} \tag{5}$$

where ζ_f and ζ_p are weighted factors to adjust the balance between the computing resource factor and the power resource factor, C_g and C_v represent the cost of block generation and validation, respectively, and χ is a latency coefficient which represents the impact of latency of block generation. The first term is the reward of video transcoding and delivery, the second term represents the reward of block generation, the third term represents the reward for validating blocks, and the last term represents the cost function of latency.

In order to maximize the revenue, all SBSs need to determine an optimal resource price to the VP and users by solving the problem as follows,

$$\max_{z_m \geqslant \gamma_m} \mathcal{U}_{SBS}^{m}(z_m). \tag{6}$$

2) Video Price Model for VP: VP's profit is determined by the number of videos and the quality levels of videos required by users as well as a number of computing resource consumptions. Let $q_{nf} \in \{0, 1\}$ represent whether user n chooses the video file f or not. If user n chooses video file f, $q_{nf} = 1$; otherwise, $q_{nf} = 0$. The utility function of VP is defined as

$$\begin{aligned} &\mathcal{U}_{VP}(f_m, y) \\ &= \sum_{m=1}^{M} a_m \min\left\{ f_m, \sum_{n=1}^{N} \frac{\beta_n \sum_{f=1}^{F}\sum_{l=1}^{L} q_{nf} B_{fl}}{T_{n,thr}} \right\} \\ &\quad - \alpha_f \sum_{m=1}^{M} z_m a_m f_m + \alpha_v (y - \phi) \sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{l=1}^{L} \beta_n q_{nf} B_{fl}, \end{aligned} \tag{7}$$

where α_f and α_v denote weighted factors which are greater than zero to adjust the balance between the resource cost and video revenue. ϕ denotes the video cost of VP, such as caching cost and backhaul cost. It is related to the number of delivered videos in networks. The first term indicates that users are guaranteed to obtain their video streaming service under tolerable delay. We assume that we do not know the computing capability of SBS m and the quality level of video segments requested from the users served by SBS m. If the computing capability of SBS is smaller than the required bitrate of transcoding video files, we need to select the larger capability to meet the users' requirements, and vice versa.

To maximize the revenue, VP should determine an optimal content price and the required computing resources by solving the following problem

$$\max_{f_m \geqslant 0, y \geqslant \phi} \mathcal{U}_{VP}(f_m, y). \tag{8}$$

3) Content Demand Model for Users: Different users under different wireless conditions require different quality levels of videos. In general, users are willing to obtain as larger bitrate as possible for good streaming quality. Taking the transmission rate and quality level of video joint into consideration, we define the utility function of user n as follows,

$$\begin{aligned} &\mathcal{U}_{user}^{n}(p_{mn}, \beta_n) \\ &= \min\left\{ \mathcal{R}_{mn}, \frac{\beta_n \sum_{f=1}^{F}\sum_{l=1}^{L} q_{nf} B_{fl}}{T_{n,thr}} \right\} \\ &\quad - \mu_v y \beta_n \sum_{f=1}^{F}\sum_{l=1}^{L} q_{nf} B_{fl} - \mu_p z_m p_{mn}, \end{aligned} \tag{9}$$

where μ_p and μ_v denote weighted factors which are greater than zero to represent the tradeoff between the power cost and video cost. The first term indicates that the balance between transmission rate and proper quality levels of videos should be well addressed. We assume that we do not know the transmission capacity of SBS and the quality level of video required by users.

If the transmission capacity of SBS is smaller than the quality level of the required video, the SBS needs to allocate more power to improve the transmission rate, and vice versa.

The user n determines the quality level of videos and the required power resource by solving the following problem,

$$\max_{p_{mn} \geqslant 0, \beta_n \geqslant 0} \mathcal{U}_{user}^n(p_{mn}, \beta_n). \tag{10}$$

IV. Analysis of the Three-State Stackelberg Game

This section presents the analysis of the three-stage Stackelberg game and introduces a backward induction method to obtain the solution. Then we analyze the interplays between different stages and propose an iterative algorithm to solve the problem.

A. Stage III: User Level Game Analysis

To gain a better video streaming service, all users would select the appropriate quality level β_n and power p_{mn} based on the resource price z_m and the video price y. Next we take user n as an example to find a feasible solution in Stage I. The utility function of user n is defined in two cases: (1) $\mathcal{R}_{mn} \leqslant \frac{\beta_n \sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}}{T_{n,thr}}$; (2) $\mathcal{R}_{mn} > \frac{\beta_n \sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}}{T_{n,thr}}$. The utility function for the first case can be written as

$$\mathcal{U}_{user}^n(p_{mn}, \beta_n) = w_{mn} \log_2 \left(1 + \frac{p_{mn}|h_{mn}|^2}{\delta^2}\right) - \mu_v y \beta_n \sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl} - \mu_p z_m p_{mn}. \tag{11}$$

To get feasible solution, the problem is decoupled into two sub-problems. We firstly keep β_n fixed and optimize p_{mn}^* to derive the optimal β_n^*. According to the definition (11), when $1 - \mu_v y T_{n,thr} > 0$, the n-th user's utility function is a concave function of p_{mn}, since

$$\frac{\partial^2 \mathcal{U}_{user}^n}{\partial p_{mn}^2} = -\frac{w_{mn}|h_{mn}|^4(1 - \mu_v y T_{n,thr})}{\ln 2 (p_{mn}|h_{mn}|^2 + \delta^2)^2} < 0. \tag{12}$$

Thus, we can derive the optimal power allocation strategy p_{mn}^* as

$$p_{mn}^* = \left[\frac{w_{mn}(1 - \mu_v y T_{n,thr})}{\ln 2 \mu_p z_m} - \frac{\delta^2}{|h_{mn}|^2}\right]^+. \tag{13}$$

Since the utility function of β_n is monotonic decreasing, β_n would take the minimized value to maximize the utility as follows,

$$\beta_n^* = \frac{w_{mn} T_{n,thr}}{\sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}} \log_2 \left(1 + \frac{p_{mn}^*|h_{mn}|^2}{\delta^2}\right) = \left[\frac{w_{mn} T_{n,thr}}{\sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}} \log_2 \left(\frac{w_{mn}|h_{mn}|^2(1 - \mu_v y T_{n,thr})}{\ln 2 \mu_p z_m \delta^2}\right)\right]^+. \tag{14}$$

When $1 - \mu_v y_f T_{n,thr} < 0$, the utility function is a convex function of p_{mn} and the minimum of the function is achieved as

$$p_{mn}^* = \left[\frac{w_{mn}(1 - \mu_v y T_{n,thr})}{\ln 2 \mu_p z_m} - \frac{\delta^2}{|h_{mn}|^2}\right]^+. \tag{15}$$

Hence, when $p_{mn} = 0$, we can get an optimal strategy of of β_n. The utility function of β_n is a monotonic decreasing function: $\mathcal{U}_{user}^n(p_{mn}, \beta_n) = -\mu_v y \beta_n \sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}$. It would achieve the maximized value when $\beta_n^* = 0$. However, when $\beta_n^* = 0$, it makes no sense in the practical scenarios. Since a user sends a video requirement and receives the service from an SBS, its transmission rate and quality level of video should be above zero.

The utility function of β_n for the second case is derived as

$$\mathcal{U}_{user}^n(p_{mn}, \beta_n) = \frac{\beta_n \sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}}{T_{n,thr}} - \mu_v y \beta_n \sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl} - \mu_p z_m p_{mn} = \left(\frac{1}{T_{n,thr}} - \mu_v y\right) \times \beta_n \sum_{f=1}^F \sum_{l=1}^L q_{fl} B_{fl} - \mu_p z_m p_{mn}. \tag{16}$$

When $(1 - \mu_v y T_{n,thr}) > 0$, $\mathcal{U}_{user}^n(\beta_n)$ is a monotonic increasing function. We can derive $\beta_n^* = [\frac{w_{mn} T_{n,thr}}{\sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}} \log_2(1 + \frac{p_{mn}^*|h_{mn}|^2}{\delta^2})]^+$ to achieve the maximized value of the utility function.

When $(1 - \mu_v y T_{n,thr}) < 0$, $\mathcal{U}_{user}^n(\beta_n)$ is a monotonic decreasing function. Although $\beta_n^* = 0$ makes the utility function get the maximized value, it is meaningless in the practical networks due to the same reason.

B. Stage II: VP Level Game Analysis

To maximize its utility function, the VP first acts as a follower to pay for the computing resources according to the SBSs' resource price z_m. Next, the VP acts as a leader to determine a video price y to the users. Similarly, we decouple the problem to get the feasible solution in Stage II. For maximizing the utility function $\mathcal{U}_{VP}$, we first fix the video price y to find the optimal f_m, and then we find the optimal video price y based on the requested computing resources f_m.

In the VP level, it will choose a number of SBSs with the lowest resource price z_m^* one by one to buy computing resource. The VP's utility function is also derived in two cases: (1) $f_m \leqslant \sum_{n=1}^N \frac{\beta_n \sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}}{T_{n,thr}}$; (2) $f_m > \sum_{n=1}^N \frac{\beta_n \sum_{f=1}^F \sum_{l=1}^L q_{nf} B_{fl}}{T_{n,thr}}$.

For the first case, due to limited computing resources, the users have to suffer a bad experience. Although this situation should be avoided, we still consider this case and derive the following utility function,

$$\mathcal{U}_{VP}(f_m, y) = \sum_{m=1}^{M} a_m f_m (1 - \alpha_f z_m) + \alpha_v (y - \phi) \sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{l=1}^{L} \beta_n q_{nf} B_{fl}. \tag{17}$$

When $1 - \alpha_f z_m < 0$, the utility function is monotonic decreasing of f_m and achieves maximum value when $f_m^* = 0$. It only happens when the selected scale rate of video is cached exactly at SBS m and delivered to the user directly.

When $1 - \alpha_f z_m > 0$, the utility function is monotonic increasing of f_m and gets the maximum value when f_m selects the maximum value as

$$f_m^* = \sum_{n=1}^{N} \left[w_{mn} \log_2 \left(\frac{w_{mn}|h_{mn}|^2 (1 - \mu_v y T_{n,thr})}{\ln 2 \mu_p z_m \delta^2} \right) \right]^+. \tag{18}$$

The utility function for the second case is derived as,

$$\mathcal{U}_{VP}(f_m, y) = \sum_{m=1}^{M}\sum_{n=1}^{N} a_m \frac{\beta_n \sum_{f=1}^{F}\sum_{l=1}^{L} q_{nf} B_{fl}}{T_{n,thr}} - \alpha_f \sum_{m=1}^{M} z_m a_m f_m + \alpha_v (y - \phi) \sum_{n=1}^{N}\sum_{f=1}^{F}\sum_{l=1}^{L} \beta_n q_{fl} B_{fl}. \tag{19}$$

We can find that the utility function is monotonic decreasing of f_m due to the send term $-\alpha_f \sum_{m=1}^{M} z_m a_m < 0$. Thus, the utility function gets the maximum value when f_m selects the minimum value as

$$f_m^* = \sum_{n=1}^{N} \left[w_{mn} \log_2 \left(\frac{w_{mn}|h_{mn}|^2 (1 - \mu_v y T_{n,thr})}{\ln 2 \mu_p z_m \delta^2} \right) \right]^+. \tag{20}$$

Next, we should calculate the feasible video price y for VP. Note that different users served by different SBSs have the different preferences for the same video. Then, the video prices would be different for different users. We first define an indicator function as

$$V_n = \begin{cases} 1 & y < \frac{w_{mn}|h_{mn}|^2 - \ln 2 \mu_p z_m \delta^2}{w_{mn}|h_{mn}|^2 \mu_v T_{n,thr}}, \quad \forall n \\ 0 & \text{otherwise.} \end{cases} \tag{21}$$

Then $\mathcal{U}_{VP}$ is rewritten as formula (22) which is shown at the bottom of this page.

Although the problem in Stage II cannot be solved directly since $\mathcal{U}_{VP}$ is a piece-wise function of y, we can transform $\mathcal{U}_{VP}$ into a continuously differentiable function with a given value of V_n. Then we introduce D_n as

$$D_n = \frac{w_{mn}|h_{mn}|^2 - \ln 2 \mu_p z_m \delta^2}{w_{mn}|h_{mn}|^2 \mu_v T_{n,thr}}, \quad \forall n \tag{23}$$

We sort all D_n in ascending order as $D_1 \leqslant D_2 \leqslant \cdots \leqslant D_N$, and get N intervals as $[0, D_1), (D_2, D_3), \ldots, (D_{N-1}, D_N)$. Then we derive $\frac{\partial^2 \mathcal{U}_{VP}}{\partial y^2}$ as follows,

$$\frac{\partial^2 \mathcal{U}_{VP}}{\partial y^2} = -\left\{ \sum_{m=1}^{M}\sum_{n=1}^{N} w_{mn} \mu_v T_{n,thr}^2 \left[\frac{2\alpha_v}{\ln 2 (1 - \mu_v y T_{n,thr})} + \frac{\mu_v (a_m (1 - \alpha_f z_m) + \alpha_v (y - \phi) T_{n,thr})}{\ln 2 (1 - \mu_v y T_{n,thr})^2} \right] \right\} < 0. \tag{24}$$

$\mathcal{U}_{VP}$ is concave except some D non-differentiable points by piecewise differentiating of it in each time interval. Therefore, the non-cooperative video price game is a concave game and exits at least one Nash equilibrium (NE) based on formula (22).

We derive $\frac{\partial \mathcal{U}_{VP}}{\partial y}$ which is shown as formula (25) at the bottom of this page. From formula (24), $\frac{\partial \mathcal{U}_{VP}}{\partial y_f}$ is a strictly monotonic decreasing function of y.

When $y \to \phi$, we can obtain that $\lim_{y \to \phi} \frac{\partial \mathcal{U}_{VP}}{\partial y} > 0$. When $y \to \infty$, we can obtain that $\lim_{y \to \infty} \frac{\partial \mathcal{U}_{VP}}{\partial y} = -\infty < 0$. The utility function of VP is a concave function except for several non-differentiable points $D_1, D_2, \ldots, D_N$. There exists at least one NE in the non-cooperative video price game. Therefore, utilizing some typical algorithms such as gradient-based algorithm and binary search algorithm, the optimal video price y can be obtained.

C. Stage I: SBSs Level Game Analysis

In Stage I, to analyze the competition relationships among SBSs, we introduce the Bertrand game which is an effective model to analyze competition among multiple sellers and their consumers [38]. We assume that each SBS is independent and selfish to gain its revenue as much as possible. All the SBSs are willing to determine their resource prices as the same to maximize their revenues. The revenue of SBS m depends not only on the resource price z_m and the resource cost γ_m but also on the resource prices $\mathbf{z}_{-m}$ determined by other SBSs.

If the SBSs set their resource price non-cooperatively, it may result in a monopoly situation. The SBS occupies the entire video trading market if the SBS sets the lowest resource price. Hence,

$$\mathcal{U}_{VP} = \sum_{m=1}^{M}\sum_{n=1}^{N} \left\{ w_{mn} \left[a_m (1 - \alpha_f z_m) + \alpha_v V_n (y - \phi) T_{n,thr} \right] \log_2 \left(\frac{w_{mn}|h_{mn}|^2 V_n (1 - \mu_v y T_{n,thr})}{\ln 2 \mu_p z_m \delta^2} \right) \right\} \tag{22}$$

$$\frac{\partial \mathcal{U}_{VP}}{\partial y} = \sum_{m=1}^{M}\sum_{n=1}^{N} w_{mn} T_{n,thr} \left\{ \alpha_v \log_2 \left(\frac{w_{mn}|h_{mn}|^2 (1 - \mu_v y T_{n,thr})}{\ln 2 \mu_p z_m \delta^2} \right) - \frac{\mu_v \left[a_m (1 - \alpha_f z_m) + \alpha_v (y - \phi) T_{n,thr} \right]}{\ln 2 (1 - \mu_v y T_{n,thr})} \right\} \tag{25}$$

every SBS tries to decrease the resource price until it cannot obtain any revenue. According to the Bertrand game model, the set of the game players is $\mathcal{M} = \{1, \ldots, m, \ldots, M\}$, the action set is z_m, and the payoff function of the SBS is $\mathcal{U}_{SBS}^m$. The resource cost set of all the SBSs can be sorted in an ascending order $\gamma_1 < \gamma_2 < \cdots < \gamma_M$.

Definition 1. (Nash-equilibrium): A resource price $\mathbf{z}^* = (z_1^*, \ldots, z_m^*, \ldots, z_M^*,)$ is in an NE if neither SBS can increase its utility $\mathcal{U}_{SBS}^m$ by unilaterally changing the price.

Proposition 1: The NE of the game is derived as $\mathbf{z}^* = \{z_1^*, \gamma_2, \gamma_3, \ldots, \gamma_M\}$, where z_1^* represents the resource price determined by the first SBS at the NE. The z_1^* can be derived as $z_1^* = \arg\max_{\gamma_1 \leqslant z_1 < \gamma_2} \mathcal{U}_{SBS}^1(z_1)$, when the SBS occupies the entire video trading market as shown in formula (26), shown at the bottom of this page.

Proof: $\mathcal{U}_{SBS}^1(z_1)$ is the first SBS's utility function of z_1. For simplicity, we take two SBSs (e.g., SBS1 and SBS 2) into consideration for analyzing the competition process among SBSs. Let γ_1 and γ_2 denote the resource costs of SBS 1 and SBS 2, respectively. We assume that $\gamma_1 < \gamma_2$. According to the Bertrand game model, both SBSs would decrease their prices to occupy the entire video trading market until they cannot get any revenue. For maximizing the profit, SBS 1 would select the highest resource price which is lower than the resource cost of SBS 2. Then all the VP and users would pay for the resource from the SBS 1 which occupies all the video trading market. Therefore, SBS 1 would determine its resource price in the range of $[\gamma_1, \gamma_2)$ to maximize its own profit. ∎

Next we introduce the indicator functions for VP and users $n \in \{1, 2, \ldots., N\}$ as below,

$$I_{VP} = \begin{cases} 1 & z_1 < \sum_{n=1}^{N} \frac{w_{1n}|h_{1n}|^2(1-\mu_v y T_{n,thr})}{\ln 2\mu_p \delta^2} \\ 0 & \text{otherwise.} \end{cases} \tag{27}$$

$$I_{user}^n = \begin{cases} 1 & z_1 < \frac{w_{1n}|h_{1n}|^2(1-\mu_v y T_{n,thr})}{\ln 2\mu_p \delta^2} \\ 0 & \text{otherwise.} \end{cases} \tag{28}$$

Thus by substituting (27) and (28) into (26), the utility function of SBS 1 becomes a piecewise function of z_1. While the problem in Stage III cannot be solved directly because of these indicator functions I_{VP} and I_{user}^n.

Without loss of generality, we can derive a differentiable continue function for given I_{VP} and I_{user}^n by introducing the following functions

$$F_{VP} = \sum_{n=1}^{N} \frac{w_{1n}|h_{1n}|^2(1-\mu_v y T_{n,thr})}{\ln 2\mu_p \delta^2}, \tag{29}$$

$$F_{user}^n = \frac{w_{1n}|h_{1n}|^2(1-\mu_v y T_{n,thr})}{\ln 2\mu_p \delta^2}. \tag{30}$$

We sort all $F_{user}^1, F_{user}^2, \ldots, F_{user}^n$, and F_{VP} in an ascending order $F_{user}^1 \leqslant F_{user}^2 \leqslant, \ldots, \leqslant F_{user}^n \leqslant F_{VP}$ and get N intervals, $[0, F_{user}^1), (F_{user}^2, F_{user}^3), \ldots, (F_{user}^n, F_{VP})$. Let ϖ_1 denote $1 + \frac{\lambda_g - \lambda_v - C_g + C_v}{\sum_{i=1, i\neq m}^{M}(z_i - \gamma_i)(\zeta_f a_i f_i^* + \zeta_p \sum_{n=1}^{N} p_{in}^*)}$ and φ_1 denote $\{F_{\max,1} - \sum_{n=1}^{N}[w_{1n}\log_2(\frac{w_{1n}|h_{1n}|^2(1-\mu_v y T_{n,thr})}{\ln 2\mu_p z_1 \delta^2})^+]\}$. By piece-wise differentiating of the utility function, we assume that $0 < z_1 < F_{user}^1$, the second derivative of $\mathcal{U}_{SBS}^1(z_1)$ is shown as follows,

$$\frac{\partial \mathcal{U}_{SBS}^2}{\partial z_2} = -\frac{\chi Task_1 w_{1n}}{\ln 2} \times \frac{\varphi_m^2 + 2z_1\varphi_1 + w_{1n}}{z_1^2 \ln 2\varphi_1^4} - \varpi_1 \times \left\{ \sum_{n=1}^{N} \frac{w_{1n}}{\ln 2 z_1^2}\left[(z_1 + \gamma_1)\zeta_f a_1 + \zeta_p \frac{2\gamma_1(1-\mu_v y T_{n,thr})}{\mu_p z_1}\right] \right\} < 0. \tag{31}$$

Thus, $\frac{\partial \mathcal{U}_{SBS}^1}{\partial z_1}$ is a monotonic decreasing function of z_1 since $\frac{\partial^2 \mathcal{U}_{SBS}^1}{\partial z_1^2} < 0$. $\frac{\partial \mathcal{U}_{SBS}^1}{\partial z_1}$ is derived as formula (32), shown at the bottom of this page. Similarly, when $z_1 \to \gamma_1$, we can obtain that $\lim_{z_1 \to \gamma_1} \frac{\partial \mathcal{U}_{SBS}^1}{\partial z_1} > 0$; when $z_1 \to F_{user}^1$, there are two cases as : $\lim_{z_1 \to F_{user}^1} \frac{\partial \mathcal{U}_{SBS}^1}{\partial z_1} \geqslant 0$ and $\lim_{z_1 \to F_{user}^1} \frac{\partial \mathcal{U}_{SBS}^1}{\partial z_1} < 0$.

$$\mathcal{U}_{SBS}^1(z_1) = \varpi_1(z_1 - \gamma_1)\Bigg(\zeta_f a_1 \sum_{n=1}^{N}\left[w_{1n}\log_2\left(\frac{w_{1n}|h_{1n}|^2(1-\mu_v y T_{n,thr})}{\ln 2\mu_p z_1 \delta^2}\right)^+\right] + \zeta_p \sum_{n=1}^{N}\left[\frac{w_{1n}(1-\mu_v y T_{n,thr})}{\ln 2\mu_p z_1} - \frac{\delta^2}{|h_{1n}|^2}\right]^+\Bigg) + \lambda_v - C_v - \chi\left\{T_I + \frac{Task_1}{F_{\max,1} - \sum_{n=1}^{N}\left[w_{1n}\log_2\left(\frac{w_{1n}|h_{1n}|^2(1-\mu_v y T_{n,thr})}{\ln 2\mu_p z_1 \delta^2}\right)^+\right]} + \xi S_B|\mathbb{M}-1|\right\} \tag{26}$$

$$\frac{\partial \mathcal{U}_{SBS}^1}{\partial z_1} = \varpi_1 \times \Bigg\{\Bigg(\zeta_f a_1 \sum_{n=1}^{N}\left[w_{1n}\log_2\left(\frac{w_{1n}|h_{1n}|^2(1-\mu_v y T_{n,thr})}{\ln 2\mu_p z_1 \delta^2}\right)^+\right] + \zeta_p \sum_{n=1}^{N}\left[\frac{w_{1n}(1-\mu_v y T_{n,thr})}{\ln 2\mu_p z_1} - \frac{\delta^2}{|h_{1n}|^2}\right]^+\Bigg) - (z_1 - \gamma_1)\left[\zeta_f a_1 \sum_{n=1}^{N}\frac{w_{1n}}{z_1 \ln 2} + \zeta_p \sum_{n=1}^{N} w_{1n}\frac{1-\mu_v y T_{n,thr}}{\ln 2\mu_p z_1^2}\right]\Bigg\} + \frac{\chi Task_1 w_{1n}}{z_1 \ln 2\varphi_m^2} \tag{32}$$

Algorithm 1: Resource Allocation Iteration Algorithm.

1: Initialization:
  a) Each SBS collects CSI and requests of all users in its coverage;
  b) Initialize the maximum number of iterations Γ and set iteration number $\tau = 0$;
  c) Initialize a default resource price $\mathbf{z}$ for each SBS.
2: **while** $\tau < \Gamma$ **do**
3:   The VP sets the video price y to their users and the amount of computing resources according to z_m;
4:   Every user chooses the quality level of required videos β_n and determines the amount of power resource p_{mn};
5:   SBSs update their prices: $z_m(\tau) = \mathcal{G}_m(\mathbf{z}_{-m}(\tau - 1))$;
6:   **if** $\|\mathbf{z}(\tau) - \mathbf{z}(\tau-1)\|/\|\mathbf{z}(\tau-1)\| \leqslant \epsilon$ **then**
7:     Output the resource allocation $\mathbf{z}$;
8:     **Break**.
9:   **end if**
10:   $\tau = \tau + 1$;
11: **end while**

The utility function $U^1_{SBS}(z_1)$ is strictly monotonic increasing within the initial interval $[0, F1)$ when $\lim_{z_1 \to F^1_{user}} \frac{\partial \mathcal{U}^1_{SBS}}{\partial z_1} \geqslant 0$. While the utility function $U^1_{SBS}(z_1)$ firstly increases with z_1 and goes down after reaching the optimal point when $\lim_{z_1 \to F^1_{user}} \frac{\partial \mathcal{U}^1_{SBS}}{\partial z_1} < 0$. Therefore, the utility function U^1_{SBS} is a concave function at the first interval and the other intervals. Therefore, for $z_1 < F_{VP}$, the utility function is a concave function except the most N non-differentiable points at $F_1, F_2, \ldots, F_n$. Similarly, the problem in Stage III can be solved to obtain the optimal z_1 using several typical algorithms such as binary search algorithm and gradient-based algorithm.

Based on the analysis above, we adopt a backward induction method to achieve the NE of the three-stage Stackelberg game. The resource allocation iteration algorithm is presented as Algorithm 1 to obtain feasible strategies. In Algorithm 1, we adopt the best response function $\mathcal{G}_m(\mathbf{z}_{-m}(\tau - 1))$ of SBS z_m at the iteration τ to maximize its revenue with the given other SBSs' strategies $\mathbf{z}_{-m}$.

D. Interplays and Stackelberg Equilibrium

This subsection discusses the existence and the uniqueness of the Stackelberg equilibrium. In the duopoly case, the convexity of the follower's reaction function plays an important role in the uniqueness of the Stackelberg equilibrium.

Proposition 2: The unique NE exists in the proposed three-stage Stackelberg game.

Proof: In the three-stage Stackelberg game, there exists at least one NE in each stage, including the resource price strategies z^*_m determined by the SBSs, the computing resource f^*_m and the video price y^* offered by the VP, and the power allocation strategy p^*_{mn} required by users. When Algorithm 1 converges, the VP cannot change the price unilaterally for improving its revenue. The convergence property of the resource allocation iteration algorithm has been proved [39]. Specifically, when the initial price value y^* is fixed, the results in the subsequent iterations are fixed. For example, at the τ-th iteration, the resource price set by the SBS is fixed. Then, at the $(\tau + 1)$-th iteration, the amount of computing resource is fixed and the search direction of the algorithm from the current iteration to the next iteration is unique [39], [40]. Thus, the resource price set by the SBS at the $(\tau + 1)$-th iteration is also fixed. Thus, the game converges to a unique payoff. Therefore, the three-stage Stackelberg Nash equilibrium is unique. ■

E. Analysis of Feasibility and Optimality

In the proposed approach, users, SBSs, and VP are enforced by smart contract terms and adjust their strategies according to the transactional information stored on blockchain. To address the interactions among these participants, we model the optimization problem, including problems (6), (8), and (10) as a hierarchical three-stage Stackelberg game. To investigate the Stackelberg equilibrium, we use backward induction to seek a perfect equilibrium for each sub-game by determining the strategies of all the players. In Stage III, the users are not coupled with each other, and thus we can analyze an optimal fraction of content demand of each user in the sub-game independently. The best response of the user can be obtained by directly solving Problem (6). In Stage II, to maximize its utility function, the VP first acts as a follower to pay for the computing resources according to the SBSs' resource price z_m. Next, the VP acts as a leader to determine a video price y to the users. The best response of the VPs can be obtained by solving Problems (6). Note that Problem (6) must be solved first since the VPs derive their individual best responses based on those of users. Similarly, Problems (8) need to be solved before solving Problem (10), since the best response of the SBS, depends on those of the VP and users.

In Algorithm 1, the SBSs need to set the resource price z_m in each iteration. In addition, the VP determines the video price y to users and how many computing resources purchased from the SBSs according to the resource price. The users select the quality level of video and decide the amount of power resource. The algorithm will stop when the prices converge. Therefore, Algorithm 1 will converge to the Stackelberg equilibrium. The reason is that the optimal video price is the best reaction function of the optimal resource allocation policy. Therefore, the resource allocation policy will achieve their optimums when the prices converge. This will also be verified in the simulation results.

V. Simulation Results and Discussions

In this section, we analyze and discuss the effectiveness of the proposed blockchain-based MEC approach for video transcoding and delivery via Monte Carlo simulation. The number of available videos is 1000. The video popularity follows a Zipf distribution with exponent 0.8 [29]. Each video f has the same length of 600 seconds. We consider that the quality level of videos in the range of 200 kbps (QVGA quality) and 2 Mbps (HD quality). The channel gain models presented in 3GPP standardization are adopted here [41]. The other main simulation parameters are presented in Table III.

TABLE III
THE SIMULATION PARAMETERS

Simulation parameters	Value
The bandwidth	20MHz
The SBSs density	400 SBSs/Km^2
The users density	600 Users/Km^2
Power spectral density of noise	-174dBm/Hz
Cache capacity of each SBS	[200-400]
Computing capability of each SBS	[1000-2000]MHz
The backhaul capacity of the m-th SBS $R_{m,b}$	$[40-100]$Mbps
The maximum transmission power of each SBS	$[1-2]$W
Block Size S_B	4MB
Maximum block interval T_I	10s
Energy consumption for processing tasks	$10-^{9}$J/cycle
The computing cost for block validation	2MHz

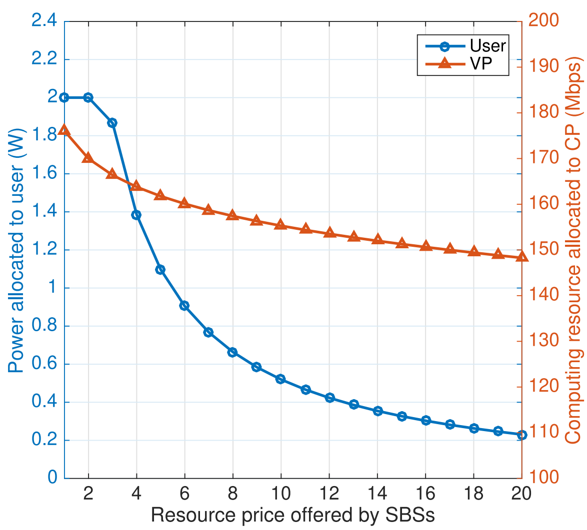

Fig. 4. Resource allocation for VP and users with various resource prices.

A. The Influence of Different Parameters on Proposed Video Transcoding Approach

In this subsection, we discuss the influence of the various resource prices offered by SBSs on the number of resources purchased by VP and users. As shown in Fig. 4, with the increasing of resource price z_m, users and VP have to reduce their required power and computing resources, respectively. To explain, the resource price is too high to afford for the users and VP, both of them will reduce their required transmission power and computing resource until stop transcoding and delivering any video.

As shown in Fig. 5, the user would decrease its video cost by adjusting the quality level of required videos β_n with increasing of video price y. We can find that the lower resource price determined by the SBSs, the higher quality level of videos can be obtained by users. On the other hand, with the increasing of video price, the user purchases less power from SBSs as shown in Fig. 6. To explain, the users would select a lower quality level of required videos and obtain a smaller bitrate size of required videos with the higher video price. Then, the user purchases less power to make the transmission rate match with the required quality level of videos.

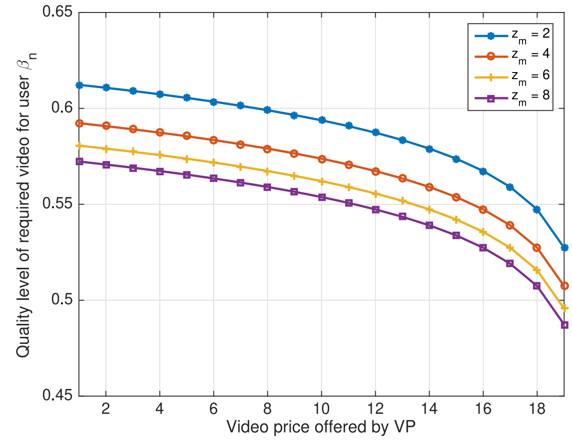

Fig. 5. Quality level of video for user with various video prices.

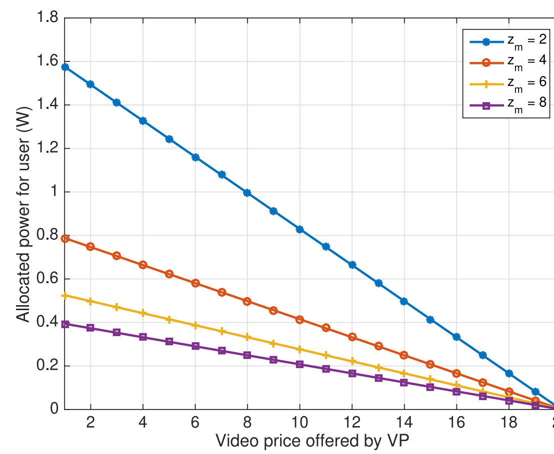

Fig. 6. Allocated power for user with various video prices offered by VP.

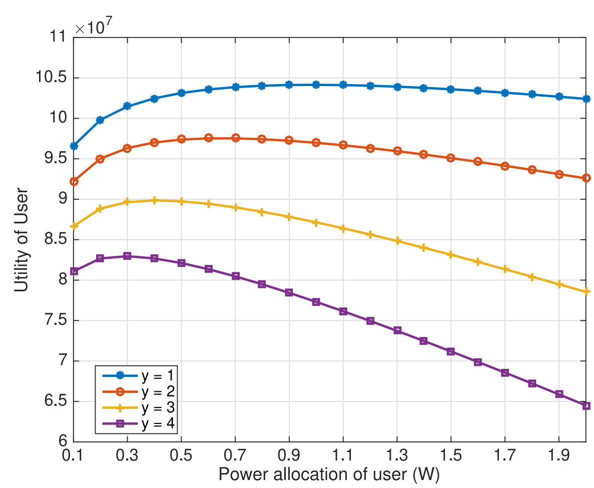

Fig. 7. Utility of user versus power allocation of user.

Figs. 7–9 show that the utility functions of the user, VP, and SBS versus power resource, video and resource price, respectively. Fig. 7 shows that all the curves go up to a peak and then go down with the increase of allocated power. The reason is that the gain of the transmission rate cannot compensate for the rise in the resource and video cost. Moreover, the higher the video

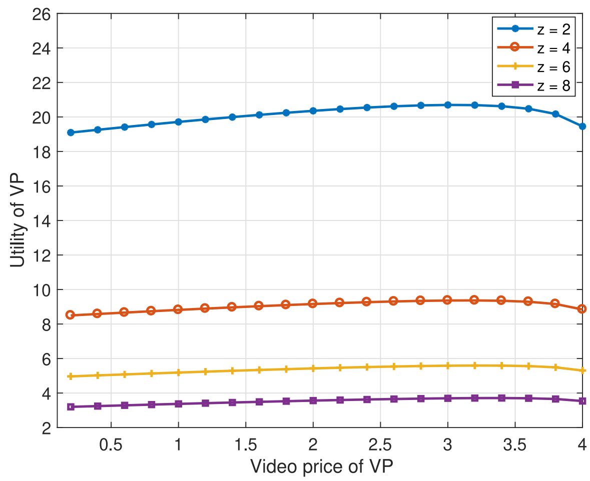

Fig. 8. Utility of user versus video price of VP.

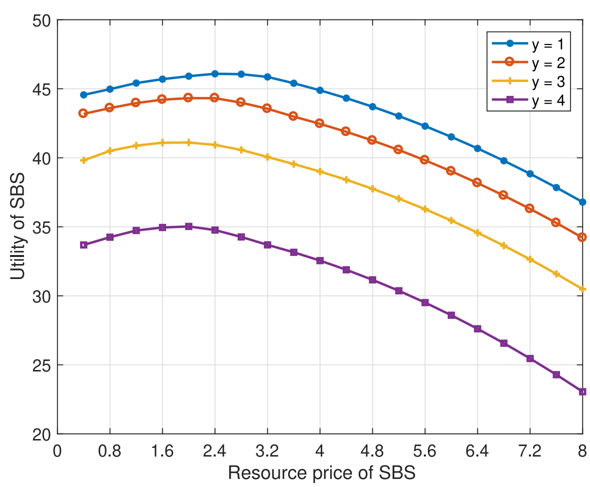

Fig. 9. Utility of user versus resource price of SBS.

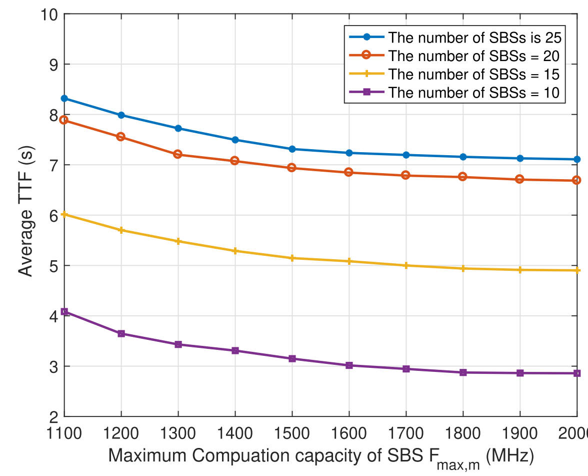

Fig. 10. Average TTF versus computation capacity.

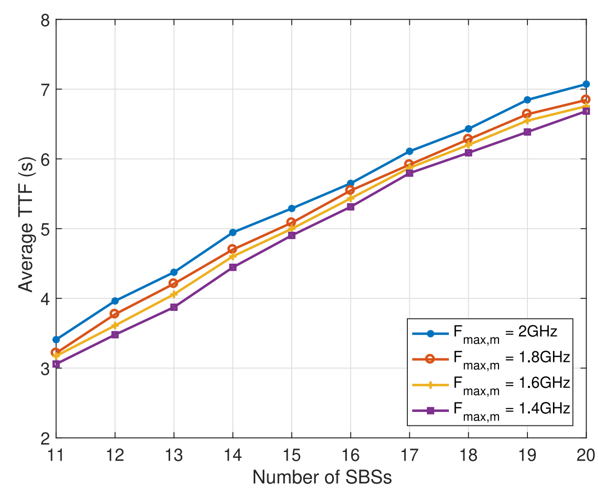

Fig. 11. Average TTF versus the number of SBSs.

price is, the lower utility of user will be. Fig. 8 shows that all the curves gradually go up to a peak and then go down with the increase of video price. Although the VP can gain high revenue with higher video price, the users may choose a low quality of video contents to save money and the VP may get lower revenue. As shown in Fig. 9, it shows that all the curves gradually go up to a peak and then go down with the increase of resource price. Similarly, with the increasing resource price, the users and the VPs may reduce their requirements of resource, and then the revenue of SBS has to decrease gradually.

Figs. 10–11 show that the average TTF versus maximum computation capacity and the number of SBSs, respectively. With the increasing computation capacity of SBS, the average TTF decreases gradually as shown in Fig. 10. The reason behind is obvious that SBSs can generate or validate blocks much faster with stronger computation capabilities. Another observation is that the average TTF becomes higher with the increasing number of SBSs. As the number of validators (SBSs) increases, it is obvious that the block validation process takes more time to definitively validate a block, which is why average TTF is increased. Similar observations can be made from Fig. 11: the average TTF increases gradually with the increasing number of SBSs.

B. The Effectiveness of Proposed Video Transcoding Approach

We select three typical schemes for comparison as follows: 1) the no-caching scheme, where SBSs without caching deliver video file from the video provider, as labelled as “No caching”; 2) the no-transcoding scheme, where SBSs cache some video files but cannot transcode these videos into multiple bitrate versions on the fly, as labelled as “No transcoding”; 3) the no-blockchain scheme, where the video files of VP cannot be delivered directly to the users via SBSs with MEC servers. These contents have to be uploaded to central servers which manage the video contents in a centralized manner. For the fairness of comparison, each scheme adopts the same simulation parameters as Table II .

1) The QoS Performance of Users: We evaluate the user' QoS regarding the average access delay which includes the transmission delay, transcoding delay, and backhaul delay [25]. We consider that the users can enjoy the videos after paying for the video services to the blockchain regardless of the block

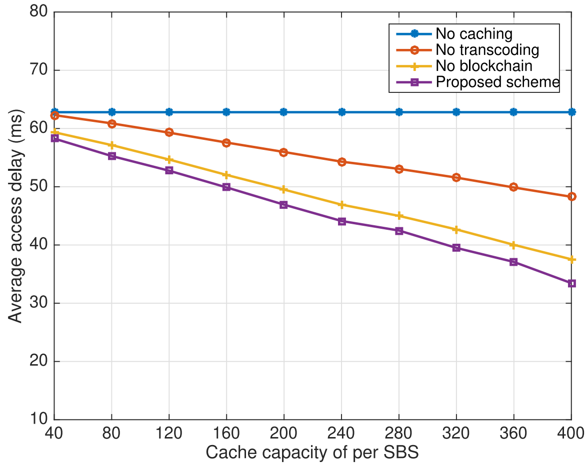

Fig. 12. Average access delay versus cache capacity.

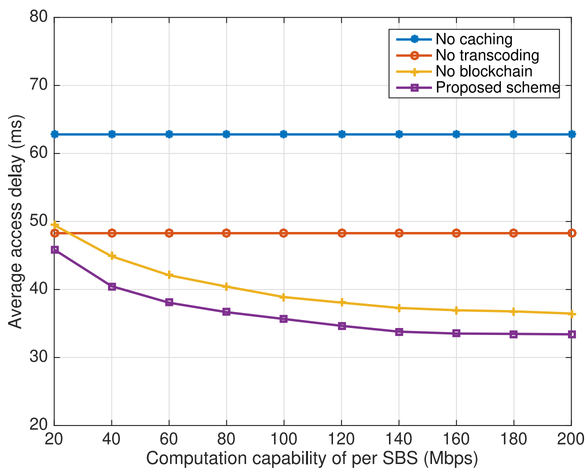

Fig. 13. Average access delay versus computation capability.

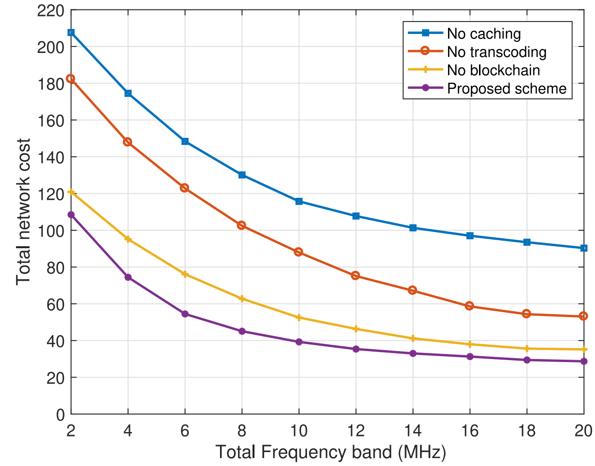

Fig. 14. Total network cost versus the frequency band.

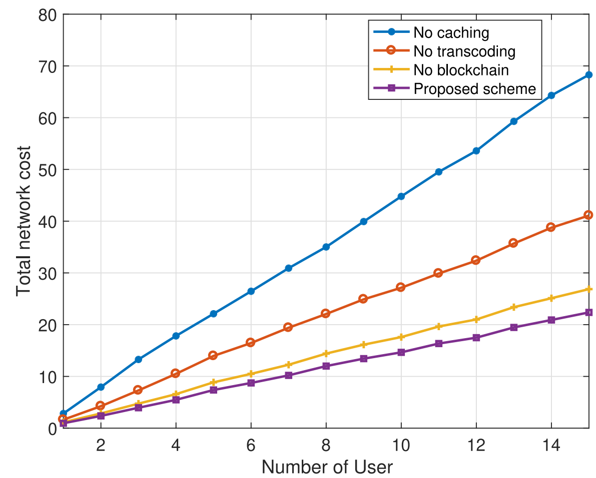

Fig. 15. Total network cost versus the number of user.

appending to the blockchain. If the transaction is fraudulent, corresponding penalty mechanisms would punish the fraud nodes (users, VPs, and SBSs) and records the information on the blockchain. Thus, the transaction delay is ignored in this paper. Fig. 12 illustrates the average access delay with the various cache capacities of SBSs. Except for "No caching" scheme, the average access delays of the other schemes decrease with the increase of cache capacities of SBSs. By transcoding and delivering the videos at SBSs in a distributed and parallel manner, the proposed approach achieves better performance. On the other hand, as shown in Fig. 13, it shows that the average access delay decreases with the increment of computing resources of SBSs by using transcoding methods. Since the required videos are cached at the SBSs exactly or forwarding to the remote VP, the "No transcoding" scheme keeps unchanged with the various computing resources. The "No caching" scheme which delivers videos from remote VP also keeps unchanged. Lastly, without leveraging blockchain technology, VPs have to upload their videos to the central server which processes the video requirements of users in a centralized manner. In this way, "No blockchain" scheme suffers longer delay compared with the blockchain-based video sharing solution.

2) The Performance of Total Network Cost: The total network cost plays an important role in optimizing network performance and improving resource utilization [42]. To evaluate the performance of network cost, we adopt network cost modelling in [26], which considers energy consumption for video transmission and transcoding as well as blocks generation and validation. As shown in Fig. 14, it can be seen that the total network cost of our proposed approach is lower than other schemes. We can also see that all the curves decrease gradually with the increasing of the frequency band. The reason is that the spectrum allocation strategy has a significant influence on optimizing the transmission rate of users. The adequate spectrum resource may reduce the transmission delay as well as the network cost significantly. From Fig. 15, we can find that the total network cost increases with the increment of the number of users. The total network cost of the "No caching" scheme is the highest compared with other schemes. The reason is that, on one hand, by applying caching, the SBS can transmit directly without fetching from remote VP via backhaul links. Hence, duplicate video transmissions are reduced, and fewer backhaul resources are needed to provide. Therefore, the total network costs of the other schemes are lower than the "No caching" scheme.

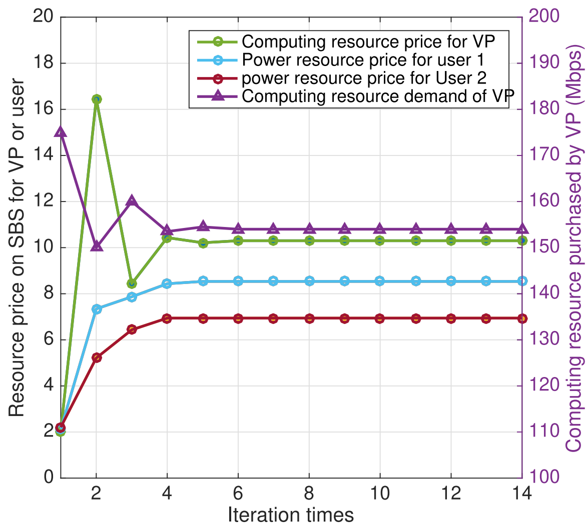

Fig. 16. Convergence of the three-stage Stackelberg game.

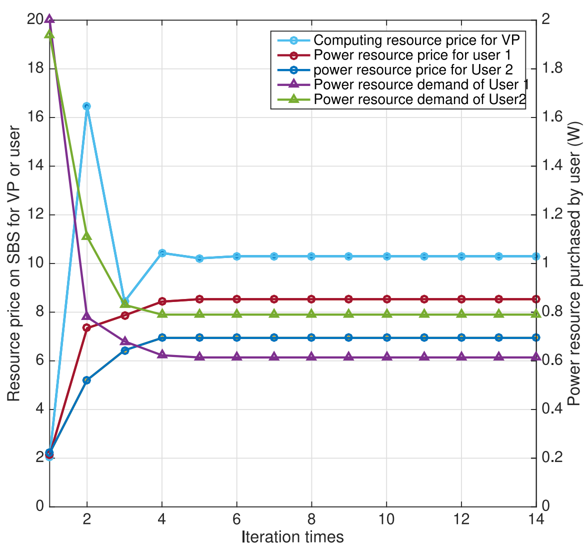

Fig. 17. Convergence of the three-stage Stackelberg game.

On the other hand, by leveraging MEC technology, the SBSs can transcode the original video into different quality levels of videos effectively. As such, the duplicated video transmission is further reduced and less backhaul resource is needed, and then, lower network cost will be. Lastly, by leveraging blockchain technology, the proposed approach has the lowest network cost since the VPs can share their video to users directly rather than uploading the video files to centre servers in wireless networks.

C. Convergence of the Proposed Game Approach

This subsection analyzes the convergence of the Stackelberg game. For ease of illustration, we take a simple scenario with one SBS and two users into account. As shown in Figs. 16 and 17, we can find that the resource prices of SBSs and the computing and power resources demands of the VP and users converge quickly. Also, it can be seen that the higher resource prices are, the lower resource demands will be.

VI. Conclusion and Future Work

In this paper, we investigated the video transcoding and delivery problem in blockchain-based MEC networks. We proposed a blockchain-based MEC network architecture, where SBSs utilized their computation as well as communication resources for providing video streaming in a distributed and secure manner. Then we envisioned several small smart contracts to build a self-organized video trading market, where all participants (i.e. VPs, SBSs, and users) were enforced by smart contract terms. Furthermore, we formulated the video transcoding and delivery problem as a three-stage Stackelberg game. The sub-game equilibrium for each stage and the interplays of the three-stage game were analyzed and an iterative algorithm were proposed to solve the problem. Simulation results show that the proposed approach gains better performance compared with other existing schemes. In future work, we will investigate the security issues regarding the malicious consensus nodes in blockchain to enhance the security by taking some reputation and contracts theory into consideration. Moreover, we will discuss the blockchain-based video streaming services in vehicular networks.

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